MEMORANDUM

Date: July 22, 2014
To: H&H Technical Committee
From: Bob Elliot and Larry Karpack, Watershed Science & Engineering
Cc: Bob Montgomery, Anchor QEA
Re: Chehalis Basin Strategy: Reducing Flood Damage and Enhancing Aquatic Species – Development and Calibration of Hydraulic Model

Introduction

In 2012 Watershed Science & Engineering (WSE), under contract to the Chehalis River Basin Flood Authority, developed a Hydrologic Engineering Center River Analysis System (HEC-RAS) hydraulic model of the Chehalis River from upstream of Pe Ell to the mouth of the river at Grays Harbor (WSE 2012). At the time of that 2012 work, only topographic data from 2006 or earlier were available for much of the floodplain. Additionally, new channel cross section survey data were only available for the lower portions of the model, downstream of Grand Mound. The current project updates and further refines the Flood Authority HEC-RAS model using new topographic and channel survey data.

The updated HEC-RAS model was re-calibrated to the 1996, 2007, and 2009 flood events. While the Flood Authority model was generally well calibrated, the addition of new and more accurate topographic and cross section data allows a more refined model calibration. Improved calibration increases the accuracy of the model for analyzing and mapping of baseline flood conditions. The work described herein addresses Task 1.3.3 - Collect New Channel Cross-Section Data Survey and Update the Chehalis Basin Hydraulic Model. Subsequent tasks will use the calibrated hydraulic model to evaluate benefits and impacts of flood reduction alternatives.

Background

In previous projects, WSE (under contract to the Flood Authority) and WEST Consultants (under contract to the U.S. Army Corps of Engineers [USACE 2013]) developed a HEC-RAS unsteady hydraulic model extending from the mouth of the Chehalis River to upstream of Pe Ell, a distance of more than 108 miles. The model also included significant portions of key tributaries including the Wynoochee River (54 miles), Satsop River (2 miles), Black River (10 miles), Lincoln Creek (4 miles), Skookumchuck River (21 miles), Hanford Creek (6 miles), Salzer Creek (5 miles), Newaukum River (10 miles), Dillenbaugh Creek (3.5 miles), and South Fork Chehalis River (5.8 miles). The model was developed primarily to evaluate existing flood conditions on the main stem Chehalis River and the effects of large-scale flood relief projects. The results are documented in a report to the Flood Authority (WSE 2012) and were also provided to the State Office of Financial Management for use in defining an appropriate path forward for basin-wide flood relief.

A consulting team led by Anchor QEA was retained by the State Office of Financial Management to further evaluate alternatives for reducing flood damage and enhancing aquatic species in the Chehalis basin. As hydrologic and hydraulic (H&H) lead on the Anchor QEA team, WSE is responsible for re-evaluating basin hydrology and updating the baseline hydraulic model. While the hydraulic model previously developed for the Flood Authority represented the best available information on hydraulic conditions in the modeled reaches, it nevertheless included significant reaches based on older data. Significant portions of channel geometry, including most of the mainstem reach from Doty to Grand Mound, still relied on cross sections collected between the late 1970s and 2001. Similarly, in some portions of the model floodplain, topographic data was based on photogrammetric or Light Detection and Ranging (LiDAR) data from 1998 or 2002.

WSE completed a comprehensive revision of the HEC-RAS hydraulic model, including updating the floodplain topography throughout the model using recent LiDAR as well as new Chehalis River channel surveys from Doty to Grand Mound. The model data defining lateral weirs, storage areas, and storage area connections were also updated and improved throughout the basin in the present study, using the recent LiDAR. Bridges that were destroyed in the December 2007 flood and have since been replaced or are planned for replacement later this year have also been added to the new model. The model has been recalibrated to the historic flood events from February 1996, December 2007, and January 2009. This memorandum describes the development and calibration of the updated hydraulic model.

Cross-Section Data

The most recent hydraulic model from the WSE study for the Flood Authority included recent (2011) Chehalis River channel surveys upstream of the Doty gage and downstream of Grand Mound. In the current project, these data were augmented with new channel surveys collected in the fall of 2013 by Pacific Geomatic Services (PGS) between Doty and Grand Mound. The new survey updates the critical Twin Cities area (Chehalis and Centralia) of the model and results in recent and reliable channel data for the entire 108 miles of Chehalis River mainstem. Locations for the 2013 cross section surveys were specified by WSE, and generally reoccupy the cross section locations from the earlier models. Additional surveys were collected to fill areas where the earlier models had cross sections spaced too far apart. New surveys were also identified and collected at several locations upstream of Doty, near Pe Ell, where the river channel location or width had changed significantly since the previous survey. Figures 1 and 2 display the cross-sections throughout all reaches of the model, and highlight in yellow those sections with resurveyed channel from 2013 (upper model only, Figure 1). As shown in green on these figures, the channel data along the tributary reaches were not resurveyed or updated for this study, as the primary focus of the present study is the mainstem Chehalis. Some of the tributary data dates back to the original Flood Insurance Study in the late 1970s, with significant portions of the other tributaries based upon 1998 to 2001 surveys. Exceptions include a 2-mile reach on the Skookumchuck River near Bucoda and the modeled lower three miles of the Satsop River (see Figures 1 and 2), both part of 2012 channel survey data collected in the previous Flood Authority project. The entire Wynoochee River reach of the model, extending 51 miles upstream to the dam, is based upon channel data from a USACE survey in 2009 (Figure 2).

An updated ground surface triangulated irregular network (TIN) was developed which merges the latest available LiDAR data throughout the basin. The majority of the Chehalis River floodplain is covered by the newer 2012 data sets (see Figure 3). Cross sections throughout the model were then cut from the new TIN to create more up-to-date floodplain topography for the model, compared to previous modeling, with the exception of the Wynoochee River upstream of River Mile 9.25 which does not have recent LiDAR data. Along the modeled tributaries of the Chehalis River, cross-section transect locations and alignments from the previous model were used without revision. The new floodplain data cut from LiDAR was merged with the channel data from the previous model, which as mentioned previously is based on older data. Within the Chehalis mainstem however, from Doty to Grand Mound, WSE carefully reviewed the previous cross section layout compared with aerial photography, shaded topography from the LiDAR, and the previous 100-year mapped floodplain. Cross-sections were realigned based upon engineering judgment to improve the accuracy of the cross-section layout and to update areas where the geometry may have changed (e.g., channel plan form). As mentioned previously, new cross-sections were also added as appropriate. The 2013 channel surveys were then merged with the new floodplain topography to create updated mainstem cross-sections throughout the Doty to Grand Mound reach. Upstream of Doty and downstream of Grand Mound, the floodplain data were merged with the channel data from the previous model, which is based upon recent 2011 surveys.

