An Evaluation of Flood Frequency Analyses for the Skagit River, Skagit County, Washington

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Background

The Federal Emergency Management Agency (FEMA) is conducting a Flood Insurance Study (FIS) for Skagit County, Washington and Incorporated Areas. The Seattle District of the U.S. Army Corps of Engineers (USACE) is the study contractor. The results of this study will be used to revise the Flood Insurance Rate Map for Skagit County.

The Skagit River is a 3,115 square mile watershed that originates in British Columbia, Canada and drains in a southwestern direction into Puget Sound north of Seattle, Washington. The hydrologic analyses for the FEMA study is documented in a report entitled “Draft Skagit River Basin, Washington, Revised Flood Insurance Study, Hydrologic Summary”, dated May 1, 2008 (USACE, 2008). Figure 1, taken from the USACE (2008) report, is a schematic of the Skagit River watershed showing location of dams and important gaging stations. The critical gaging station is the Skagit River near Concrete, Washington (station 12194000), drainage area of 2,737 square miles, that has long-term record from 1924 to present including four historic floods whose values have been the subject of much discussion. These historic floods occurred in November 1897, November 1909, December 1917, and December 1921 before the gaging station was established near Concrete and are the largest floods used in the USACE (2008) unregulated frequency analysis.

The USACE (2008) report is an update of a November 10, 2005 report by the same title. USACE updated their hydrologic analysis in May 2008 for the Skagit River because:

- the U.S. Geological Survey (USGS) revised the annual peak discharges for the four historic floods (Mastin, 2007) for the gaging station near Concrete, and
- regulated flow data from a previous USACE analysis were found for the period 1924-43 and were incorporated into the analysis.

The impact of the historic peak discharge revisions and new data resulted in the regulated 1-percent annual chance (base) discharge decreasing from 226,400 cfs to 209,500 cfs.

Flood frequency analyses for the Skagit River are complicated by the fact that five hydroelectric power reservoirs with flood-control capabilities have been constructed on the Skagit River or a major tributary from 1924 to 1961 plus the regulation procedures have changed over time (see Figure 1 for locations of the dams). The general modeling approach used by USACE (2008) for such a regulated watershed was to develop unregulated flows, perform frequency analyses on the unregulated flows, route the unregulated flood hydrographs through the current reservoir system, and then perform frequency analyses on the regulated peak flows.

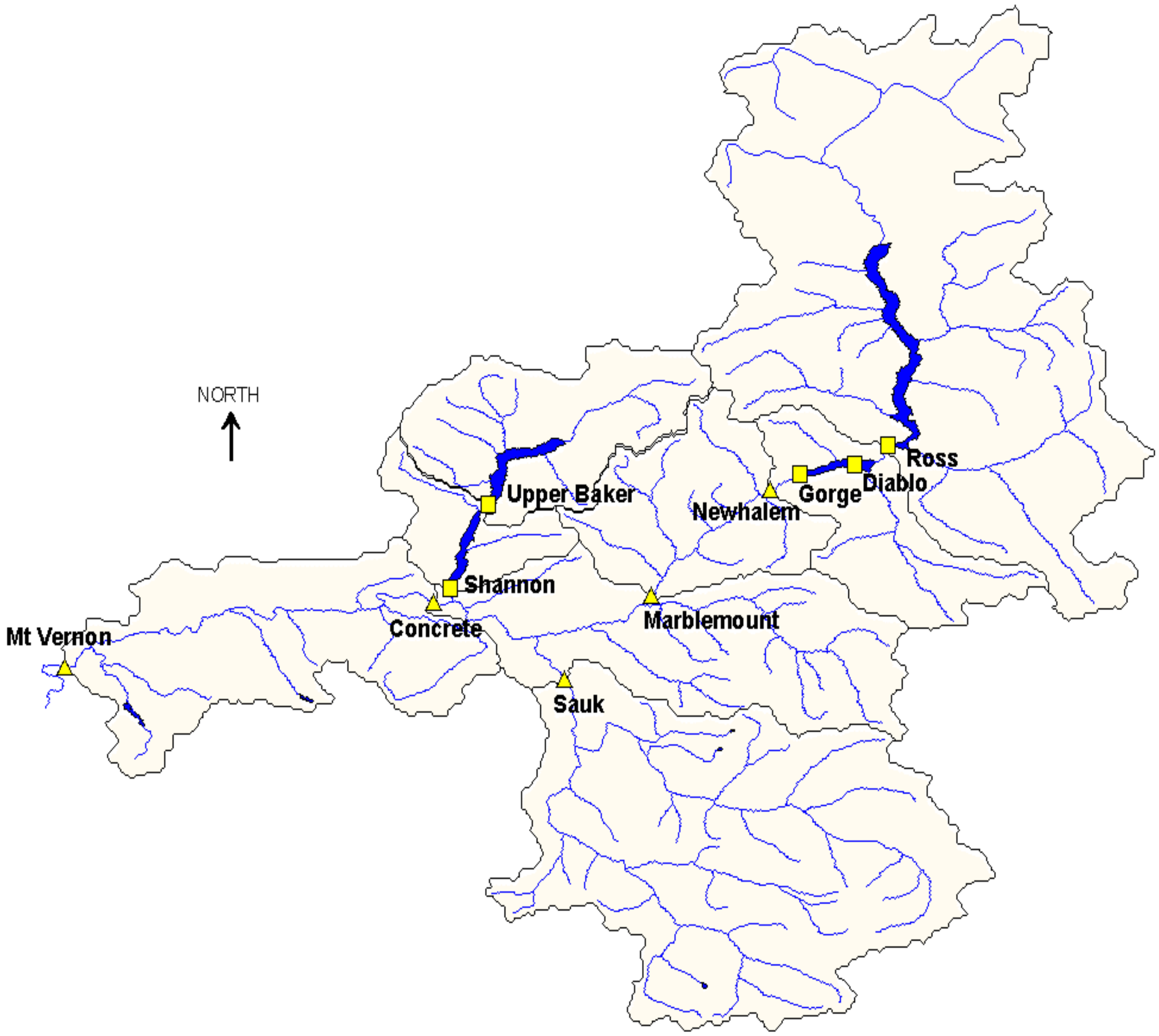

Figure 1. A map of the Skagit River watershed showing the location of dams (squares) and important gaging stations (triangles).

