MEMORANDUM

Date: February 28, 2019
To: Bob Montgomery, Anchor QEA
From: Bob Elliot, Tim Tschetter, and Larry Karpack, WSE
Re: Chehalis River Existing Conditions RiverFlow2D Model Development and Calibration

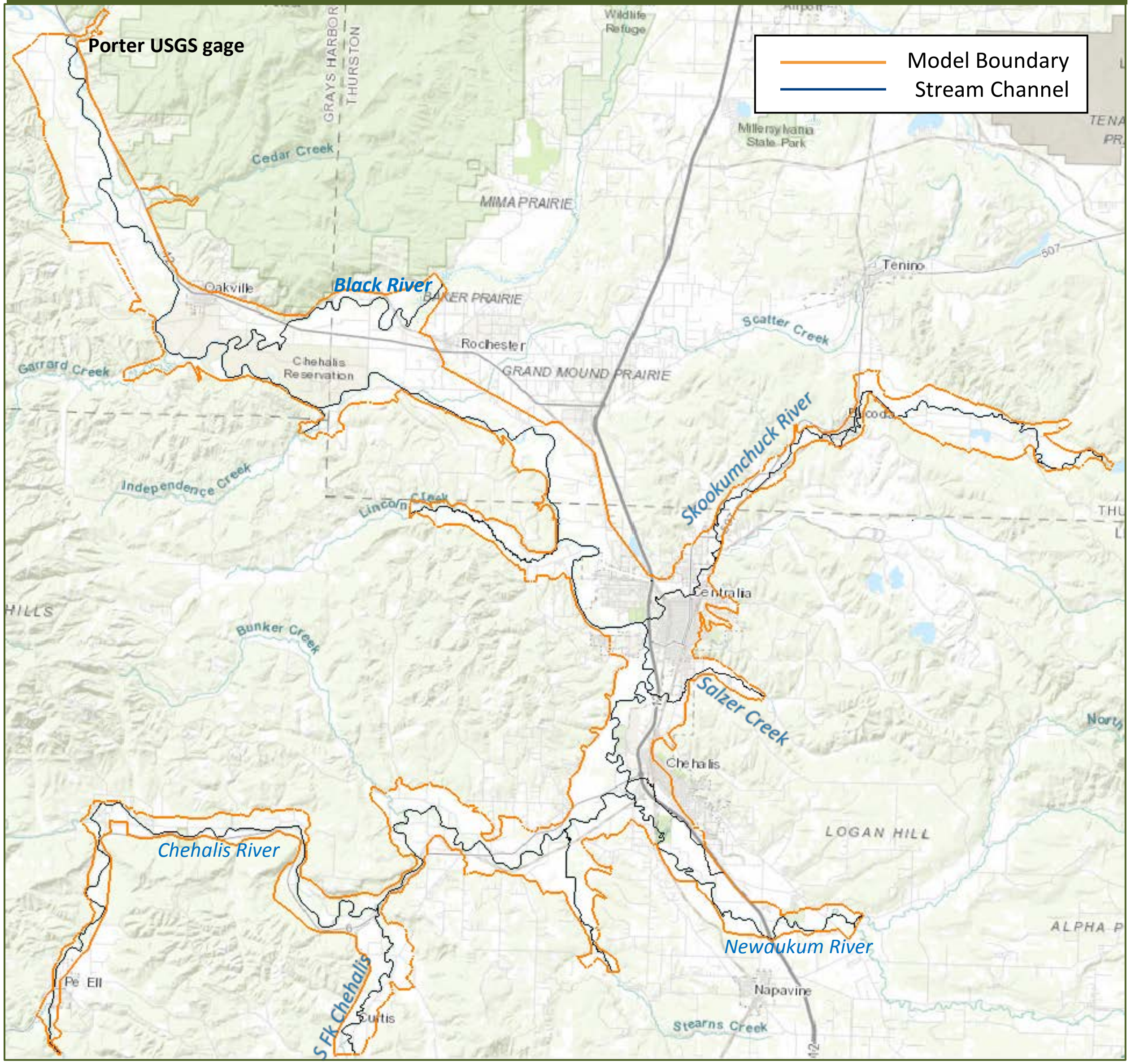
Introduction

This technical memorandum summarizes hydraulic analyses undertaken by Watershed Science and Engineering (WSE) to develop and calibrate a two-dimensional (2D) unsteady numerical model of the Chehalis River and floodplain. The model extends from the site of the proposed dam, about 1.5 miles upstream of Pe Ell in Lewis County, downstream approximately 75 miles past the Twin Cities of Chehalis and Centralia, to the Porter Bridge on Porter Creek Road in Grays Harbor County. Included is the 9 mile reach of the Chehalis River in Thurston County near Grand Mound and Rochester. More than 125 miles of river and associated floodplain are represented in the model, including major tributaries. These include the lower 6 miles of the South Fork Chehalis River below Lost Valley Road, 11 miles of the mainstem Newaukum River below Jackson Highway (confluence of the North and South Forks), 22 miles of the Skookumchuck River below Skookumchuck Dam, and the lower 11 miles of the Black River. Downstream reaches of the following lesser tributary streams and their floodplains which are located within backwater influence of the Chehalis River were also included in the model: Stearns Creek, Dillenbaugh Creek (which also receives overflows from the Newaukum), Salzer Creek, Lincoln Creek, Independence Creek, Garrard Creek, Cedar Creek and Porter Creek. Figure 1 shows the extent of the Chehalis 2D model, which extends to Porter where a USGS streamflow gage is available to provide a suitable rating curve for the downstream boundary. The model could be further extended downstream to Grays Harbor in the future if time and resources allow.

The Chehalis River 2D model encompasses areas previously modeled in HEC-RAS (Hydrologic Engineering Center – River Analysis System) as one-dimensional (1D) river reaches as well as numerous level-pool storage areas. The 2D model provides improved spatial representation to more accurately simulate floodplain hydraulics as needed to quantify flood risk or evaluate habitat restoration alternatives. Development of the 2D model was completed primarily using ArcGIS and the SMS (Surfacewater Modeling System) pre- and post-processing software. Simulations were completed using Hydronia's RiverFlow2D Plus finite volume modeling program using graphical processing unit (GPU) capabilities to significantly improve simulation speed, necessary to achieve reasonable run times for this size of model.

The model was calibrated and verified by evaluating a large set of high water marks from the January 2009 and December 2007 events, along with measured stage and discharge hydrographs at several (predominantly USGS) gage locations with continuous recorders. An additional run was completed for the February 1996 flood event and checked against measured data from about 40 locations.

Figure 1
Extent of RiverFlow2D model of the Chehalis River



Model Development

Base Topography

The floodplain topography for the Chehalis River 2D model used the terrain surface originally compiled for the 1D model (WSE, 2014b), which consisted of various LiDAR data primarily dated 2012 (Figure 2). Along the South Fork Chehalis, Stearns Creek, Newaukum River and portions of the Skookumchuck, more recent topo-bathymetric (green) LiDAR collected in 2017 was used (Anchor, 2017). This also provided some bathymetry for the river channel but was generally limited to near bank and shallow areas (see Figure 3). Gaps in the green LiDAR bathymetry and throughout the remaining main channels were filled by interpolating the channel cross-sections from the existing HEC-RAS 1D model. The existing channel cross-sections along the Chehalis River were obtained from multiple sources, including 2013 bathymetric surveys from Doty to Grand Mound, and 2011 surveys upstream of Doty and downstream of Grand Mound (see WSE, 2014b). Along the Newaukum and other tributaries, the channel cross-sections typically originated with older 1D models developed for FEMA or the Corps of Engineers, with the most recent data from the early 2000s and the earliest likely from the 1970s. All topographic data were adjusted to the NAVD88 vertical datum and were mosaiced to a single 3-foot raster using ArcGIS.

