SKAGIT COUNTY DEPARTMENT OF PUBLIC WORKS

Skagit River at The Dalles looking upstream from The Dalles bridge, 7 November 2006 (120,000 cfs)

RE-EVALUATION OF THE MAGNITUDE OF HISTORIC FLOODS ON THE SKAGIT RIVER NEAR CONCRETE
REVISED FINAL REPORT

MARCH 2010

nhc northwest hydraulic consultants

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REVISIONS

May 2009
The original final report for this work was issued on 30 October 2008. The May 2009 revision incorporates minor edits to more fully reflect uncertainty in the December 1921 high water elevation at the Upper Dalles gage.

March 2010
A new Section 2.0 was added to discuss the basis for the slope-area measurements of the December 1921 flood. Minor changes were made to the text to discuss new information provided since May 2009. Additional work was done on the hydraulic model to demonstrate the robustness of model results.

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1.0 INTRODUCTION

The principal purpose of this report is to provide a re-evaluation of the magnitude of historic floods on the Skagit River near Concrete (USGS gage 12194000). The report also proposes revised unregulated flood quantiles based on our re-evaluation of historic flood magnitudes. The report has been prepared for Skagit County Public Works to submit to the Federal Emergency Management Agency, the United States Geological Survey and the United States Army Corps of Engineers, for the purpose of improving confidence in the estimates of the magnitudes of historic floods and unregulated flood quantiles.

Current estimates of design flood quantiles on the lower Skagit River are influenced to a large degree by the magnitude of historic floods which occurred in 1897, 1909, 1917 and 1921 (water years 1898, 1910, 1918 and 1922). The estimated peak discharge for the flood of 13 December 1921 is of particular importance since that estimate provides the basis for the estimated magnitudes of the other events.

The peak discharge for the 13 December 1921 flood was determined by J.E. Stewart at the location of the Skagit River near Concrete gage by means of indirect discharge measurements. Field investigations were conducted in late 1922 and early 1923 to identify and survey high water marks and channel cross-sections. Using these data and an assumed channel roughness, three slope-area measurements were made for a reach of the Skagit immediately below The Dalles and one contracted-opening estimate was made at The Dalles[1]. The average of those four measurements (240,000 cfs) was published as the peak discharge.

Stewart's original estimate of the December 1921 peak discharge of 240,000 cfs has been the subject of several reviews by the USGS including, most notably, n-verification studies in the early 1950s and in 2005 (Mastin and Kresch, 2005), and a re-evaluation in 2007 (Mastin, 2007). The 2007 re-evaluation of the 1921 peak discharge resulted in a downward adjustment to the currently-published magnitude of 228,000 cfs and a corresponding reduction in the estimated magnitude of the other historic floods. This adjustment relied on an n-verification study using data from the flood of November 1949 and a more sophisticated computational approach than used by Stewart.

The agency reviews of the 1921 peak discharge measurement conducted to date, appear to have focused on three main points:

- the appropriate channel roughness (Stewart's original slope-area measurement relied on the estimated channel roughness for the Skagit River near Sedro Woolley, approximately 30 miles downstream from Concrete);

[1] The contracted-opening estimate is no longer used because of uncertainty.

- selection of the most appropriate reach for the slope-area measurement; and,
- refinements to the computational approach.

Very little if any attention seems to have been paid to the reliability of or uncertainty in Stewart's high water marks which are the fundamental basis for the slope-area measurements.

The work described in this report discusses uncertainty in the slope-area measurements which provide the basis for the currently published historic peak discharges and then describes an alternative approach to estimating the 1921 peak discharge by means of hydraulic modeling.

We note that neither the US Army Corps of Engineers nor FEMA have a mechanism for explicitly accounting for uncertainty in historic discharge measurements.[2] Further, we interpret the Corps risk-based approach to flood damage reduction (see ER1105-2-101) as requiring use of best estimates of data values rather than values which are inherently conservative. As will be shown in this report, hydraulic modeling provides strong indications that the currently published magnitude of the December 1921 historic flood is conservatively high, despite the downward adjustment made by the USGS in 2007 (Mastin, 2007).

The focus of hydraulic modeling in this report is on use of high water information from the Town of Concrete to provide alternative estimates of the magnitude of the December 1921 flood (and by association the magnitudes of the earlier historic events). The approach adopted was to identify high water information for the December 1921 flood between The Dalles and Concrete and to develop a hydraulic model of this reach (building on and refining a pre-existing USACE model), which could then be used to estimate the peak discharge consistent with the available high water data. Advantage is taken of a contemporary newspaper report on first-hand observations of flooding in Concrete as well as high water measurements surveyed by Stewart between The Dalles and Concrete. None of this information has been previously used in federal agency estimates of the December 1921 peak discharge.

It is recognized that hydraulic modeling as presented here has inherent uncertainties. However it is our position that uncertainties in hydraulic modeling should be weighed against uncertainties in the slope-area measurements when evaluating the magnitude of the 1921 event and that the full body of available of information should considered.

[2] Confidence limits applied to the Corps flood frequency analyses do NOT account for uncertainty in discharge measurements.

2.0 UNCERTAINTY IN SLOPE-AREA MEASUREMENTS FOR THE DECEMBER 1921 FLOOD

The slope-area measurements for the 1921 peak discharge are based on high water marks and river cross-section surveys for the reach of the Skagit River below The Dalles shown in Figures 1 and 2. Stewart's slope-area measurements were conducted for reaches XS1-XS2, XS2-XS3 and XS1-XS3, between river miles 53.17 (XS-3) and 53.94 (XS-1), as also shown on Figure 6. Due to adverse hydraulic conditions in reach XS1-XS2, the most recent work by Mastin (2007) relies solely on Stewart's data for the reach XS2-XS3.

High water marks (HWMs) for the December 1921 flood were identified by Stewart in field work conducted from mid-November 1922 through early 1923, a year after the flood. Stewart provides very few details on the nature of the HWMs in the reach below The Dalles used for the slope-area estimates. From information in his 1922/1923 field notes, the HWMs in this reach all appear to be natural indicators such as "moss scoured off of tree" (Stewart 1922/1923 field book, page 79). There is no indication that Stewart was able to tie any HWMs in this reach into eye witness reports of flood levels. We know from experience that identification of HWMs from natural indicators one year after a flood can be very uncertain. For example, for the same reach of the Skagit below The Dalles, the USGS had difficulty in identifying reliable HWMs from the October 2003 flood in field work conducted nine months after the event (Mastin and Kresch, 2005). In that case, the scatter in HWMs at any particular location was as much as 6 feet.

Stewart's HWMs are documented in his 1922/1923 field book and in a collection of loose notes provided by USGS Tacoma; cross-section survey data are provided in the 1922/1923 field book; and slope-area calculations are provided in an unpublished 1923 report (Stewart, 1923). The 1923 report shows the assumed water level fall between cross-sections and the hydraulic properties at cross-sections (cross-sectional area, wetted perimeter, etc), however it should be noted that there is no clear tie between the field-surveyed HWMs and the actual calculations.

The available HWMS are summarized in Table 1 and the HWMs along with the water surface profile assumed by Stewart, as inferred from the 1923 report, are shown in Figure 3. The data are shown relative to the Stewart's Lower Dalles gage (located on Figure 2), as in the original field notes, with HWM elevations also shown to NGVD29[3] assuming a Lower Dalles datum of 142.84m (Stewart [field book page 67] reports a Lower Dalles datum of 141.04 MSL – see discussion of datum discrepancy in Section 3.2). HWM data pertinent to the slope-area reach are only available from 7 locations between the Lower Dalles gage and XS-2. No data are available to provide absolute HWM elevations between XS-2 and XS-3 (Stewart's field book [page 79] includes a high water mark at the lower end of his slope-area reach, but only provides an elevation to an arbitrary datum).

[3] All elevations in this report are to NGVD 1929 unless otherwise stated.

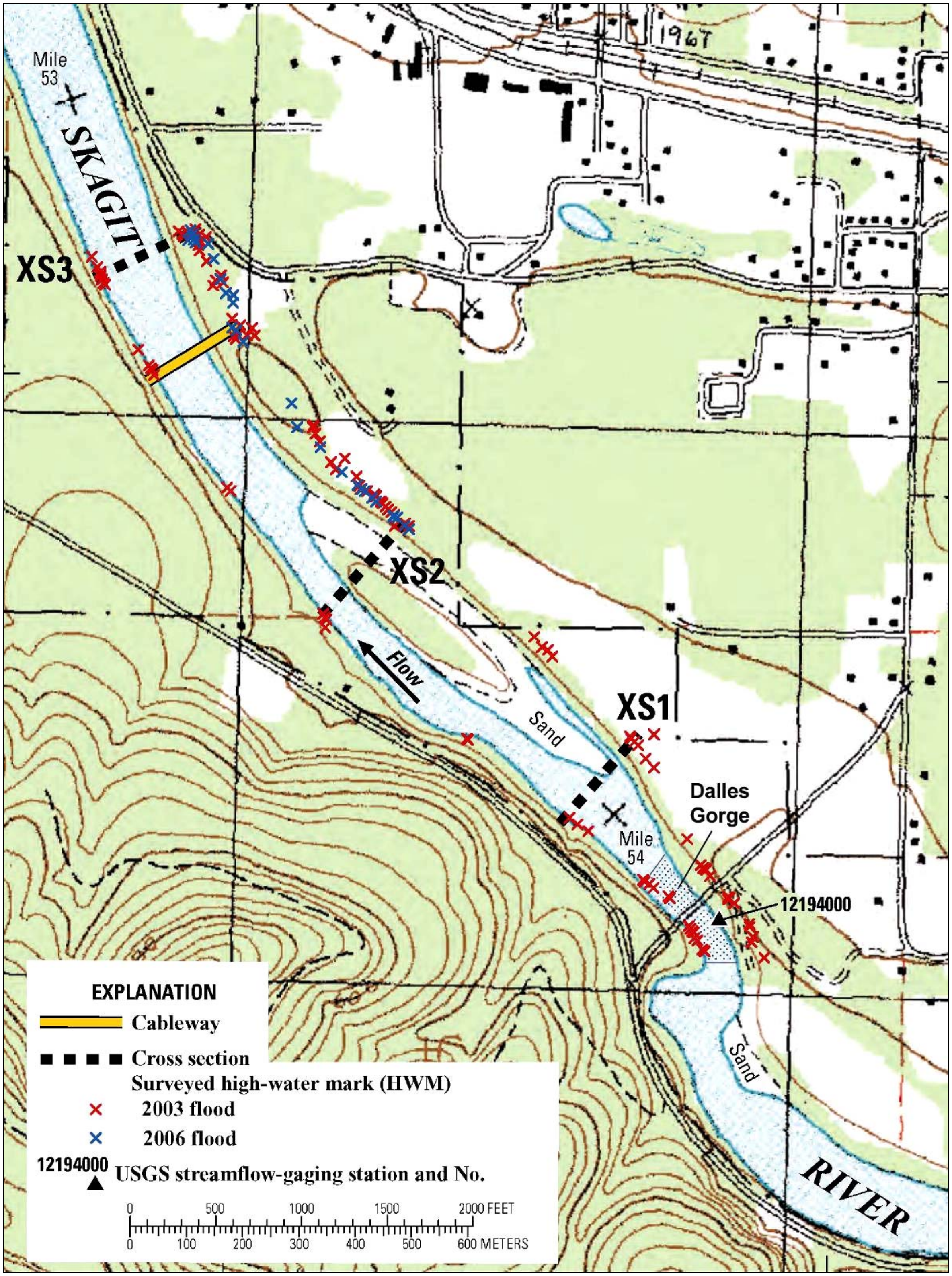

Figure 1. Topographic map of the slope-area measurement reach on the Skagit River near Concrete. (Source: USGS SIR 2007-5159)

Figure 2. Location map of slope-area reach

Table 1: Summary of 1921 High Water Marks

Station (ft relative to Lower Dalles gage)	HWM Elevation (ft, Lower Dalles datum)	HWM Elevation (ft, NGVD29)
0+00	30.00	172.84
5+25	29.68	172.52
8+65	29.06	171.90
9+85	30.37	173.21
15+25	28.62	171.46
20+90	28.40	171.24
24+70	28.97	171.81

Notes: Elevation to NGVD assumes Lower Dalles gauge datum of 142.84 m.

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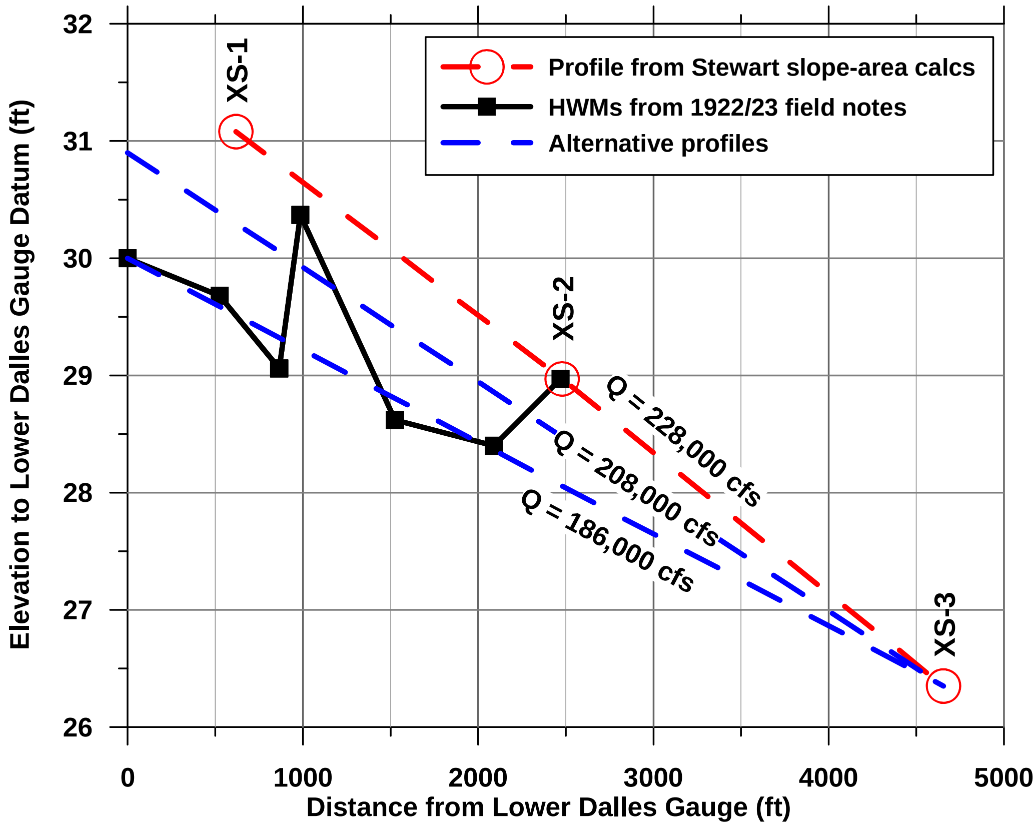


Figure 3. Stewart's 1921 HWMs and water surface profile used in slope area calculations

The profile in Figure 3 for Stewart's slope-area calculations (showing the current peak discharge estimate of 228,000 cfs) is assumed for the purposes of presentation to pass through the HWM at XS-2. The slope of the profile is based on the fall between XS1 – XS2 (2.11 ft) and between XS2 – XS3 (2.62 ft) as used in both the 1923 calculations and in the recent reevaluation by Mastin (2007) for an average slope of 0.0012. Also shown on Figure 3 are two alternative interpretations of water surface profiles (slopes of about 0.001 and 0.0008) and corresponding approximate discharges (208,000 cfs and 186,000 cfs).

It is not known how Stewart determined the 1921 water surface profile or the falls between cross-sections which are critical to determination of discharge. Any interpretation of the data is hampered by the lack of 1921 HWMs between XS2 and XS3, this being the reach relied on by the USGS (Mastin, 2007) for recomputation of the 1921 peak discharge.

High water marks in the slope-area reach are available for two recent fairly large events: October 2003 (peak discharge 166,000 cfs) and November 2006 (peak discharge 145,000 cfs). The HWMs for October 2003 were identified and surveyed in the field almost one year after the event and show such scatter that a water surface profile cannot be defined with confidence for that event. HWMs for the November 2006 event were staked on the right bank of the river by NHC within a few hours of the peak and subsequently surveyed by Skagit County (see cover photo taken during this field investigation). These 2006 HWMs and the 1921 HWMs are plotted in Figure 4, along with an estimated water surface profile for the 2006 event. HWMs for this event were also determined for reach XS2-XS3 by the USGS about two weeks after the event and are shown in Figure 2 of SIR 2007-5159.

The November 2006 profile shows a break in slope at about station 31+00 (point 162), with a slope of about 0.0016 upstream from that point, and 0.00076 downstream. The break in slope coincides with the downstream end of the large right-bank gravel bar/island (see Figures 1and 2) which is now forested but which, based on a 1937 aerial photograph (see Figure 11), is assumed to have been bare in 1921. Under current conditions, the bar is believed to be inundated at a flow of about 80,000 cfs.

While the water surface profile for the November 2006 flood is well defined, it provides little guidance for interpretation of the 1921 HWMs. Stewart's slope-area calculations for reach XS2-XS3 assume a water surface slope of 0.0012 compared with a slope of 0.00076 from the November 2006 data downstream from the gravel bar. USGS interpretation of its 2006 data (relying only on HWMs between XS2 and XS3) shows a slope of 0.00114. There is clearly considerable scope for uncertainty in the slope area measurements which strongly suggest that alternative approaches to estimation of the peak should be considered.