Purpose of this Review

Even though the USGS revised the peak discharges for the four historic floods in 2007, some local communities believe the revised discharges are still too high. Because the four historic floods are higher than any estimated unregulated peaks in the systematic record, they collectively have some influence on the magnitude of the 1-percent annual chance flood discharge. Pacific International Engineering (PIE), working as a consultant for the Cities of Burlington and Mount Vernon, and Dike Districts 1 and 12, performed independent hydrologic and hydraulic analyses for the Skagit River and estimated different peak discharges for the four historic floods. Using their revised historic peak flows, PIE (2008) performed unregulated and regulated frequency analyses for the Skagit

River. Their work is summarized in a report entitled “Skagit River Basin Hydrology - Existing Conditions” dated October 2008 (PIE, 2008).

Northwest Hydraulic Consultants (NHC), working as a consultant for Skagit County, performed independent hydrologic and hydraulic analyses and estimated different peak discharges for the four historic floods. Using their revised historic peak flows, NHC (2008) performed unregulated frequency analyses for the Skagit River near Concrete. Their analyses are described in a report entitled “Re-evaluation of the Magnitude of Historic Floods on the Skagit River near Concrete – Final Report”, dated October 2008 (NHC, 2008).

On March 17, 2010, FEMA had a meeting with Skagit County, the City of Burlington and their consultants (NHC and PIE) and the USGS and USACE to discuss issues related to the estimation of peak discharges for the four historic floods. Prior to this meeting NHC and PIE provided the following documents:

- “Re-evaluation of the Magnitude of Historic Floods on the Skagit River near Concrete – Revised Final Report”, dated March 2010, NHC,
- “Technical Memorandum – Review and Reevaluation of Skagit River 1921 Flood Peak Discharge”, dated March 2010, PIE.

The information and analyses discussed in the October 2008 reports by PIE and NHC and the information in the documents distributed for the March 17, 2010 meeting are discussed below.

Peak Discharges for Four Historic Floods

A major issue associated with the frequency analysis for the Skagit River near Concrete is the peak discharge of four historic floods that occurred in November 1897, November 1909, December 1917, and December 1921 prior to construction of the reservoirs. The peak discharges for these floods were determined originally by James Stewart, USGS, from field investigations made in 1918 and 1922-23 and documented in unpublished reports. The peak discharges were first published in USGS Water Supply Paper 1527 dated 1961 (Stewart and Bodhaine, 1961). Before the peak discharges were published for these four historic floods in 1961, the USGS performed at least two technical reviews of Stewart’s analyses in the 1950 to 1952 time period. These subsequent analyses resulted in different and lower peak discharges. However, USGS made the decision in 1961 to publish the peak discharges as originally estimated by Stewart because the differences in the peak discharges from the various analyses were less than 10 percent. Recently, PIE (2008) and NHC (2008) have estimated revised values for the four floods. The peak discharges for the November 1897, November 1909, December 1917, and December 1921 floods estimated by different analysts are summarized in Table 1.

Table 1. Summary of four historic peak discharges, in cubic feet per second (cfs), for the Skagit River near Concrete, Washington.

Source	**November 1897**	**November 1909**	**December 1917**	**December 1921**
USGS (1950)	230,000	220,000	190,000	210,000
USGS (1951-52)	265,000	240,000	205,000	225,000
USGS (1961)	275,000	260,000	220,000	240,000
USGS (2007)	265,000	245,000	210,000	228,000
PIE (2008)	181,200	179,000	158,700	169,700
NHC (2008)	220,000	205,000	185,000	195,000

The variability of estimates in Table 1 indicates there is uncertainty associated with the determination of peak discharges for these historic floods as reflected by the location and quality of the high water marks, cross-sectional data, and Manning's n values. The analyses and reports prepared by Stewart in 1918 and 1922-23 in determining the historic peak discharges were more detailed than the documentation generally available for historic floods at most gaging stations although his procedures were not as detailed and thorough as those used by USGS today.

USGS (2007) Re-evaluation of the Four Historic Floods

The peak discharge for the December 1921 flood was estimated by Stewart in 1923 with a slope-area computation and is the basis for estimating the other three earlier historic floods. The USGS re-evaluated and revised the peak discharge for the December 1921 flood in 2007 from 240,000 cfs as originally published by Stewart and Bodhaine (1961) to 228,000 cfs (Mastin, 2007). The revision was based on:

- Manning's n value of 0.0315 verified using data collected during the November 1949 flood,
- Cross sections 2 and 3 as surveyed by Stewart,
- Cross section 2 was subdivided but the same n value (0.0315) was used for both subareas, and
- Water surface slope of 0.00120 as determined by Stewart.

The revisions to Stewart's original computations include a Manning's n value of 0.0315 rather than 0.033 as used by Stewart, use of two cross sections (2 and 3) rather than all three cross sections surveyed by Stewart, and subdivision of cross section 2 for channel roughness. Mastin (2007) rated the re-computation of the December 1921 peak discharge as a "fair" measurement implying that the peak discharge of 228,000 cfs was within 15 percent of the actual value.

The USGS also recomputed the December 1921 peak discharge using Manning's n value of 0.033 estimated from the October 2003 flood and the water-surface slope from the November 2006 flood (0.00114). Again cross section 2 as surveyed by Stewart was subdivided. This computation resulted in a peak discharge of 219,000 cfs for the December 1921 flood.

The USGS decided to use the n value as verified using data for the November 1949 flood because channel conditions in 1949 were likely more similar to conditions in 1921. Mastin (2007) provides 1932 and 1948 photographs showing the island/sand bar downstream of the gaging station as mostly bare of vegetation. When the October 2003 and November 2006 floods occurred, this sand bar was densely forested.

The historic floods of November 1897, November 1909, and December 1917 were estimated from a revised rating curve that included the 1925 water year discharge measurements, the highest current-meter measurements and constraining the rating curve to pass through the recomputed December 1921 peak discharge of 228,000 cfs. The USGS (2007) revised values for the other three historic floods are given in Table 1.

On May 6, 2010, USGS sent out a letter to all attendees of the March 17, 2010 meeting commenting on information presented at that meeting and reiterating that no revisions are warranted in the four historic peak discharges. This document is referenced in subsequent discussions.