Figure 1
Cross Section and Weir Layout for Upper Chehalis Basin Hydraulic Model

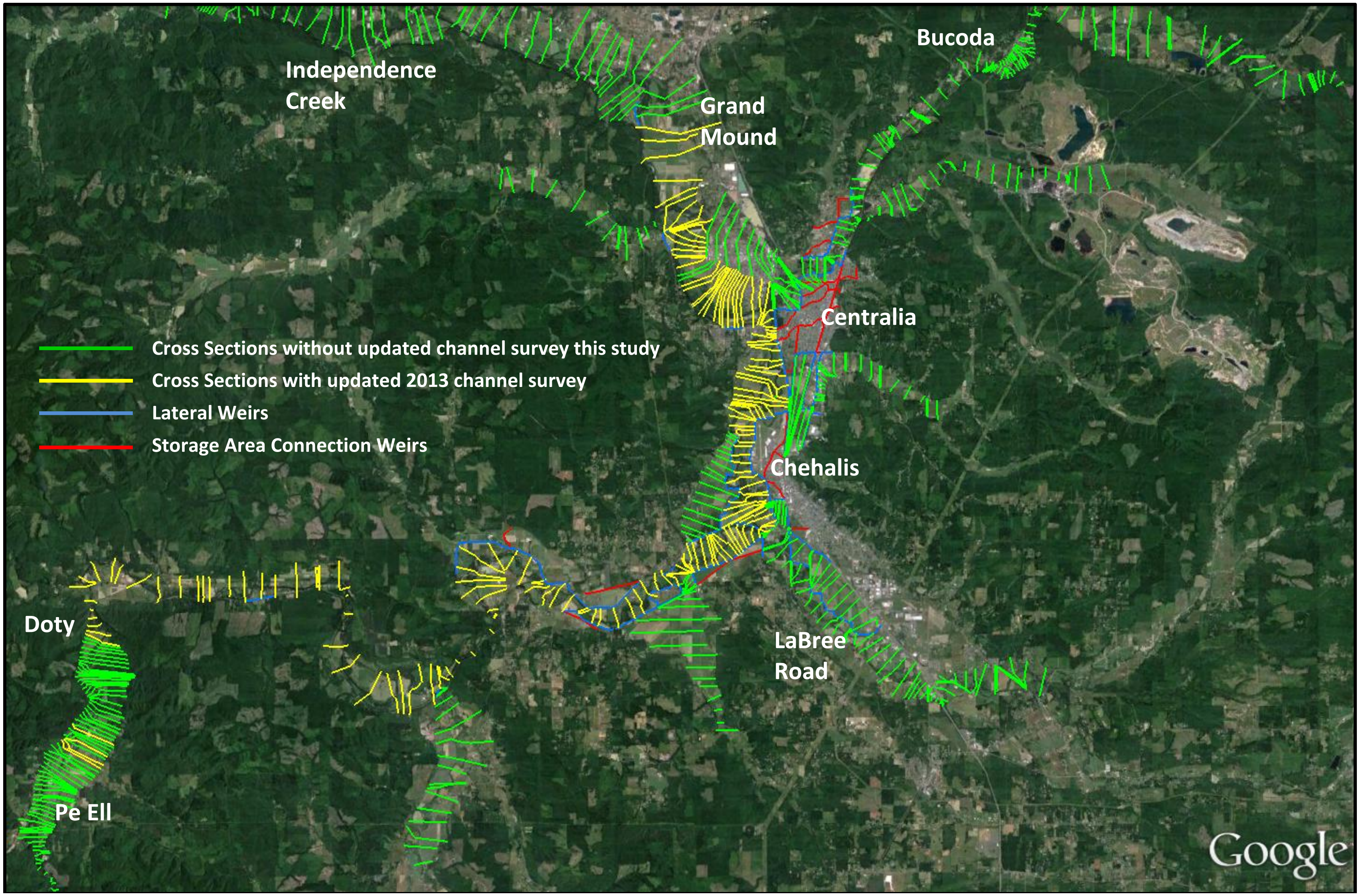


Figure 2
Cross Section and Weir Layout for Lower Chehalis Basin Hydraulic Model

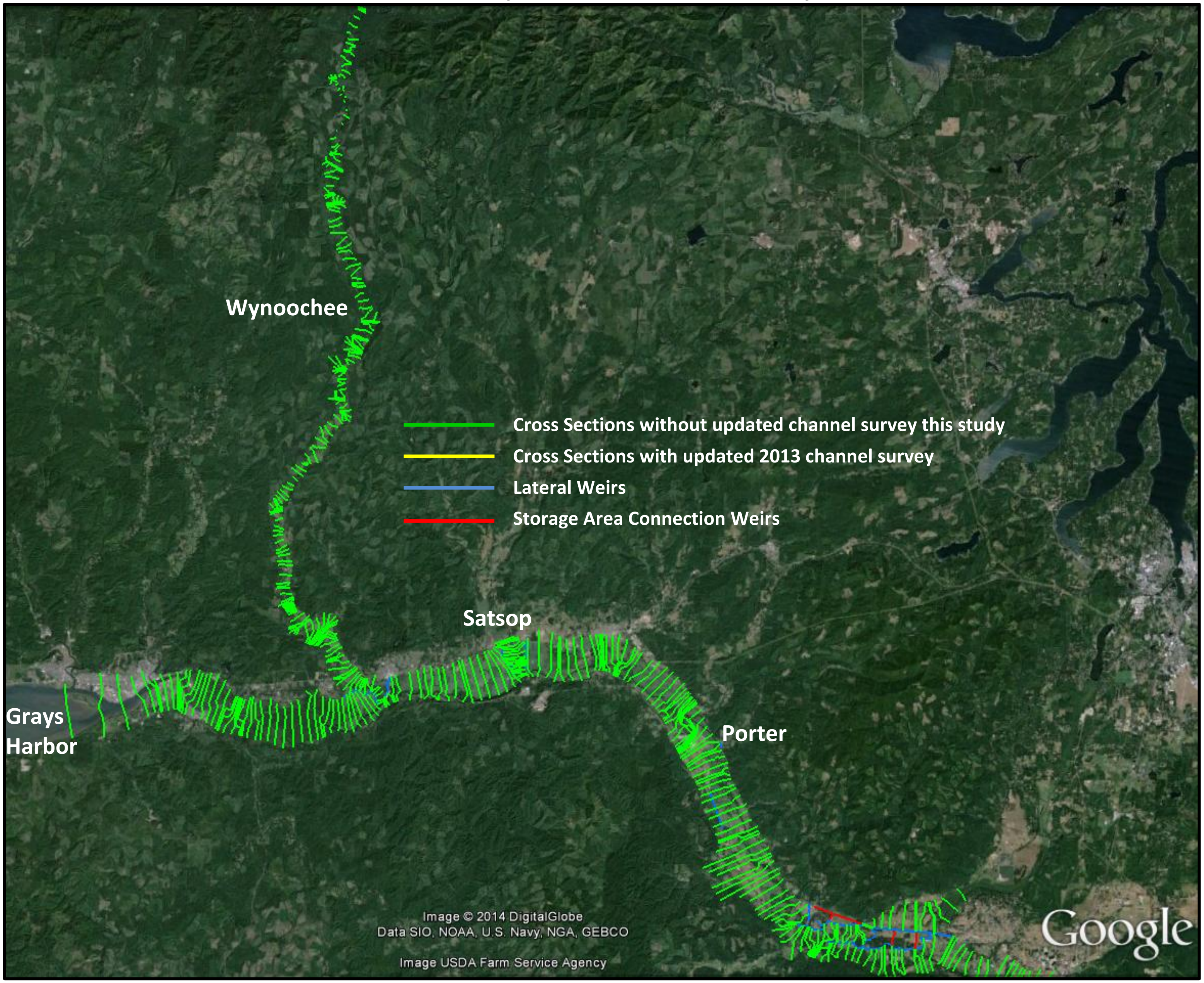
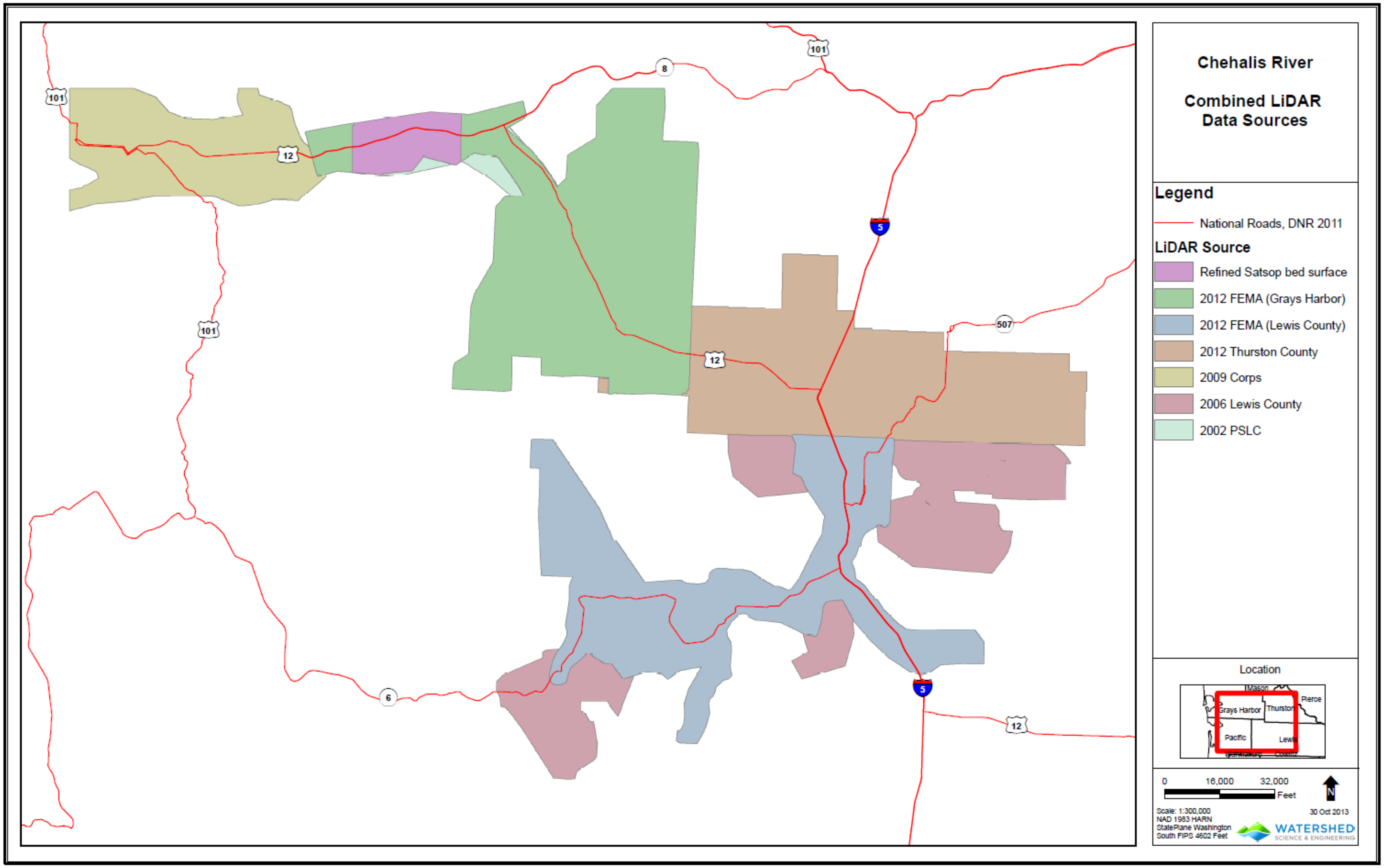


Figure 3
Combined LiDAR Data Sources for Model Floodplain Topography



The Satsop River portion of the previous model, which includes the lower three miles downstream from Montesano Elma Road (old Highway 12), was based upon a 2004 gravel pit restoration project by WEST in 2004. A more recent two-dimensional model study was completed by WSE in 2013 for Grays Harbor County. Cross sections on the Satsop were adjusted, relocated, and reoriented to more accurately mimic simulated water surface elevations and velocity vector directions from the two-dimensional model (see Figure 2). The cross-sections were cut from a refined surface TIN developed for that project which combined 2012 LiDAR with the 2012 channel surveys.

Updated main channel and overbank reach lines were drawn in GIS along the mainstem extending from above Doty (Pe Ell) to downstream of Grand Mound (Independence Creek; see Figure 1), and used to update the cross section reach lengths for the Chehalis River reaches 1 through 19. The lower Chehalis River downstream of Independence Creek, as well as all tributaries, used reach lengths established from previous modeling. Main channel bank stations were re-established from Doty to Grand Mound, by visual observation of the merged cross sections. Throughout the rest of the model, bank stations from the previous modeling were initially specified but checked throughout and adjusted as required.

Ineffective areas in the previous model were, in many locations, based upon older models and had not been updated or refined. Examination of the detailed TIN (from LiDAR) and aerial photography reveals many oxbows or remnant channels and other localized depressions in the floodplain. These floodplain features can store flood water but do not typically convey significant flow and as such need to be removed from the effective conveyance area in the model. The entire 108 mile reach of the mainstem Chehalis River was closely examined to identify all areas of ineffective flow conveyance, including natural depressions as well as those caused by bridge roadways and embankments. Cross-section ineffective areas were then adjusted and/or added as necessarily to more accurately represent these areas.

Other Model Geometry Inputs

The improved accuracy of the new topographic data provided opportunity to update the stage-volume tables of the Storage Areas (SA) in the model, as well as revise the SA boundaries. Careful observation of color shaded display of the topographic data revealed numerous locations where the high ground defining and separating SAs needed to be revised. In many areas, roadways assumed to be high ground in the previous model did not actually represent the highest ground or control of flow into or out of storage areas. Instead, other natural (or anthropogenic) ridges control the flow. Extensive revisions were thus made to the SA boundaries, and new volumes computed from the LiDAR surface over a range of elevations, to develop new SA tables.

New SAs were also created at a few locations to better simulate flow connectivity across roads or other embankments, as follows. The Airport SA formerly continued east across Interstate 5 between Chamber Way and West Street. A new weir was cut along this portion of the freeway (see below), with a new SA created for this area of North Chehalis to the east of Interstate 5. The China Creek storage area of South Centralia formerly extended south across SR 507, but for the new modeling was subdivided along a shallow ridge of high ground just north of SR 507. Two new SAs were also created within residential areas just south of the Skookumchuck River in Centralia, downstream of Pearl Street. Past modeling studies used a similar approach to evaluate levee options along the Skookumchuck River to protect these residential areas. An area near the Lincoln Creek confluence, west of Galvin Road and south of Lincoln Creek Road, was also added to properly account for possible flooding within the town of Galvin. Lastly, a narrow area between Oakville and the Black River channel behind (north of) the railroad grade was also added to capture possible flooding there.

Flow exchange between SAs and model reaches, or other SAs, are simulated by weirs (either lateral structures or SA connections in the model). These were re-cut from the LiDAR based upon the updated SA boundary lines.

Other lateral structure weirs, exchanging flow between reaches, were also updated throughout the model. New lines were drawn along the high ground dividing reaches as revealed by the updated LiDAR, and updated elevations cut from the LiDAR TIN. Figures 1 and 2 show the location and revised alignments (cut lines) for all the weirs in the model. Many of these lateral structures had been based upon very old and coarse weir data from old models, or were simply not fully represented in previous modeling, such as the lower Wynoochee and Satsop rivers. The Airport Levee and Interstate 5 near the City of Chehalis, however, had been surveyed by Washington State Department of Transportation (WSDOT) in 2012 and were updated in the previous model, with an adjustment for the 2.5 feet high jersey barrier along Interstate 5. The weirs defining these areas were therefore not modified in the current model, as the recent ground survey is more accurate and reliable than LiDAR. Revisions, however, were made to the lateral structure at north end of the Airport Levee to reflect recent modifications completed as part of WSDOT's Louisiana Avenue to Airport Road Connection Project. This includes slight modifications to the intersection of these two roads where they pass over the levee, as well as the addition of twin flap-gated relief culverts.