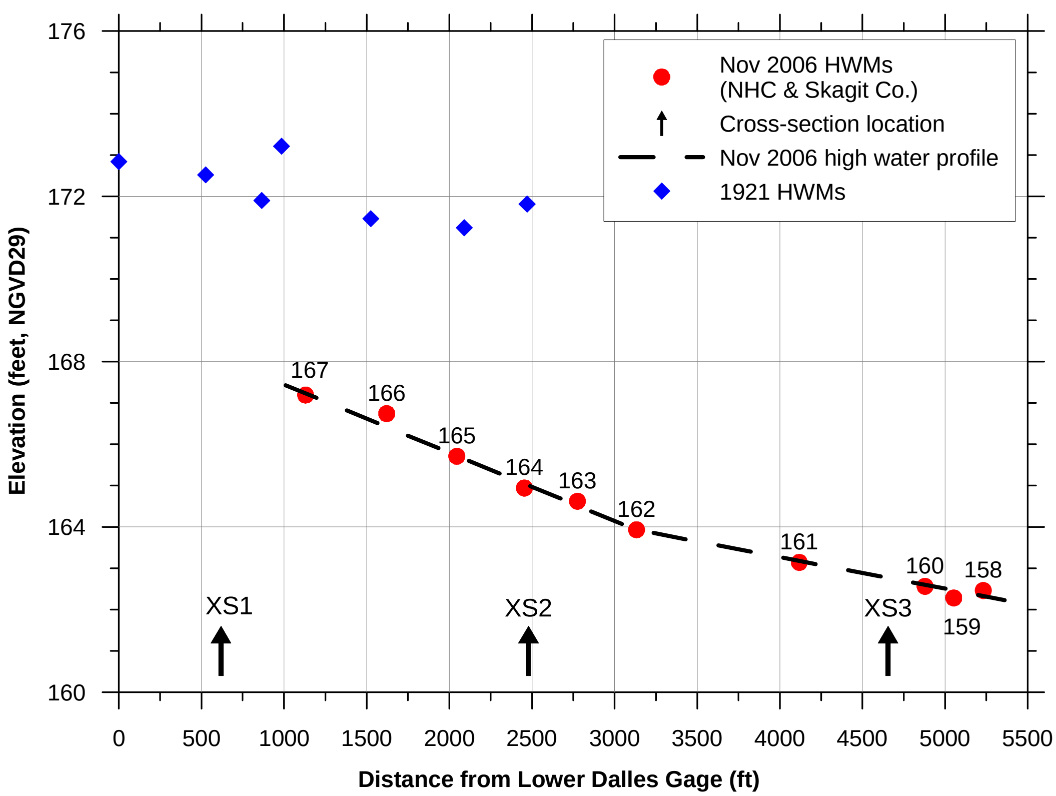


Figure 4. November 2006 and December 1921 HWMs

3.0 DETERMINATION OF 1921 HIGH WATER ELEVATIONS BETWEEN CONCRETE AND THE DALLES

3.1 Interpretation of Concrete Herald Report

The 13 December 1921 flood was the main story on the front page of the 17 December 1921[4] issue of The Concrete Herald, with office and print plant in Concrete. With regard to the situation in the immediate vicinity of Concrete, the relevant paragraph, which would have been based on first-hand observations, reads as follows:

> *About three o'clock in the afternoon it [i.e. the Skagit River] went over the banks in Crofoot addition and the residents of that part of town began to move out, being taken care of at the homes of friends in the higher part of town until the flood subsided. The waters also crept up around some of the dwellings in East Concrete, and some of the residents moved out for the night. In Crofoot addition only three residences remained above the high water mark, the water being to a depth of an inch to 14 inches in the others. No particular damage was done, except for small articles outside being washed away, and the job of cleaning out the mud left by the flood. The Vlist, Milton and Hempsenyer families lost a considerable number of chickens and several loads of wood were washed away. In East Concrete practically no damage was done.*

and on an inside page of the same issue:

> *Dick Williams was very busy with his canoe Monday evening taking residents of Crofoot's addition to their dwellings during the height of the flood.*

The Crofoot Addition is that area of Concrete in the Skagit and Baker River floodplains south of the present alignment of SR-20 and immediately west of the confluence of the Baker and Skagit (see Figure 5). East Concrete is in the floodplain immediately east of the Baker River.

[4] The Concrete Herald was a weekly newspaper at the time of the December 1921 flood.

Figure 5. Crofoot Addition of Concrete and East Concrete, WA (2001).

In making use of the Concrete Herald report, we face a couple of problems:

- are the depths of water quoted, depths in living spaces, or in crawl spaces and basements?
- how can depths of water be most reliably translated into water surface elevations?

In determining whether depths of water are depths above finished floor levels (i.e. in living spaces) or depths in basements and crawl spaces, we have to recognize some potential inconsistencies in the Concrete Herald report:

"No particular damage was done, except for small articles outside being washed away, and the job of cleaning out the mud left by the flood". In a present day context with interior walls clad

with sheet rock, with interior furnishing such as fitted carpets, and with basements and crawl spaces occupied by furnaces and water heaters, etc., even a few inches of water above finished floor levels could result in considerable damage. Given that "no particular damage" was done, this would suggest that the reported depths were depths of water in basements or crawl spaces and not depths above finished floor. However in 1921, these houses probably had few fixed interior furnishings, interior walls were sheathed with wood (or perhaps in some cases lathe and plaster), and there may have been no below-floor electrical or mechanical equipment. Shallow flooding above finished floor level in 1921 might therefore be expected to have resulted in little damage. Further, it seems unlikely that anyone would spend time *"cleaning out the mud left by the flood"* if the flood waters were confined to basements and, more particularly, crawl spaces. A flood depth of 14 inches (the maximum reported) over a short duration would not in any case be expected to leave anything more than a fine dusting of silt (as seen after the 2003 flood), which again is unlikely to have warranted the cleaning of basements and crawl spaces. As a final point, crawl spaces in the houses visited in the course of the recent investigations have variable heights, with ground elevations in at least one of the crawl spaces inspected varying by more than a foot. The precision of the reported flood depths (an inch to 14 inches) seems to be inconsistent with the varying depths of water that would be expected in crawl spaces.

In investigations by the City of Burlington on 3 April 2008, portions of the exterior siding were removed from several houses in the Crofoot Addition in an attempt to identify water marks from historic flooding in the wall cavities. There was no visual evidence of high water marks in the wall cavities of any of the houses examined. It was hoped that the absence of water marks would provide evidence that water levels in 1921 did not exceed finished floor levels. An outstanding issue in use of this approach has been in determining what a high water mark from 1921 would look like 86 years after the fact. There is photographic evidence that a business at 612 Fairhaven Avenue in downtown Burlington was flooded in December 1921. Sections of original interior lathe and plaster wall were cut from this building during investigations by the City of Burlington on 19 March 2008. It had been hoped that the sections removed would show a clear high water line. No such line was found. The vertical studs to which the lathe was nailed showed some subtle marks that might have been caused by high water, but the evidence is far from conclusive. There was no visual evidence of high water marks on the lathe itself. In the absence of high water marks from the Fairhaven Avenue building (or any other information on what to expect from a 1921 high water mark), the absence of high water marks in the Crofoot Addition provides no reliable information on water levels in 1921. Wood samples from the Fairhaven Avenue and Crofoot investigations were further examined by the firm of Wiss, Janney, Elstner Associates, Inc. (WJE) for the City of Burlington in an attempt to establish an upper bound on flood levels in Crofoot. Their findings were also inconclusive.

At present, there is no conclusive evidence to demonstrate whether the reported December 1921 flood depths in the Crofoot Addition were above or below finished floor levels. However, in our opinion, considering all the information currently available, we believe that the flood depths reported in the Concrete Herald were most likely depths **above** finished floor level.

The lowest existing residence dating from 1921 that has been identified in the Crofoot Addition is 45956 Albert Street, with a finished floor elevation of 184.93 feet NGVD 1929[5]. According to the Skagit County Assessor's records, this house was built in 1912. It is possible that other lower residences existed in 1921 that have since been demolished, or otherwise modified, but we have no way of either identifying such residences or of determining their elevations. Assuming the maximum reported depth of water of 14 inches was above the finished floor level at 45956 Albert Street, gives a maximum December 1921 water surface elevation in the Crofoot Addition of at most 186.1 ft. The only house dating from 1921 in East Concrete for which we have a finished floor elevation is 46335 Forest Place at 186.61 ft. Visually, this house appears to be one of the lowest, if not the lowest, house dating from 1921 in East Concrete. From the FIS (Federal Emergency Management Agency, 1989), the head loss between Crofoot and East Concrete is roughly 0.5 feet at a discharge of 226,000 cfs (the currently published 1921 peak discharge is 228,000 cfs), which would put the December 1921 water level at 46335 Forest Place essentially at the finished floor level. This is inconsistent with the statement in the Concrete Herald article that the *"waters also crept up around some of the dwellings in East Concrete"*, so the estimated 1921 peak water level of 186.1 ft. in the Crofoot Addition is probably high. Nevertheless, we have taken the estimate of 186.1 ft NGVD 1929 as the best estimate of high water level in the Crofoot Addition in the December 1921 flood and the basis for estimating the December 1921 peak discharge in Section 4.0 of this report.

3.2 Interpretation of Stewart's Field Notes

This section examines information from Stewart's 1922/23 field book on high water marks between Concrete and The Dalles, with emphasis on estimation of the maximum water surface elevations in the 13 December 1921 flood.

We surmise that Stewart installed two staff gages at The Dalles in December 1922 – referred to in Stewart's field book as the Upper Dalles Gage and the Lower Dalles Gage. The gage locations, as inferred from Stewart's notes, are shown on Figure 2. The Upper Dalles gage consisted of a vertical upper section and a lower elevation inclined gage. Stewart's notes (page 34/35) for 23 December 1922 refer to *"placing foot graduation marks on inclined gage"*.

The Upper Dalles gage is referred to in USGS WSP 552 (Surface Water Supply of the United States 1922), which describes the "Skagit River at The Dalles, near Concrete" gage as follows:

> *Vertical and inclined staff on right bank installed December 23, 1922.*

[5] Surveys were conducted by Skagit County.

Stewart's field notes include details of surveys which establish a zero datum for the Upper Dalles gage.

Pages 22/23 and 30/31 of Stewart's notes both record data from surveys starting at a USGS bench mark with elevation 230.51 ft MSL. The elevation for this benchmark is to mean sea level and appears to have been determined through surveys conducted by the USGS, most likely in 1898. The benchmark is described in USGS Bulletin 674 (Spirit Leveling in the State of Washington 1896 to 1917, inclusive) as follows:

> *Baker[6], 0.25 mile west of, at bottom of hill, 40 feet north of fence corner, 50 feet north of road, in granite boulder; copper bolt stamped 231 T.U.L."*

The field book on page 22/23 under the heading "Levels at Concrete", and dated 28 November 1922, refers to measuring down from a point on a freight car to the rail below, noted as being 300 ft below the depot. From this point, the survey route has a total of 6 turning points to a *"1921 flood mark at Wolfs Residence"* at an elevation 184.55 ft MSL. According to research by the City of Burlington, Wolf owned several parcels of land in or near to the Crofoot Addition of Concrete. While we do not know exactly where Wolf's residence was, we assume that this flood mark provides a reasonable estimate of the 1921 high water elevation in the Crofoot Addition.

A similar survey recorded on pages 30/31 and 32/33 of Stewart's notes was conducted on 22 December 1922, again apparently crossing the rail track and then proceeding through 6 turning points to a *"1921 HW at Wolfs residence"* of 184.53 ft MSL. The survey then continues through a further 11 turning points to what was evidently a temporary bench mark consisting of a spike in a maple tree on the *"side of road going to old ferry about 100 yds from end of ferry road 60 or 70 ft downstr from gage"*.

The gage referred to here is believed to be a pre-existing staff gage associated with the ferry crossing. The Corp's 1911 survey of the Skagit River shows a "ferry cable" and "River Gauge" approximately 5,000 ft below the confluence of the Skagit and the Baker; this is believed to be the location referred to by Stewart.

Stewart's notes (pages 84/85) for 27 January 1923 establish a zero elevation of 150.58 ft MSL for the gage at the old ferry crossing and reports a 1921 high water on the gage of 32.0 ft for an absolute maximum water surface elevation for the December 1921 flood of 182.58 ft MSL. Stewart's source for the high water reading on the gage is not stated in his notes, and we do not know whether the reported 32.0 ft gage reading was taken by others at the time of the flood or whether it was a high water mark observed by Stewart at the time of his survey.

[6] Baker was incorporated as the Town of Concrete in 1909.

While we do not know the precise locations of the USGS benchmark, Wolf's residence, or the "old ferry", we believe that we can infer their approximate locations from the above information with sufficient confidence to provide useful data for evaluating hydraulic model results given the relatively modest water surface slope in the vicinity of the Crofoot Addition (of the order of 0.0005 during flood conditions).

From the ferry crossing, Stewart (pages 84/85 and 86/87) continued his 22 December 1922 survey to the Upper Dalles gage, establishing a gage zero elevation of 140.89 ft MSL and surveying a gage height of 34.29 ft from a previously identified 1921 high water mark. Later, Stewart found a higher flood mark and adjusted the maximum gage height for December 1921 to 34.86 ft, resulting in a 1921 high water elevation of 175.75 ft MSL. Stewart subsequently extended his survey to the Lower Dalles gage, with a gage zero elevation of 141.04 ft.

USGS WSP 612 (Surface Water Supply of the United States 1925), reporting stream flow data from September 15, 1924 to September 30, 1925, describes the Skagit River near Concrete gage as follows:

> *Since December 10, 1924, Stevens continuous recorder in concrete shelter, on right bank at The Dalles. Gage used prior to December 10, 1924, was vertical and inclined staff on right bank about 200 feet above present gage. Both gage readings refer to same datum, 163 feet above sea level.*

According to 1925 gaging station notes, the gaging station was constructed during the fall of 1924. The gage datum of *"163 feet above sea level"* is clearly incorrect. We assume that for the purposes of the WSP, the USGS simply estimated an elevation from available topographic maps instead of relying on detailed surveys. Importantly, WSP 612 notes that *"both gage readings refer to same datum"*.

Evidence to support the statement that "*both gage readings refer to the same datum*" can be found in USGS discharge measurement notes from 16 September 1924 and "Level Notes" from 6 April 1932, provided by USGS Tacoma. However these in our opinion are not conclusive. The 16 September 1924 discharge measurement notes for example show more or less identical gage readings at the Upper Dalles gage and at the *"recorder site"* (the measured discharge is reported as 5,740 cfs), but according to the 1925 station notes, gage construction at this site was *"during the fall"* of 1924 and the recorder was not installed until 10 December 1924.

We do not know when the USGS formally established a zero elevation datum for the current gage at The Dalles, however WSP 1527 published in 1961 provides the following description:

> *Water stage recorder. Datum of gage is 130.0 ft above mean sea level, datum of 1929. Dec.10, 1924, to Oct. 27, 1937, water-stage recorder at present site, at datum 12.69 ft higher.*

This implies a gage datum for both the original stage recorder installed in 1924 and Stewart's Upper Dalles gage (assuming the statement that the gages are on the same datum is correct) of:

130.0 + 12.69 = 142.69 ft NGVD 1929.

The zero datum for the current gage of 130.0 ft NGVD29 has been confirmed in surveys conducted by Skagit County and the USGS (Bob Prater, Skagit County, personal communication, 2008). We therefore assume that the above figure (142.69 ft NGVD 1929) is correct, but note that it is inconsistent with Stewart's field notes which give a datum for the Upper Dalles gage of 140.89 ft MSL, a difference of 1.8 ft. It seems unlikely that the reason for the inconsistency can be fully resolved. Possible explanations could include:

- Vertical datum adjustments between 1898 (the year in which the USGS benchmark in Concrete appears to have been established) and NGVD 1929.
- Error in the elevation of the USGS bench mark in Concrete relied upon by Stewart.
- Error in Stewart's survey. (We note that Stewart did not perform closed loop surveys and the possibility of error in his work cannot be dismissed.)
- Error in the statement in WSP 612 that the Upper Dalles staff gage and the recorder installed in 1924 were on the same datum.

This datum inconsistency would also apply to Stewart's survey of the Lower Dalles gage datum. Stewart (field notes page 67) shows a gage zero elevation of 141.04 MSL; it appears that the correct datum for this gage may be 1.8 ft higher at 142.84 NGVD29.

Taking the current "official" gage datum as correct, then the December 1921 HWM elevations (to NGVD29) at the Upper Dalles gage, at the Wolf residence in Crofoot, and at the old ferry crossing could all be up to 1.8 ft higher than reported by Stewart. Note the currently published high water elevation for the December 1921 flood (gage height of 47.6 ft on a gage datum of 130.0 ft NGVD29) is 177.6 ft NGVD29, i.e. 1.8 ft higher than determined by Stewart.

Assumed high water elevations for the 1921 flood for the reach from The Dalles to Concrete, along with assumed locations for the Wolf residence and old ferry crossing, are summarized in Table 2. These points can be located (by River Mile) on the map of the study reach in Figure 6.

Table 2. December 1921 High Water Data – The Dalles to Concrete

Description	Location	1921 High Water Elevation (ft NGVD 1929)
Upper Dalles gage	RM 54.17	175.8 – 177.6
Old Ferry Crossing gage	RM 55.34	182.58 – 184.38
Wolf residence	RM 56.5	184.55 – 186.35
Crofoot (from Concrete Herald)	RM 56.35	Max 186.1

4.0 HYDRAULIC MODELING AND RE-EVALUATION OF 1921 PEAK DISCHARGE

4.1 Current Conditions

A 1-D steady-state HEC-RAS model was developed covering the reach of the Skagit from RM 51.1 (about 3 miles below The Dalles) to RM 56.77 (just above the confluence with the Baker River). As noted in Section 2, the slope-area measurements reach used by Stewart is just below The Dalles from RM 53.17 to RM 53.94. The model relied on the following cross-section data:

- in-channel and overbank sections from the 1976 FIS from RM 51.1 to RM 52.4
- in-channel sections from surveys conducted in October 2004 with overbank geometry from the 1976 FIS from RM 52.55 to RM 54.5
- ten new in-channel and overbank cross-sections surveyed by Skagit County in 2008 between RM 54.71 and RM 56.77

The study reach with cross-section locations and other points of interest, superimposed on a 2001 aerial photograph is shown in Figure 6.