NHC (2008) Re-evaluation of the Four Historic Floods

<u>NHC (2008) Approach</u>

NHC (2008) estimated the December 1921 peak discharge using a different approach than USGS. The NHC (2008) analysis of the 1921 flood relies heavily on a description of this flood in the December 17, 1921 issue of *The Concrete Herald* newspaper that indicated flood depths were an inch to 14 inches deep in residences in the Crofoot Addition. The Crofoot Addition is that area of Concrete just west of the confluence of the Baker and Skagit Rivers. The finished floor elevation of the lowest existing residence dating from 1921 in the Crofoot Addition at 45956 Albert Street was determined to be 184.93 feet NGVD 1929. A flood depth of 14 inches was added to the finished floor elevation to get a flood elevation of 186.1 feet NGVD 1929 for the 1921 flood. A HEC-RAS model was developed for the Skagit River from River Mile (RM) 51.1 to RM 56.77. The gaging station near Concrete (station 12194000) is located at RM 54.1. The peak discharge that gave an elevation of 186.1 feet at the residence in the Crofoot Addition (RM 56.35) was 195,000 cfs and was recommended by NHC (2008) as the revised value for the December 1921 flood.

Briefly the steps and assumptions in the NHC (2008) analysis are as follows:

- Develop a 1D steady-state HEC-RAS model using cross-sectional data from in-channel and overbank sections from the 1976 FIS, in-channel sections surveyed in October 2004, and in-channel and overbank sections surveyed in 2008.

- Calibrate the HEC-RAS model using discharge data for the October 21, 2003 flood and peak elevations at the USGS gaging station, a residence in the Crofoot Addition and the current rating curve at the USGS gaging station.
- Vary the expansion/contraction coefficients in the HEC-RAS model, use ineffective flow areas and high channel roughness for the left bank of The Dalles gorge to calibrate to the 2003 high water marks. NHC (2008) points out that field conditions in The Dalles gorge deviate considerably from one-dimensional flow assumptions of the HEC-RAS model so adjustments to the model were needed.
- Compare current (1976 to 2008) cross sections to those surveyed in 1911 by USACE. NHC (2008) concluded that channel conditions had not changed significantly since 1911, thus justifying the use of recent cross-sectional data to estimate the 1921 flood.
- Estimate the 1921 peak discharge as the discharge corresponding to an elevation of 186.1 feet at the Crofoot Addition residence at 45956 Albert Street.

NHC (2008) estimated a peak discharge of 195,000 cfs for the December 1921 flood using the HEC-RAS model with high expansion/contraction coefficients. This value is 14.5 percent less than the USGS published value of 228,000 cfs. NHC (2008) developed a rating curve at the Crofoot Addition residence at 45956 Albert Street by running the HEC-RAS model for various flow values. The high water data collected and discussed by Stewart in his field notes were used to estimate elevations for the November 1897, November 1909 and December 1917 floods. The elevations for the historic floods differed somewhat from those published by USGS but the relative ranking of the floods remained the same. NHC (2008) used the flood elevations and the rating curve at the Crofoot Addition residence to estimate flood discharges for the 1897, 1909 and 1917 floods. The revised flood discharges estimated by NHC (2008) for all four historic floods are given in Table 1.

NHC (2008) used their revised estimates of the four historic floods and the USACE estimates of unregulated peak flows from 1924 to 2007 in a Bulletin 17B analysis (Interagency Advisory Committee on Water Data (IACWD), 1982). These analyses were performed with and without the 1897 flood because it has the most uncertainty. The estimate of the 1-percent annual chance flood discharge decreased less than 2 percent by omitting the 1897 flood. NHC (2008) estimate of the unregulated 1-percent annual chance flood including the 1897 flood is 254,000 cfs as compared to 278,000 cfs from the USACE (2008), a difference of about 9 percent.

<u>Comments on the NHC (2008) Analysis</u>

The following comments are pertinent to the NHC (2008) analysis:

- The re-computation of the December 1921 peak discharge is based primarily on flood depths in residences reported in a newspaper article. The assumption is made that the 14-inch flood depth is applicable to an existing residence at 45956 Albert Street. This elevation data is considered less credible than multiple high water marks surveyed in the field by James Stewart 11 months after the flood.

- As pointed out by NHC (2008), the modeling of the flow through The Dalles gorge is difficult and subject to several uncertainties such as the applicable expansion/contraction coefficients and the applicability of the cross-sectional data. The slope-area reach as used by USGS was based on a uniform (contracting) reach downstream of The Dallas Gorge and based on cross-sectional data collected in 1923 for the purpose of indirectly estimating the December 1921 peak discharge and was not subject to the uncertainties of modeling flow through the Dalles Gorge.
- NHC (2008) maintains that 1911 cross-sectional data are similar to data collected in the 1976 to 2008 time period and therefore it is appropriate to use the recent cross-sectional data to estimate the December 1921 flood. However, Figure 6 in the NHC report indicates that the streambed elevation in 1911 differed by more than 5 feet in some places and was more than 10 feet higher than current data through the Dalles Gorge. Since NHC (2008) did not use the 1911 data, this does not impact their analyses but does raise questions about the accuracy (or datum) of the 1911 data and whether the Skagit River channel has changed over time.
- Although NHC was able to match the current USGS rating, the HEC-RAS models underestimated the high water mark elevation for the 1921 flood at the Upper Dalles gage. This is likely due to the complexities of modeling the flow through The Dalles Gorge and differences in cross-sectional data and n values from 1921 to current conditions.

NHC (2010) Additional Information

For the March 17, 2010 meeting, NHC provided a March 2010 revised version of their report that included a new section titled “Uncertainty in Slope-Area Measurements for the December 1921 Flood”. This new section described the sources of uncertainty in the USGS slope-area measurement. The major concerns expressed by NHC were:

- There are only seven high water marks to support the Stewart’s slope-area measurement for the December 1921 flood and there were no high water marks between cross sections 2 and 3,
- A plot of the seven high water marks does not support the water-surface slope used by Stewart for his slope-area measurement,
- Based on high water marks surveyed by NHC and Skagit County for the November 2006 flood, there appears to be a break in water surface between cross sections 2 and 3.

In the May 6, 2010 letter sent out by Mark Mastin, USGS, he identified 13 high water marks surveyed by Stewart for the December 1921 flood and pointed out that five high water marks support the water-surface slope of 0.00119 used by Stewart for the slope-area computation. In addition, Mastin plotted high water marks surveyed by USGS and NHC for the November 2006 and these high water marks define a water-surface slope of 0.00114, very similar to the slope used by Stewart. This new information provided by USGS provides support for the slope-area measurement for the December 1921 flood.