Figure 2
LiDAR sources used to create Chehalis River floodplain topographic surface

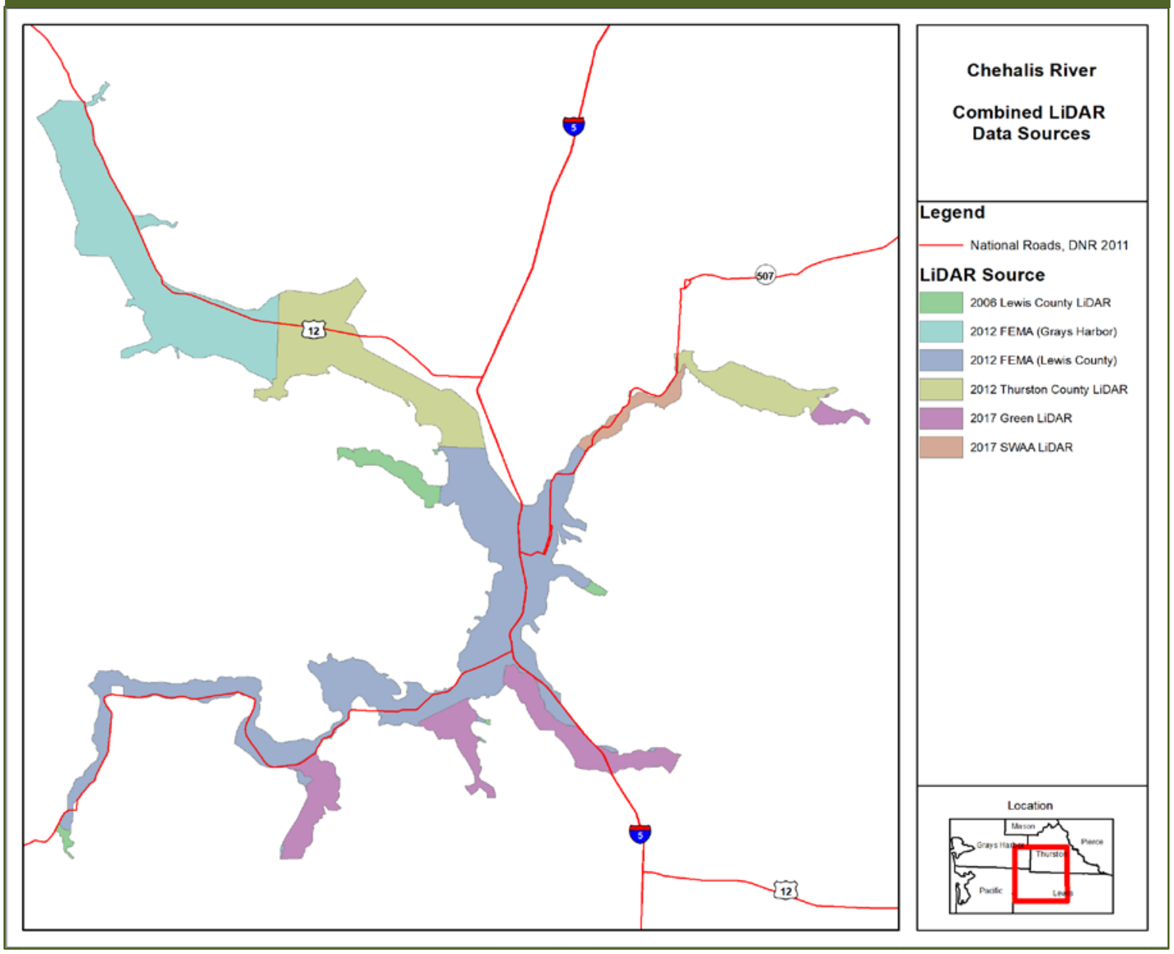
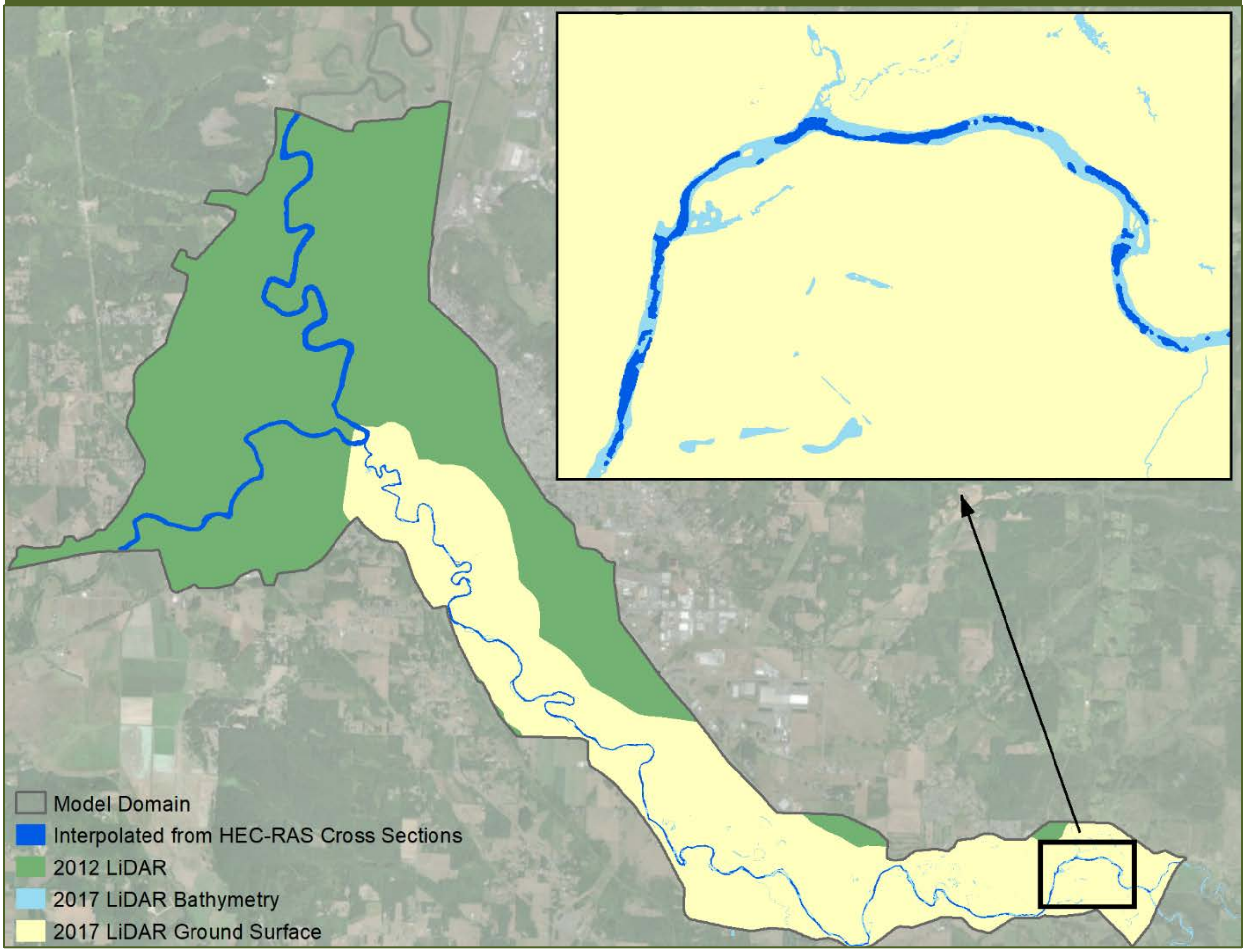


Figure 3
Data sources used to create Newaukum River topographic surface



The terrain data and all 2D model inputs and outputs use the following coordinate system and datum:

- State Plane Coordinate System, Zone: Washington South (FIPS 4602).
- Horizontal Datum: NAD83 (WASHINGTON-OREGON HPGN), feet.
- North American Vertical Datum of 1988 (NAVD88) vertical datum.