As noted by others, hydraulic conditions through The Dalles are complex. The river takes two abrupt 90 degree turns immediately upstream from The Dalles gorge which results in flow reversal along the left bank just below the entrance to the gorge and considerable turbulence (see Figure 2 and the cover photo taken during field investigations on 7 November 2006 at a discharge of 120,000 cfs). The hydraulic conditions through the gorge are not well suited to hydraulic modeling and actual field conditions deviate considerably from the one-dimensional flow assumptions of the HEC-RAS model.

The fundamental hydraulic modeling problem is that of quantifying energy losses through The Dalles gorge. Uncertainty in energy losses through The Dalles has been one of the principal issues raised by the federal agencies in considering use of hydraulic modeling as an alternative to the slope-area measurement for determining the magnitude of the 1921 flood. In the modeling effort described here, we explicitly address uncertainty in energy losses through The Dalles and demonstrate that hydraulic model estimates of the magnitude of the 1921 flood are relatively insensitive to that uncertainty.

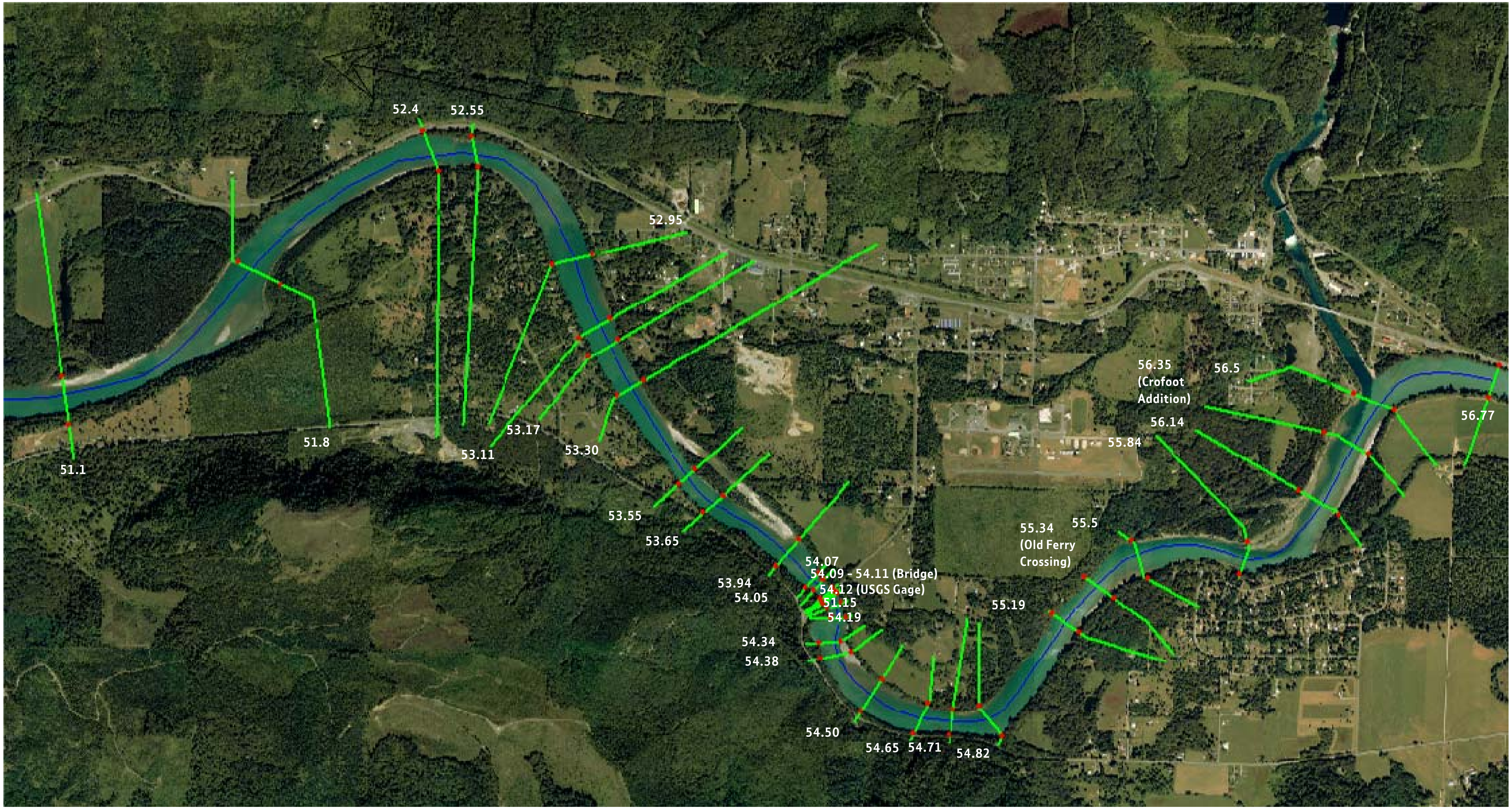


Figure 6. Schematic Plot of Study Reach with Cross-Sections and other Locations of Interest.

A current condition steady-state HEC-RAS model was calibrated against:

- a range of water levels and corresponding discharges taken from the current stage-discharge rating (Rating 6) for the USGS gage at The Dalles.
- peak water level and peak discharge data from the 21 October 2003 flood for two locations: the USGS gage site at The Dalles (peak discharge 166,000 cfs, peak water level 172.21 ft NGVD29), and the Jenkins residence in the Crofoot Addition (peak discharge 166,000 cfs, peak water level 182.65 ft NGVD29)[7].

Given the large scatter in other October 2003 HWMs surveyed by the USGS below The Dalles (Mastin and Kresch, 2005), no explicit attempt was made calibrate to these, however, attempts were made to adjust model parameters so that simulated water levels below The Dalles were in general agreement with the overall trend of the scattered HWMs.

Considerable difficulties were encountered in achieving a model calibration which both matched the USGS gage rating over a wide range of flows and which also reasonably matched the HWMs below The Dalles. Emphasis was given to matching the gage stage-discharge rating in preference to the HWMs below The Dalles. Sensitivity runs were later conducted to investigate the effects of apparent model deficiencies in the reach below The Dalles.

To achieve satisfactory modeling of flow through The Dalles and reproduction of the stage-discharge rating required introduction of high energy losses through this reach by specifying model parameter values outside their normal range. Three different approaches to modeling flow through The Dalles were investigated in detail:

- Use of high expansion and contraction coefficients through The Dalles. This increases energy losses wherever there are significant changes in cross-sectionally averaged velocity between cross-sections.
- Use of an ineffective flow area along the left bank from the entrance to The Dalles to just below the highway bridge to reflect the left bank flow separation and flow reversal downstream from the entrance to the gorge.
- Use of a high channel roughness for the left bank of The Dalles gorge to increase energy losses through The Dalles.

Of the three approaches investigated, the most promising results were obtained using increased expansion and contraction coefficients. Model results using the ineffective flow area option were found to be very sensitive to the location and extent of the ineffective area, and satisfactory reproduction of The Dalles stage-discharge rating could not be obtained using a physically

[7] Mr. Jenkins provided a photograph of his house at 7752 South Dillard Avenue taken on the morning following the October 2003 flood, clearly showing a high water line on the siding of the house. The elevation of the high water line was estimated from survey information obtained by Skagit County.

reasonable model configuration. Model results using increased left bank channel roughness were also problematic in that the composite channel roughness computed by HEC-RAS was felt to be unreasonable and, again, satisfactory calibration to The Dalles stage-discharge rating could not be achieved. The modeling approach finally selected for application in this study assumed large expansion and contraction coefficients through The Dalles. It should be stressed that in this application, the expansion/contraction coefficients simply provide a mechanism for imposing energy losses in the hydraulic model.

Model calibration was achieved by adjusting Manning's roughness and the expansion and contraction coefficients for the short reach through The Dalles gorge. Calibration was essentially performed in two steps: from the downstream end of the study reach at RM 51.1 to the present gage site; and from the present gage site to Concrete.

RM 51.1 – RM 54.12

From the downstream end of the study reach to the present gage site at The Dalles (RM 51.1 to RM *54.12*), in-channel roughness was determined by calibration as 0.030. Composite reach-averaged "n" values for the overbank were estimated assuming roughness ranged from 0.06 for open pasture to 0.20 for dense woodland. Overbank land cover conditions were determined from 2001 aerial photographs and from field work conducted since November 2006. Expansion and contraction coefficients were determined by calibration to ensure good reproduction of Rating 6 at the present gage site. The in-channel roughness and expansion/contraction coefficients are provided in Table 3 on page 20.

RM 54.15 – RM 56.77

Upstream from the present gage site, model calibration is complicated by lack of information on head loss between the gage site and the entrance to The Dalles.

Stewart's original Upper Dalles gage is reported to have been about 200 ft upstream from the present gage, but may have been as much as 300 ft upstream.[8] The drop in water level between the two gage sites has been the subject of limited discussion[9]. Mastin (letter to C. Martin, 10 February 2005) states that *"As the flows increase, the draw down through the gorge seems to begin further upstream somewhere upstream of the current gage location. The HWMs from the October 2004[10] peak flow, gage height of 42.14, showed a drop of 0.5 to 1.5 feet from the old site to the current gage site depending on which HWMs are chosen to represent the slope"*.

[8] Stewart's field notes (page 62) show "upper end of Dalles 695 ft above lower gage", or about 300 ft above the present gage, whereas various USGS publications (e.g. WSP 612), indicate that the Upper Dalles gage was about 200 ft above the present gage.

[9] Note that the published gage heights for the historic events are from Stewart's Upper Dalles gage and have not been corrected to account for the drop in water level between the Upper Dalles gage and the present gage.

[10] This is a typographical error – the event referred to is October 2003.

However an earlier memo by Flynn (internal USGS memo, 16 July 1954), in a discussion of historic flood peaks, states *"from the falls measured in the slope-area determination*[11]*, the fall between the two gage sites is probably on the order of 0.2 ft"*. There is clearly much uncertainty regarding head loss near the entrance to The Dalles which will only be resolved by field observations in future large floods.

From a hydraulic modeling point of view, the difficulty with the reach above the present gage site is that given the lack of reliable data on head loss through The Dalles, we cannot establish a unique, optimal model parameter set. High expansion and contraction coefficients in The Dalles affect the water surface profile as far upstream as Concrete, thus calibration to the 2003 high water mark in Crofoot involves a trade-off between expansion/contraction losses through The Dalles and channel roughness losses between the present gage site and Crofoot. In other words, calibration to the Crofoot HWM can be achieved either by using high expansion/ contraction coefficients in The Dalles in combination with a low in-channel roughness, or by using lower expansion/contraction coefficients in conjunction with a larger in-channel roughness.

In view of this uncertainty, two alternative representations of the reach from the present gage site to the upstream end of the study reach at RM 56.77 were developed, which we refer to as the "high expansion/contraction coefficient model" and the "low expansion/contraction coefficient model", with expansion/contraction coefficients and in-channel roughness above the gage site (i.e. upstream from RM 54.12) determined by calibration to the 2003 HWM in Crofoot. Overbank roughness was determined from examination of 2001 aerial photographs and field reconnaissance, as for the reach below The Dalles.

HEC-RAS model parameters for the two alternative current (2003) condition models are provided in Table 3. The calibrated water surface profiles from the two models for the October 2003 flood are shown in Figure 7, and the modeled stage-discharge relationship at RM 54.12 is compared with the published stage-discharge Rating 6 in Figure 8. Note that in Figure 7, the legend High EC and Low EC refer to the high and low expansion/contraction coefficient models respectively. Note also that for reference purposes, Table 3 also provides typical values recommended by the USACE (2008) for contraction and expansion coefficients.

The entrance to The Dalles gorge is at RM 54.19 with the next upstream cross-section at RM 54.34 being just upstream from the first of the two 90° bends above The Dalles. The expansion/ contraction coefficients in the two alternative current condition models bracket what we consider to be reasonable upper and lower limits on expansion/contraction losses in the approach to The Dalles and in the short reach of The Dalles upstream from the USGS gage (i.e. from RM 54.34 to RM 54.12).

[11] This refers to the slope-area measurement for the 1949 flood, which had a peak discharge of 154,000 cfs.

Table 3. HEC-RAS Current Condition Model Parameters.

Reach	Contraction Coefficient	Expansion Coefficient	In-Channel Roughness
High expansion/contraction coefficient model (High EC)			
RM 51.1 – RM 53.65	0.1	0.3	0.03
RM 53.94 – RM 54.05	0.3	0.5	0.03
RM 54.07 – RM 54.12	0.6	0.9	0.03
RM 54.15 – RM 54.34	0.6	0.9	0.028
RM 54.38	0.3	0.5	0.028
RM 54.50 – RM 56.77	0.1	0.3	0.028
Low expansion/contraction coefficient model (Low EC)			
RM 51.1 – RM 53.65	0.1	0.3	0.03
RM 53.94 – RM 54.05	0.3	0.5	0.03
RM 54.07 – RM 54.12	0.6	0.9	0.03
RM 54.15 – RM 56.77	0.1	0.3	0.033
Typical values for expansion contraction coefficients (USACE, 2008)			
Gradual transitions	0.1	0.3	
Typical bridge sections	0.3	0.5	
Abrupt transitions	0.6	0.8	

Note that the two alternative current condition models are identical below the present gage site at RM 54.12 and only differ above the gage site. The current condition models match the stage-discharge rating very well over a wide range of flows (Figure 8). The two current condition models also match the October 2003 water level in the Crofoot Addition (Figure 7). However the models understate October 2003 water levels below The Dalles by up to 3 feet. No way was found to both maintain good reproduction of the stage-discharge rating over a wide range of flows **and** provide significantly better agreement with the 2003 HWMs below The Dalles. This shortcoming is addressed further in Section 4.3 which describes an additional current condition model which improves the simulation of HWMs below The Dalles but with some degradation of model performance in terms of match to the stage-discharge rating.

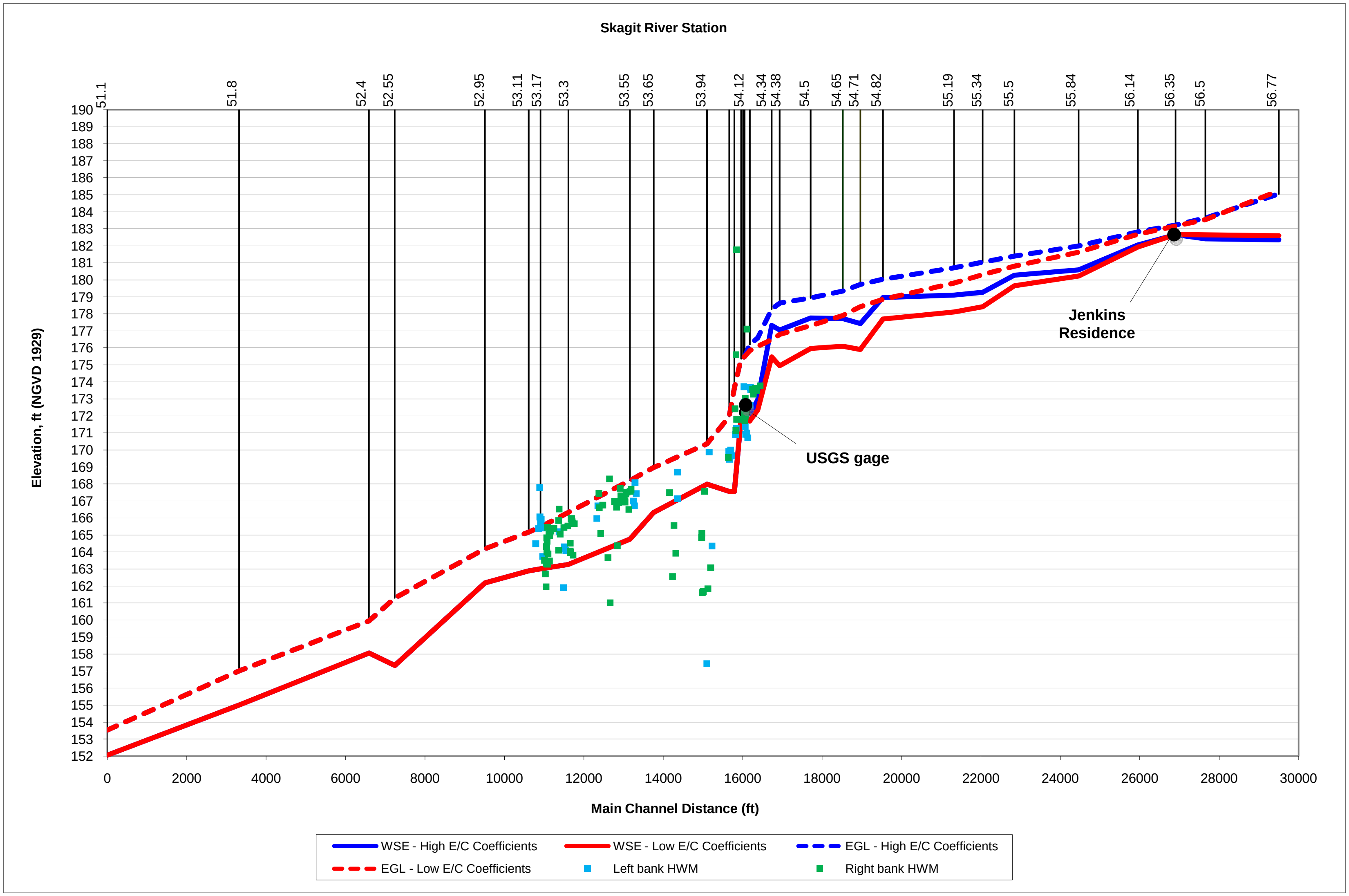


Figure 7. Water Surface and Energy Grade Line Profiles for Study Reach (October 2003 Calibration - 166,000 cfs).