Summary Comments on the NHC analyses

In summary, the USGS peak discharge for the 1921 flood is considered more reasonable than the NHC (2008) estimated value because:

- It is based on a slope-area measurement made downstream of the Dalles Gorge that is not subject to the HEC-RAS modeling uncertainties.
- The cross-sectional data and high water marks were surveyed in the field by James Stewart approximately 11 months after the 1921 flood.
- Manning's n values were verified by USGS using data for the November 1949 flood.
- At least five high water marks surveyed by Stewart and others in 1922-23 support the water-surface profile used in the 1923 slope-area computation and these high water marks are considered more appropriate for estimating the 1921 peak discharge than a high water mark determined from a newspaper article.

FEMA (2009) is now using one standard error (comparable to a 68-percent confidence interval) to determine if flood discharges are statistically different (November 2009 version of Appendix C: *Guidance for Riverine Flooding Analyses and Mapping*, http://www.fema.gov/library/viewRecord.do?id=2206.) The USACE (2008) unregulated frequency analysis was based on 79 years of systematic record with a historic period of 110 years (1897 to 2007) to include the four historic floods. Assuming the "effective" record length is 95 years (an average of the systematic and historic record lengths), the standard error of the USACE 1-percent annual chance unregulated discharge of 278,000 cfs is +15.5 and -13.4 percent (321,000 cfs and 240,700 cfs, respectively) (Kite, 1988). The NHC (2008) estimate of 254,000 cfs differs from the USACE estimate by about 9 percent, is within one standard error and not statistically different from the USACE estimate using FEMA (2009) criteria.

The NHC (2008) analysis does not warrant revising the USACE (2008) estimate of the 1-percent annual chance unregulated flood discharge. Performing a regulated frequency analysis was apparently not in the scope of work for the NHC study.

PIE (2008) Re-evaluation of the Four Historic Floods

PIE (2008) Approach

PIE (2008) estimated the revised peak discharges for the four historic floods using a different approach than USGS or NHC. The PIE (2008) analysis for the December 1917 and December 1921 floods relies on high water marks surveyed by James Stewart, USGS, at the Wolfe Residence about 2 miles upstream of the Concrete gaging station (RM 54.1) and at the confluence with the Baker River. The PIE (2008) analysis for the November 1897 and November 1909 floods relies on high water marks determined by

James Stewart at Savage Ranch (about RM 45.2) and Kemmerick Ranch (about RM 45.2) which are upstream of the Town of Hamilton.

The approach taken for the 1917 and 1921 floods included:

- Develop a 1D steady-state HEC-RAS model for the Skagit River and Baker River using cross sections from the 1976 FIS, cross sections surveyed by Skagit County in 2008 and by PIE in 2004 and with supplemental ground elevations from 2007 Lidar data. PIE developed a second model with revised in-channel sections using data from the 1911 USACE survey.
- Calibrate the HEC-RAS models to high water marks from the October 2003 flood using high water marks at the gaging stations and the Jenkins House in the Crofoot Addition. The downstream starting elevation for the models was provided by USGS for the Concrete gaging station.
- Assume high expansion and contraction losses for the sections in the Dalles Gorge due to two 90-degree turns of the river channel.
- Develop stage-discharge relations at the Wolfe Residence for the two HEC-RAS models using a range of discharges and estimate peak discharges for the December 1917 and December 1921 floods based on Stewart's high water marks.

PIE (2008) estimated the peak discharges for the 1917 and 1921 floods as 158,700 cfs and 169700 cfs, respectively. These values are shown in Table 1. The HEC-RAS model with cross sections modified from the 1911 USACE was used to estimate the final discharges because it was assumed the 1911 channel conditions were more indicative of conditions during these floods.

The approach taken for estimating the peak discharges for the November 1897 and November 1909 floods included:

- Utilize a modified version of an unsteady HEC-RAS model originally developed by USACE.
- Develop stage-discharge relations at Kemmerick Ranch and Savage Ranch using a range of discharges.
- Utilize the difference in elevation between the 1921 flood and the 1897 and 1909 floods to estimate peak discharges for the 1897 and 1909 floods. The discharge of 169,700 cfs for the 1921 flood, as determined at the Wolfe Residence, was used in these computations.

PIE (2008) estimated the peak discharges for the 1897 and 1909 floods as 181,200 cfs and 179,000 cfs, respectively. These values are shown in Table 1.

<u>Comments on the PIE (2008) Approach</u>

For estimating the peak discharges for the December 1917 and December 1921 floods, PIE (2008) used the high water elevations as surveyed by Stewart. There has been much discussion of the datum used by Stewart in determining the elevations of his high water marks. Stewart did most of his field work in 1922-23 before the NGVD 1929 datum was established. However, based on investigations by USGS, PIE and NHC, it appears that the pre-1929 elevations based on mean sea level were close to the NGVD 1929 datum.

There was no gaging station on the Skagit River when Stewart was conducting his 1922-23 field investigations so he established an inclined staff gage (called the Upper Dalles Gage) about 200 feet upstream of the location of the existing recording stations. Documentation provided by the USGS indicates that the Upper Dalles Gage and the existing recording station are at the same datum.

Information on the datum issue includes the following facts:

- The USGS used a datum of 142.7 ft for the Upper Dalles Gage to convert the elevations of the historic floods as surveyed by Stewart to NGVD 1929. This yields an elevation of 177.6 ft for the December 1921 flood at the current gaging station at Concrete (12194000).
- PIE (2008) has pointed out information in Stewart's field notes that indicates the datum used by Stewart was actually 140.9 ft which gives an elevation of 175.8 ft for the December 1921 flood at the Concrete gaging station.
- PIE (2008) used the lower elevations for the gaging station and high water marks as reported in Stewart's draft report in their HEC-RAS model. In addition, PIE used the 1911 USACE in-channel data which contributes to lower discharges because the in-channel elevations for the 1911 data are higher (less cross sectional area) than the current cross-sectional data.
- A November 5, 2008 letter from Mark Mastin, USGS, Tacoma, to representatives of PIE, NHC and Skagit County, summarizes the available information on the datum issue. When the recording station was established in 1924, it was set to the same datum as the inclined staff gage (Upper Dalles Gage) upstream. The datum of the recording station was later determined to be 142.7 ft NGVD.
- The evidence provided in the November 5, 2008 USGS letter is not conclusive but the preponderance of information indicates that the datum of the Upper Dalles Gage (inclined staff gage) is likely 142.7 ft NGVD.
- This implies that 1.8 ft should be added to the high water marks for the 1917 and 1921 floods as reported by Stewart and used in the PIE (2008) HEC-RAS analysis.