Throughout most of the model, bridge data were not updated from the previous model. Few bridges have been replaced since the original modeling was undertaken, and there was not sufficient time in the schedule to obtain drawings and plan sets for all of the bridges in the system to check in the model. In some bridge locations, where it appeared the previous data was insufficient or erroneous, updated top of roadway data were obtained from the new LiDAR TIN, but in most locations the roadway data from the previous modeling was retained. An exception to this is the bridges in the upper Chehalis that failed in the 2007 flood. The bridge at Chandler Road has since been replaced, and the Dryad rail-to-trail bridge is presently under construction. The Leudinghaus and Spooner rail-to-trail bridges are scheduled to be replaced later in 2014, with the former bridge to be relocated about 0.5 mile upstream. HEC-RAS models and bridge plans for each were provided by Northwest Hydraulic Consultants (NHC) and were used to update the present model.

Calibration and Verification

WSE completed a detailed peer review of the U.S. Geological Survey's (USGS's) observations and published measurements at the Doty stream flow gage during December 2007 flood event. This has resulted in a recommended reduction to the peak flow and a revised hydrograph to be used for inflow to the hydraulic model. This is documented in a separate technical memorandum by WSE (2014a). The revised inflow hydrograph, as recommended in the WSE peer review, was used in the updated hydraulic model for the December 2007 flood event. Maximum water surface results from that simulation were compared to the extensive set of flood high water marks that were obtained for that event. Because the previous hydraulic modeling was calibrated to a peak inflow at the upstream end of the model that was 15% higher, it was anticipated that significant increases in the Manning's *n* roughness coefficient might be required to offset the lower peak flow and maintain reasonable calibration. However, in general, it was determined that a reasonable calibration was able to be achieved in the new model with very limited adjustments of the roughness coefficients and other model parameters (i.e., weir coefficients, etc.).

Channel roughness coefficients along the mainstem Chehalis River range between Manning's *n* values of 0.040 and 0.050 above the Wynoochee River, and 0.036 below the Wynoochee confluence. The larger tributary rivers are similar, but within a broader range generally from 0.028 to 0.055. Other smaller tributaries with limited high water mark data were mostly left unchanged from previous modeling, and typically use higher Manning's *n* values consistent with smaller and more vegetation-choked creek channels. Overbank roughness coefficients throughout the model generally range from about 0.050 to 0.14, depending upon the vegetation on the floodplain. Compared to the previous HEC-RAS models developed for the Federal Emergency Management Agency (FEMA) and the Flood Authority, roughness coefficients are similar in most reaches; although, the previous modeling had more reaches of channel exceeding 0.050, including 0.060 on the Chehalis River from SR 6 to Mellen Street in the Flood Authority model.

Note that the new model not only represents updated cross section geometry that in many reaches may more closely represents the channel conditions in 2007, but also represents a more accurate model in general with regard to ineffective areas, weirs, and other inputs, for the reasons described previously. The result is a calibrated hydraulic model that, in most locations, matches or even improves upon the December 2007 high water mark comparison from the previous model. The December 2007 event was run with updated geometry that includes both the newly built and/or proposed bridges that were washed out in that flood (see previous section titled Other Model Geometry Inputs), as well as an alternative simulation maintaining the old bridge geometries from the previous model. Also included in the alternative run was a log jam and failure that occurred just downstream of the Pe Ell water treatment plant, near River Mile 105 (simulated as an inline weir). The high water marks more closely match the run using the older geometries, which predict a higher backwater behind each bridge that more accurately represents the high water that would have occurred before each bridge failed. The calibration (and verification) geometry also reflects the previous former Sickman Ford bridge condition without the new overflow openings that were recently constructed.

The updated model calibrated to December 2007 was then validated or verified to the January 2009 and February 1996 flood events. Additional slight adjustments were made to some of the model inputs (roughness, weir coefficients) to match the measured high water marks from these two events as close as possible. These two events have a smaller database of high water marks than the 2007 event. There were no high water mark measurements near the failed bridges of Reach 1, so it was not necessary to re-simulate the 1996 event with the former bridges. After final adjustment of inputs for these two events, the December 2007 event was then simulated a final time, to confirm that the final model adjustments did not compromise the initial calibration of this event. Figures 4 and 5 plot the computed water surface elevation for each historic event along the upper Chehalis River mainstem (above Independence Creek), compared to the measured high water marks. Tables 1 and 2 compare the measured and computed water surface elevations throughout the model. As is typical when collecting flood observations, there is moderate scatter in many of the high water mark elevations, with varying accuracy, which the model is unable to perfectly replicate. Furthermore, river morphology and floodplain modifications have occurred since these floods events took place. The model cross-section geometries represent near-present conditions (2011 to 2013) along the mainstem Chehalis River, which was not necessarily the condition during each of these floods. Nevertheless, on average, overall, the model still comes within 0.1 foot of matching the high water mark data, with nearly 75% of the locations are within 1 foot of the measured elevation (see Tables 1 to 3). To further evaluate the percentage or number of high water mark locations within thresholds other than one foot, a histogram analysis was completed examining the simulated to measured data for all three events. Figure 6 presents a chart of the results. Table 3 further summarizes the results, presenting the number of high water mark locations and percentage thereof that fall within a specified range of simulated water surface differences. Table 3 shows that 53 of the 259 total high water mark measurements fall within (plus or minus) 0.2 foot of the simulated results, or 20%. On the other hand, 234 points or 90% of the measured locations fall within 2.0 feet of the simulated results. The simulated model results are within 0.5 foot of the measured high water marks at about half of the locations.

Figure 4
Comparison of Computed Water Surface Elevations to High Water Marks (Reaches 1 and 3)

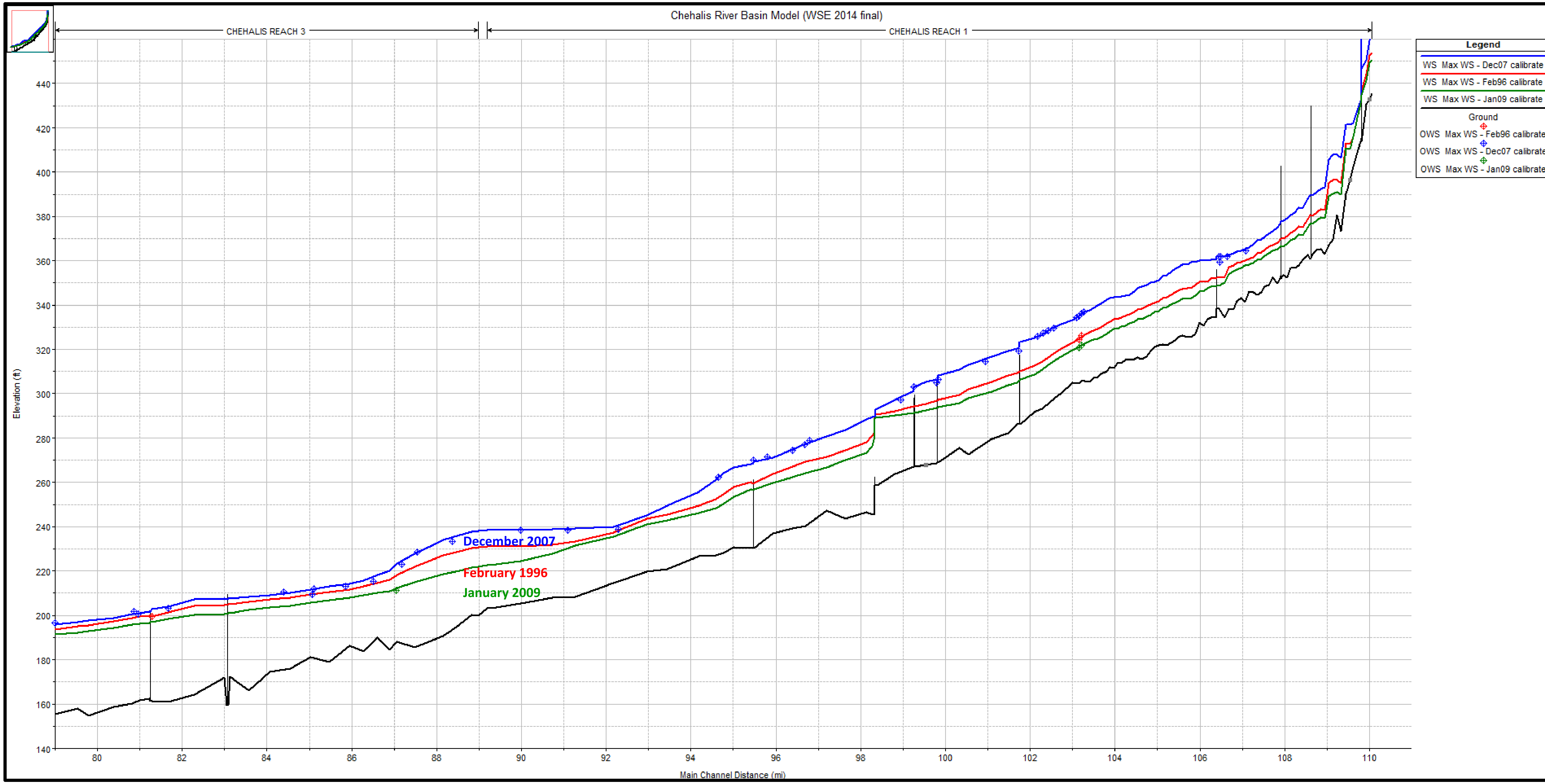


Figure 5
Comparison of Computed Water Surface Elevations to High Water Marks (Reaches 5 to 19)

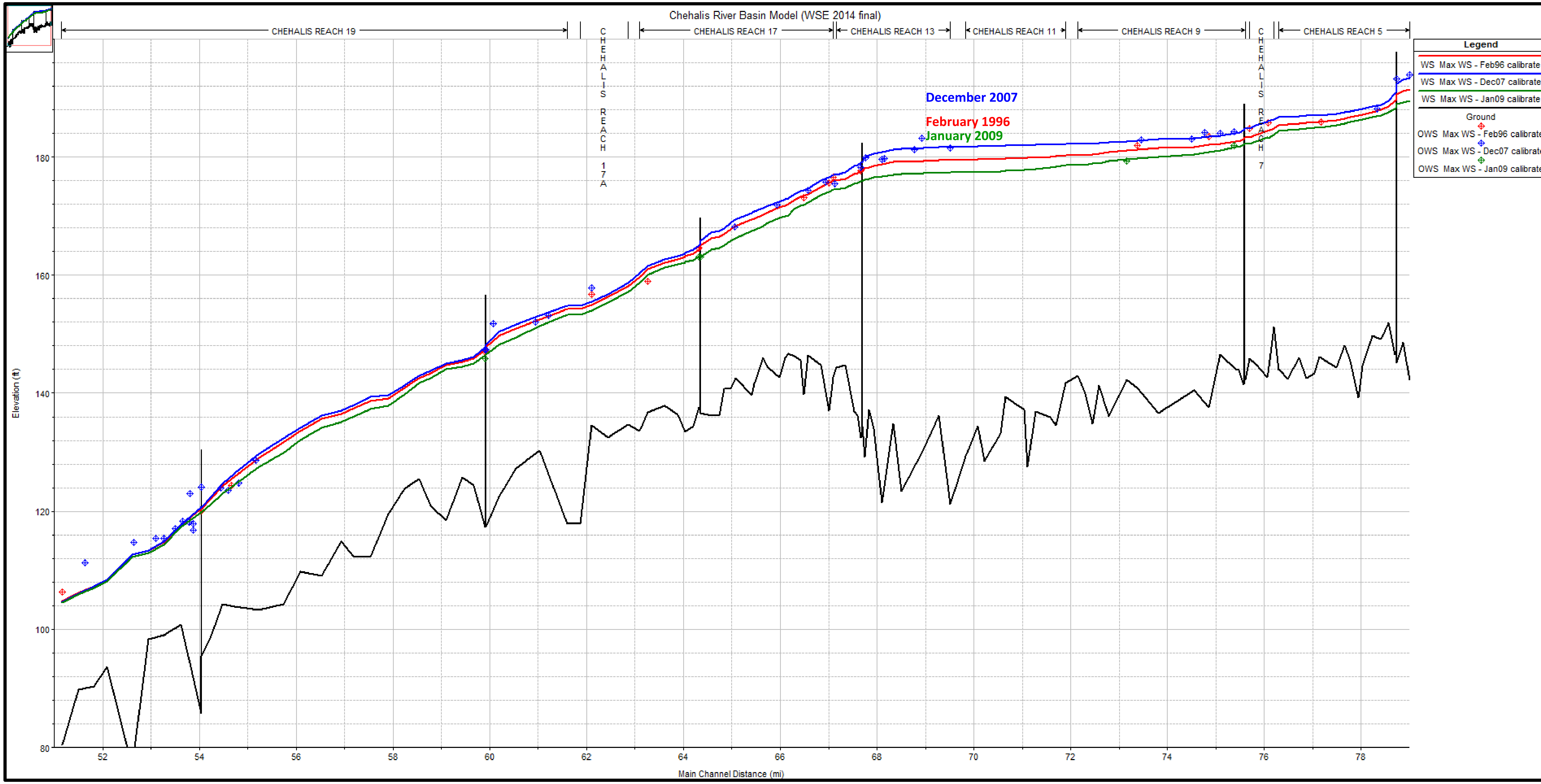


Table 1

Tabulated Differences Between Observed and Simulated Stages for December 2007 Calibration Event