Material Definitions

Land cover material types within the model were defined using two methods. The majority of floodplain land cover throughout the model domain was developed using National Agricultural Imagery Program (NAIP) multispectral imagery[1]. NAIP imagery is acquired biennially throughout the nation during agricultural growing seasons. The land cover classification process utilizes the four bands (red, green, blue, and near infrared) of the NAIP imagery and textural analysis to delineate the following six categories of land cover: pavement, buildings, bare dirt, pasture grass, lawn or turf, shrubs, forest, and

[1] https://www.fsa.usda.gov/programs-and-services/aerial-photography/imagery-programs/naip-imagery/

water. The resulting soil and vegetation material types provide reasonably accurate and up-to-date material type classifications. A different method was used to classify the land cover in the Newaukum River floodplain to maintain consistency with a concurrent RiverFlow2D model development project for the forks of the Newaukum River above Jackson Highway (NHC, 2018). This procedure relates vegetation height from the 2017 LiDAR (as shown in Figure 3) to land cover and roughness. Details for this procedure can be found in WSE (2018).

River and stream channels were delineated separately from both the NAIP and LiDAR floodplain material representations to define the main channel roughness. For the larger Chehalis River channel, separate lines were delineated near the toe of the channel banks, resulting in separate material definitions for the low flow channel bed and the channel banks. A single material type (bank to bank) was delineated for each tributary.

Manning's n-values (i.e. roughness coefficients) for each land use material type were initially assigned based upon aerial interpretation and engineering judgement, then refined through model calibration (see Calibration section below for details). Table 1 summarizes the material land use coverages and corresponding final n-values assigned to each.

Mesh Development

Model breaklines were digitized using LiDAR topography to add detail to the mesh along key topographic features (i.e. channel banks and thalwegs, elevated roadway prisms, terraces, sloughs) and in areas where the topography changes rapidly over distances that are smaller than the default meshing distance. The river main channels were defined by breaklines delineated within the low flow channel and along both banks with sufficient resolution in the resulting mesh to reasonably define the channel thalweg, toe and top of bank.

The delineated breaklines were imported into the SMS software to define element edges and node locations in the 2D model. Each line was populated with vertices which were spaced to represent the desired mesh density throughout the model (i.e. element resolution and node spacing) to ensure a detailed representation of key topographic features. An initial triangular mesh of computational nodes and elements was then developed based upon these and other meshing attributes (e.g. paving type, density, bias, etc.). The terrain surface and material land coverage described previously were then interpolated onto the mesh. Initial Manning's n-value roughness coefficients were assigned to each material categories (as identified in Table 1), and further refined through model calibration.

Table 1
Material Definitions and Final Roughness Coefficients

LAND USE	MANNING'S N-VALUE
Mow/Till, Grass (<1')	0.06
Tall Grass, Small Shrub (1'-4')	0.07
Shrubs (4'-6')	0.1
Young Woodland (6'-12')	0.12
Young Mixed Forest (12'-20')	0.12
Forest (>20')	0.14
Chehalis channel banks	0.04
Chehalis channel bed	0.025
South Fork channel	0.04
Stearns channel	0.04
Newaukum channel	0.045
Dillenbaugh channel	0.05
Salzer channel	0.04
Hanaford channel	0.04
Skookumchuck channel above River Mile (RM) 12.7	0.04
Skookumchuck channel below River Mile (RM) 12.7	0.03
Lincoln channel	0.04
Independence channel	0.03
Black channel	0.03
Side Channel	0.04
Road/pavement	0.02
Pond	0.04
Developed	0.2
Buildings (partial)	0.5
Buildings (full)	0.99

Regional as well as localized refinements were subsequently made to the computational mesh as needed, to selectively improve element resolution and nodal terrain representation along tops of elevated roadways, within bridge openings and channels, and other areas. Appendix A shows the final mesh and model ground contours for two representative areas near the City of Chehalis, to provide examples of the level of mesh density and topographic detail in the 2D model.

Nominal node spacing in the model was varied depending on the location in relation to the channel and the channel width. The following generally characterize the spacing of nodes throughout the model:

- Main channel thalweg and toe: 20 to 40 feet
- Main channel banks, sloughs and side-channels: 40 to 60 feet
- Tops of elevated roadways: 50 to 60 feet
- Floodplain (away from channel): 50 to 70 feet
- Bridge openings: varied, but typically 40 feet or less

Hydraulic Structures

RiverFlow2D allows simulation of hydraulic structures, including weirs, culverts and bridges (piers and bridge decks). Bridge deck and pier data were initially added to the 2D model based upon the bridge geometries in the HEC-RAS 1D model, without field verification or any plans or drawings. Pier losses are computed at individual model elements in RiverFlow2D based upon the pier dimensions and an assigned drag coefficient Cd. Bridge deck data (low chord and top of road) can be added as model nodestring sections along the bridge alignment, to simulate pressure flow and overtopping using 1D assumptions. Table 2 summarizes the locations of bridges included in the 2D model, including the corresponding river mile (RM) from HEC-RAS, and denotes whether the bridge deck and/or piers are represented. Several bridge decks elevated considerably higher than expected flood levels were not included.

The Willapa Hills Trail bridge and trestle on the Newaukum River provides a very large opening at a sharp bend in the river. Modeling this opening using the 2D elements was considered to be more accurate than the alternative 1D bridge representation in RiverFlow2D. This bridge did not surcharge during the largest Newaukum Flood on record, the January 2009 flood, although pressure flow is possible during events with significant backwater from the Chehalis River.

For some bridges a very large composite pier width was used in the previous HEC-RAS model to represent the total width of all piers. These locations were field verified and modified in the 2D model to reflect approximate measurements of the actual widths and number of piers. RiverFlow2D computes pier head loss using a momentum balance method based upon the size of the obstruction and an assigned drag coefficient. An alternative method to explicitly represent individual piers within the computational mesh was considered but ultimately not used as the alternative method is not practical for small piers (e.g. timber piles), comprising the majority of bridge piers in the model. Neither method is inherently more conservative than the other and considering the intended use of this model is to evaluate large scale flood damage reduction projects the selected approach was felt to be appropriate.