If a high water mark of 186.35 ft is used at the Wolfe Residence rather than 184.55 ft (as reported by Stewart), then PIE's estimate of the December 1921 flood becomes about 183,000 cfs using the 1911 cross-sectional data and about 188,000 cfs using the current cross-sectional data. PIE's estimates of the December 1921 flood ranged from 169,700 cfs to 173,900 cfs.

One would think that the 1911 cross-sectional data is more representative of conditions in 1917 and 1921 than more recent cross sections surveyed since 1976 but there may be accuracy or datum issues with the 1911 data. In places the 1911 streambed elevations differ by several feet from the current cross-sectional data and through the Dalles Gorge, the 1911 streambed elevation is more than 10 feet higher than the current elevation.

In summary, the USGS peak discharge for the December 1921 flood and the other three floods are considered more reasonable than the PIE (2008) estimated discharges for the following reasons:

- The PIE (2008) revised peak discharges for the four historic floods were based on elevations that are likely 1.8 ft too low. If the elevations of the four historic floods are increased by 1.8 ft, then the historic peak discharges will increase by about 10 percent.
- The 1911 cross-sectional data as used by PIE differs in places by several feet with the current data and raises questions about the accuracy or datum of the 1911 data.
- The PIE (2008) HEC-RAS steady state analysis is subject to the same uncertainties of using the high expansion/contraction coefficients in the Dalles Gorge as discussed for the NHC (2008) analysis.
- The USGS slope-area measurement made downstream of the Dalles Gorge is not subject to the HEC-RAS modeling uncertainties.
- The cross-sectional data collected for the slope-area measurement were obtained approximately 11 months after the flood and should be more pertinent to channel conditions during the 1921 flood.
- Manning's n values were verified by USGS using data for the November 1949 flood.
- Thirteen high water marks were surveyed by Stewart and others in 1922-23 for the slope-area reach downstream of the Concrete gaging station for the December 1921 flood. At least five of these high water marks support the water-surface slope used in Stewart's slope-area computation.

PIE (2008) used their revised estimates of the four historic floods and unregulated peaks for the observed record in a Bulletin 17B analysis (IACWD, 1982) to obtain a 1-percent annual chance unregulated discharge of 240,800 cfs. The PIE (2008) estimate is about 13 percent less than the USACE estimate of 278,000 cfs. As discussed earlier, plus and minus one standard error about the USACE estimate is 321,000 cfs and 240,700 cfs, respectively, so the PIE estimate is within this error band and not statistically different based on FEMA (2009) criteria.

PIE (2010) Additional Information

For the March 17, 2010 meeting, PIE provided a "Technical Memorandum – Review and Reevaluation of Skagit River 1921 Flood Peak Discharge", dated March 2010. This memorandum discussed the datum issue for the Stewart high water marks, deficiencies in the Stewart's slope-area computation, reevaluation of the December 1921 peak discharge using revised data for the slope-area measurement, and using the stage-discharge relation at the Concrete gaging station.

The **new** information and data summarized in the PIE (2010) Technical Memorandum are briefly described as follows:

- Low-flow water surface elevations surveyed by Stewart in December 1922 and January 1923 were compared to those surveyed by USACE in 1911 and PIE and Skagit County in 2004 and 2008. The discharges at the time of the surveys were estimated primarily using daily flows recorded downstream at the Sedro Woolley gaging station (12199000). The comparisons provided by PIE indicated that the low-flow elevations surveyed by Stewart agreed more closely with elevations surveyed by others using Stewart's datum of 140.9 ft NGVD rather than 142.7 ft NGVD as used by USGS.
- PIE's issues with Stewart's slope-area measurement included use of the incomplete energy equation, possible incorrect flow area for cross section 3, unsupported water-surface slope for the upper slope-area reach (cross section 1 to 2), and the effect of surging on the high water marks.
- PIE made revisions in the slope-area measurement and did some sensitivity tests with different n values and revised the high water mark elevations for the December 1921 flood by subtracting -0.5 to 2.0 feet of surge.
- PIE also estimated a revised peak discharge for the December 1921 flood by transferring Stewart's high water marks to the current gaging station and using the current stage-discharge relation.

As described in the PIE (2010) Technical Memo, "Factors that could affect low-flow water surface elevations surveyed by different parties include change in channel bottom geometry due to sediment degradation/aggradation, temporary debris deposition, slight flow variation, and survey accuracy. These factors may significantly affect low-flow water surface elevations". The low-flow elevations obtained by Stewart in 1922-23 were compared to USACE elevations surveyed in 1911 and those by PIE and Skagit County in 2004 and 2008, respectively. It is likely that the low-water channel did change over time as significant floods occurred between the different surveys. Additionally is not clear that the low-water elevations obtained by the different parties were in the same location. For these reasons, the low-flow elevation comparisons made by PIE are not a compelling reason to conclude that the USGS datum of 142.7 ft NGVD is incorrect.

PIE made several revisions to the input data for the slope-area measurement and determined lower peak discharges for the December 1921 flood than published by USGS. The use of the incomplete energy equation by Stewart is not a factor because Mastin (2007) recomputed this measurement using the complete energy equation. With regard to the incorrect flow area for cross section 3, Stewart's judgment and decisions at the time of the measurement should be more reliable than making judgments over 80 years later. The water-surface slope used by Stewart in the slope-area measurement is supported in the upper slope-area reach by high water marks documented in Mastin's May 6, 2010 letter. Lastly, reducing the high water mark elevations for surge is highly subjective and, as discussed in Mastin's May 6, 2010 letter, the variation in the elevations of the high water marks was due as much to differences in timing and types of marks and their resulting quality than to any surge effect. PIE's revised estimates of the December 1921 peak discharge ranging from 177,000 to 184,000 cfs are not considered as reasonable as the USGS published value of 228,000 cfs.