DECEMBER 2007				
	Nearest Section	Measured Stage	Simulated Stage	Difference
Reach	(RM)	(Feet NAVD)	(Feet NAVD)	(Feet)
UPPER CHEHALIS MAINSTEM	105.53	364.43	365.28	0.8
	105.16	362.06	362.27	0.2
	104.97	361.95	361.83	-0.1
	104.97	359.31	361.78	2.5
	104.97	362.03	361.77	-0.3
	101.92	336.80	336.62	-0.2
	101.85	336.22	335.83	-0.4
	101.8	335.15	335.06	-0.1
	101.549	334.20	334.34	0.1
	101.12	329.73	329.88	0.1
	101.12	328.48	328.41	-0.1
	100.95	327.47	326.79	-0.7
	100.76	325.74	325.79	0.1
	100.41	319.21	320.62	1.4
	99.77	314.49	315.68	1.2
	98.47	306.61	308.38	1.8
	98.44	305.11	306.49	1.4
	97.86	303.05	302.79	-0.3
	97.49	297.26	298.56	1.3
	95.5	278.96	278.10	-0.9
	95.5	277.18	277.23	0.1
	95.16	274.49	274.99	0.5
	94.76	271.42	270.67	-0.8
	94.26	269.88	268.88	-1.0
	93.44	262.17	262.34	0.2
	91.06	238.93	240.78	1.8
	90.1	238.38	238.97	0.6
	88.9	238.62	238.57	-0.1
	87.56	233.48	235.24	1.8
	86.42	228.41	228.51	0.1
	86.01	223.20	224.48	1.3
	85.53	215.15	217.33	2.2
	85.05	212.98	213.87	0.9
	84.3	212.08	211.87	-0.2
	84.3	209.27	211.80	2.5
	84.07	210.41	209.73	-0.7
	81.42	203.11	203.89	0.8
	80.96	200.66	200.95	0.3
	80.57	201.80	200.58	-1.2
	78.97	196.44	195.81	-0.6
			Reach average:	**0.4**
			Percent within 1 ft:	**70%**

MIDDLE CHEHALIS MAINSTEM	77.92	193.97	193.42	-0.6
	77.65	193.20	192.44	-0.8
	77.39	188.20	188.74	0.5
	74.57	184.29	183.97	-0.3
	74.25	184.00	183.66	-0.3
	74.02	184.10	183.44	-0.7
	73.73	183.10	183.22	0.1
	72.8	182.90	182.83	-0.1
	69.22	181.60	181.69	0.1
	68.67	183.20	181.54	-1.7
	68.67	181.30	181.49	0.2
	67.86	179.80	180.99	1.2
	67.86	179.60	180.90	1.3
	67.51	179.90	179.97	0.1
	67.43	178.20	179.04	0.8
	66.95	175.50	177.00	1.5
	66.73	175.77	176.31	0.5
	66.47	174.42	174.71	0.3
	65.8	171.93	172.33	0.4
	64.9	168.20	169.22	1.0
	61.96	157.90	155.46	-2.4
	61.05	153.13	153.66	0.5
	61.05	152.03	152.81	0.8
	60.22	151.80	149.49	-2.3
	59.917	147.32	148.25	0.9
	59.909	147.34	147.84	0.5
			Reach average:	**0.1**
			Percent within 1 ft:	**73%**

LOWER CHEHALIS MAINSTEM	55.24	128.61	129.20	0.6
	54.729	124.77	127.02	2.3
	54.476	123.60	125.44	1.8
	54.476	124.01	124.35	0.3
	54.045	124.06	120.77	-3.3
	54.037	124.06	120.81	-3.3
	54.037	116.73	119.54	2.8
	54.037	117.83	119.51	1.7
	53.625	122.92	119.07	-3.9
	53.625	118.17	118.88	0.7
	53.625	118.29	118.01	-0.3
	53.625	117.03	116.79	-0.2
	53.264	115.42	114.84	-0.6
	52.61	114.72	112.78	-1.9
	51.499	111.34	106.57	-4.8
	33.593	53.16	53.41	0.3
	19.51	32.20	31.96	-0.2
	12.5	17.34	17.00	-0.3
			Reach average:	**-0.5**
			Percent within 1 ft:	**50%**

DECEMBER 2007				
	Nearest Section	Measured Stage	Simulated Stage	Difference
Reach	(RM)	(Feet NAVD)	(Feet NAVD)	(Feet)
SOUTH FORK CHEHALIS	5.29	259.81	258.67	-1.1
	4.75	253.15	253.46	0.3
	3.5	244.58	245.97	1.4
	3.5	243.98	244.98	1.0
	3.01	243.20	243.81	0.6
	3.005	244.10	243.45	-0.7
	3.004	241.32	243.31	2.0
	1.81	238.31	238.65	0.3
	1.81	238.14	238.65	0.5
	1.24	238.38	238.60	0.2
	0.14	236.80	238.42	1.6
STEARNS	2.32	194.08	194.85	0.8
	0.73	194.33	194.35	0.0
NEWAUKUM	4.11	206.60	206.19	-0.4
	1.03	187.52	187.36	-0.2
	0.09	187.65	187.08	-0.6
DILLENBAUGH	0.321	186.96	186.31	-0.7
	0.043	185.49	184.91	-0.6
SCHEUBER	2.598	186.40	183.40	-3.0
	0.695	183.27	182.83	-0.4
	0.317	182.40	182.44	0.0
SALZER	3.4	181.50	181.89	0.4
	2.32	181.76	181.88	0.1
	2.22	181.80	181.89	0.1
	1.3201	181.90	182.06	0.2
	1.28	181.80	182.06	0.3
	1.15	182.10	182.06	0.0
	0.86	181.80	182.06	0.3
	0.65	181.80	182.07	0.3
	0.65	181.70	182.07	0.4
SKOOKUMCH	20.7	330.97	330.72	-0.3
	6.4	210.32	210.50	0.2
	2.41	186.55	185.83	-0.7
	0.61	176.40	177.36	1.0
	0.49	177.50	177.35	-0.2
LINCOLN	2.7	158.20	158.27	0.1
	1.6	157.80	158.27	0.5
	1.1	157.80	158.27	0.5
	0.9	158.00	158.26	0.3
	0.88	157.70	158.26	0.6
	0.4	157.90	158.01	0.1
	0.2	158.05	155.33	-2.7
BLACK	9.83	112.13	114.24	2.1
	9.14	112.36	113.66	1.3
	9.09	110.75	113.24	2.5
	7.05	109.90	108.75	-1.2
	6.54	103.70	104.49	0.8
	6.54	103.86	104.05	0.2
	5.64	105.34	102.79	-2.6
	5.64	103.92	102.78	-1.1
SATSOP	2.87	40.11	40.12	0.0
			Reach average:	**0.1**
			Percent within 1 ft:	**76%**

STORAGE AREAS	SA #101	188.24	188.05	-0.2
	SA #2	182.20	182.13	-0.1
	SA #201	181.74	182.12	0.4
	SA #302	187.14	186.58	-0.6
	SA 34	113.95	111.80	-2.2
	SA 34	112.61	111.80	-0.8
	SA 35	107.44	104.54	-2.9
	SA #5	180.70	179.90	-0.8
	SA #5	180.40	179.90	-0.5
	SA #608	181.70	181.88	0.2
	SA #608	181.50	181.88	0.4
	SA #609	177.40	177.12	-0.3
	SA #610	178.48	177.35	-1.1
	SA #610	177.71	177.35	-0.4
	SA #611	178.59	179.90	1.3
			Reach average:	**-0.5**
			Percent within 1 ft:	**73%**

ALL LOCATIONS			*Overall average:*	**-0.08**
			Percent within 1 ft:	**71%**

Red shading indicates locations where simulated water surface exceeds the measured stage by more than one foot.

Table 2

Tabulated Differences Between Observed and Simulated Stages for February 1996 and January 2009 Validation Events

FEBRUARY 1996

Reach	Nearest Section (RM)	Measured Stage (Feet NAVD)	Simulated Stage (Feet NAVD)	Difference (Feet)
CHEHALIS MAINSTEM	101.85	326.10	325.67	-0.4
	101.8	324.41	324.81	0.4
	81.03	199.37	199.67	0.3
	76.1	185.93	185.95	0.0
	75.09	185.75	184.37	-1.4
	74.82	184.90	183.33	-1.6
	74.02	183.40	182.03	-1.4
	72.8	181.90	181.27	-0.6
	67.86	179.61	178.80	-0.8
	67.43	177.70	177.60	-0.1
	66.88	176.54	175.99	-0.5
	66.73	175.61	175.56	-0.1
	66.36	173.12	173.38	0.3
	64.2	164.53	164.30	-0.2
	63.2	158.90	161.05	2.2
	61.96	156.73	154.90	-1.8
	59.917	147.06	147.72	0.7
	59.909	146.91	147.40	0.5
	59.334	146.95	147.40	0.5
	54.476	124.43	125.47	1.0
	54.045	120.11	120.43	0.3
	51.159	106.36	104.82	-1.5
	50.022	99.72	99.66	-0.1
	45.217	87.21	87.73	0.5
	42.283	71.20	76.52	5.3
	33.593	52.26	53.35	1.1
NEWAUKUM	4.11	206.49	206.12	-0.4
	1.66	187.90	187.11	-0.8
DILLENBAUGH	1.25	187.10	186.51	-0.6
	0.09	185.41	183.62	-1.8
SALZER	1.56	180.40	179.98	-0.4
	1.28	180.40	179.98	-0.4
	0.36	180.12	179.70	-0.4
SKOOKUMCH	20.7	333.98	334.63	0.6
	6.4	215.87	215.70	-0.2
	3.84	201.66	200.91	-0.8
	2.42	190.69	190.84	0.2
	2.21	188.40	188.89	0.5
	2	187.70	187.49	-0.2
BLACK	9.09	113.00	112.93	-0.1
	4.62	100.95	101.54	0.6
	3.44	97.48	98.39	0.9
	2.5	96.12	95.78	-0.3
SATSOP	2.87	37.00	38.58	1.6
			Average:	**0.0**
			Percent within 1 ft:	**75%**

Red shading indicates locations where simulated water surface exceeds the measured stage by more than one foot.