Table 2

Bridges Simulated in RiverFlow2D Model

STREAM	ROADWAY	APPROX RM*	DECK	PIERS
Chehalis River	Willapa Hills Trail (near Pe Ell)	107.1		X
Chehalis River	Pe Ell Highway 6	106.39		X
Chehalis River	Elk Creek Road	100.425	X	X
Chehalis River	Dryad Willapa Hills Trail	98.455	X	
Chehalis River	Chandler Road	97.875	X	
Chehalis River	Leudinghaus Road	94.77	X	
Chehalis River	Willapa Hills Trail (near Gage)	86.005	X	
Chehalis River	Willapa Hills Trail (near Adna)	82.5925	X	X
Chehalis River	Adna Highway 6	80.995	X	X
Chehalis River	Willapa Hills Trail	77.935	X	X
Chehalis River	Highway 603	77.63499	X	X
Chehalis River	Chehalis Highway 6	74.715		X
Chehalis River	Mellen Street	67.445	X	X

Chehalis River	Galvin Road main	64.22501	X	X
Chehalis River	Galvin Road overflow	64.22501	X	
Chehalis River	Prather Road	59.913		X
Chehalis River	Independence Road	54.04		X
Chehalis River	Sickman Ford main	43.982		X
Chehalis River	Sickman Ford overflow	43.982	X	X
Chehalis River	Porter Creek Road	33.595	X	
South Fork Chehalis River	Beaver Creek Road	3.004	X	
Stearns Creek	Scenic Steam RR	0.725	X	
Newaukum River	Jackson Highway main	9.735	X	
Newaukum River	Jackson Highway overflow	9.735	X	X
Newaukum River	Kirkland Road	7.895		X
Newaukum River	Interstate 5 freeway	7.455		X
Newaukum River	Rush Road	7.115		X
Newaukum River	Labree Road	4.115	X	X
Newaukum River	BNSF mainline	1.48	X	X
Newaukum River	Willapa Hills Trail	0.5575		X
Newaukum River	Shorey Road	0.085	X	X
Newaukum River	Scenic Steam RR	0.065	X	X
Dillenbaugh Creek	Interstate 5 Main Street off-ramp	0.129	X	
Dillenbaugh Creek	Interstate 5 freeway	0.105	X	
Dillenbaugh Creek	Interstate 5 Main Street off-ramp	0.085	X	
Dillenbaugh Creek	Riverside Drive	0.058	X	
Salzer Creek	BNSF mainline	0.875	X	X
Salzer Creek	Tacoma Rail line	0.415	X	X
Salzer Creek	Interstate 5 freeway	0.385	X	X
Salzer Creek	Airport Road	0.3	X	X
Skookumchuck River	Skookumchuck Road upstream	18.315	X	
Skookumchuck River	Private road RM 17.5	17.505	X	
Skookumchuck River	Goebel Road	15.805	X	X
Skookumchuck River	Skookumchuck Road downstream	14.555	X	
Skookumchuck River	Tono Road	10.845	X	X
Skookumchuck River	BNSF mainline	9.81	X	
Skookumchuck River	Connor Road	7.305	X	X
Skookumchuck River	Highway 507 (Bucoda Highway)	6.425	X	X
Skookumchuck River	Highway 507 (Downing Road)	4.815	X	X
Skookumchuck River	Highway 507 (Pearl Street)	2.4175	X	
Skookumchuck River	BNSF (SE of Blakeslee Junction)	1.5575	X	X
Skookumchuck River	Tacoma Rail line	1.4975	X	X
Skookumchuck River	Harrison Street	0.615	X	X
Skookumchuck River	Interstate 5 freeway	0.215	X	X
Scatter Creek	Jordan Street	1.4	X	
Scatter Creek	Private access	0.2	X	
Black River	BNSF (west of Rochester)	9.115	X	
Black River	Moon Road	7.045	X	X
Black River	Highway 12	4.095	X	
Black River	Howanut Road	1.195	X	X

*Note: RMs listed are HEC-RAS stationing.

Numerous culverts were added to the 2D model, based upon data in the HEC-RAS 1D model. The majority of these are represented in HEC-RAS as part of lateral structures where smaller tributary creeks or drainage ditches pass beneath elevated roadway embankments. As with the majority of bridge data, the culverts have not been verified by WSE through field survey or as-built plans, with a few exceptions. Two large 7-foot culverts exist at the north end of the Chehalis-Centralia Airport levee, near Airport Road and Louisiana Avenue, for which design drawings provided the necessary details for the HEC-RAS model. However, these culverts are flap gated to prevent backflow from the Chehalis River into the airport area. Because flap gates cannot be represented in RiverFlow2D, these culverts were not included in the 2D model. This will not affect the rising limb or the peak of the flood simulations, only the drainage from the airport area after the flood has passed. Additional analysis would be required to evaluate interior drainage and/or recession of flooding in the Airport area.

Culvert details were also available for two additional culverts not included in the HEC-RAS model: the 3-foot diameter Nicholson Creek culvert into the Chehalis River under the Willapa Hills Trail (about 1 mile downstream of the Leudinghaus Bridge); and a small 2-foot culvert under Independence Road just East of its crossing over the Chehalis River, which was recently surveyed. A culvert inventory assembled by WDFW was provided to WSE by Anchor QEA and used to confirm the presence of most of the HEC-RAS culverts and identify several additional culverts. The inventory however did not provide the details needed to include these in the model, i.e. culvert size, length, and invert elevations so they were not added to the 2D model. During large floods it is likely these would have a little effect on the model results as they are quite small relative to the flood flows simulated in the model. Table 3 summarizes the culverts included in the 2D model.

Roadway embankments in the model are included within the computational mesh, i.e. defined by elements with node elevations determined from the LiDAR surface. This is likely the most accurate approach during large floods (the primary focus of this modeling) or in the case of low embankments, where significant weir submergence is expected. The alternative method is to delineate weirs along the roadways, which uses the empirically-derived weir equation and user defined weir coefficients. For high unsubmerged embankment overtopping or weir crests that are too narrow to be reasonably defined by a row of elements, this method may be preferable. The weir option was employed only along Interstate 5, not for the roadway embankment itself but to define the 2.5-foot high and narrow crested jersey barriers that separate the north and south bound lanes.

Table 3
Culverts Simulated in RiverFlow2D Model

STREAM OR WATERCOURSE	ROADWAY OR OTHER FEATURE
Nicholson Creek	Willapa Hills Trail
Van Ornum Creek	Bunker Creek Road
Drainage into Chehalis River	Bunker Creek Road near Adna
Drainage into Chehalis River	Highway 6 just west of Adna bridge
Dillenbaugh Creek	Rice Road at Interstate 5
Drainage into Dillenbaugh Creek	Interstate 5 Rice Road on-ramp
Drainage into Dillenbaugh Creek	Interstate 5 at Rice Road
Drainage path from Dillenbaugh Creek	Main Street just east of Interstate 5
Drainage into Chehalis River	Interstate 5 near West Street
China Creek	Interstate 5 just north of Mellen Street
Plummer Lake drainage	Interstate 5 just north of China Creek
Coffee Creek	Reynolds Avenue east of Blakeslee Junction
Scatter Creek overflow	Independence Road east of Chehalis River bridge
Drainage path from Chehalis to Black River	Highway 12 at Moon Road
Nicholson Creek	Willapa Hills Trail
Van Ornum Creek	Bunker Creek Road
Drainage into Chehalis River	Bunker Creek Road near Adna
Drainage into Chehalis River	Highway 6 just west of Adna bridge
Dillenbaugh Creek	Rice Road at Interstate 5
Drainage into Dillenbaugh Creek	Interstate 5 Rice Road on-ramp
Drainage into Dillenbaugh Creek	Interstate 5 at Rice Road
Drainage path from Dillenbaugh Creek	Main Street just east of Interstate 5
Drainage into Chehalis River	Interstate 5 near West Street

Boundary Conditions

All inflows to the hydraulic model are derived from the HEC-RAS model. These inflows were developed by WEST Consultants under contract to the U.S. Army Corps of Engineers (USACE, 2014). Inflows include upstream hydrographs on the Chehalis River, the South Fork Chehalis, Stearns Creek, Newaukum River, Dillenbaugh Creek, Salzer Creek, Lincoln Creek, Independence Creek and Black River. Point lateral inflows are included at tributaries including: Elk, Stillman, Bunker, Deep, Berwick, Coal, Hanaford, Coffee, Scatter, Garrard, Cedar and Porter Creeks. Additional inflows, corresponding to the distributed lateral inflows in the HEC-RAS model, were added to the RiverFlow2D model at appropriate locations. The model's downstream boundary condition is based upon a stage-discharge rating curve developed by the USGS for their gage at Porter.