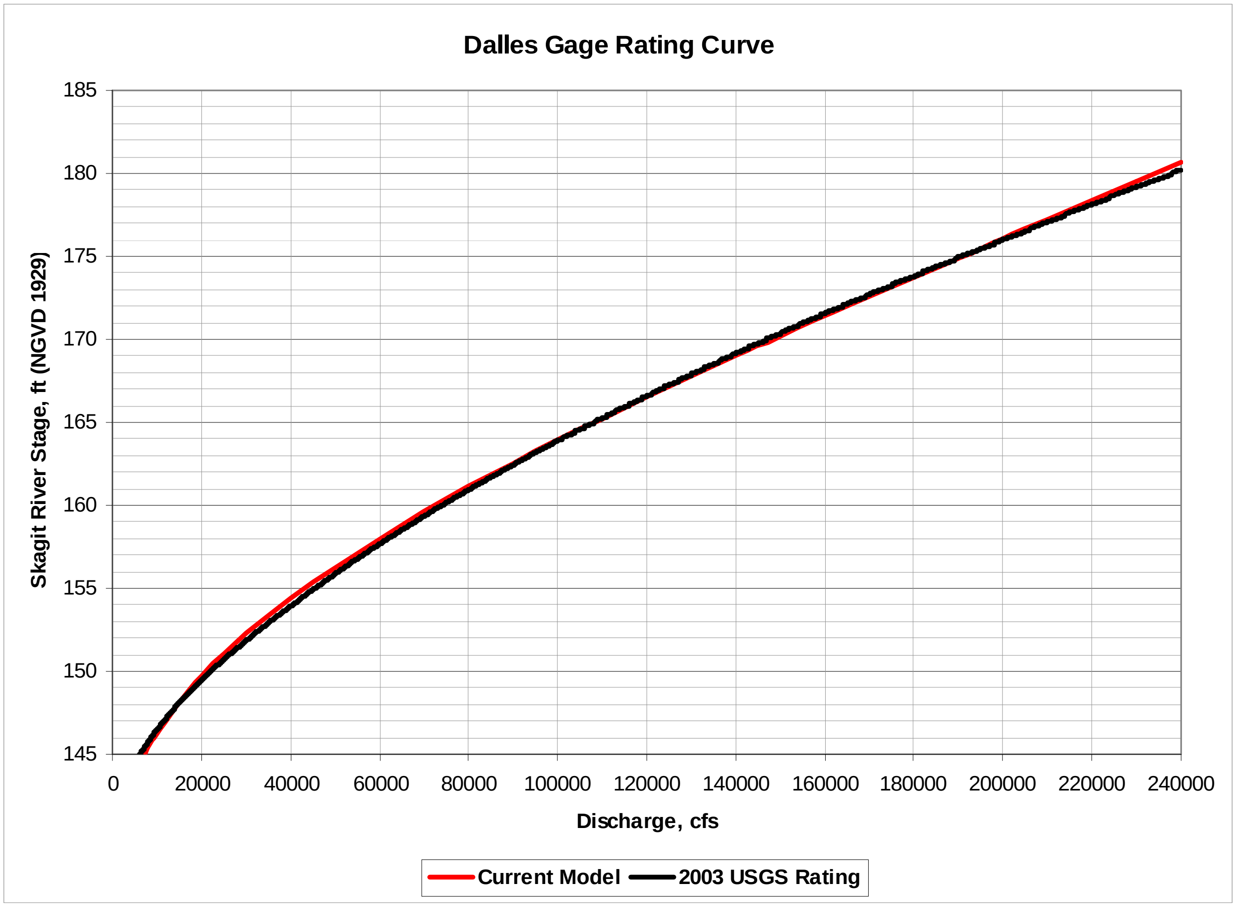


Figure 8. Comparison of Stage-Discharge Rating at RM 54.12 from Current Conditions HEC-RAS Model against USGS Rating 6.

4.2 1921 Conditions

Differences between current hydraulic conditions and conditions in 1921 were evaluated through comparison of data from the Corp's 1911 channel survey[12] with the most recent channel survey data, and through comparison of a 1937 aerial photo mosaic of the area with 2001 aerial photographs.

Elevations on the Corp's 1911 survey map are provided relative to Extreme Low Water of Puget Sound. USGS WSP 1527 (page 52) describing the Skagit River near Sedro Woolley gage states:

> *Datum of gage is extreme low sea level of Puget Sound (levels by Corps of Engineers), which is 8.93 ft below mean sea level, unadjusted.*

For current purposes we have assumed that extreme low water of Puget Sound is 8.93 ft below NGVD 1929, which is equivalent to assuming that the mean sea level datum referred to in WSP 1527 is the same as NGVD 1929.

Detailed soundings from the Corp's 1911 survey are only available for the low water channel. Since full cross-sections are not available, the 1911 geometry cannot be used with confidence for hydraulic modeling of floods. Nevertheless, the soundings do provide valuable information on the stability of the channel and the general magnitude and direction of changes in channel geometry.

Selected in-channel cross-sections from above The Dalles from the 1911 survey are compared with cross-sections from the current condition HEC-RAS models in Figure 9, and the thalweg profile from 1911 is compared against that from the current condition HEC-RAS models in Figure 10. The comparison shows relatively small differences in channel geometry between 1911 and the present. The channel in the current condition models is on average about 4 feet deeper than in 1911 over much of the reach between The Dalles and the confluence with the Baker River. Below The Dalles to RM 53.1, differences are not as consistent. In general, the current condition channel below The Dalles is somewhat deeper than the 1911 channel, except between RM 53.3 and RM 53.94 where the 1911 channel is deeper.

[12] "Skagit River from Baker River to Sedro-Woolley, W'n". Surveyed under the direction of Major J.B. Cavanaugh, Corps of Engineers, U.S. Army, August 24 to September 19, 1911. Map sheet at scale of 400 ft to the inch. Unknown sheet number.

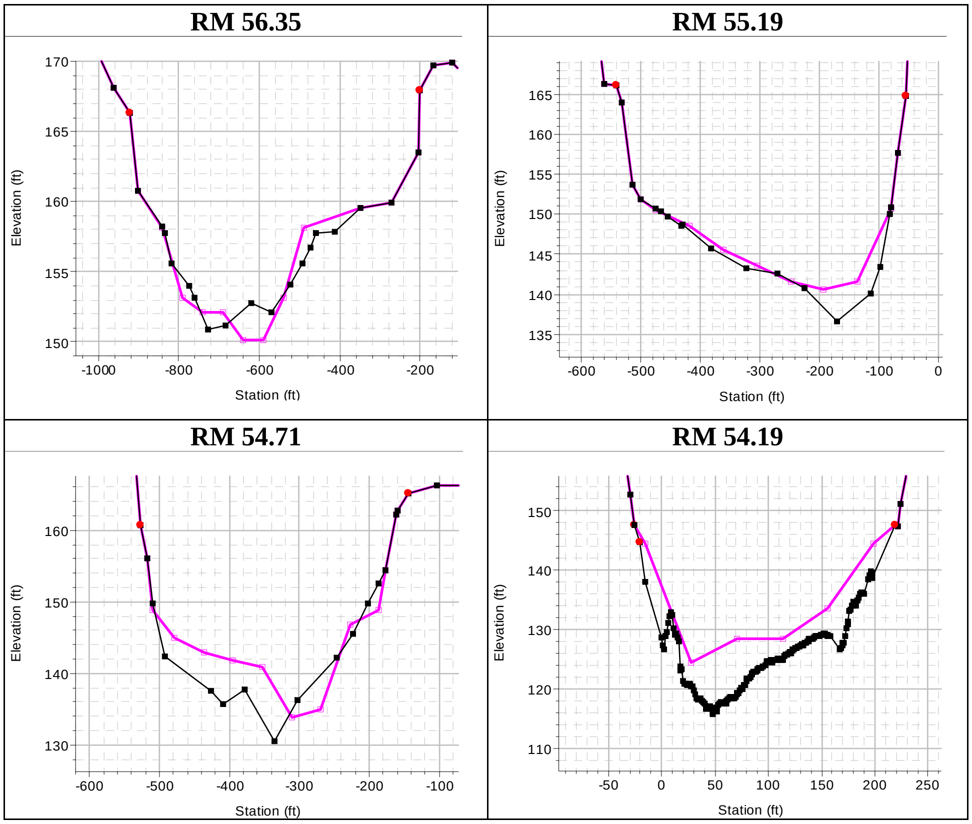


Figure 9. Comparison of Cross-Section Geometry Between 1911 (pink) and Current Condition Models (black).

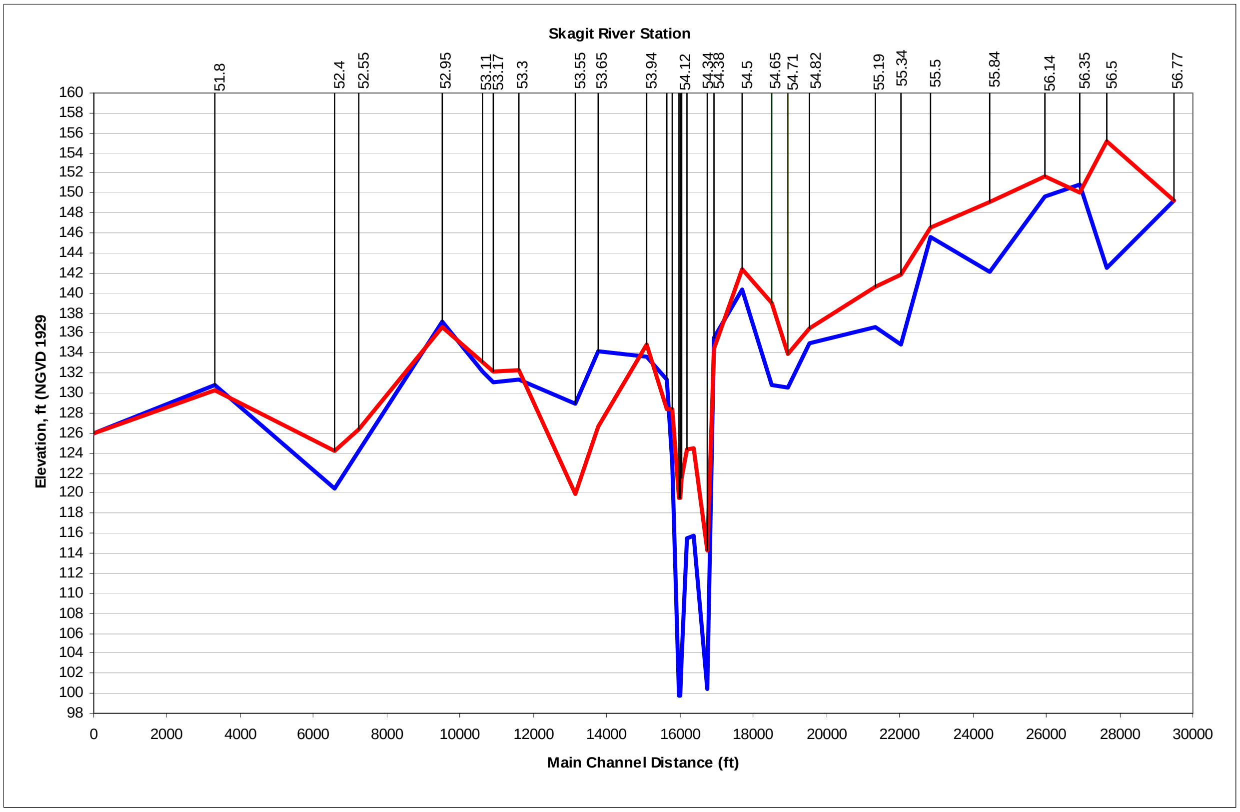


Figure 10. Thalweg Comparison between 1911 (red) and Current Condition Models (blue).

Comparison of bank lines from the 1937 and 2001 aerials shows the reach of the river from below The Dalles to the Baker River confluence to be reasonably stable with no indication of any significant change in bank lines.

Changes in overbank conditions from 1921 to present were inferred from comparison of 2001 aerial photographs against the 1937 aerial mosaic and annotations on the 1911 Corps survey map. The only potentially significant changes from 1921 to date is on the right bank from about RM 55.5 upstream to the confluence with the Baker River where gravel bars shown as more or less devoid of vegetation in the 1937 aerial are now well vegetated. The portion of the 1937 photo mosaic covering this area is provided in Figure 11. The gravel bar just below The Dalles at about RM 53.65 is similarly bare in 1937 but is now well-vegetated. It is assumed that overbank conditions in 1921 were similar to those in 1937.

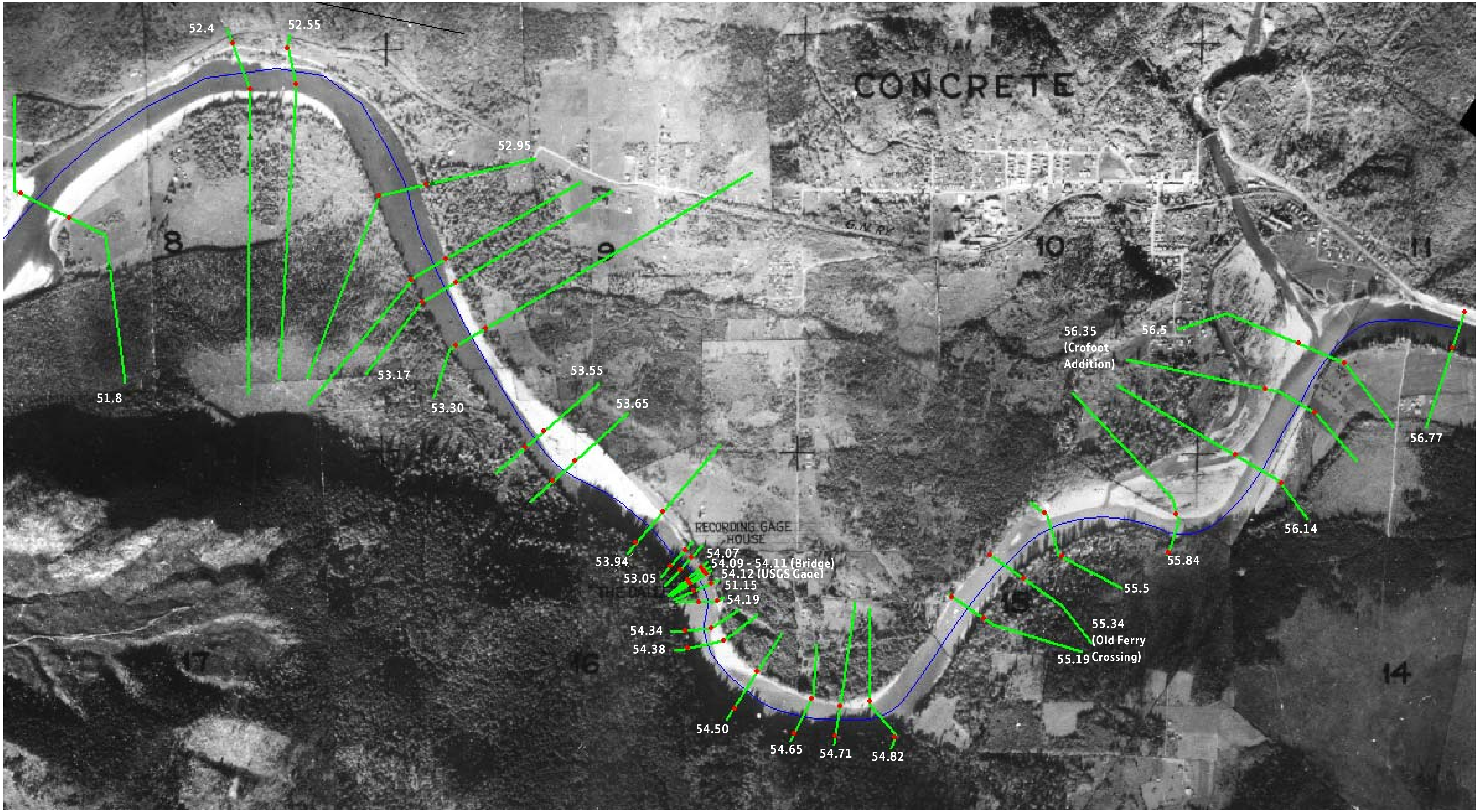


Figure 11. 1937 Aerial Photo with Cross-Sections and other Locations of Interest.

For purposes of modeling 1921 conditions, we have assumed the "current" condition cross-sectional geometry for the entire study reach but with the inferred 1921 overbank roughness upstream from The Dalles. Roughness downstream from The Dalles was kept as in the current condition models to maintain the current stage-discharge rating at The Dalles. The current rating (Rating 6) and the 1925 rating (Rating 1) are shown in Figure 12, adapted from Mastin and Kresch (2005). The rating at the site is very stable and has shown little variation since the gage site was established in late 1924. Note that discharge measurement 40 on 27 February 1932, (measurement discharge of 135,000 cfs) plots at almost exactly the same position on the rating as measurement 475 on 21 October 2003 (measurement discharge 138,000 cfs). Note also that at low stages, the 1925 rating shows somewhat lower discharges than the current rating for the same stage.