PIE's use of the current stage-discharge relation at the Concrete gaging station involves assumptions about the locations of the high water marks, and locations of the old gages and the slope of the water surface between them. These assumptions are not consistent with information provided by USGS. A further assumption is that the datum of 140.9 ft NGVD is applicable for the Stewart high water marks. As discussed above, the preponderance of information provided by USGS indicates the datum for the Stewart high water marks was 142.7 ft NGVD. PIE's revised estimate of 178,000 cfs for the December 1921 peak discharge using the current stage-discharge relation is not considered as reasonable as the USGS published value of 228,000 cfs.

Unregulated Frequency Analyses

The unregulated flood frequency estimates developed by USACE, NHC and PIE for the Skagit River near Concrete, WA are summarized in Table 2. The differences are primarily related to the different estimates of the four historic floods.

Table 2. Summary of unregulated flood discharges for the Skagit River near Concrete, WA (12194000).

Source	**10-percent discharge (cfs)**	**2-percent discharge (cfs)**	**1-percent discharge (cfs)**	**0.2-percent discharge (cfs)**
USACE (2008)	159,000	241,000	278,000+	373,000
NHC (2008)	153,000	222,000	254,000	325,000
PIE (2008)	146,800	212,100	240,800	309,500

+ Plus and minus one standard error 321,000 cfs and 240,700 cfs, respectively.

Regulated Frequency Analyses

USACE (2008) developed unregulated mean daily flow data for the Skagit River using natural flow data for major tributaries like Thunder River, Sauk River, Cascade River and Baker River. The unregulated mean daily flows and regression equations were used to estimate peak unregulated flow and 3-day flows. These data were used to develop balanced flood hydrographs for several frequencies including the 10-, 2-, 1- and 0.2-percent annual chance floods using the October 2003 flood to shape the hydrographs. The unregulated hydrographs were then routed through the reservoirs to produce a consistent set of regulated data.

PIE (2008) used the USACE unregulated flood hydrographs and HEC-5 and HEC-RAS models to develop their own regulated flow estimates for the 10-, 2-, 1- and 0.2-percent annual chance floods at the Concrete gaging station. PIE first performed a frequency analysis using the observed regulated record from 1956 to 2007 at the Concrete gaging station. The regulated routed flows for the 10-, 2-, 1- and 0.2-percent annual chance events were then compared to the observed frequency curve for the period 1956 to 2007. The data are compared in Figure 2 which is Figure 21 in the PIE (2008) report.

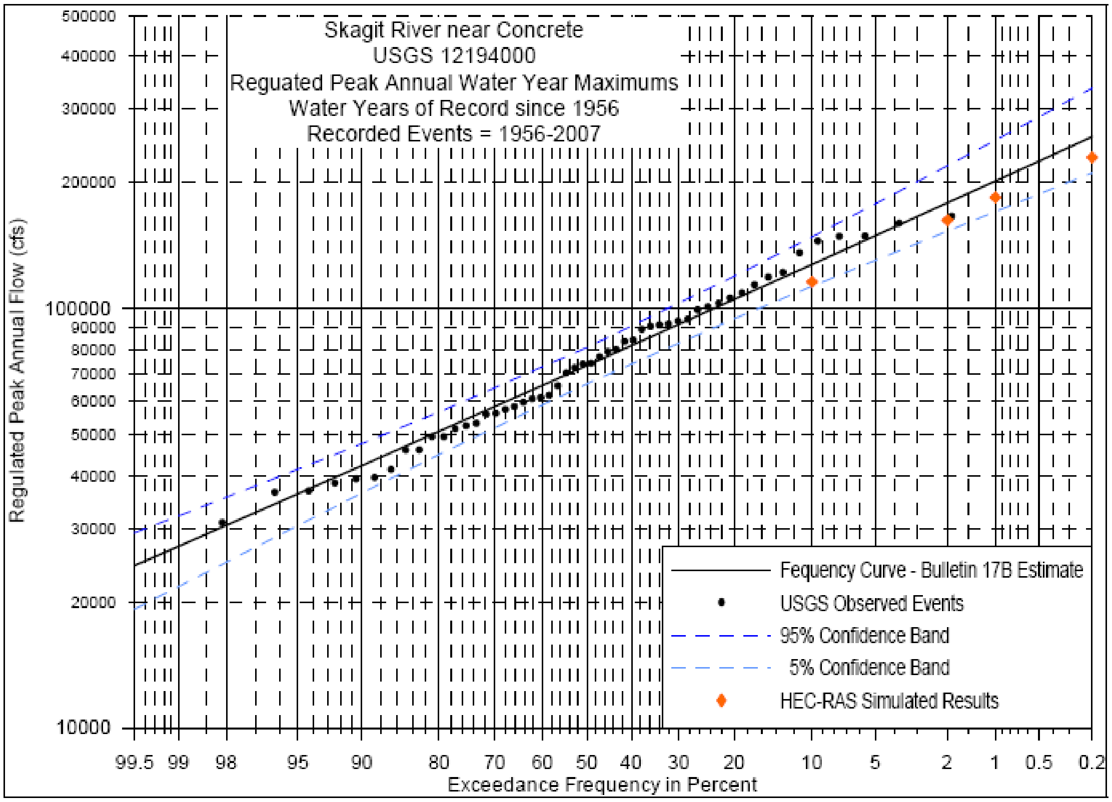

Figure 2. Flood frequency curve for regulated peak discharges observed by USGS at Concrete compared with the HEC-RAS simulated regulated peak flows at Concrete (Figure 21 from PIE (2008)).

The HEC-RAS routed flows in Figure 2 for the 10-, 2-, 1- and 0.2-percent chance floods are less than the regulated frequency curve based on the observed record from 1956 to 2007. The unregulated flood hydrographs that were routed to give the HEC-RAS simulated results in Figure 2 were based on the four historic floods and other unregulated peak data from 1925 to 1955. The PIE (2008) estimates of the four historic floods have been significantly reduced from those published by USGS and their impact on the regulated frequency curve is now minimal.

The USACE (2008) and PIE (2008) regulated and unregulated flood discharges and their ratios are summarized in Table 3. A confidence limits analysis for the USACE (2008) regulated frequency curve indicates that plus and minus one standard deviation for the 1-percent annual chance flood of 209,490 cfs are 244,300 cfs and 179,600 cfs, respectively. The PIE (2008) 1-percent annual chance discharge of 184,400 cfs falls within one standard deviation and is not statistically different from the USACE estimate according to FEMA (2009) criteria.