Calibration

January 2009

Model development proceeded incrementally, beginning with the Newaukum River and adjacent Dillenbaugh Creek and floodplain. Calibration of the initial Newaukum model is detailed in WSE (2018), which primarily focuses on the January 2009 event. Final calibration to this event, both along the Newaukum River and elsewhere, is summarized in this section.

Although the December 2007 event is the flood of record on the entire Chehalis River mainstem and most tributaries west of the Twin Cities, January 2009 was in fact a more intense storm in the Cascade foothills to the east and produced higher flows along the Newaukum and Skookumchuck Rivers. Following the January 2009 flood event, the USGS surveyed 167 high water marks (HWM) along the lower Newaukum River and floodplain extending from the mouth upstream to Kirkland Road (USGS, 2010). Many of these HWMs are in clusters with obvious anomalies (i.e. elevations that are several feet different from nearby marks). WSE examined all of the HWM data and eliminated 24 of these due to poor correlation with multiple nearby measurements. Six additional HWMs along lower Dillenbaugh Creek and the Chehalis River below Dillenbaugh were obtained from other sources and used in the calibration. In total, 149 HWM data points were within the RiverFlow2D model domain, with the majority along the Newaukum River as shown in Figure 4. Approximately 60 percent of the points fall between or within 10 feet of the Newaukum channel banks, with the remaining 40 percent on the overbank floodplain. The other HWM locations for the January 2009 flood are primarily along Salzer Creek and within Bucoda on the Skookumchuck River, as illustrated in Figure 5. Stage records at five USGS streamflow gages on the Chehalis River, two on the Skookumchuck River, and one on the Newaukum River, along with the National Weather Service (NWS) gage on the Chehalis River at Mellen Street were also examined and comparisons made between the measured and simulated stage hydrographs.

Figure 4
January 2009 High Water Marks along Newaukum River (including Dillenbaugh Creek)

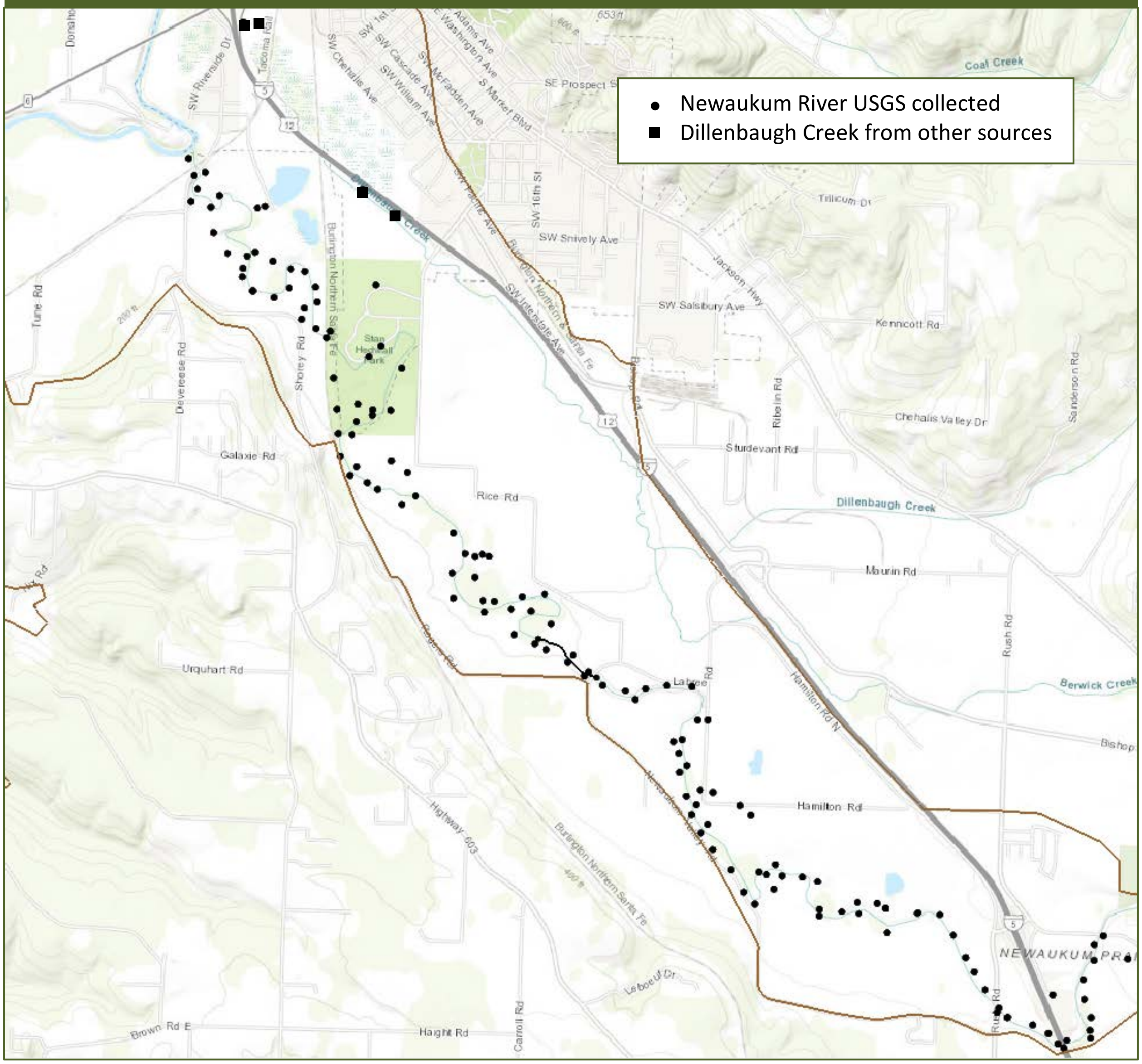
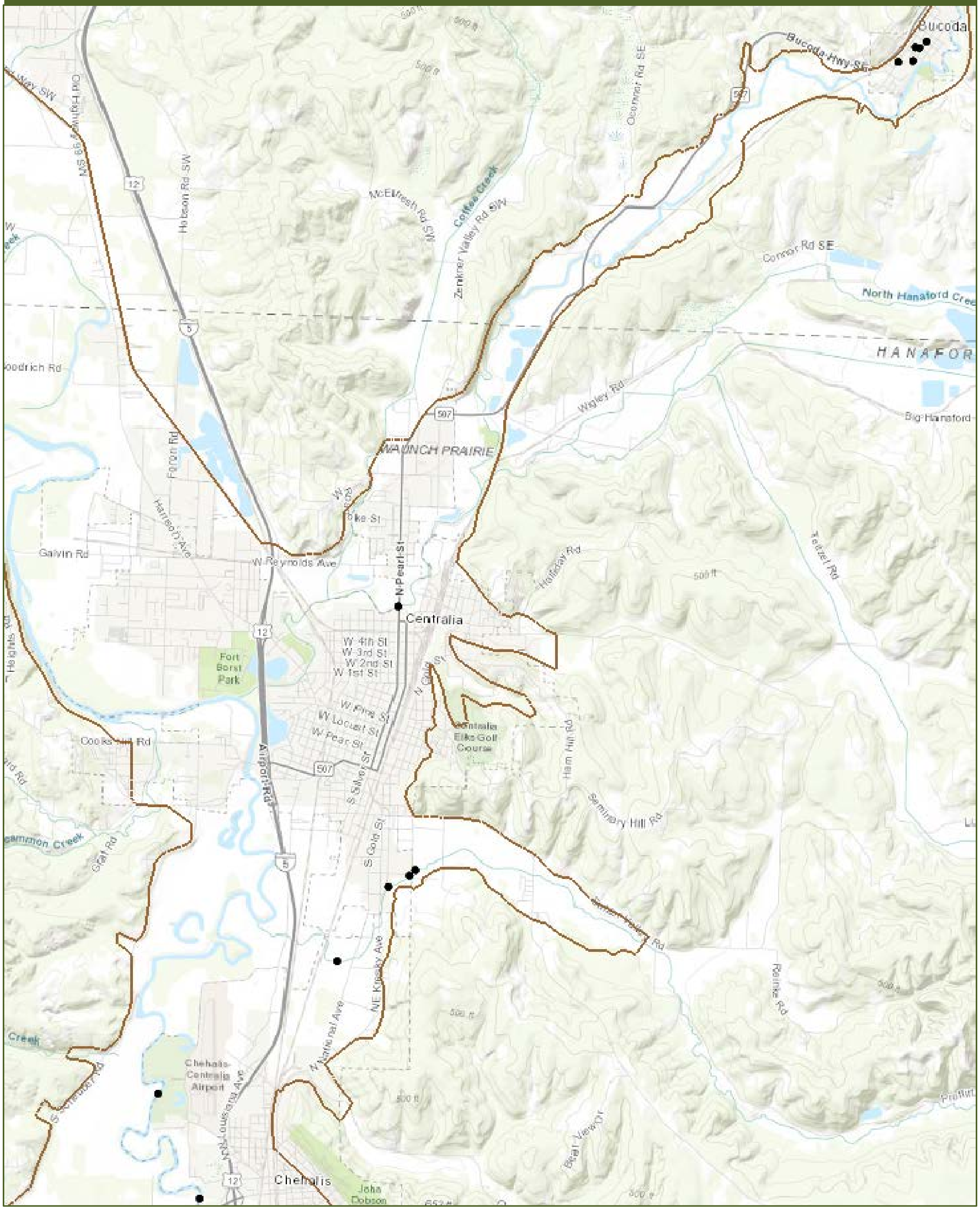