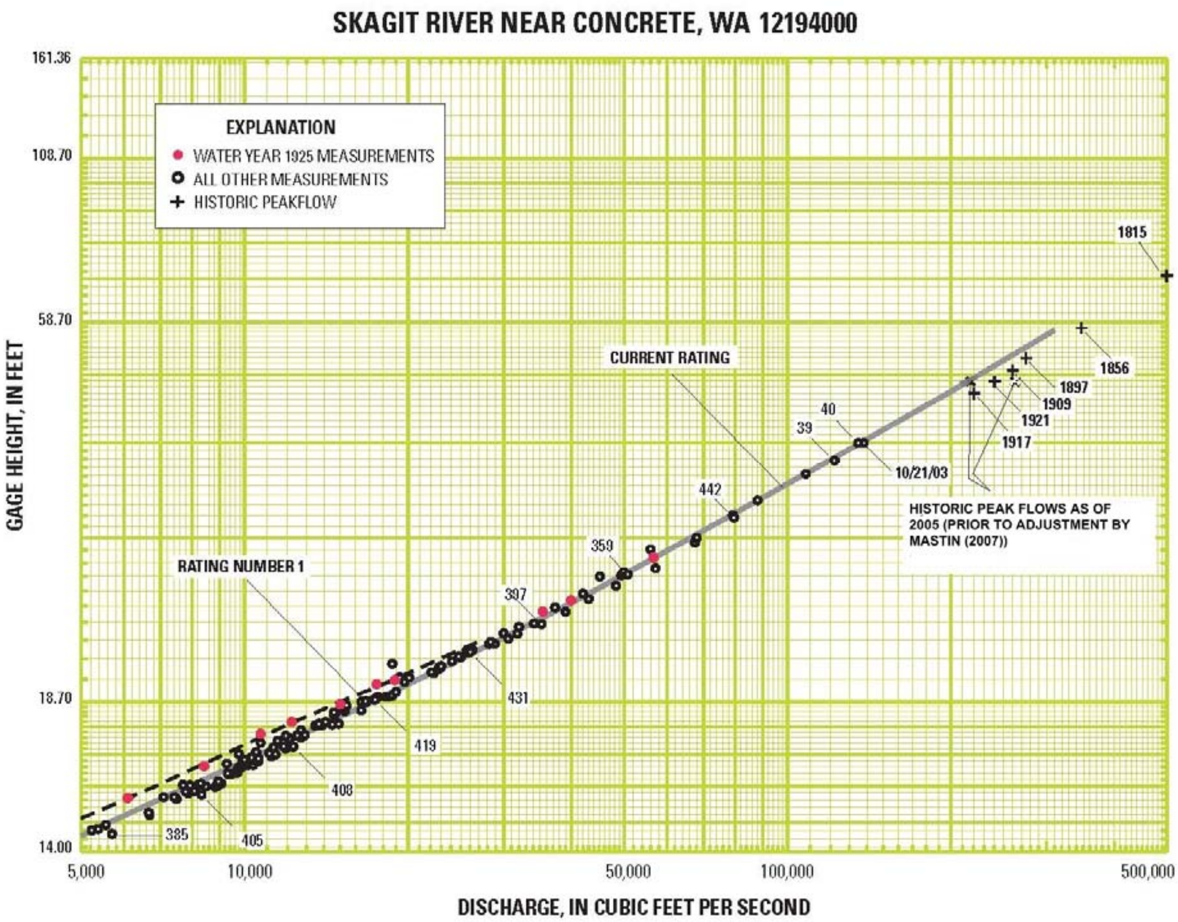


Figure 12. Stage-discharge ratings, discharge measurements and published historic peak discharges as of 2005 for the Skagit River near Concrete (adapted from Mastin and Kresch, 2005).

The two current conditions HEC-RAS models (i.e. the high expansion/contraction coefficient model and the low expansion/contraction coefficient model) were thus each modified to reflect 1921 conditions upstream from The Dalles to produce two alternative “1921” models:

- Current channel geometry with 1921 overbank roughness and high expansion/contraction coefficients.
- Current channel geometry with 1921 overbank roughness and low expansion/contraction coefficients.

Given that the available information indicates a somewhat larger channel today than in 1911, we believe that hydraulic models using current channel geometry with estimated 1921 overbank roughness should provide a conservatively high estimate of 1921 channel capacity and result in somewhat overstating the discharge corresponding to a particular 1921 water level in Crofoot (see Section 4.3 Sensitivity Runs).

The 1921 models were run with a range of discharges to determine that discharge which produced a water level in Crofoot of 186.1 ft NGVD29 – the high end estimate of the water level for the December 1921 flood deduced from the Concrete Herald report. The models were also run with a discharge of 228,000 cfs, corresponding to the current published estimate of the December 1921 peak discharge.

Model results are summarized in Table 4 and water surface profiles and energy grade lines for the two alternative 1921 models are provided in Figures 13 and 14 for the following:

- Discharge of 228,000 cfs, corresponding to the current published estimate of the December 1921 peak discharge.
- Discharge producing a water level in Crofoot of 186.1 ft NGVD.

Table 4. 1921 Model Results Summary

Model	WSE in Crofoot Corresponding to Discharge of 228,000 cfs	Discharge producing WSE of 186.1 ft. in Crofoot
1921 – High Expansion/ Contraction Coefficients	190.77 ft.	195,000 cfs
1921 – Low Expansion/ Contraction Coefficients	189.73 ft.	200,000 cfs

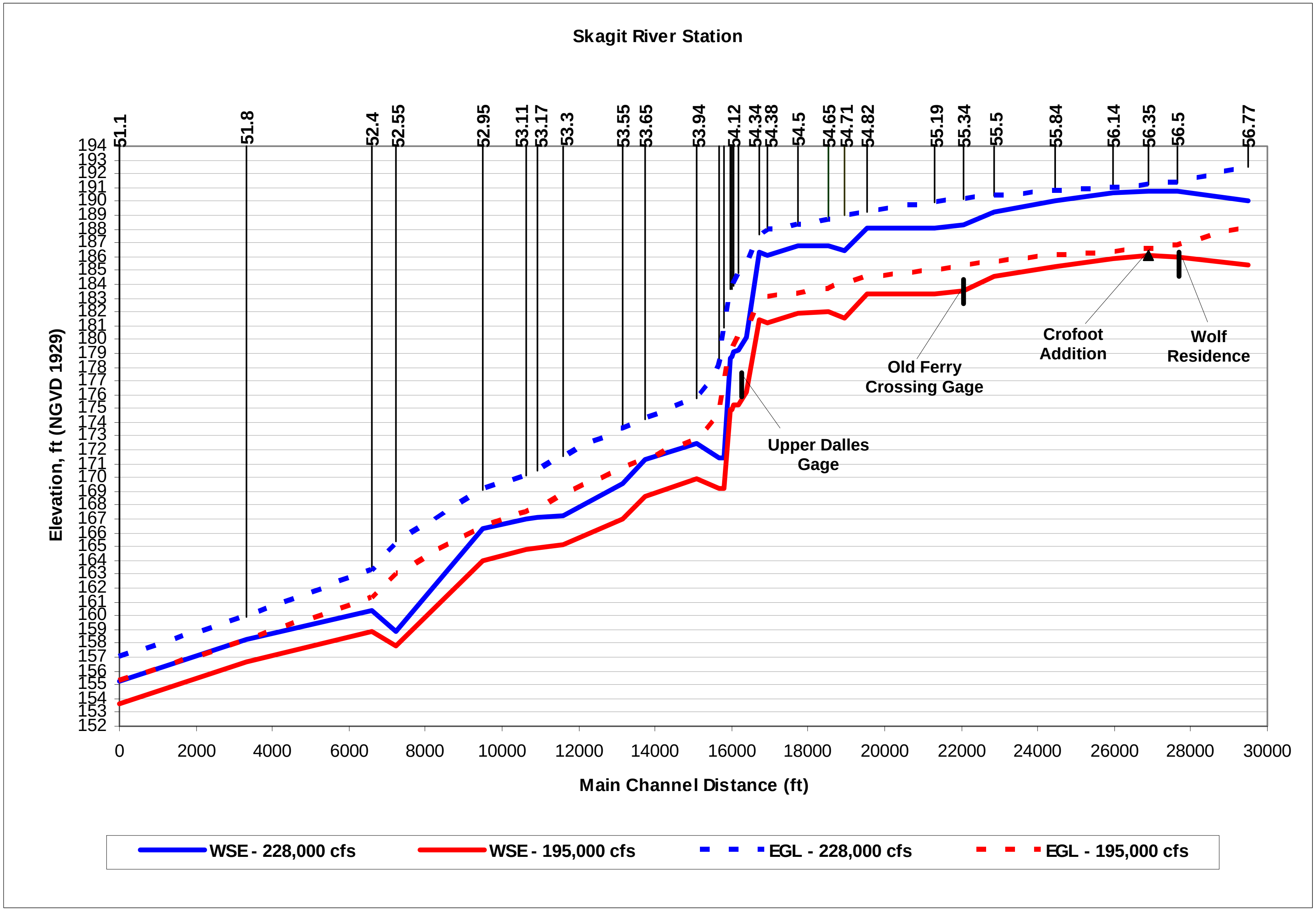


Figure 13. 1921 Model Flood Profiles – High Expansion/Contraction Coefficient

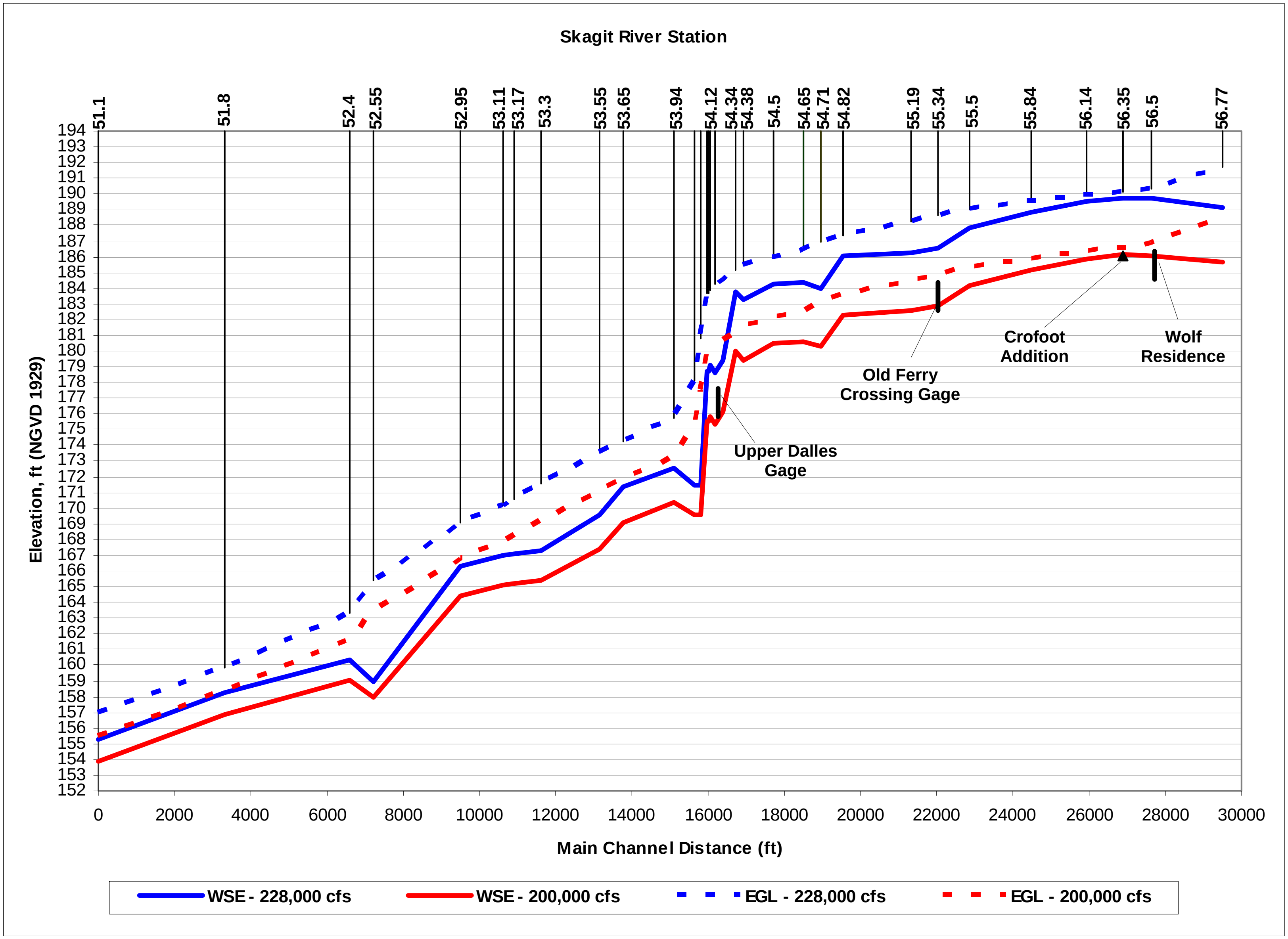


Figure 14. 1921 Model Flood Profiles – Low Expansion/Contraction Coefficients

Also shown on Figures 13 and 14 are the 1921 high water data between The Dalles and Concrete as summarized in Table 2 (in Section 3.2, page 14 above):

- HWM in the range 184.55 – 186.35 ft NGVD29 at the Wolf Residence. The exact location of this HWM is not known with certainty, but work by the City of Burlington and Pacific International Engineering places it north of the Crofoot Addition. The location shown in the profile plots on Figures 13 and 14 is probably accurate within about ±500 ft.
- HWM in the range 182.58 – 184.38ft NGVD29 at a gage near the "old ferry crossing". Again, the exact location of the gage is not known with certainty but the location shown in the profile plots on Figures 13 and 13 is believed to be accurate to within about ±200 ft.
- HWM in the range of 175.8 – 177.6 ft NGVD29 at the Upper Dalles gage. This is plotted 200 ft upstream from the current USGS gage site, but, as noted previously, may have been as much as 300 ft upstream.

The 1921 model results are relatively insensitive to the choice of high or low expansion/ contraction coefficients at The Dalles, with discharges of 195,000 cfs and 200,000 cfs respectively required to produce a target water level of 186.1 ft in Crofoot. Both 1921 model results fall within the range of high water elevation at the old ferry crossing and closely match the high-end HWM at the Wolf Residence. Matching the high-end HWM at the Wolf Residence would of course be expected since it is close to the Crofoot Addition and the high-end HWM at the Wolf Residence is close to the Crofoot target elevation of 186.1 ft. Both models however understate the HWM elevation at the Upper Dalles gage site. The HWM at that location ranges from 175.8 to 177.6 ft NGVD29, whereas the high and low expansion/ contraction coefficient models produce water levels of 175.63 ft and 175.04 ft respectively.

Given the complexity of the hydraulic conditions, we would not necessarily expect to be able to reproduce water levels at all locations through The Dalles. The HEC-RAS model parameters were selected by calibration to match the rating curve at the present gage site. Steep drops in water surface elevation through The Dalles are associated, in the HEC-RAS model, with expansion/contraction losses caused by the "holes" in the channel bed shown in the thalweg profile in Figure 10. As such, detailed model results and the precise magnitude and location of these drops are quite sensitive to the model geometry. From the point of view of assuring realistic estimation of the stage/discharge relationship at Crofoot, it is more important to ensure reasonable simulation of total head loss through The Dalles and to consider the effects of uncertainty in head loss on the simulation results.

4.3 Sensitivity Runs

A number of sensitivity runs were made to evaluate the effects of uncertainty in model parameters on conveyance. The “base line” model for the sensitivity runs was taken as the model with current channel geometry, 1921 overbank roughness upstream from The Dalles and high expansion/contraction coefficients. The following changes were investigated:

- In-channel roughness was increased by 10% from The Dalles to the Baker River.
- Overbank roughness upstream from The Dalles was decreased by 30%.
- Expansion/contraction coefficients were decreased by 20% for cross-sections from the entrance to The Dalles to the section upstream from the current Dalles gage (i.e. between RM 54.34 and RM 54.15).
- Low flow channel geometry was replaced by cross-section geometry data from the 1911 Corps survey from The Dalles to the Baker River. We assume that the 1911 data more closely reflects 1921 low flow channel geometry than the current condition models.

The purpose of restricting changes to the reach upstream of The Dalles was to preserve the model’s stage-discharge relationship at the present USGS gage site. As discussed in the previous section, and as shown in Figure 12, available measurements from 1925 to date show this to be a stable rating which is well-defined, with only modest extrapolation, to at least 200,000 cfs.

For each of the above changes, the HEC-RAS model was used to produce a water surface profile corresponding to a discharge of 195,000 cfs (the discharge for which the base line model produced a water level in Crofoot of 186.1 ft NGVD29) and to determine the discharge producing a 1921 water level in Crofoot of 186.1 ft NGVD29. The results of the sensitivity runs, showing water surface elevations in Crofoot corresponding to a discharge of 195,000 cfs, and discharges producing a water surface elevation in Crofoot of 186.1 ft, are provided in Table 5.

Table 5. Sensitivity Runs Results Summary.

Model Configuration	WSE in Crofoot Corresponding to Discharge of 195,000 cfs	Discharge producing WSE of 186.1 ft in Crofoot
1921 base-line model	186.1 ft	195,000 cfs
In-channel roughness increased 10%	186.6 ft	191,000 cfs
Overbank roughness decreased 30%	186.0 ft	195,500 cfs
Expansion/contraction coefficients decreased 20% at The Dalles	185.2 ft	202,000 cfs
1921 Channel Geometry	187.3 ft	187,000 cfs

Notes: The 1921 base-line model uses current channel geometry, 1921 overbank roughness upstream from The Dalles and high expansion/contraction coefficients.

All changes applied upstream from the current gage site.

In addition to the above, several runs were made to investigate the effects of changes in model parameters below The Dalles on simulation results. As shown in Figure 7, the two alternative current condition calibration models (the current condition high expansion/contraction and low expansion/contraction coefficient models) under-simulate the USGS HWMs for the October 2003 flood below The Dalles. As noted previously, no reasonable way was found of matching both the 2003 HWMs below The Dalles and providing a good match to the gage rating. The current condition model with the high expansion/ contraction coefficients was modified as follows:

- Channel roughness below The Dalles was increased to 0.035 and contraction/expansion coefficients in The Dalles were reduced so as to:
    - improve simulation results for October 2003 below The Dalles, and,
    - maintain acceptable reproduction of the stage-discharge rating for flows in the range 150,000 to 200,000 cfs.
- Roughness above The Dalles was increased to 0.033 to reproduce the observed 2003 water level at the Jenkins residence in Crofoot.

The results of these changes are shown in Figures 15 and 16.