Table 3. Summary of regulated and unregulated flood discharges in cubic feet per second (cfs) and their ratios for the USACE (2008) and PIE (2008) analyses.

Event	**USACE regulated**	**USACE unregulated**	**USACE ratio**	**PIE regulated**	**PIE unregulated**	**PIE ratio**
10-percent	116,300	159,000	0.731	116,100	146,800	0.791
2-percent	180,260	241,000	0.748	162,600	212,100	0.767
1-percent	209,490	278,000	0.754	184,400	240,800	0.766
0.2-percent	316,530	373,000	0.849	229,400	309,500	0.741

As shown in Table 3, the ratio of the regulated to unregulated flood discharges for the PIE analysis is actually decreasing as the flood event becomes more extreme while the USACE ratio increases as it should. As the magnitude of the flood event increases and the flood storage in the reservoirs decreases, the regulated and unregulated flood discharges should converge. At the 0.2-percent annual chance event, the PIE (2008) unregulated and regulated frequency curves are still diverging. This is illustrated in Figure 3. The skew for the PIE (2008) regulated frequency curve is about -0.35 and -0.142 for the unregulated curve implying they are diverging.

The available flood storage in the Skagit River reservoirs includes 74,000 acre-feet for Upper Baker Reservoir and 120,000 acre-feet for Ross Reservoir for a total of 194,000 acre-feet. This amounts to 71 acre-feet of storage per square mile for the 2,737-square-mile watershed upstream of Concrete. The dedicated flood storage is not a significant amount and one would expect to see the 1- and 0.2-percent annual chance regulated flood discharges converging with the unregulated values.

This is the case for the USACE (2008) analyses as shown in Table 3 and in Figure 4. The skew for the USACE (2008) regulated frequency is about 2.0 and 0.0 for the unregulated curve implying the frequency curves are converging.

Comparison of Unregulated and Regulated Frequency Curves for the Skagit River developed by PIE (2008)

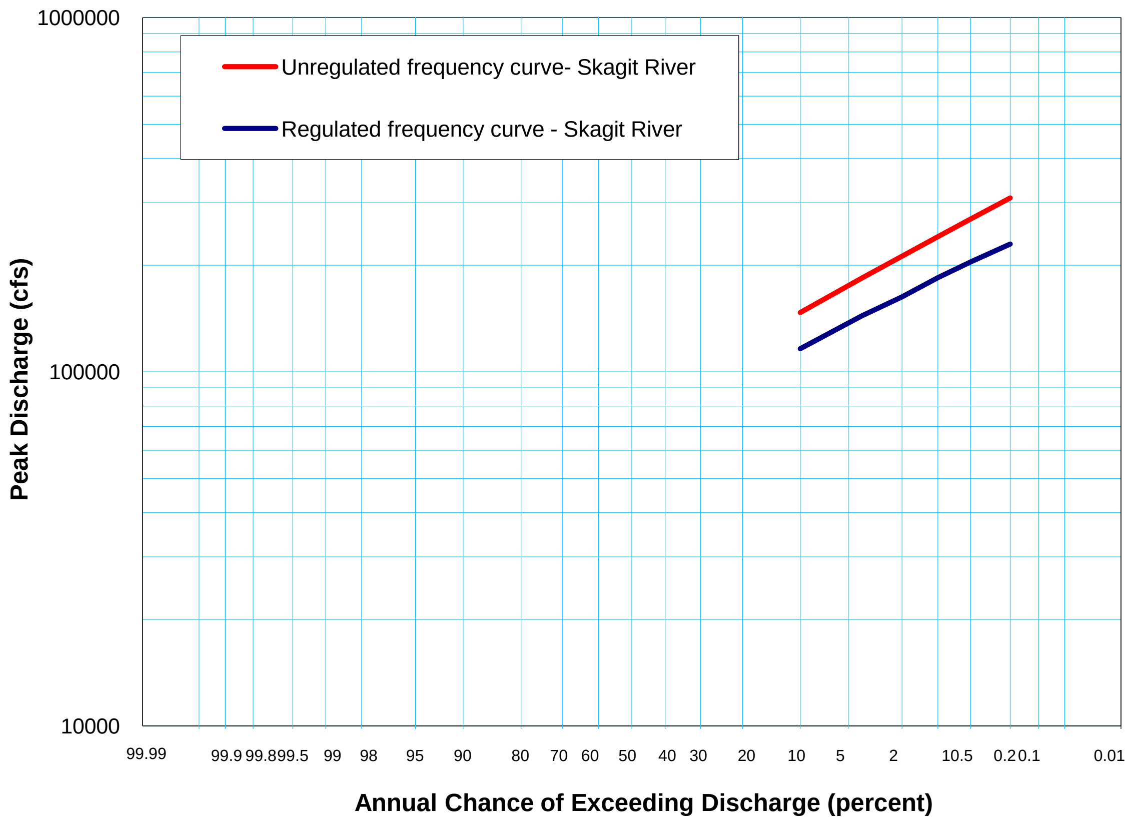

Figure 3. Comparison of unregulated and regulated frequency curves for the Skagit River near Concrete, WA as develeped by PIE (2008).

The diverging of the regulated and unregulated frequency curves was prevalent in an earlier 2005 analysis performed by PIE. This issue was discussed in a February 2006 review by FEMA. In response to the FEMA 2006 review, PIE pointed out that their 2005 frequency curves would converge at about 4 times the 1-percent annual chance flood discharge. This may also be the case for the PIE (2008) analysis that the frequency curves will converge for some very large flood event. However, it seems the PIE (2008) regulated and unregulated frequency curves should be converging for a large flood like the 0.2-percent chance flood given the dedicated flood storage (71 acre-feet per square mile) in the Skagit River watershed.