Figure 5
Additional January 2009 High Water Marks (downstream of Newaukum)



Simulations were completed for the January 2009 flood event, with boundary conditions and an initial set of roughness coefficients (n-values) specified as described previously. Multiple iterations were run with refinements made to the n-values to achieve the best possible calibration. NAIP land use types with similar vegetation heights to the corresponding LiDAR material categories (see first six entries in Table 1) maintained the same Manning's n-values. With such a large set of HWM points along the Newaukum River, and the variability and expected accuracy of the data, it is impossible for a model to exactly match every HWM. The results of each simulation were evaluated and the calibration refined until the best statistical match to all of the points was achieved. WSE (2018) provides a detailed statistical evaluation of the results and comparison to the HWM data along the Newaukum River, based upon the initial Newaukum model. The final model including the full extension of the Chehalis River from above Pe Ell to Porter resulted in slight differences to the calibration along the Newaukum River. This was due in part to the land use classifications outside of the 2017 LiDAR using the National Land Cover Database (NLCD) in the earlier work rather than NAIP which is more refined and more recent. This affected the material coverages along the Dillenbaugh floodplain which includes Newaukum overflows. Slight refinements to the floodplain roughness coefficients were made as a result of this, and as part of the extended calibration beyond the Newaukum corridor.

The average error for the Newaukum (and Dillenbaugh) HWM points shown in Figure 4 is approximately 0.04 feet, about the same as the original Newaukum RiverFlow2D model (-0.03 feet) as expected. Almost half (66 out of 147) of the simulated results fall within +/- 0.5 foot of the measured HWMs, and about 75 percent (110 out of 147) within +/- 1.0 foot. Given the large population of HWM points, these results produce a reasonably close calibration. See WSE (2018) for further details and more specific discussion of the original January 2009 model calibration along the Newaukum River and floodplain.

The remaining points (Figure 5), calibrate reasonably well with the exception of the upper three points on Salzer Creek which are under-predicted by more than 4 feet. The 1D model was likewise unable to calibrate to these points. There are several possible explanations for this: one, there may have been a bust in either the identification and collection of or the survey of these three points; two, there may have been debris blockages (which would not be represented in the model) at one or more of the several bridge crossings just downstream; or three, the locally generated flow in Salzer Creek was considerably greater than assumed in the model. Salzer Creek is ungaged, and the inflows (replicated from the HEC-RAS model) were estimated and translated from hydrology based on the USGS gages on the Skookumchuck. Elsewhere, the remaining HWM points within the Twin Cities area all fall within 0.2 feet of the measured HWMs. This includes the lower point on Salzer Creek (within the Chehalis River backwater), two points on the Chehalis River near Chehalis, and one on the Skookumchuck River in Centralia. The cluster of points in Bucoda reports an average difference of -0.4 feet or better.

Recorded stage as well as discharge hydrographs were also compared to model results to evaluate the reasonableness of the rise and fall of the hydrographs as well as the timing of peak stages as an indication of accuracy in model routing. Figure 6 presents hydrograph comparisons for stage along with the resulting difference at the peak. Plots are included for USGS gages at or near Doty, Adna, Highway 6 (City of Chehalis WWTP – wastewater treatment plant), Grand Mound and Porter on the Chehalis River; Labree Road (near Chehalis) on the Newaukum River; and Bloody Run Creek and Bucoda on the Skookumchuck River. Also included is the National Weather Service (NWS) gage at Mellen Street near Centralia's wastewater treatment plant. Both on the Chehalis and the Skookumchuck Rivers, the upstreammost gages replicate the hydrograph shape the best but have the largest errors at the flood peak (Doty, Adna and Bloody Run Creek). Further downstream there is generally greater deviation throughout the stage hydrograph due to compounding error in the flood routing; however, results at the peak tend to increasingly improve as indicated by reduced error. Timing of the simulated peak is also generally good, typically within about two hours or less of the observed peak. Discharge comparison plots are provided in Figure 7 for the rated USGS gages on the Chehalis River (Grand Mound and Porter) and Skookumchuck (Bloody Run Creek and Bucoda). The published USGS discharge data at Doty and Labree Road (which includes overflows to Dillenbaugh Creek) directly provide the upstream model inflows for the Chehalis and Newaukum Rivers, respectively. As such they are not included in the figure since they replicate the data very closely as expected. Examining the peak flows, Grand Mound is over-predicted by more than 10 percent, although Porter downstream matches reasonably close (as do the two locations on Skookumchuck River). However, replication of discharge hydrograph shape and timing is the poorest at Porter, but reasonably good at the other locations further upstream.