Figure 15 shows water surface and energy grade profiles for the current condition high expansion/contraction coefficient model (blue line) from Figure 7 and for the current condition model as modified to better reproduce USGS HWMs for the October 2003 flood (red line). The model reproduction of the October HWMs below The Dalles is significantly improved. However this improvement is at the expense of the match of model results to the gage rating (compare Figures 8 and 16). Nevertheless, the model still provides a good match to the rating in the flow range of greatest interest – above about 140,000 cfs.

This modified model of 2003 conditions was then further modified as before to represent inferred 1921 overbank conditions and run iteratively to determine the discharge required to match the 1921 water level (186.1 ft NGVD29) in the Crofoot Addition. The discharge determined in this way was 196,000 cfs, in close agreement with the 1921 base-line model results in Table 5 and demonstrating that hydraulic model estimates of 1921 peak discharges are relatively insensitive to uncertain hydraulic conditions and modeling difficulties below The Dalles.

The sensitivity runs demonstrate that:

- Hydraulic model estimates of the 1921peak discharge using the observed water level in Concrete are relatively insensitive to uncertainties in both energy losses at The Dalles and hydraulic conditions below The Dalles.
- Peak discharge estimates from the hydraulic model presented here appear to be significantly less sensitive to uncertainty than the 1921 slope-area measurement.

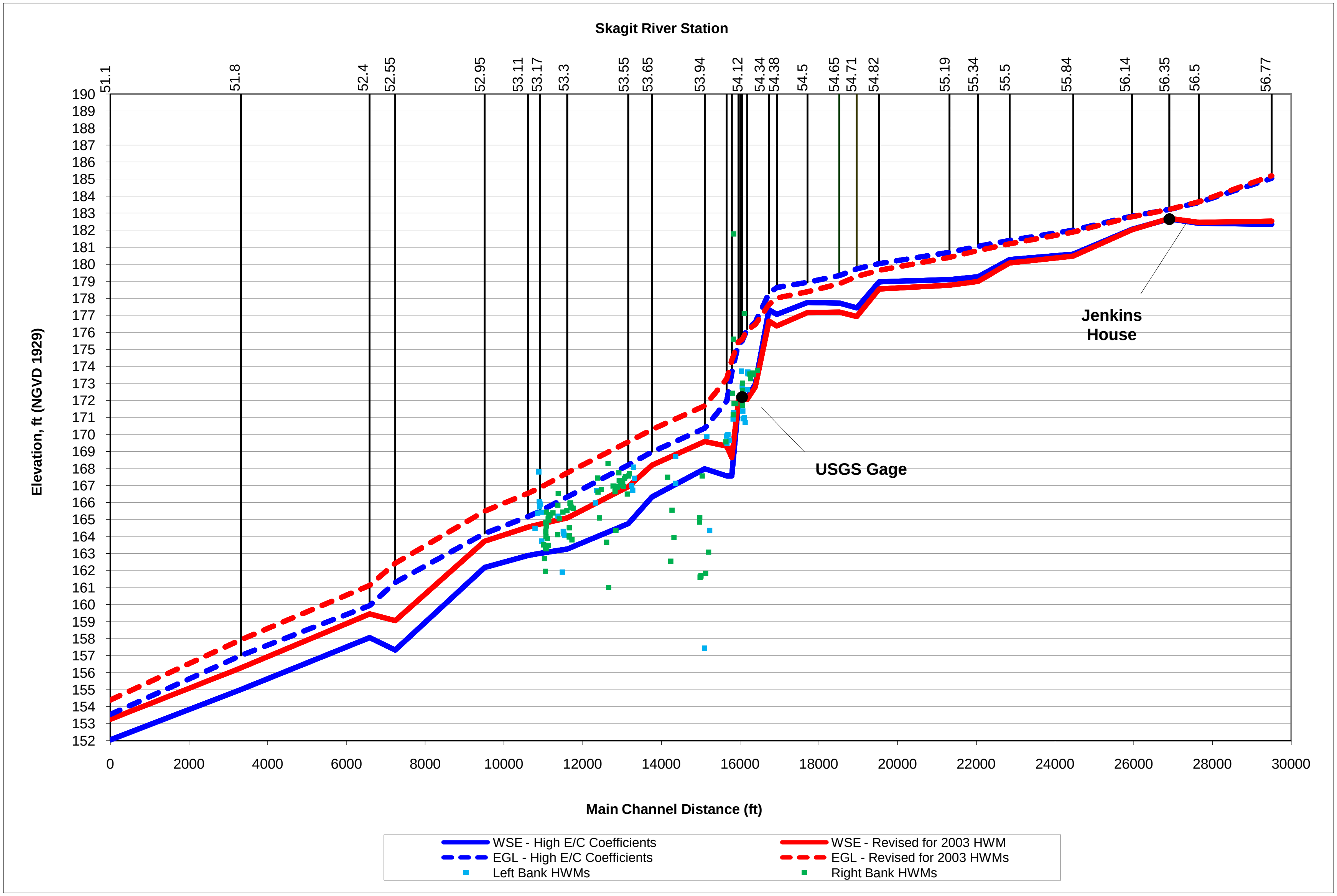


Figure 15. Profiles for Current Condition High E/C Model and Model Modified to Improve October 2003 Simulation (Q=166,000 cfs)

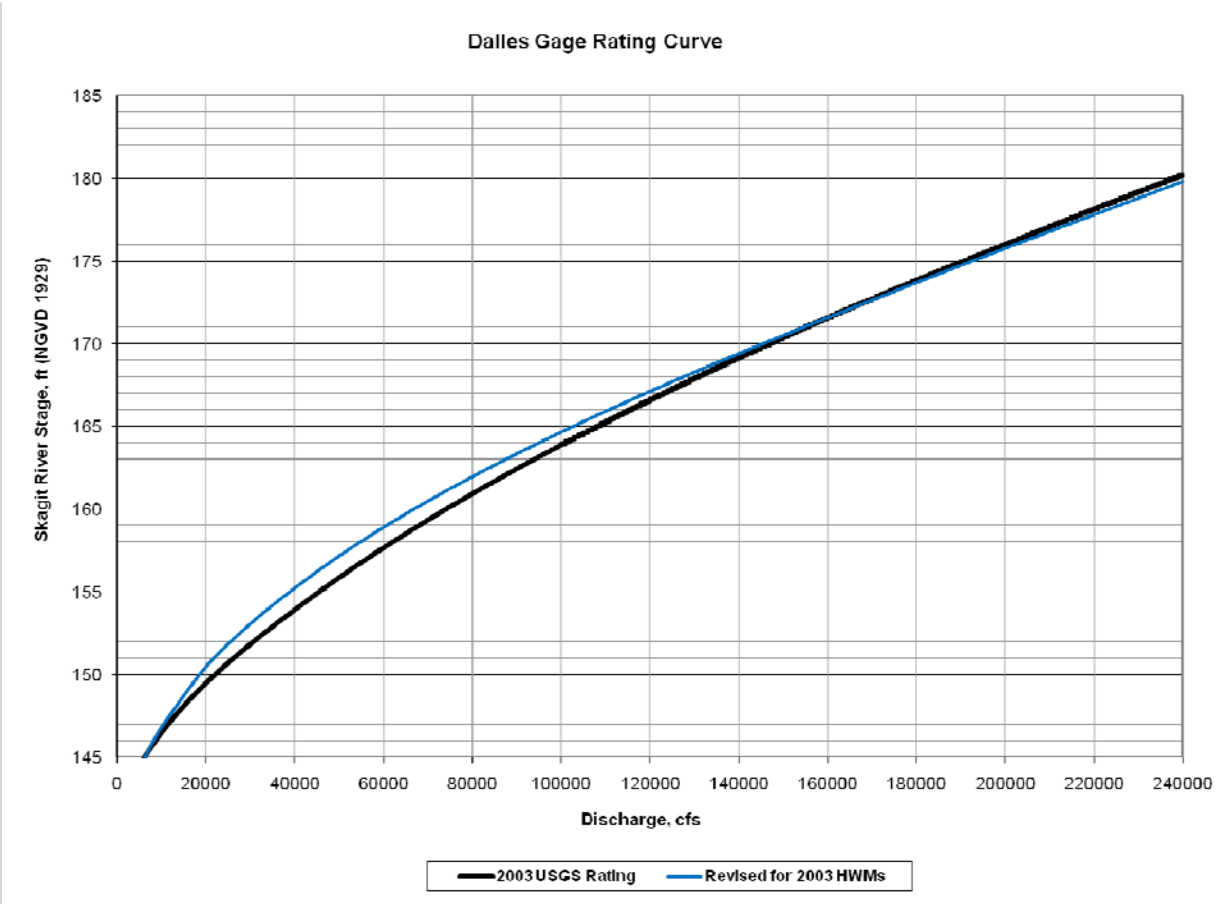


Figure 16. Comparison of Stage-Discharge Rating at RM 54.12 from Modified Current Condition Model against USGS Rating 6

4.4 Assessment of Hydraulic Model Results

Estimates of the peak discharge from 1921 range from about 187,000 cfs using the HEC-RAS model described above with 1921 channel geometry and overbank conditions (see Table 5), to the currently published value of 228,000 cfs. A somewhat conservative[13] HEC-RAS model relying on current channel geometry produces simulated water surface elevations in the Crofoot Addition ranging from 189.7 to 190.8 ft at a discharge of 228,000 cfs for the combinations of model parameters bracketing their probable actual values (see Table 4). Based on first-hand observations reported in the Concrete Herald, the maximum water level in the Crofoot Addition during the 1921 flood was at most 186.1 ft. These water levels are shown in Figure 17 superimposed on a photograph of the lowest existing house in the Crofoot Addition dating from 1921 (45956 Albert Street).

Figure 17. 45956 Albert Street, showing December 1921 water level as inferred from Concrete Herald report (186.1 ft), and estimated water level corresponding to a discharge of 228,000 cfs (189.7 ft)

[13] Conservative in the sense that the model overstates discharge corresponding to a given water level or, conversely, understates water level for a given discharge.

In our estimation of the 1921 peak discharge, we are putting considerable weight on the accuracy of the Concrete Herald report. Using a somewhat conservative HEC-RAS model, the published 1921 discharge of 228,000 cfs would have resulted in a maximum water level about 3.5 to 4.5 ft deeper than was apparently experienced. The hydraulic model results, and the assessment of uncertainty in those results, indicate that the published peak discharge of 228,000 cfs for the 1921 event is high. Based on the high water data from Crofoot and hydraulic model analysis, the peak discharge was more likely in the range of 195,000 to 200,000 cfs.

Previous attempts to use hydraulic modeling to estimate the peak discharge on the Skagit River near Concrete have been discounted because of concerns surrounding the effects of uncertainty in energy losses through The Dalles. The analyses presented here have explicitly considered that uncertainty and have demonstrated that uncertainty in head loss at The Dalles and uncertainty in hydraulic conditions below The Dalles, both have a relatively modest impact on peak discharge estimates determined by means of a hydraulic model.

After consideration of model results, a final 1921 model was developed using mid-range values for expansion/contraction coefficients in the approach to The Dalles and an in-channel roughness of 0.030 for the entire study reach. A copy of the final 1921 model and supporting models is provided on DVD in the pocket at the back of this report. The final 1921 model results produce:

- A discharge of 195,000 cfs corresponding to a water level of 186.1 ft in the Crofoot Addition.
- A water level of 190.7 ft in the Crofoot Addition corresponding to a discharge of 228,000 cfs.

A stage/discharge rating at Crofoot produced using the final 1921 model is shown in Figure 18, and water surface profiles from the final 1921 model for discharges of 195,000 cfs and 228,000 cfs are provided in Figure 19. We recommend that a revised peak discharge of 195,000 cfs be adopted for the December 1921 flood.

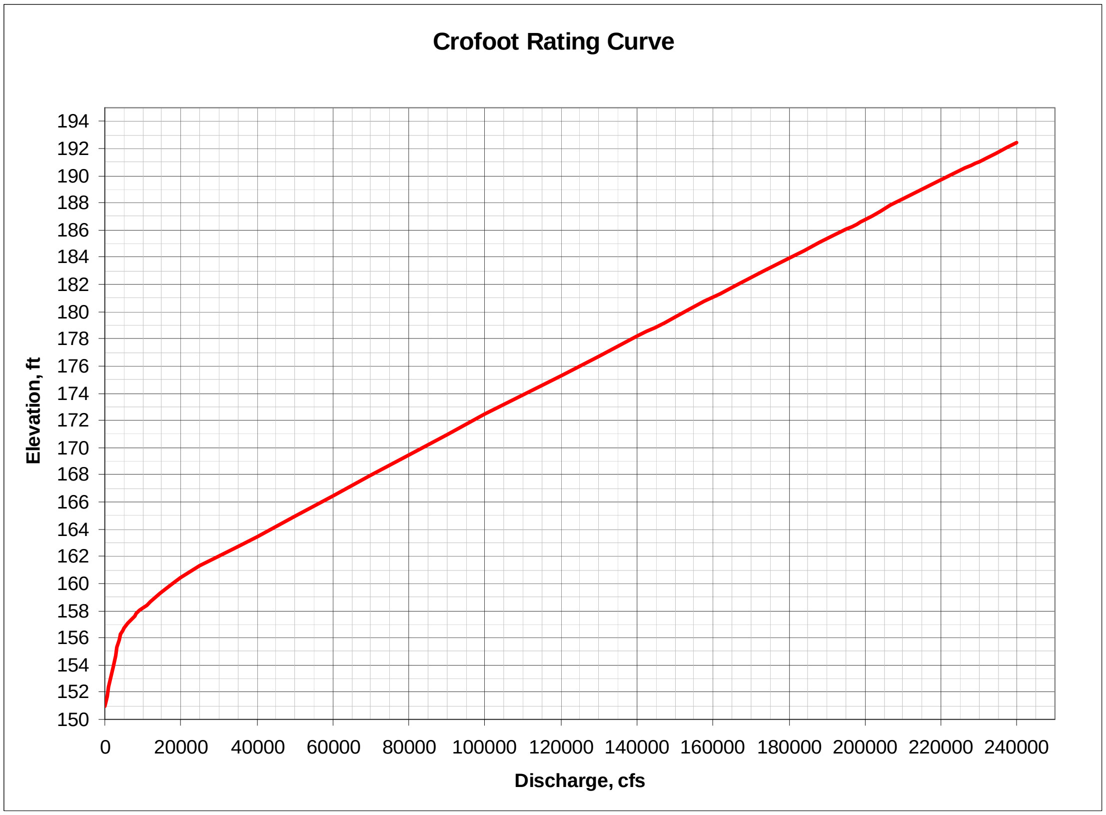


Figure 18. 1921 Rating Curve at Crofoot.

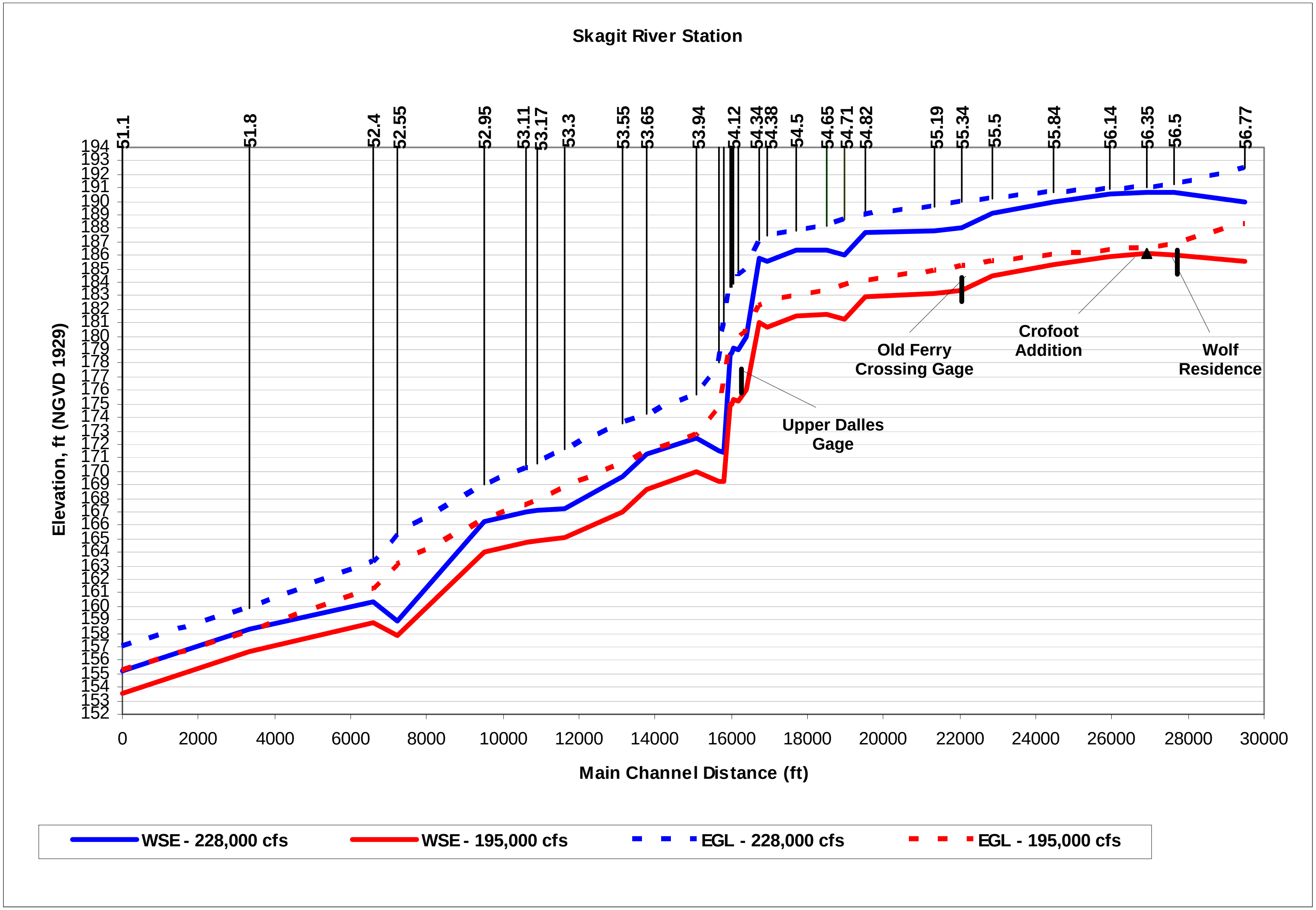


Figure 19. Final 1921 Model Water Surface Profiles.