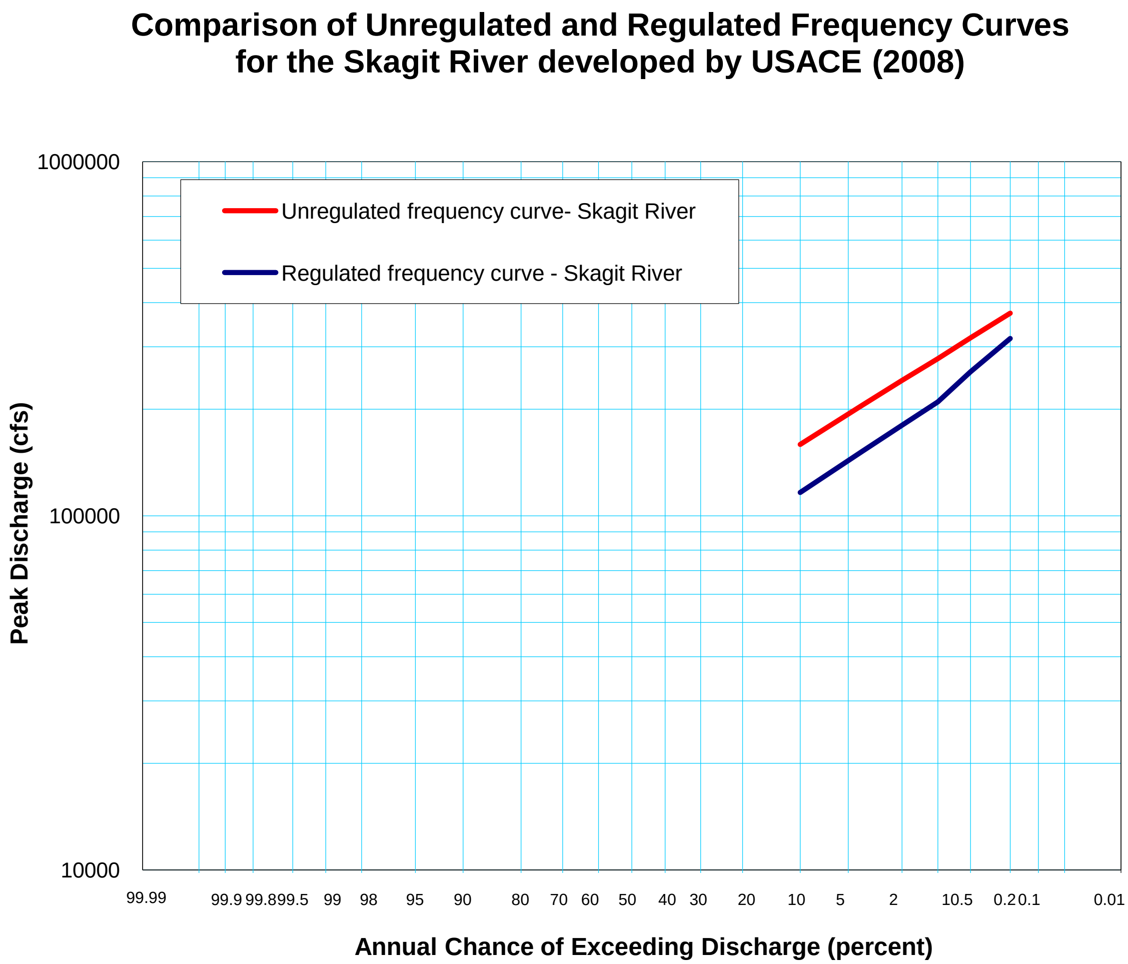

Figure 4. Comparison of unregulated and regulated frequency curves for the Skagit River near Concrete, WA as develeped by USACE (2008).

Summary

A major issue with flood frequency analyses for the Skagit River near Concrete is the magnitude of the peak discharges for four historic floods that occurred in November 1897, November 1909, December 1917, and December 1921. The values for these floods were originally published by USGS in 1961 and recently revised by Mastin (2007). However, some local communities believe the revised values are still too high. The magnitudes of the four historic floods as published by USGS are larger than any estimated unregulated peaks in the observed record since 1925. USACE (2008) used the USGS published discharges in flood frequency analyses in support of a Flood Insurance Study for FEMA.

Analyses by NHC (2008) and PIE (2008) resulted in different estimates of the four historic floods. These analyses were reviewed to determine if different values should be adopted for the Flood Insurance Study.

Based on this review, it was concluded that the USGS estimated peak discharges for the four historical floods were more reasonable because:

- The NHC (2008) and PIE (2008) HEC-RAS steady state analyses are subject to the uncertainties of using the high expansion/contraction coefficients in the Dalles Gorge.
- The USGS estimates were based on a slope-area measurement made downstream of the Dalles Gorge that is not subject to the HEC-RAS modeling uncertainties.
- The cross-sectional data and high water marks were surveyed in the field by James Stewart, USGS, approximately 11 months after the 1921 flood.
- Thirteen high water marks were surveyed by Stewart and others in the slope-area reach downstream of the Concrete gaging station for the December 1921 flood. At least five of these high water marks support the water-surface slope used in the slope-area computation.
- Manning's n values were verified by USGS using data for the November 1949 flood.
- The PIE (2008) revised peak discharges for the four historic floods were based on elevations that are likely 1.8 ft too low. If the elevations of the four historic floods are increased by 1.8 ft, then the PIE (2008) historic peak discharges will increase by about 10 percent.
- The 1911 cross-sectional data as used by PIE differs in places by several feet with the current data and raises questions about the accuracy or datum of the 1911 data.

Because the USGS estimated historic flood discharges are considered more reasonable, they should be used in the USACE (2008) analyses. The unregulated flood discharges as estimated by USACE (2008) are considered more reasonable than those from the PIE (2008) and NHC (2008) analyses. However, as shown in Table 2, the NHC (2008) and PIE (2008) estimates of the unregulated 1-percent annual chance flood are within one standard error of the USACE (2008) estimate and are not considered statistically different from a hydrologic perspective using FEMA criteria (2009).

For the USACE (2008) regulated 1-percent annual chance flood of 209,490 cfs, plus and minus one standard deviation are 244,300 cfs and 179,600 cfs, respectively (+16.6 and -14.3 percent). The PIE (2008) regulated estimate of 184,400 cfs falls within this interval and is not considered statistically different from a hydrologic perspective using FEMA (2009) criteria. However, it is recognized that differences of about 15 percent in the 1-percent annual chance discharge represents about 30,000 cfs and could mean a difference of approximately 2 feet in the water-surface elevation for the with-levees condition.

Based on this review, it was concluded that no changes are warranted in the USACE (2008) hydrologic analysis.

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