Figure 6
Comparisons of January 2009 Recorded and Simulated Stage Hydrographs

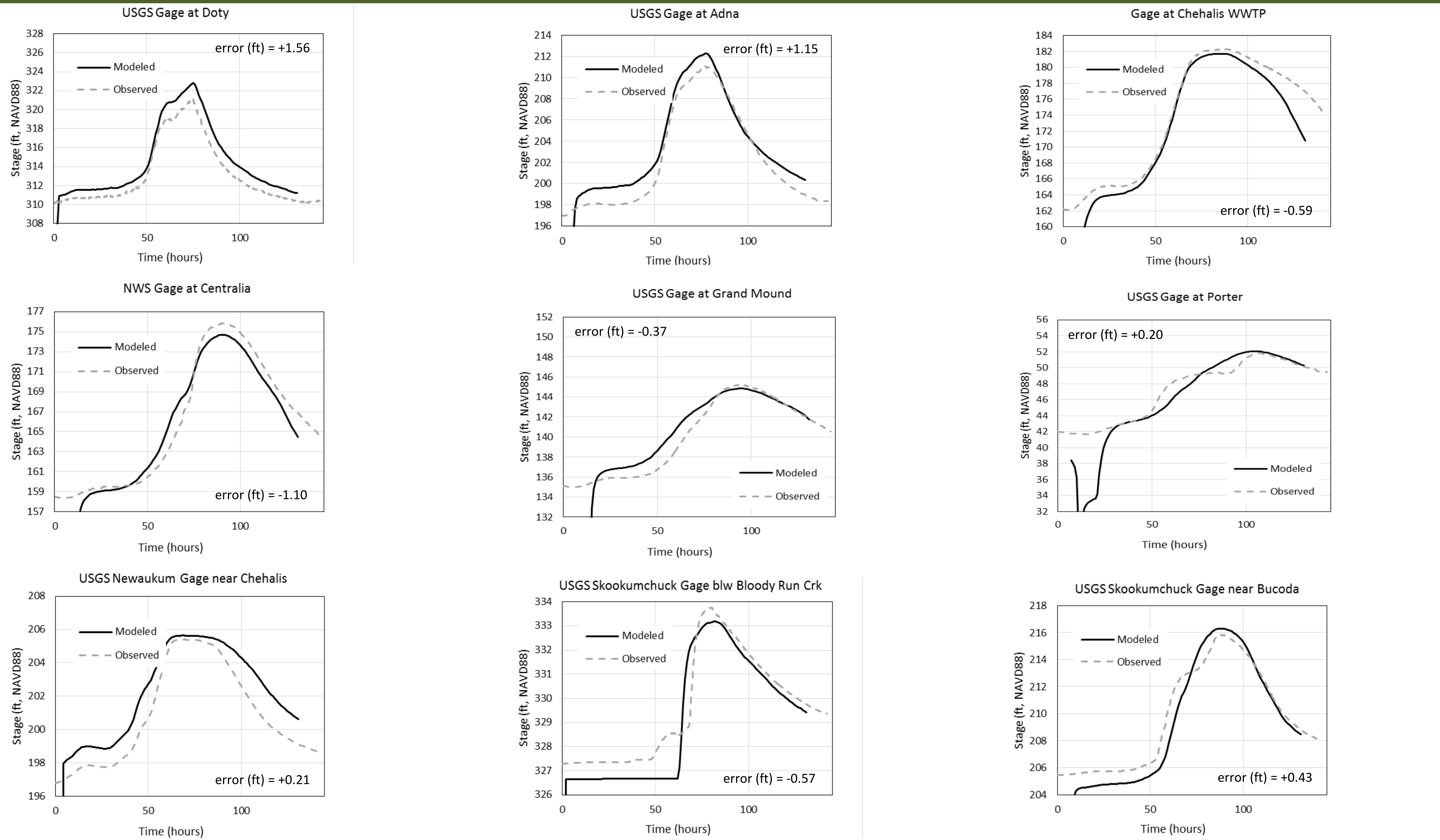
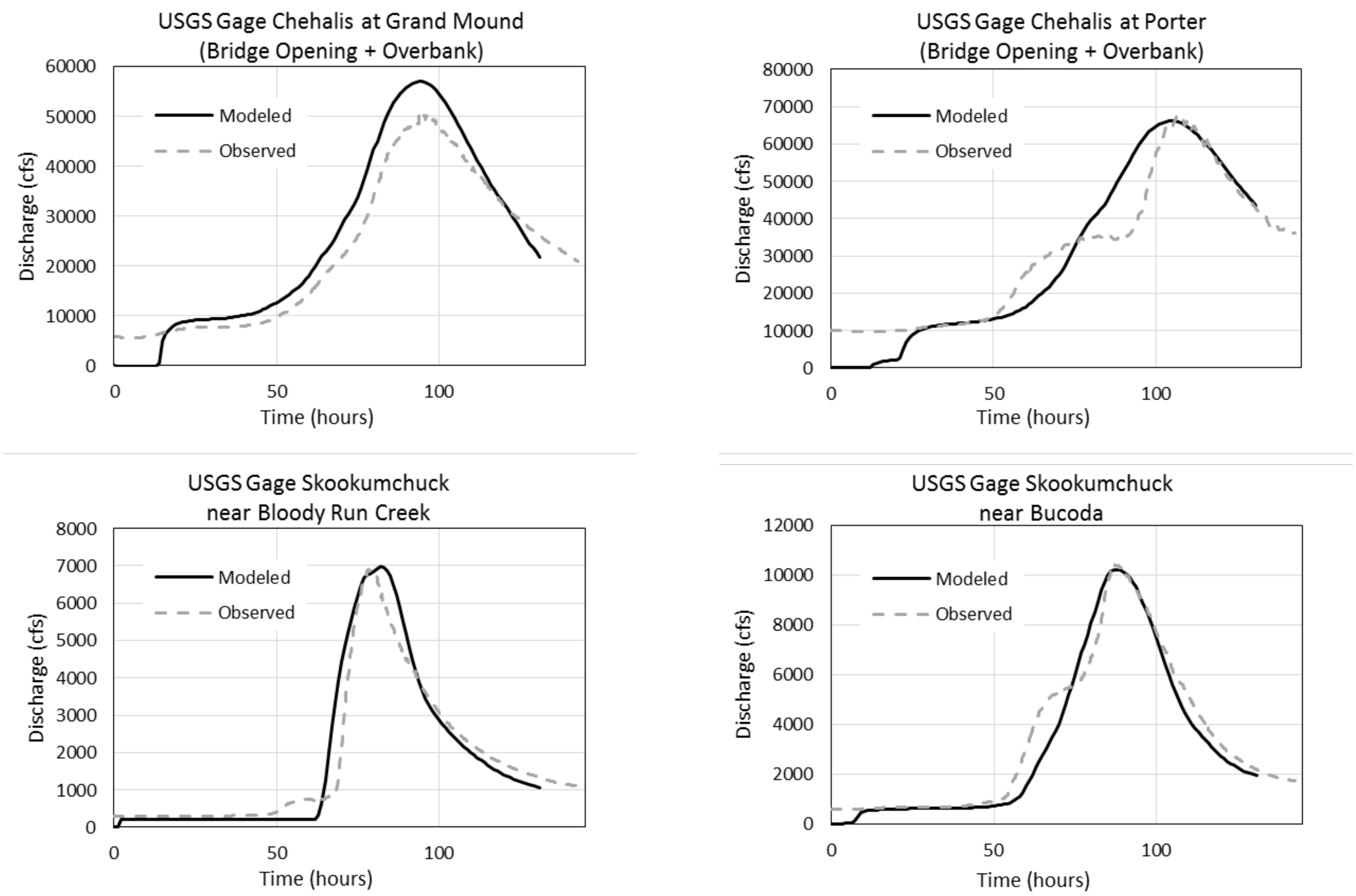


Figure 7
Comparisons of January 2009 Recorded and Simulated Discharge Hydrographs



December 2007

The December 2007 flood event was considerably larger than the 2009 event on the Chehalis River, along both the mainstem and South Fork which have their headwaters in the Willapa Hills. Considerable HWM peak data exist throughout the model domain, as shown in Figure 8, including 140 surveyed HWMs as well as observed stage hydrographs at the USGS streamflow gages. There are fewer points, however, along the Newaukum River as the USGS did not collect post flood data following the 2007 event. There are also no HWM data along the Skookumchuck where this event was much smaller than January 2009. We are also not aware of any HWM data within the Grays Harbor County portion of the model, between the Black River confluence and Porter.