5.0 ESTIMATION OF PEAK DISCHARGES FOR 1897, 1909 AND 1917 FLOODS

The published peak discharges for the 1897, 1909 and 1917 floods were determined by:

- Estimating the difference in maximum water level during the flood in question and the 1921 flood.
- Applying that difference to the estimated 1921 gage height at The Dalles to determine a gage height for the flood in question.
- Estimating the discharge corresponding to that gage height from the gage stage-discharge rating drawn through the stage-discharge point for the 1921 flood.

In this section we review the basis for the published peak discharges for these events and provide a re-evaluation of those data.

Identification of high water marks from the historic events was the focus of Stewart's field work in 1922 and early 1923. A summary of high water data from Stewart's 1922/23 field notes is provided in Table 6 for locations between Cockreham Island (RM 38) and Sauk (RM 63) along with published gage heights at The Dalles. Table 7 shows the differences between high water levels for 1897 and 1909, 1897 and 1921, 1909 and 1921, and 1917 and 1921. The only significant tributary inflow in this reach is from the Baker River, hence we would expect relative differences in high water marks for the various events to be reasonably consistent. Stewart likely had additional information from field work conducted in 1918. Unfortunately his 1918 field book has not been found.

5.1 Flood of November 1897

The basis for the published gage height for the 1897 flood seems particularly uncertain. It is described in WSP 1527 (page 28) as follows:

> *Stewart found two floodmarks near Concrete for the flood of 1897. One, on a barn on the right bank about a mile upstream from Concrete, was transferred by levels to the footing of a hotel in Concrete on which the other floodmark had been made in 1909. The difference between the two marks was 5 feet. After allowing 2 feet for the slope of the water surface, the flood of 1897 was estimated to be 3 feet higher than the flood of 1909. Later, in 1922, Stewart ran levels to a stump that a Mr. Magnus Miller stated was 1.5 feet out of the water during the flood of 1897. From these levels the flood of 1897 was found to be 3.6 feet higher than the flood of 1909[14] at Concrete.*

[14] This reference to 1909 is an error in WSP 1527. Stewart's field notes show that this 3.6 foot difference is relative to a 1921 high water mark.

Table 6. High Water Elevations for Historic Floods (Cockreham Island to Sauk)

Location	RM	Page(s)	1897	1909	1917	1921	Comments
Cockreham	38	134	17.9	17.4	17.4	16.2	
Hamilton	40	14	-	96.17	95.62	96.46	Elevations to USGS benchmark.
Kemmerick Ranch	45	26	100.0	-	-	99.22	
Savage Ranch	46	26	-	115.05	113.70	114.38	
Savage Ranch	46	26	-	116.80	-	116.29	
Pressentin Ferry	47	24	100.0		-	97.23	1921 HWM noted as approximate.
Fesslar's Ranch	52	10	-	26.6	-	25.91	
Upper Dalles gage	54	58, 75	-	36.16	-	34.86	Elevations converted to gage height, Upper Dalles gage.
Wolf residence	56	18	-	-	100.0	101.52	
Baker R. Hwy Bridge	56	22	10.0	-	-	6.4	Reflects water levels on the Baker R. rather than the Skagit.
Wash. Cement Plant	56	0	-	4.5	-	2.25	Field notes indicate HWMs may be from Baker R.
McDaniel residence	56	18	-	10.0	-	8.73	
Everett Ranch	56	23	0.	0.75	-	-	Discounted as incorrect by Stewart for unstated reasons.
Everett Ranch	56	141	2.0	0.	-	-	
Robertson's Barn	58	2	-	5.49	3.66	5.2	1917 inferred from notes.
John Larson Ranch	~61	20	99.63	100.02	-	99.79	Discounted by Stewart because of small range of value
P. Larson	~62	100	0.67	0.	-	-	Location uncertain - probably between Sauk and Faber Ferry
Dalles gage (published)	**54**	**n/a**	**51.1**	**49.1**	**45.7**	**47.6**	Gage height on current gage

Notes:

1. All elevations in feet to relative datum unless noted otherwise
2. Page number refers to Stewart's 1922/1923 field book
3. RMs approximate to nearest mile

Table 7. Differences between High Water Elevations for Historic Floods (Cockreham Island to Sauk)

Location	RM	1897-1909	1897-1921	1909-1921	1917-1921
Cockreham	38	0.5	1.7	1.2	1.2
Hamilton	40	-	-	-0.29	-0.84
Kemmerick Ranch	45	-	0.78	-	-
Savage Ranch	46	-	-	0.67	-0.68
Savage Ranch	46	-		0.51	
Pressentin Ferry	47	-	2.77	-	-
Fesslar's Ranch	52	-		0.69	-
Upper Dalles gage	54	-	-	1.3	-
Wolf residence	56	-	-	-	-1.52
Baker R. Hwy Bridge	56	-	3.6	-	-
Wash. Cement Plant	56	-	-	2.25	-
McDaniel residence	56	-	-	1.27	-
Everett Ranch	56	-0.75	-	-	-
Everett Ranch	56	2.0	-	-	-
Robertson's Barn	58	-	-	0.29	-1.54
John Larson Ranch	~61	-0.39	-0.16	0.23	-
P. Larson	~62	0.67	-	-	-
Average		0.4	1.7	0.8	-0.7
Maximum		2.0	3.6	2.25	1.2
Minimum		-0.75	-0.16	-0.29	-1.54
Dalles gage (published)	**54**	**2.0**	**3.5**	**1.5**	**-1.9**

The flood elevations in Concrete probably were affected to a considerable extent by the flow of Baker River. The relationship between the two floods at that point may have been quite different from the relationship at the gaging station site.

Note that there is no information on the 1897 flood from The Dalles. The published gage heights (Table 6) show 1897 as being 2.0 feet above 1909 and 3.5 feet above 1921.

Reading Stewart's 1922/1923 field notes now, in 2008, it is apparent that the basis for the estimated gage height for the 1897 event, the largest of the four historic floods, is very weak.

The first of the two data sources cited in WSP 1527 has to be regarded as very doubtful. The two foot allowance for the water surface slope is of critical importance in the estimate of the water level difference between 1897 and 1909. The basis for Stewart's two foot allowance is not known. However, using a HEC-RAS model provided by the Seattle District USACE, the water surface of the Skagit drops about 10 ft. in the one mile reach above the confluence with the Baker at a discharge of 240,000 cfs[15]. If the barn and hotel were really one mile apart, the 2 foot allowance for water surface slope may be a significant underestimate; using water surface slope estimates from the HEC-RAS model would result in the 1897 high water elevation at the hotel being several feet **lower** than in 1909 and not 3 feet higher at stated in WSP 1527.

From the published gage heights, the text of WSP 1527 notwithstanding, it is not clear that Stewart actually relied on his estimate of water level difference at the hotel. It appears that published values may instead have relied on information from the Everett ranch, shown on Government Land Office (GLO) maps of 1881 as being on the right bank of the Skagit about one-quarter mile upstream from the confluence with the Baker River.

On page 23 of Stewart's 1922/1923 notes, we find:

Leonard Everett says 1897 flood about 9" lower than 1909

However, this is later discounted by Stewart, without any reason being provided, in favor of information from Magnus Miller[16], which can be found on page 141 of the field notes:

At Everett Ranch above Concrete Magnus Miller says 1897 water came to middle of 2nd shake. About 3' above Beam for rafters. This was shed on side of barn.

Leonard Everett says 1909 flood came just to bottom of shakes

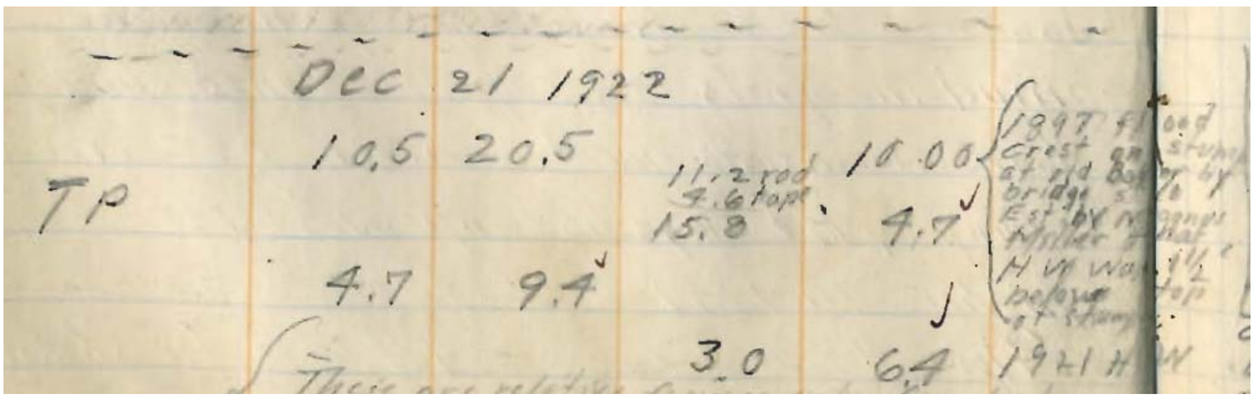
[15] The steady-state simulation assumed 240,000 cfs for the Skagit River above the Baker River and 25,000 cfs on the Baker River for a combined flow equal to the currently published 1897 peak of 265,000 cfs for the Skagit River at The Dalles.

[16] Miller platted the community of Baker on the west bank of the Baker River in 1890.

On the basis of which difference (some information from Miller, some from Everett), accounting for the pitch of the shed roof and so forth, Stewart determined that the 1897 flood was 2 ft higher than 1909.

Given that Stewart was apparently interviewing Miller and Everett in late 1922 or early 1923, one has to ask how reliable their memories would have been of an event in 1897, 25 years earlier. Why would Miller remember that in 1897 water came to the "middle of 2^{nd} shake"? And why rely on a rather convoluted calculation of the difference between 1897 and 1909 water levels in place of Everett's direct statement that the 1897 flood was nine inches **lower** than 1909?

The second of the two data sources cited in WSP 1527 can be found on page 22 of Stewart's field notes:



The barely decipherable note reads:

> *1897 flood crest on stump at old Baker Hy bridge site. Est by Magnus Miller that HW was 1½' below top of stump.*

The reliability of this critical piece of information should also be questioned. It again relies on the memory of Magnus Miller of fine details of an event that took place **25 years** earlier. Why would Magnus Miller remember that this particular stump was 1.5 ft out of the water? The location of this stump at the "old Baker Hy bridge" is also a concern. From a 1913 photograph of Concrete, the highway bridge referred to was probably a steel truss bridge at a location close to the current Henry Thompson Bridge and about 3,000 ft upstream from the mouth of the Baker River. As pointed out by Stewart, flood elevations at this point "*probably were affected to a considerable extent by the flow of Baker River*". And then of course, how does one relate differences in flood level at this point to differences at the gage site at The Dalles, about 3 miles downstream?

From Table 7, differences between estimated high water elevations for 1897 and 1909 vary from -0.75 feet to +2.0 feet. Similarly differences between 1897 and 1921 vary from -0.16 feet to 3.6

feet. As noted above, the differences between published gage heights at The Dalles for 1897 and 1909 and between 1897 and 1921 are 2.0 feet and 3.5 feet respectively.

Of the 1897 HWMs, only that at the John Larson Ranch was based on a physical mark (in that case an axe mark). However Stewart believed that John Larson's HWM's were unreliable and discounted them. All other reported 1897 HWMs apparently relied on the memory of eye witnesses.

It seems unlikely that the standard of evidence relied on for determining the 1897 gage height would be acceptable today. Given the absence of reasonable consistency in the 1897 data, the 1897-1921 elevation difference used by Stewart for determining the published 1897 gage height was presumably based to a large extent on judgment. There is no doubt that a major flood occurred in 1897 but of uncertain magnitude. In the absence of an approved method for handling uncertainty in discharge estimates in flood frequency analysis[17], and considering the range of water level differences in Table 6, we have assumed for the purposes of this re-evaluation an 1897 high water 2.0 feet above 1909 in Crofoot, as in the currently published data. The implication of excluding the 1897 flood from analysis is also considered in Section 7.

5.2 Flood of November 1909

Stewart was able to obtain significantly more information on the 1909 flood than on the 1897 flood. Considering the water level differences between 1909 and 1921 in Table 7 and excluding the high and low values results in a reasonably consistent set of data with all differences within a range of about 1 ft. For the purposes of this re-evaluation, we have assumed that the 1909 HWM was 1.3 feet above 1921 in the Crofoot Addition, as indicated by HWMs at the McDaniel residence, just above the confluence of the Baker and the Skagit.

5.3 Flood of December 1917

There is relatively little data available on the December 1917 flood. The published gage height for 1917 is 1.9 feet below that of 1921, however the basis for that gage height difference is unknown. For the purpose of this re-evaluation, we have assumed that 1917 was 1.5 feet below 1921 in the Crofoot Addition, as indicated by data from the Wolf residence.

5.4 Estimation of Peak Discharges

Estimated water level differences in Crofoot for the 1897, 1909 and 1917 floods were applied to the 1921 HWM in Crofoot of 186.1 feet to produce estimated high water elevations for these events. Discharges corresponding to those water surface elevations were then determined from

[17] Neither the Corps nor FEMA have an approved analytical technique for accounting for uncertainty in discharge estimates in flood frequency analysis.

the stage-discharge rating for Crofoot shown in Figure 18. The resulting water surface elevations and peak discharges are provided in Table 8 below:

Table 8: Revised Historic Water Levels and Peak Discharges at Crofoot.

Flood	Water Level (ft NGVD)	Peak Discharge (cfs)
November 1897	189.4	220,000
November 1909	187.4	205,000
December 1917	184.6	185,000
December 1921	186.1	195,000

6.0 ESTIMATION OF 1-DAY AND 3-DAY HISTORIC DISCHARGES

6.1 1-Day Maximum Winter Volumes

In the most recent (early 2008) analyses by the Corps[18], a relationship between peak and 1-day unregulated maximum winter discharges for the Skagit River near Concrete was established by regression, using observed data from years where the unregulated and regulated 1-day discharges were within 5% of each other. Data from those years were assumed to be essentially unregulated. The regression relationship is used by the Corps in two ways:

- to estimate unregulated peak discharges from the reconstructed record of 1-day unregulated discharges (see Section 7.0), and,
- to estimate 1-day historic discharges from the estimated peak historic discharges.

The relationship developed in the most recent work by the Corps is:

$$Q_{Peak} = 1.1749\ Q_{1\text{-}Day}\ ;\ R^2 = 0.9758$$

This relationship was applied to the revised estimates of historic peak flows from Table 8 to produce updated estimates of one-day historic volumes as listed in Table 9.

6.2 3-Day Maximum Winter Volumes

The most recent (early 2008) analysis by the Corps provides an updated relationship between 1-day and 3-day unregulated maximum winter discharges. The relationship, which relies on regression of 1-day against 3-day average unregulated discharge data from water years 1944-1991 and 1994-2007, gives:

$$Q_{3\text{-}Day} = 0.7587\ Q_{1\text{-}Day}\ ;\ R^2 = 0.9468$$

The regression of maximum three-day against maximum one-day data produces a spuriously high correlation coefficient since the maximum three-day volume includes the maximum one-day volume. This issue has no bearing on estimates of three-day volumes, however those estimates would be less reliable than indicated by the high R^2 above.

The regression relationship was applied to the estimated historic 1-day volumes from Table 9 to produce updated estimates of three-day historic volumes, also listed in Table 9.

From contemporary accounts of the 1897 flood, (see for example WSP 1527, pages 27 and 28) this event evidently had an unusually high peak and relatively small volume. The regression

[18] This approach is different from that used in the Corps' August 2004 Draft Hydrology Technical Documentation.

approach to estimating one and three-day historic flood volumes likely results in overstatement of the 1897 flood volume. As noted in Section 5.1, the basis for the estimate of the peak flow in 1897 is quite uncertain. Estimates of the 1-day and 3-day volumes for the 1897 flood are even more uncertain.

Table 9: Revised Discharge Estimates for Historic Floods
Skagit River near Concrete

Flood	Peak (cfs)	One-Day (cfs)	Three-Day (cfs)
November 1897	220,000	187,000	142,000
November 1909	205,000	174,000	132,000
December 1917	185,000	157,000	119,000
December 1921	195,000	166,000	126,000

7.0 FLOOD FREQUENCY ANALYSES

Flood frequency analyses were conducted for unregulated peak, one-day and three-day maximum winter discharges for the Skagit River near Concrete. The analyses were done following U.S. Water Resources Council Bulletin 17B guidelines using the U.S. Army Corps of Engineers' HEC-FFA software. The Seattle District USACE provided their most recent (August 2008) HEC-FFA input sequences which were used as the basis for analyses with revised historic discharge data.

The August 2008 USACE analyses include updated estimates of unregulated peak flows for the Skagit River near Concrete from 1924 through 2007. (This includes a rather significant upward adjustment to the unregulated peak flow for October 2003, from 185,685 cfs to 205,651 cfs). As noted in Section 6.0, the Corps established a regression relationship between peak and 1-day unregulated maximum winter discharges for the Skagit River near Concrete using observed data from years where the unregulated and regulated 1-day discharges were within 5% of each other. Data from those years were assumed to be essentially unregulated. To estimate unregulated peak flows, the regression relationship

$$Q_{Peak} = 1.1749\ Q_{1\text{-}Day}\ ;\ \ R^2 = 0.9758$$

was applied by the Corps to unregulated 1-day maximum winter discharges for all years of data in the systematic record except for the 1990, 1995, 2003 and 2006 floods, where the Corps relied on more detailed analyses of hourly unregulated hydrographs. The regression relationship was even applied to those years which were assumed unregulated and which were used in establishing the relationship in the first place. We regard this as an error, however the impact on estimates of the 100-year unregulated peak discharge was found to be negligible and the Corps August 2008 estimates of unregulated peak flows from 1924 through 2007 have been used as is in the present analyses.