JANUARY 2009

Reach	Nearest Section (RM)	Measured Stage (Feet NAVD)	Simulated Stage (Feet NAVD)	Difference (Feet)
CHEHALIS MAINSTEM	101.85	321.97	321.82	-0.2
	101.8	320.92	321.16	0.2
	85.99	211.10	212.07	1.0
	74.57	181.95	181.63	-0.3
	72.58	179.30	179.63	0.3
	64.25	163.11	163.08	0.0
	64.2	163.11	163.03	-0.1
	59.917	145.27	146.51	1.2
	59.909	145.86	146.35	0.5
	33.593	51.85	51.76	-0.1
	19.51	32.10	31.56	-0.5
	12.5	19.47	17.68	-1.8
NEWAUKUM	7.89	242.81	242.32	-0.5
	7.7	241.58	241.36	-0.2
	7.7	239.81	240.05	0.2
	7.54	237.71	239.20	1.5
	7.48	237.56	238.55	1.0
	7.42	237.42	236.71	-0.7
	7.32	236.36	235.61	-0.8
	7.21	234.02	233.84	-0.2
	7.13	233.81	233.55	-0.3
	6.87	230.69	231.32	0.6
	6.87	230.00	230.54	0.5
	6.66	227.48	227.50	0.0
	6.43	225.60	224.32	-1.3
	6.43	223.89	222.95	-0.9
	6.03	220.35	220.39	0.0
	5.62	216.92	216.85	-0.1
	5.28	213.94	213.67	-0.3
	5.01	211.71	211.35	-0.4
	4.68	210.39	209.68	-0.7
	4.35	206.73	208.40	1.7
	4.11	206.68	206.28	-0.4
	4.1	205.62	205.93	0.3
	3.86	202.51	203.31	0.8
	3.38	200.36	200.19	-0.2
	2.97	197.61	197.01	-0.6
	2.85	195.71	194.49	-1.2
	2.62	193.62	192.79	-0.8
	2.27	190.69	189.75	-0.9
	1.92	189.03	187.79	-1.2
	1.66	187.94	187.02	-0.9
	1.49	185.95	186.22	0.3
	1.46	185.81	186.04	0.2
	1.3	185.40	185.59	0.2
	0.06	184.68	184.28	-0.4
DILLENBAUGH	1	185.40	186.10	0.7
	0.792	185.40	186.02	0.6
	0.155	182.40	183.79	1.4
	0.142	182.40	183.71	1.3
SALZER	2.32	181.70	178.41	-3.3
	2.25	181.70	178.31	-3.4
	2.05	181.20	177.42	-3.8
	1.15	176.40	177.35	0.9
SKOOKUM	20.7	333.74	333.60	-0.1
	6.4	215.66	215.50	-0.2
	2.415	189.98	190.31	0.3
	2.41	190.83	190.43	-0.4
BUCODA	0.78	250.80	250.65	-0.2
	0.69	249.00	249.35	0.3
	0.64	248.90	249.02	0.1
	0.4	245.50	246.00	0.5
BLACK	6.54	105.03	103.01	-2.0
	5.64	103.22	101.58	-1.6
STORAGE AREA	SA 36	103.155	98.59	-4.6
			Average:	**-0.3**
			Percent within 1 ft:	**77%**

Figure 6
Histogram of Water Surface Elevation Differences for Model Simulation of 2007, 1996, and 2009 Floods

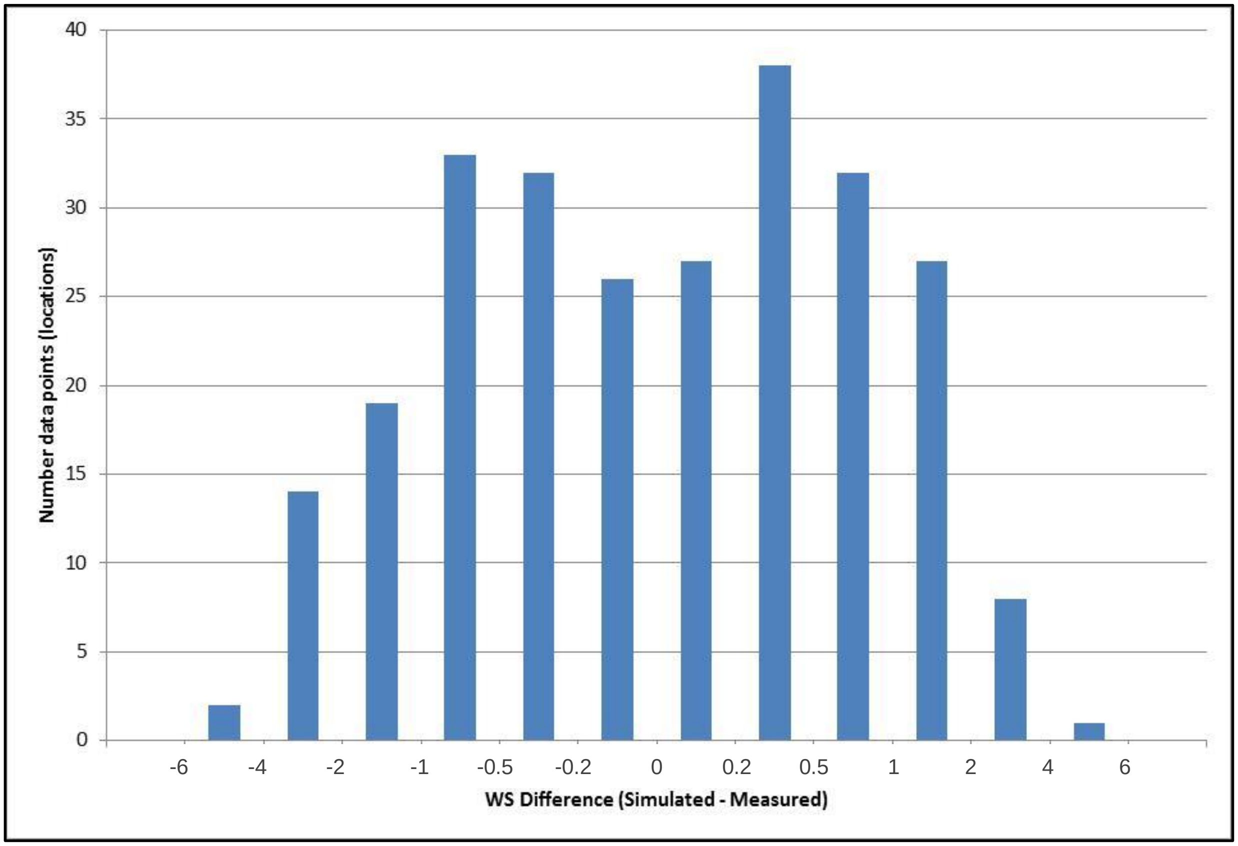


Table 3
Summary of Simulated versus Observed Water Surface Elevations for 2007, 1996, and 2009 Floods

	ABSOLUTE VALUE OF WATER SURFACE ELEVATION DIFFERENCE			
	0 – 2 FEET	0 – 1 FEET	0 – 0.5 FEET	0 – 0.2 FEET
Number of points out of 259 within specified range:	234	189	124	53
Percentage of points within range:	90%	73%	48%	20%

For the primary December 2007 calibration event, the average differences and percentage of simulated values within 1 foot of the observed high water marks were further summarized by reach as follows: Upper Chehalis above Stearns Creek, Middle Chehalis (Twin Cities), Lower Chehalis below Grand Mound gage, all tributaries, and all storage areas. Results are included in Table 1, and generally indicate consistency throughout the model, with more than 70% of values within 1 foot of the high water mark data and average differences within 0.5 foot for each of the sub reaches. The lone exception is the Lower Chehalis Mainstem reach below Grand Mound, which comprises mostly high water mark data for the very complex area near model Reach 19 where multiple sloughs and overflow connections with the Black River exist between Rochester and Oakville. This area is very two-dimensional in nature, and more difficult to characterize with even a branched flow one-dimensional model such as HEC-RAS. There is also considerable uncertainty in the lateral inflow hydrographs used in the model for both the Black River and Independence Creek. Lastly, as revealed in Figure 5 towards the left end of the plot, there is wide scatter in the observed high water mark data in this area, thus it is impossible to closely match many of the data points. Note that because there is considerably less high water mark data within many of the reaches, a similar reach based evaluation was not undertaken for the 2009 and 1996 flood events.

Manning's *n* roughness coefficients used in the HEC-RAS model represent the appropriate roughness values necessary for calibrating to the peak conditions of measured flood events. It was discovered from examining the Doty gage (WSE, 2014a), however, that smaller flows required less channel roughness in order to more closely match the lower end of the USGS rating curve at Doty. Larger flood events, on the other hand, which flood the thicker vegetation along the upper banks of the channel, required higher roughness. There were other uncertainties regarding the 2007 event, such as heavy debris, which may have also influenced needing a larger Manning's *n* value. In order to reasonably replicate the USGS rating curve through the entire unsteady simulation, flow roughness factors were implemented, which are part of the HEC-RAS plan data and not the geometry data. These allowed adjusting the roughness based on the discharge, and specifically reducing the roughness for smaller discharges to enable a closer match to the USGS rating curve. This method was chosen over that of vertical variation of n values in the geometry data for a number of reasons. Most importantly, one can easily apply flow roughness factors over long reaches of the model, which is much easier than specifying vertical *n* value variation by depth for every cross section within the desired reach. Previous modeling of the Chehalis basin also relied on flow roughness factors, within other reaches of the model. It is important to remember the use of the flow roughness factors and their inclusion in the plan data rather than the geometry data file. To replicate rating curves over the full range of flows, the fully calibrated model requires these to be linked together. It will not be possible for another modeler to utilize or import the geometry alone and reproduce the same low flow results. Figure 7 presents a reasonable fit between the single value rating curve established from the model results to the USGS rating curve in effect at the time of the December 2007 event, rating number 17.1 (WSE 2014a).

The USGS rating curves at the Grand Mound and Porter gages were also examined, and it was determined that similar roughness adjustments would be needed to more closely match the lower end of the most recent USGS rating curves at these locations. Therefore, varying flow roughness factor tables have been applied throughout the mainstem Chehalis River, from the upstream end above Pe Ell in Reach 1 through Reach 23 on the lower Chehalis River (as far as the Satsop River confluence, where one begins to see the tidal effects). It was more difficult at these locations to match the latest USGS rating curves while at the same time calibrate and verify the model to the measured flow and stage data recorded by the USGS during these past flood events, due to changing channel conditions and shifts in the rating curves since the floods occurred. Figures 8 and 9 compare the looped rating curves predicted by the model at Grand Mound and Porter, respectively, to the latest USGS ratings. Included in these plots are rating curves that are predicted by the model when the flow roughness factors are only applied to Reach 1 (for the Doty gage) but not downstream to correct for Grand Mound and Porter. A less desirable fit results without the flow roughness factors.

The flow roughness table values vary throughout based on what was required to match as close as reasonably possible the rating curves at these USGS gage locations as well as the recorded stages and flows from the two gages at the Twin Cities treatment plants, just below SR 6 and Mellen Street. These two gages suggest a smaller variation in roughness than at the USGS gages, thus a smaller adjustment was used in the flow roughness tables. This reach of the river differs from others on the Chehalis, with a flatter slope and in general less bank vegetation, which may be the reason for the lower roughness variation. For consistency, flow roughness factors were applied throughout the Chehalis River (to the Satsop confluence), which includes long reaches without stream flow gages. Because of the reduced channel capacity and additional overbank flooding one sees further downstream of Doty, the roughness adjustments below Reach 1 were mostly confined to in-channel flows.