The following flood frequency analyses were conducted for unregulated peak, one-day and three-day discharges:

- using the August 2008 USACE HEC-FFA input sequences which rely on published values for historic peak discharges.
- using the August 2008 USACE HEC-FFA input sequences but with revised values for historic discharges from Table 9.
- using the August 2008 USACE HEC-FFA input sequences but excluding the 1897 event and with revised values for other historic discharges from Table 9.

The frequency analyses conducted for this study and the resulting 100-year quantiles (based on computed probability and expected probability) are summarized in Table 10 and plots for analyses with the revised historic data, including 1897, (runs 2, 5, and 8) are provided in Figures 20, 21 and 22. HEC-FFA input files are provided in digital form on the DVD at the back of this report.

The log-Pearson Type III (LP3) distributions in Figures 20 through 22 provide a relatively poor fit to the revised data series, with the largest data points trending below the fitted curve and the 1897 event plotting below the 5% confidence limits on all three plots.

Exclusion of the 1897 event on the grounds of data uncertainty has little effect on the estimated flood quantiles for peak and one-day flows (see Table 10) and does not significantly improve the goodness of fit. The somewhat larger impact of excluding 1897 from the analysis of three-day flows is due to the effect in HEC-FFA of rounding the adopted skew to the nearest 0.1.

Despite the relatively poor fit of the LP3 distribution, recognizing the uncertainty in the data, we recommend adoption of peak, one-day and three-day LP3 100-year quantiles from runs 2, 5 and 8 of Table 10.

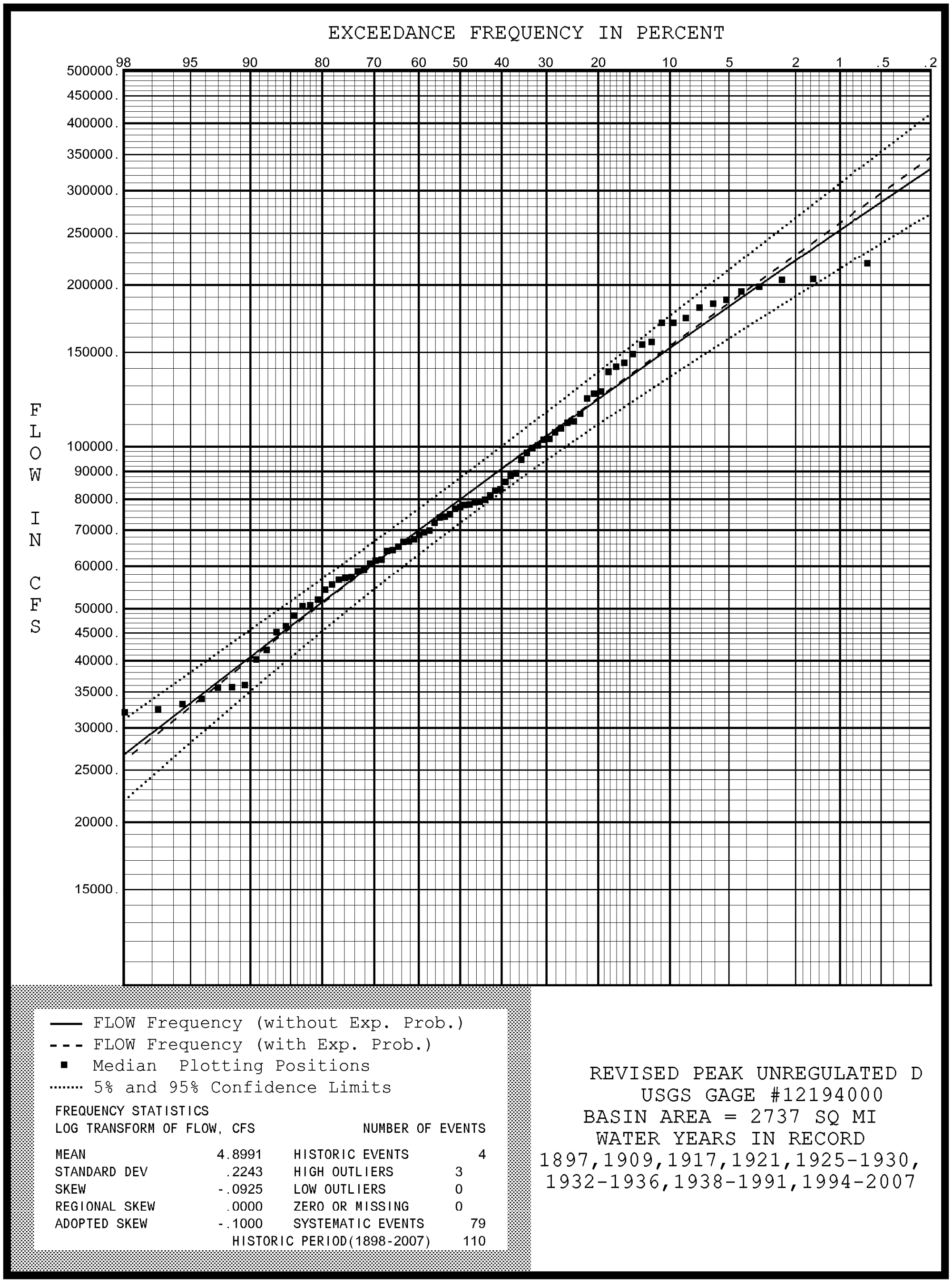


Figure 20. Frequency Analysis, Revised Unregulated Peak Discharge, Skagit River near Concrete.

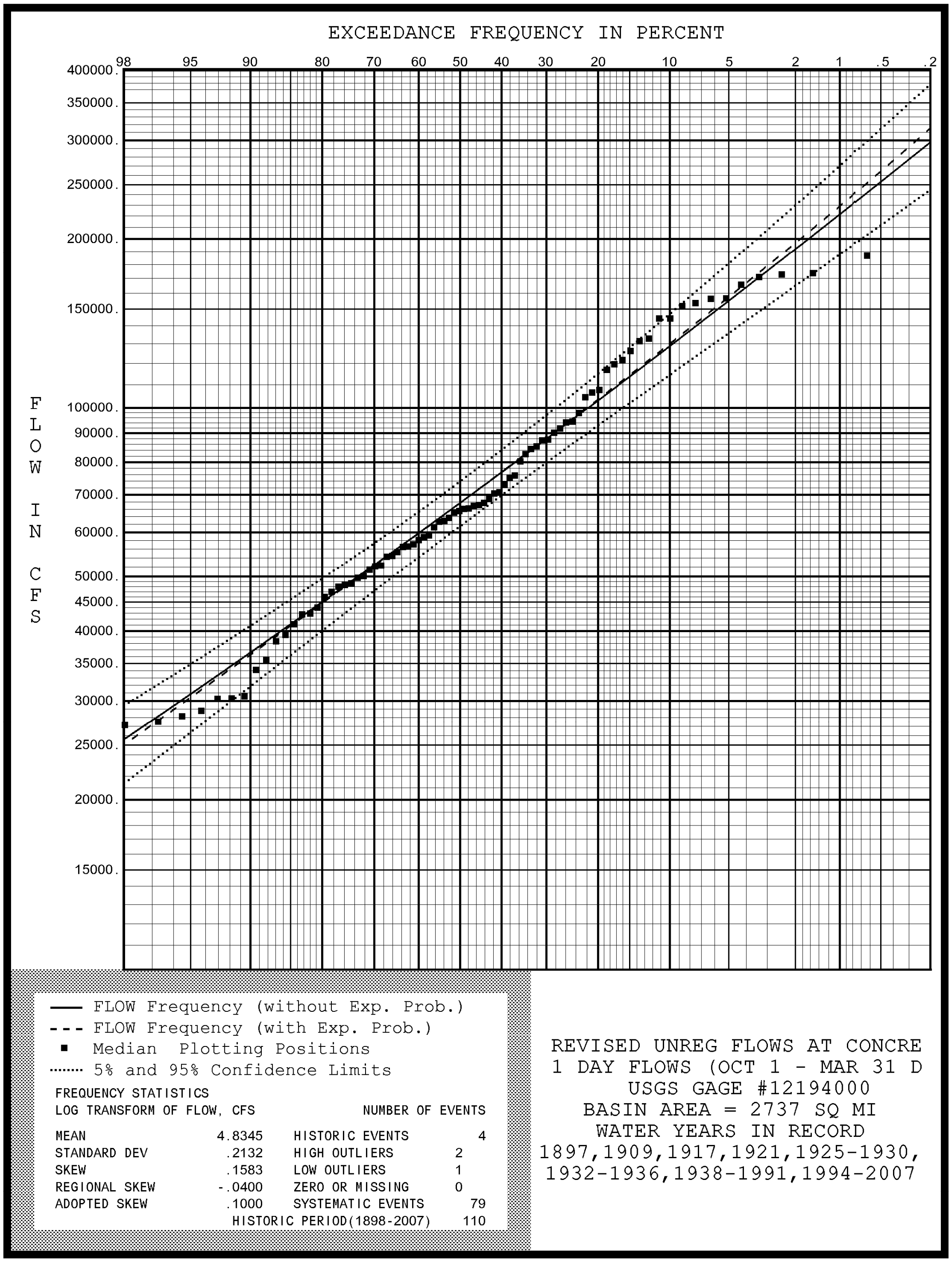


Figure 21. Frequency Analysis, Revised Unregulated 1-Day Discharge, Skagit River near Concrete.

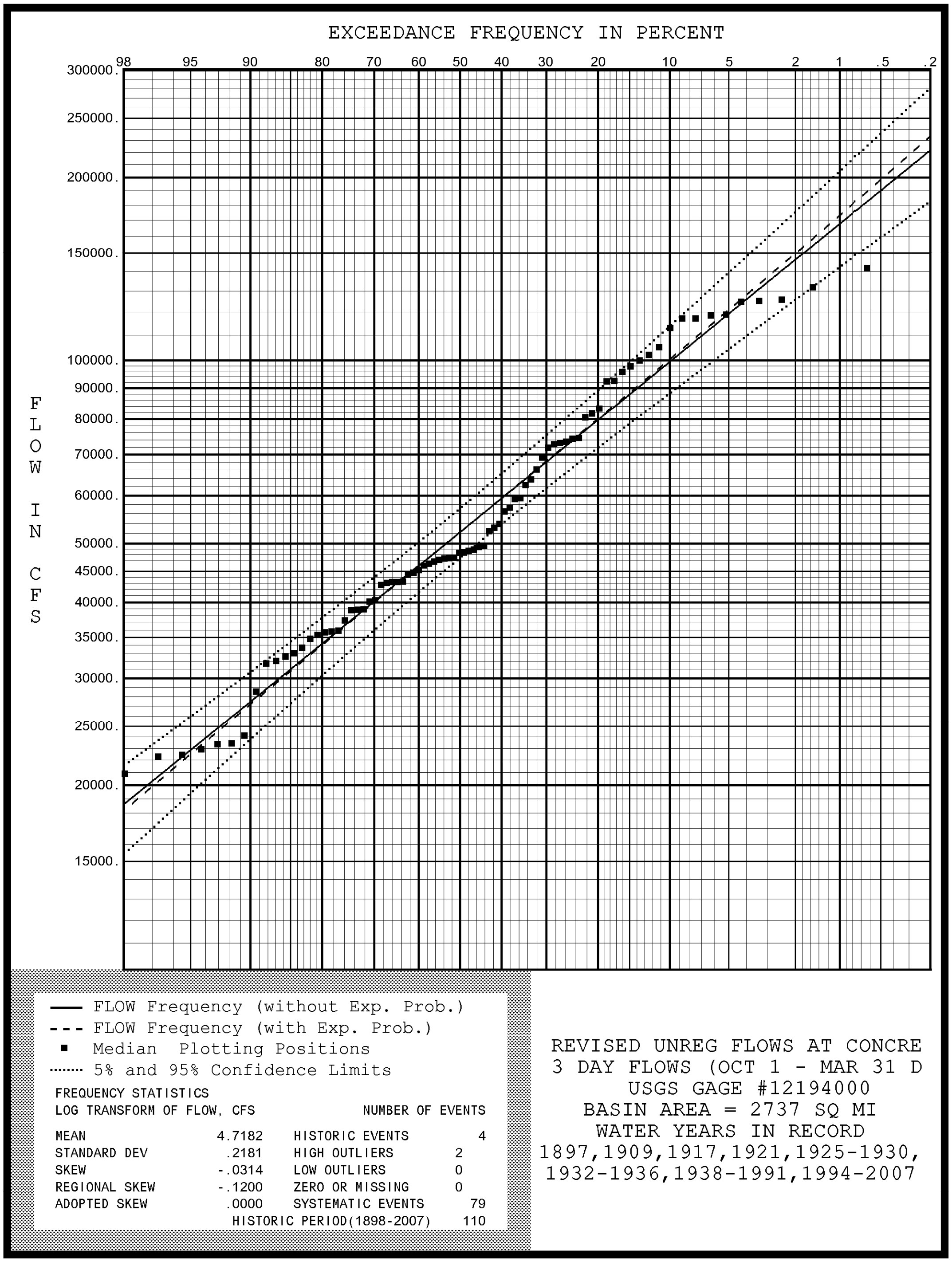


Figure 22. Frequency Analysis, Revised Unregulated 3-Day Discharge, Skagit River near Concrete.

Table 10. Results of Flood Frequency Analysis, Skagit River near Concrete

Description	Input File	100-Year Discharge (cfs)	
		Computed Probability	Expected Probability
Unregulated peak winter discharge			
1. USACE analysis using published historic data	WPKCONUR.DAT	278,000	288,000
2. As 1. but using revised historic data from Table 8	PK2.DAT	254,000	261,000
3. As 2. but excluding 1897	PK3.DAT	251,000	259,000
Unregulated 1-day winter discharge			
4. USACE analysis using published historic data	W1DCONUR.DAT	242,000	251,000
5. As 4. but using revised historic data from Table 8	1D2.DAT	222,000	229,000
6. As 5. but excluding 1897	1D3.DAT	219,000	226,000
Unregulated 3-day winter discharge			
7. USACE analysis using published historic data	W3DCONUR.DAT	176,000	182,000
8. As 7. but using revised historic data from Table 8	3D2.DAT	168,000	174,000
9. As 8. but excluding 1897	3D3.DAT	160,000	165,000

8.0 CONCLUSIONS

Re-evaluation of the December 1921 peak discharge on the Skagit River near Concrete shows that the currently published value of 228,000 cfs is high and is inconsistent with available high water data from the Crofoot Addition of Concrete. Hydraulic modeling of the Skagit River from Concrete to a point several miles downstream from The Dalles shows that to be consistent with high water data in Concrete, the 1921 peak discharge should be revised downward to about 195,000 cfs. Peak discharge estimates for other historic floods in 1897, 1909 and 1917 have also been revised downward on the basis of differences in water level between those floods and the 1921 flood. The current and proposed revised estimates for peak, one-day, and three-day discharges are summarized in Table 11 below.

Table 11. Current and Proposed Revised Discharge Estimates for Historic Floods Skagit River near Concrete

Flood	Peak (cfs)		One-Day (cfs)		Three-Day (cfs)	
	USGS Published	Revised	Current USACE Estimate	Revised	Current USACE Estimate	Revised
November 1897	265,000	220,000	224,691	187,000	170,473	142,000
November 1909	245,000	205,000	207,733	174,000	157,607	132,000
December 1917	210,000	185,000	178,057	157,000	135,092	119,000
December 1921	228,000	195,000	193,319	166,000	146,671	126,000

While the current published estimate of the 1921 peak discharge is inconsistent with reported flood levels in the Crofoot Addition, we have been unable to identify the reason for such inconsistency. The currently published discharge estimate was determined by slope-area measurement. The most likely source of error in that estimate is in high water data which were identified in the field about a year after the event. By contrast, the high water data relied on for the revisions proposed in this report are based on a newspaper account from a first-hand observer published within a few days of the flood. We also note that discharge estimates below The Dalles appear to be much more sensitive to uncertainty that upstream of The Dalles.

Although not relied on in our analysis, the proposed revisions are consistent with other qualitative information on the historic floods above The Dalles.

According to Stewart (Stewart, 1923, Exhibit B) flows in the 1897, 1909, 1917 and 1921 floods were all *"confined within the banks of the main channel"*. From surveys conducted by Skagit County in 2007, water levels above about 185.5 ft NGVD29 at RM 55.1 would have entered a right bank spill channel and bypassed The Dalles. From the hydraulic modeling conducted for this study, the threshold flow above which water would have entered the spill channel is about 210,000 cfs. At the published 1921 peak discharge of 228,000 cfs, the hydraulic model results show that there would have been about two feet of water flowing through the spill channel. If such overflow had occurred it presumably would have been noted by Stewart, who would have crossed the spill channel several times in the course of his investigations at The Dalles.

Adoption of revised discharge estimates for the historic floods results in corresponding adjustments to estimates of the 100-year unregulated winter discharges for the Skagit River near Concrete, as summarized in Table 12.

Table 12. 100-Year Unregulated Winter Discharges Based on Current and Proposed Revised Historic Data, Skagit River near Concrete

Duration	100-Year Discharge (cfs) based on Current Estimates for Historic Data		100-Year Discharge (cfs) based on Revised Historic Data	
	Computed Probability	Expected Probability	Computed Probability	Expected Probability
Peak	278,000	288,000	254,000	261,000
One-Day	242,000	251,000	222,000	229,000
Three-Day	176,000	182,000	168,000	174,000

9.0 REFERENCES

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