Figure 7
Simulated Doty Rating Curve from December 2007 Hydraulic Model at Compared to USGS Rating Number 17.1

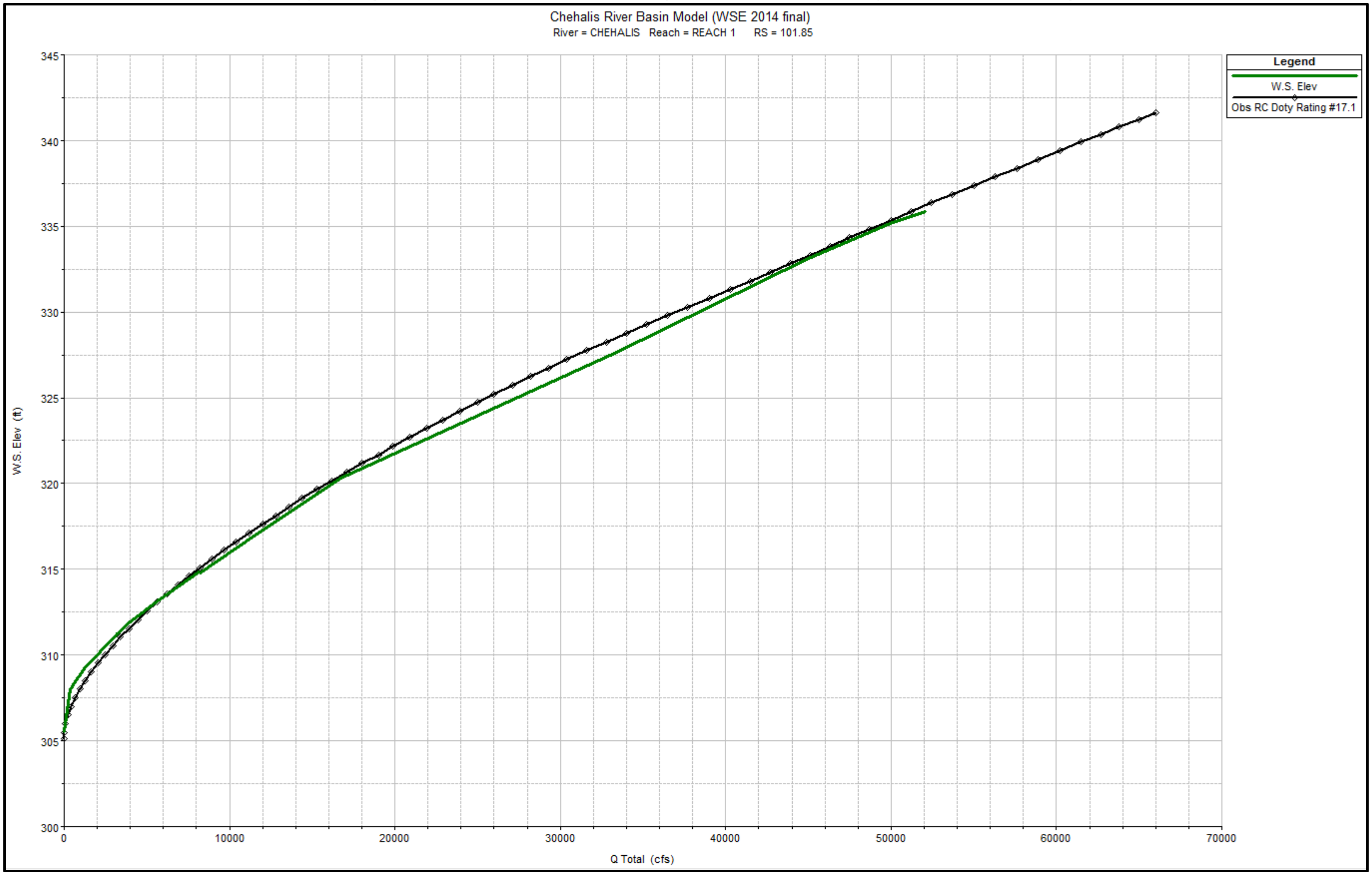


Figure 8

Grand Mound Rating Curves from December 2007 Model Results With and Without Flow Reduction Factors Compared to USGS

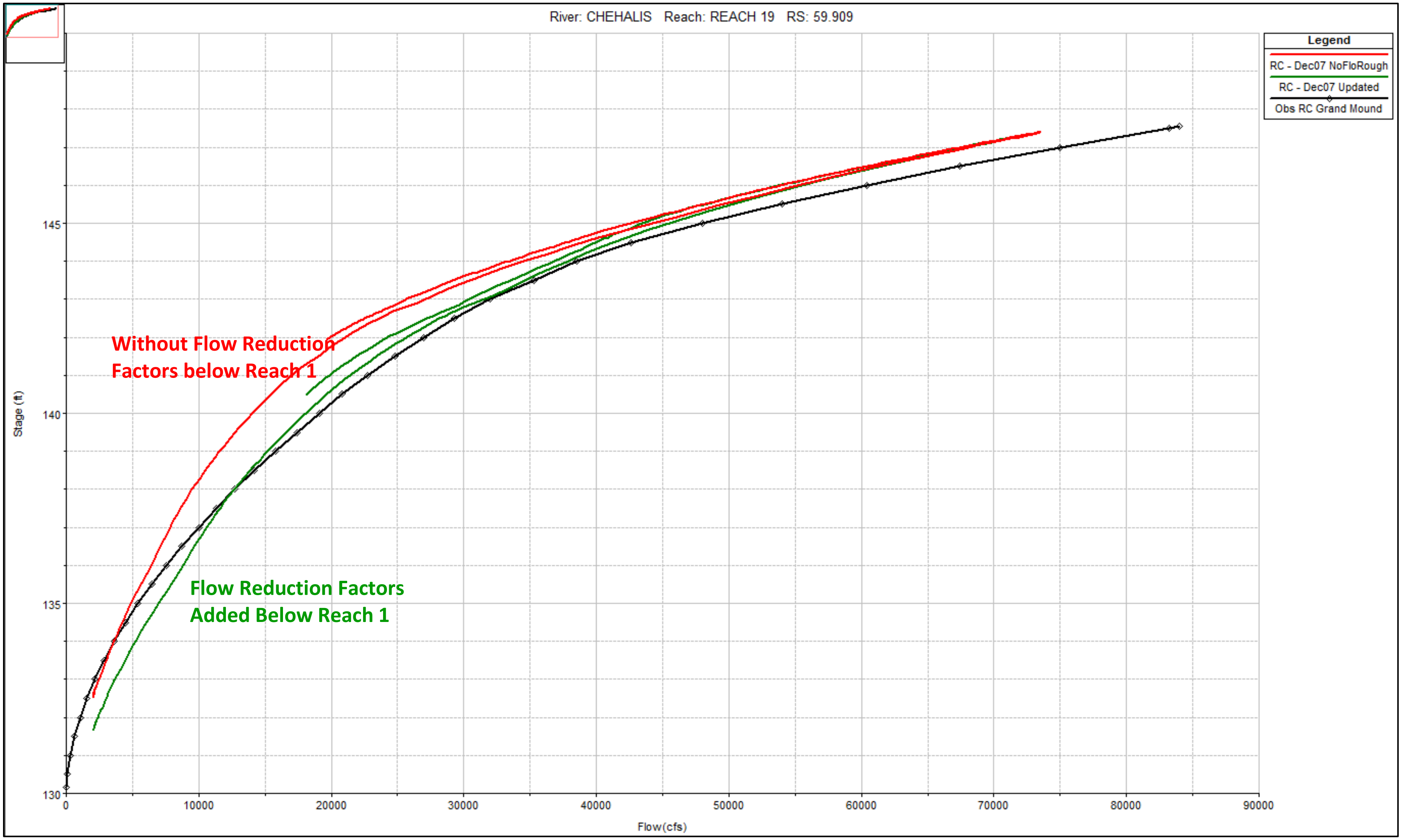
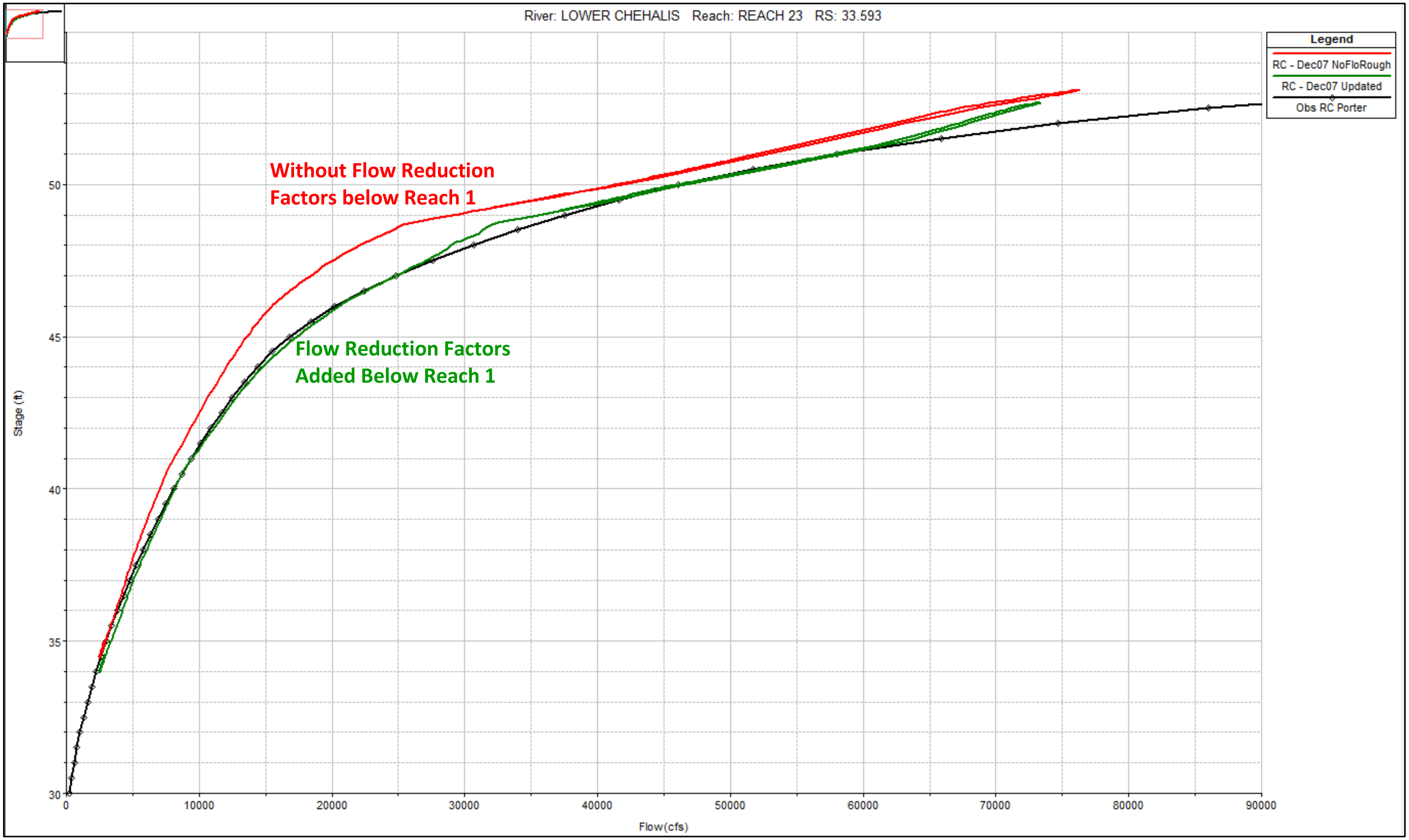


Figure 9

Porter Rating Curves from December 2007 Model Results With and Without Flow Reduction Factors Compared to USGS



The Skookumchuck River stream flow gages at Bucoda, Bloody Run, and Centralia were also examined, and required higher Manning's *n* roughness at the very lowest flows, unlike the Chehalis River. This could be a result of outdated channel bed data throughout most of the Skookumchuck and possible recent sedimentation that the model may not be representing. Note there is also a USGS gage and rating curve on the Newaukum River at LaBree Road (Figure 1), which USGS believes accounts for the total Newaukum flow including that which spills over into Dillenbaugh Creek (based on having taken a direct discharge measurement upstream of the flow split near the peak of the February 1996 flood). Because the hydraulic model separates the Newaukum and Dillenbaugh flow, modeling the split flow rather than the combined flow, the rating curve on the Newaukum could not be compared to the model results and no flow roughness factors were applied on that river.

Synthetic Storm Design Events

Baseline simulations representing the 500-year, 100-year, 20-year, 10-year and 2-year simulations have been completed with the final calibrated model, representing both the existing (without-dam) condition as well as with the proposed flood retention facility upstream of Pe Ell. For each with-dam model run, the upstream model inflow above Pe Ell was first routed by Anchor QEA through their reservoir simulation model. For all design event runs, the model geometry was updated to use the new (or soon to be completed) replacement bridges in the upper Chehalis Basin, as well as the new Sickman Ford overflow openings. Furthermore, cross section and weir geometries were modified, based upon previous HEC-RAS modeling, to represent WSDOT's Mellen Street to Blakeslee Junction (MTB) project.

When compared to the previous modeling completed by WSE for the Flood Authority in 2012, the 100-year water surface elevations within the Twin Cities reach are slightly different. Between the Newaukum and Skookumchuck confluences, the new simulation results are somewhat lower, but generally by less than 0.5 foot. This is due in part to a slight reduction in the upstream Doty inflow hydrograph resulting from the updated hydrologic analysis (WSE 2014a). Downstream of the Skookumchuck River, to the Grand Mound gage, the new simulations show slightly higher water surface elevations, up to about one foot. Here, changes in model topography as well as roughness coefficients determined through model calibration yielded the somewhat different result.

Modeling efforts have been completed using the full range of synthetic flood events to evaluate additional alternatives for WSDOT along Interstate 5, as well as to map flood depths and identify flood impacted buildings throughout the basin for the economic analyses of this project.

Summary and Conclusions

WSE completed a major revision to the Chehalis River Basin unsteady HEC-RAS hydraulic model. Because the model is unsteady, complete with hydrograph inputs and storage areas (SAs) as well as cross sections that account for storage effects, it is an appropriate and suitable tool for evaluating the various channel and floodplain projects and analyses underway for the Chehalis River Basin Flood Hazard Mitigation Alternatives Analysis Project. Along the mainstem Chehalis River, the revised model is essentially new, with updated channel and floodplain topography as well as refined reach lengths, storage area volumes and connections, and ineffective flow areas. The model has been calibrated to the December 2007 flood event for which a large body of high water mark data exists. Upstream inflow to the model was based upon revised estimates for the USGS Doty hydrograph for that event. The model was then verified to flood events in 1996 and 2009. Flow roughness factors were used to further adjust channel roughness to allow the model to reasonably capture the full rating curve at each USGS stream flow gage location.

Hydraulic analyses using the revised HEC-RAS model have been completed for a broad range of flood hazard reduction alternatives. Model simulations have been performed for the 500-year, 100-year, 20-year, 10-year, and 2-year synthetic storm events as well as three historical flood conditions (February 1996, December 2007, January2009). Simulations have been conducted for the existing (without-dam) condition as well as with the proposed flood retention facility and the Airport levee. Other simulations performed to date include evaluation of WSDOT Alternative 1 (Interstate 5 floodwalls and berms) and WSDOT Alternative 2 (raising Interstate 5) including sub-alternatives to investigate the effects of the Airport and Southwest Chehalis levees and various Dillenbaugh Creek and Salzer Creek bridge alternatives. In addition runs have been conducted to evaluate the effect of small scale projects, potential wetland mitigation banks, and various combinations of the aforementioned scenarios. A comprehensive list of the model runs completed to date is included in Appendix A. The list shows the HEC-RAS plan, geometry, and flow input files for each run as well as the HEC-RAS short ID. Data, including simulated model outputs in HEC-DSS format is available for all of these runs and flood inundation mapping in GIS format is also available for many of the runs.

Selected model simulations were also re-run under the assumption of potential future increases in flow due to climate change. Two climate change scenarios were evaluated, one assuming an across the board increase in model inflows of 18% and the other assuming an increase of 90%. The 18% increase corresponds to the reported average increase for rain dominant basins in the Pacific Northwest based on analyses by the University of Washington Climate Impacts Group (Snover, 2013). The 90% increase reflects recent analyses that use more refined methods for downscaling global climate model data to account for orographic and other basin specific effects at a finer resolution (Salathé, 2014). For model simulations that are assumed to include the proposed upstream flood retention facility, the climate-increased inflow above Pe Ell was first routed by Anchor QEA through their reservoir simulation model. Appendix B lists the climate change model runs completed to date including the plan, geometry, and flow files and short ID for each run. Model output data in HEC-DSS format is available for all of these runs and flood inundation mapping in GIS format is available for many of the runs.

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Appendix A

Chehalis.prj (baseline hydrology without climate change)

Flood Event	Geometry	Dam	I-5	I-5 Airport Sub-alts	I-5 Dillenbaugh Sub-alts	I-5 Salzer Bridge Sub-alts	Other Sub-alts or Scenarios	HEC-RAS input files			
								Geometry	*Flow*	*Plan*	*Short ID*
Feb-96	Pre-2007	Without	No Project					1	1	1	Feb96 calibrate
Dec-07	Pre-2007	Without	No Project					1	2	2	Dec07 calibrate
Jan-09	Pre-2007	Without	No Project					1	3	3	Jan09 calibrate
Feb-96	Current	Without	No Project					2	1	4	Feb96 baseline
Dec-07	Current	Without	No Project					2	2	5	Dec07 baseline
Jan-09	Current	Without	No Project					2	3	6	Jan09 baseline
500-Year	Current	Without	No Project					2	4	7	500yr baseline
100-Year	Current	Without	No Project					2	5	8	100yr baseline
20-Year	Current	Without	No Project					2	6	9	20yr baseline
10-Year	Current	Without	No Project					2	7	10	10yr baseline
2-Year	Current	Without	No Project					2	8	11	2yr baseline
Dec-07	Current	With	No Project					2	10	12	Dec07 FC res
100-Year	Current	With	No Project					2	13	13	100yr FC res
Feb-96	Current	With	No Project	With Airport Levee (complete)				3	9	14	Feb96 FC ArptLev
Dec-07	Current	With	No Project	With Airport Levee (complete)				3	10	15	Dec07 FC ArptLev
Jan-09	Current	With	No Project	With Airport Levee (complete)				3	11	16	Jan09 FC ArptLev
500-Year	Current	With	No Project	With Airport Levee (complete)				3	12	17	500yr FC ArptLev
100-Year	Current	With	No Project	With Airport Levee (complete)				3	13	18	100yr FC ArptLev
20-Year	Current	With	No Project	With Airport Levee (complete)				3	14	19	20yr FC ArptLev
10-Year	Current	With	No Project	With Airport Levee (complete)				3	15	20	10yr FC ArptLev
2-Year	Current	With	No Project	With Airport Levee (complete)				3	16	21	2yr FC ArptLev
Feb-96	Current	Without	Floodwalls and Berm	Without Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		4	1	22	1996 Alt1 noApt
Dec-07	Current	Without	Floodwalls and Berm	Without Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		4	2	23	2007 Alt1 noApt
Jan-09	Current	Without	Floodwalls and Berm	Without Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		4	3	24	2009 Alt1 noApt
500-Year	Current	Without	Floodwalls and Berm	Without Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		4	4	25	500yr Alt1 noApt
100-Year	Current	Without	Floodwalls and Berm	Without Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		4	5	26	100yr Alt1 noApt
20-Year	Current	Without	Floodwalls and Berm	Without Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		4	6	27	20yr Alt1 noApt
10-Year	Current	Without	Floodwalls and Berm	Without Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		4	7	28	10yr Alt1 noApt
2-Year	Current	Without	Floodwalls and Berm	Without Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		4	8	29	2yr Alt1 noApt
Feb-96	Current	With	Floodwalls and Berm	Without Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		4	9	30	FC96 Alt1 noApt
Dec-07	Current	With	Floodwalls and Berm	Without Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		4	10	31	FC07 Alt1 noApt
Jan-09	Current	With	Floodwalls and Berm	Without Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		4	11	32	FC09 Alt1 noApt
500-Year	Current	With	Floodwalls and Berm	Without Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		4	12	33	FC500 Alt1 noApt
100-Year	Current	With	Floodwalls and Berm	Without Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		4	13	34	FC100 Alt1 noApt
20-Year	Current	With	Floodwalls and Berm	Without Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		4	14	35	FC20 Alt1 noApt
10-Year	Current	With	Floodwalls and Berm	Without Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		4	15	36	FC10 Alt1 noApt
2-Year	Current	With	Floodwalls and Berm	Without Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		4	16	37	FC2 Alt1 noApt
Feb-96	Current	Without	Floodwalls and Berm	With Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		5	1	38	1996 Alt1 AptLev
Dec-07	Current	Without	Floodwalls and Berm	With Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		5	2	39	2007 Alt1 AptLev
Jan-09	Current	Without	Floodwalls and Berm	With Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		5	3	40	2009 Alt1 AptLev
500-Year	Current	Without	Floodwalls and Berm	With Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		5	4	41	500yr Alt1 AptLv
100-Year	Current	Without	Floodwalls and Berm	With Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		5	5	42	100yr Alt1 AptLv

Flood Event	Geometry	Dam	I-5	I-5 Airport Sub-alts	I-5 Dillenbaugh Sub-alts	I-5 Salzer Bridge Sub-alts	Other Sub-alts or Scenarios	HEC-RAS input files			
								Geometry	*Flow*	*Plan*	*Short ID*
20-Year	Current	Without	Floodwalls and Berm	With Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		5	6	43	20yr Alt1 AptLev
10-Year	Current	Without	Floodwalls and Berm	With Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		5	7	44	10yr Alt1 AptLev
2-Year	Current	Without	Floodwalls and Berm	With Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		5	8	45	2yr Alt1 AptLev
Feb-96	Current	With	Floodwalls and Berm	With Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		5	9	46	FC96 Alt1 AptLev
Dec-07	Current	With	Floodwalls and Berm	With Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		5	10	47	FC07 Alt1 AptLev
Jan-09	Current	With	Floodwalls and Berm	With Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		5	11	48	FC09 Alt1 AptLev
500-Year	Current	With	Floodwalls and Berm	With Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		5	12	49	FC500 Alt1 AptLv
100-Year	Current	With	Floodwalls and Berm	With Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		5	13	50	FC100 Alt1 AptLv
20-Year	Current	With	Floodwalls and Berm	With Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		5	14	51	FC20 Alt1 AptLev
10-Year	Current	With	Floodwalls and Berm	With Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		5	15	52	FC10 Alt1 AptLev
2-Year	Current	With	Floodwalls and Berm	With Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		5	16	53	FC2 Alt1 AptLev
Feb-96	Current	Without	Floodwalls and Berm	With expanded Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		6	1	54	1996 Alt1 ExpLev
Dec-07	Current	Without	Floodwalls and Berm	With expanded Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		6	2	55	2007 Alt1 ExpLev
Jan-09	Current	Without	Floodwalls and Berm	With expanded Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		6	3	56	2009 Alt1 ExpLev
500-Year	Current	Without	Floodwalls and Berm	With expanded Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		6	4	57	500yr Alt1 ExpLv
100-Year	Current	Without	Floodwalls and Berm	With expanded Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		6	5	58	100yr Alt1 ExpLv
20-Year	Current	Without	Floodwalls and Berm	With expanded Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		6	6	59	20yr Alt1 ExpLev
10-Year	Current	Without	Floodwalls and Berm	With expanded Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		6	7	60	10yr Alt1 ExpLev
2-Year	Current	Without	Floodwalls and Berm	With expanded Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		6	8	61	2yr Alt1 ExpLev
Feb-96	Current	With	Floodwalls and Berm	With expanded Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		6	9	62	FC96 Alt1 ExpLev
Dec-07	Current	With	Floodwalls and Berm	With expanded Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		6	10	63	FC07 Alt1 ExpLev
Jan-09	Current	With	Floodwalls and Berm	With expanded Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		6	11	64	FC09 Alt1 ExpLev
500-Year	Current	With	Floodwalls and Berm	With expanded Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		6	12	65	FC500 Alt1 ExpLv
100-Year	Current	With	Floodwalls and Berm	With expanded Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		6	13	66	FC100 Alt1 ExpLv
20-Year	Current	With	Floodwalls and Berm	With expanded Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		6	14	67	FC20 Alt1 ExpLev
10-Year	Current	With	Floodwalls and Berm	With expanded Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		6	15	68	FC10 Alt1 ExpLev
2-Year	Current	With	Floodwalls and Berm	With expanded Airport Levee	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		6	16	69	FC2 Alt1 ExpLev
Dec-07	Current	Without	Floodwalls and Berm	With Airport Levee	Single Minimum Culvert	Existing with Railing Floodwalls		7	2	70	2007 Alt1 DlnClv
100-Year	Current	Without	Floodwalls and Berm	With Airport Levee	Single Minimum Culvert	Existing with Railing Floodwalls		7	5	71	100 Alt1 DlnClv
Dec-07	Current	With	Floodwalls and Berm	With Airport Levee	Single Minimum Culvert	Existing with Railing Floodwalls		7	10	72	FC07 Alt1 DlnClv
100-Year	Current	With	Floodwalls and Berm	With Airport Levee	Single Minimum Culvert	Existing with Railing Floodwalls		7	13	73	FC100 Alt1DlnClv
Dec-07	Current	Without	Floodwalls and Berm	With Airport Levee	Dillenbaugh Realigned Gated I-5	Existing with Railing Floodwalls		8	2	74	2007 Alt1 DlnRln
100-Year	Current	Without	Floodwalls and Berm	With Airport Levee	Dillenbaugh Realigned Gated I-5	Existing with Railing Floodwalls		8	5	75	100 Alt1 DlnRln
Dec-07	Current	With	Floodwalls and Berm	With Airport Levee	Dillenbaugh Realigned Gated I-5	Existing with Railing Floodwalls		8	10	76	FC07 Alt1 DlnRln
100-Year	Current	With	Floodwalls and Berm	With Airport Levee	Dillenbaugh Realigned Gated I-5	Existing with Railing Floodwalls		8	13	77	FC100 Alt1DlnRln
100-Year	Current	Without	Raise I-5 (no Cheh lev)	Without Airport Levee	Raised Existing or Elevated New	Raised Existing or Elevated New		9	5	78	100yr Alt2 noLev
100-Year	Current	With	Raise I-5 (no Cheh lev)	Without Airport Levee	Raised Existing or Elevated New	Raised Existing or Elevated New		9	13	79	FC100 Alt2 noLev
Dec-07	Current	With	Floodwalls and Berm	With Airport Levee	Existing Bridges with Floodwalls	Blocked with Flood Gates		10	10	80	FC07 Alt1SlzGte
100-Year	Current	With	Floodwalls and Berm	With Airport Levee	Existing Bridges with Floodwalls	Blocked with Flood Gates		10	13	81	FC100 Alt1SlzGte
Dec-07	Current	Without	Floodwalls and Berm	With Airport Levee	Realigned Gated I-5 Raised RR	Existing with Railing Floodwalls		11	2	82	2007 Alt1 DlnRR
100-Year	Current	Without	No Project				Hanaford Mitigation Bank	12	5	83	100 Hnfrd MitBnk
100-Year	Current	With	Floodwalls and Berm	With Airport Levee	Existing Bridges with Floodwalls	Blocked with Flood Gates	Salzer Mitigation Bank	13	13	84	FC100 Alt1SlzBnk
100-Year	Current	Without	Floodwalls and Berm	With Airport Levee	Single Submerged Culvert	Submerged Culvert Farm Bridge		14	5	85	100 Alt1 DlnSgl
100-Year	Current	Without	Floodwalls and Berm	With Airport Levee	Double Submerged Culvert	Submerged Culvert Farm Bridge		15	5	86	100 Alt1 DlnDbl

Appendix B

Climate.prj (with climate change)

Flood Event	Geometry	Dam	I-5	I-5 Airport Sub-alts	I-5 Dillenbaugh Sub-alts	I-5 Salzer Bridge Sub-alts	Other Sub-alts or Scenarios	HEC-RAS input files			
								Geometry	*Flow*	*Plan*	*Short ID*
Dec07+18%	Current	Without	No Project					1	17	1	Dec07 base +18%
500yr+18%	Current	Without	No Project					1	18	2	500yr base +18%
100yr+18%	Current	Without	No Project					2	19	3	100yr base +18%
20yr+18%	Current	Without	No Project					2	20	4	20yr base +18%
10yr+18%	Current	Without	No Project					2	21	5	10yr base +18%
2yr+18%	Current	Without	No Project					2	22	6	2yr base +18%
Dec07+18%	Current	With	No Project	With Airport Levee (complete)				4	23	7	Dec07 FCapt +18%
500yr+18%	Current	With	No Project	With Airport Levee (complete)				4	24	8	500yr FCapt +18%
100yr+18%	Current	With	No Project	With Airport Levee (complete)				4	25	9	100yr FCapt +18%
20yr+18%	Current	With	No Project	With Airport Levee (complete)				4	26	10	20yr FCapt +18%
10yr+18%	Current	With	No Project	With Airport Levee (complete)				4	27	11	10yr FCapt +18%
2yr+18%	Current	With	No Project	With Airport Levee (complete)				4	28	12	2yr FCapt +18%
Dec07+18%	Current	Without	Floodwalls and Berm	With Airport Levee (complete)	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		5	17	13	Dec07 I5apt +18%
500yr+18%	Current	Without	Floodwalls and Berm	With Airport Levee (complete)	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		5	18	14	500yr I5apt +18%
100yr+18%	Current	Without	Floodwalls and Berm	With Airport Levee (complete)	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		6	19	15	100yr I5apt +18%
20yr+18%	Current	Without	Floodwalls and Berm	With Airport Levee (complete)	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		6	20	16	20yr I5apt +18%
10yr+18%	Current	Without	Floodwalls and Berm	With Airport Levee (complete)	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		6	21	17	10yr I5apt +18%
2yr+18%	Current	Without	Floodwalls and Berm	With Airport Levee (complete)	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		6	22	18	2yr I5apt +18%
Dec07+18%	Current	With	Floodwalls and Berm	With Airport Levee (complete)	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		6	23	19	Dec07 I5 FC +18%
500yr+18%	Current	With	Floodwalls and Berm	With Airport Levee (complete)	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		6	24	20	500yr I5 FC +18%
100yr+18%	Current	With	Floodwalls and Berm	With Airport Levee (complete)	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		6	25	21	100yr I5 FC +18%
20yr+18%	Current	With	Floodwalls and Berm	With Airport Levee (complete)	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		6	26	22	20yr I5 FC +18%
10yr+18%	Current	With	Floodwalls and Berm	With Airport Levee (complete)	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		6	27	23	10yr I5 FC +18%
2yr+18%	Current	With	Floodwalls and Berm	With Airport Levee (complete)	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		6	28	24	2yr I5 FC +18%
Dec07+90%	Current	Without	No Project					1	29	25	Dec07 base +90%
500yr+90%	Current	Without	No Project					1	30	26	500yr base +90%
100yr+90%	Current	Without	No Project					1	31	27	100yr base +90%
20yr+90%	Current	Without	No Project					1	32	28	20yr base +90%
10yr+90%	Current	Without	No Project					1	33	29	10yr base +90%
2yr+90%	Current	Without	No Project					1	34	30	2yr base +90%
Dec07+90%	Current	With	No Project	With Airport Levee (complete)				3	35	31	Dec07 FCapt +90%
500yr+90%	Current	With	No Project	With Airport Levee (complete)				3	36	32	500yr FCapt +90%
100yr+90%	Current	With	No Project	With Airport Levee (complete)				3	37	33	100yr FCapt +90%
20yr+90%	Current	With	No Project	With Airport Levee (complete)				3	38	34	20yr FCapt +90%
10yr+90%	Current	With	No Project	With Airport Levee (complete)				3	39	35	10yr FCapt +90%
2yr+90%	Current	With	No Project	With Airport Levee (complete)				3	40	36	2yr FCapt +90%
Dec07+90%	Current	Without	Floodwalls and Berm	With Airport Levee (complete)	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		5	29	37	Dec07 I5apt +90%
500yr+90%	Current	Without	Floodwalls and Berm	With Airport Levee (complete)	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		5	30	38	500yr I5apt +90%
100yr+90%	Current	Without	Floodwalls and Berm	With Airport Levee (complete)	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		5	31	39	100yr I5apt +90%
20yr+90%	Current	Without	Floodwalls and Berm	With Airport Levee (complete)	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		5	32	40	20yr I5apt +90%
10yr+90%	Current	Without	Floodwalls and Berm	With Airport Levee (complete)	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		5	33	41	10yr I5apt +90%
2yr+90%	Current	Without	Floodwalls and Berm	With Airport Levee (complete)	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		5	34	42	2yr I5apt +90%

Flood Event	Geometry	Dam	I-5	I-5 Airport Sub-alts	I-5 Dillenbaugh Sub-alts	I-5 Salzer Bridge Sub-alts	Other Sub-alts or Scenarios	HEC-RAS input files			
								Geometry	*Flow*	*Plan*	*Short ID*
Dec07+90%	Current	With	Floodwalls and Berm	With Airport Levee (complete)	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		5	35	43	Dec07 I5 FC +90%
500yr+90%	Current	With	Floodwalls and Berm	With Airport Levee (complete)	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		5	36	44	500yr I5 FC +90%
100yr+90%	Current	With	Floodwalls and Berm	With Airport Levee (complete)	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		5	37	45	100yr I5 FC +90%
20yr+90%	Current	With	Floodwalls and Berm	With Airport Levee (complete)	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		5	38	46	20yr I5 FC +90%
10yr+90%	Current	With	Floodwalls and Berm	With Airport Levee (complete)	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		5	39	47	10yr I5 FC +90%
2yr+90%	Current	With	Floodwalls and Berm	With Airport Levee (complete)	Existing Bridges with Floodwalls	Existing with Railing Floodwalls		5	40	48	2yr I5 FC +90%