Simulations were completed for the December 2007 event and results compared to the set of HWM data. Given the large number of HWM points for this particular event widely spread throughout the model domain, it is useful to evaluate these on a reach by reach basis. Table 4 summarizes the results averaged by reach. Overall and in most reaches, the mimicry is good with an average difference within 0.1 feet, however there are a few exceptions. Results above the Lincoln Creek confluence, both on the lower 1.5 miles of Lincoln itself as well as the Chehalis River until about 1 mile above Galvin Road, are all on the order of 1 foot too high. The upper reach of the mainstem Chehalis does not calibrate as well as the reaches downstream, although the results are skewed by an outlier near Nicholson Creek which simulates 3.7 feet below the measured HWM. Multiple HWM points collected near the USGS Doty gage as well as one HWM further upstream near the proposed dam site are likewise low by about two to three feet. It should be pointed out that there is considerable uncertainty to the upstream Chehalis River inflow, as the USGS Doty gage was inoperable during considerable portions of the December 2007 flood including the peak (WSE, 2014a).

Recorded stage as well as discharge hydrographs were compared to model output to examine the reasonableness of results throughout the simulation as well as the timing of results as an indicator of accuracy in model routing. Results were compared simultaneously with the January 2009 simulation and further refinements made to the n-values to achieve the best possible calibration for both events. Figure 9 presents hydrograph comparisons for stage along with the resulting difference or error in feet at the peak. Neither the Doty gage (as mentioned above) nor the Adna gage were operable during this event and therefore provide no data for comparison. Stage plots are provided for the remaining gages at or near Highway 6 (City of Chehalis WWTP), Mellen Street NWS, Grand Mound and Porter on the Chehalis River; Labree Road (near Chehalis) on the Newaukum River; and, Bloody Run Creek and Bucoda on the Skookumchuck River. All of the simulated results match the measured peak within 0.75 feet, and all but two locations (WWTP and Grand Mound) fall within about 0.25 feet. The timing of the peak as well as replicated stage hydrograph shape looks very good at most locations and reasonable at all. Discharge comparison plots are included in Figure 10 for rated USGS gages on the Chehalis River (Grand Mound and Porter) and Skookumchuck (Bloody Run Creek and Bucoda). The published USGS discharge data at Labree Road was used directly as the upstream model inflow for the Newaukum River and is not included as a comparison. Examining the peak flows, Grand Mound is over-predicted by about 10 percent, while at Porter downstream the match is reasonably close, similar to what was observed in the January 2009 simulation. On the Skookumchuck River, the upper gage near Bloody Run Creek hits the peak nearly spot on whereas the lower gage near Bucoda is low by about 10 percent. Replication of discharge hydrograph shape and timing looks reasonable though not perfect at each location.

Figure 8
December 2007 High Water Marks (and Model Extent)

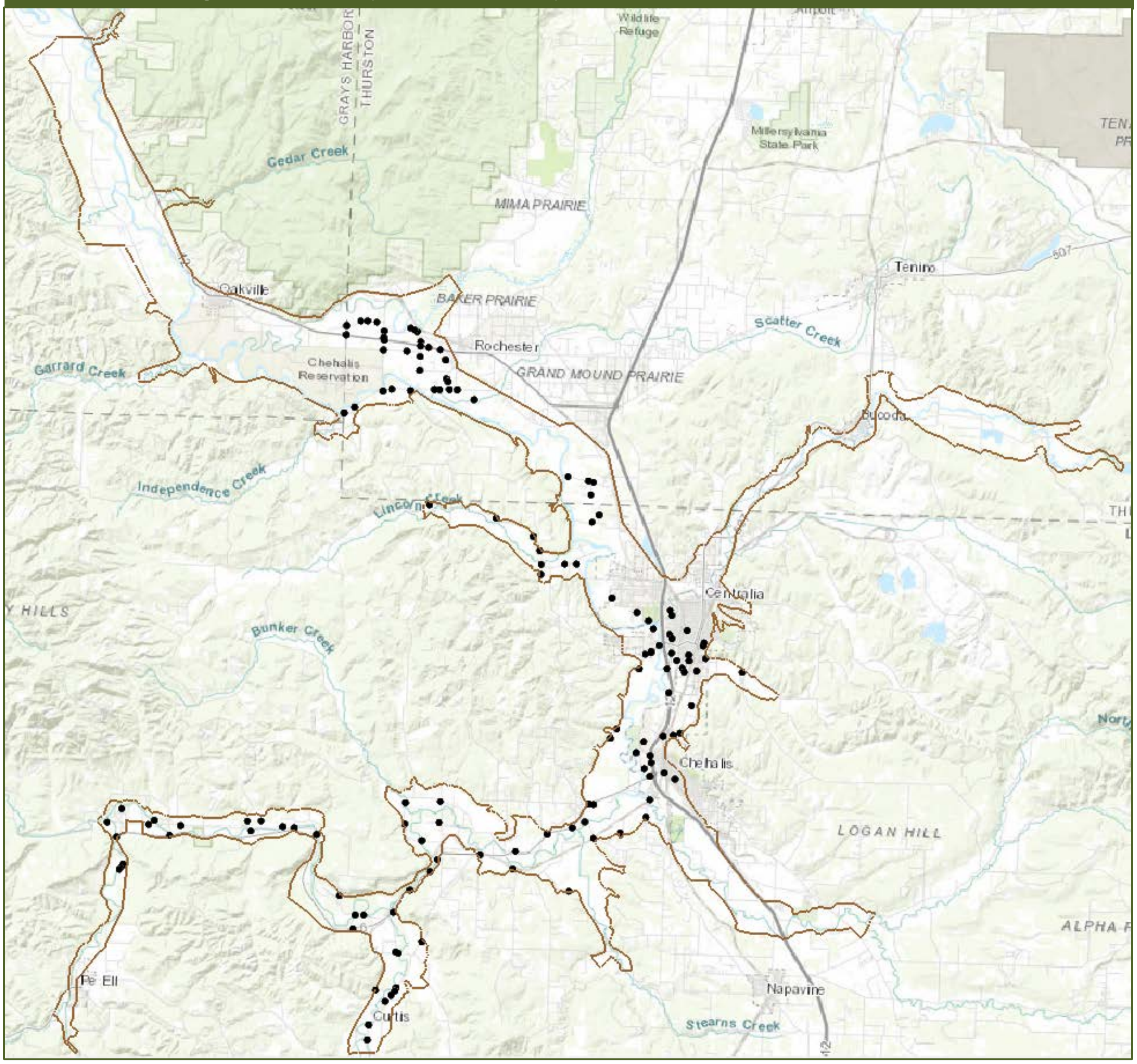


Table 4

Summary of December 2007 HWM Comparisons by Reach

RIVER	REACH (RIVER MILE)	NUMBER OF POINTS	AVERAGE DIFFERENCE, FEET*
Chehalis	Dam site to Doty gage (RM 108.5-101.5)	5	-2.68
Chehalis	Doty to South Fork (RM 101.5-88.0)	16	-0.76
Chehalis	South Fork to Newaukum (RM 88.0-75.25)	21	-0.13
Chehalis	Newaukum to Salzer Creek (RM 75.25-69.5)	10	0.29
Chehalis	Salzer Creek to Skookumchuck (RM 69.5-67.0)	20	0.36
Chehalis	Skookumchuck to Lincoln Creek (RM 67.0-61.75)	4	0.76
Chehalis	Lincoln Creek to Black River (RM 61.75-47.0)	38	-0.07
South Fork	Throughout (RM 6.0-0.0)	11	0.16
Dillenbaugh Creek	Lower (RM 0.5-0.0)	3	-0.03
Salzer Creek	Throughout (RM 4.0-0.0)	3	0.14
Skookumchuck	Lower (RM 1.0-0.0)	2	0.18
Lincoln Creek	Throughout (RM 4.0-0.0)	7	0.56
TOTAL	*all*	*140*	*-0.08*

*simulated – measured

Figure 9
Comparisons of December 2007 Recorded and Simulated Stage Hydrographs

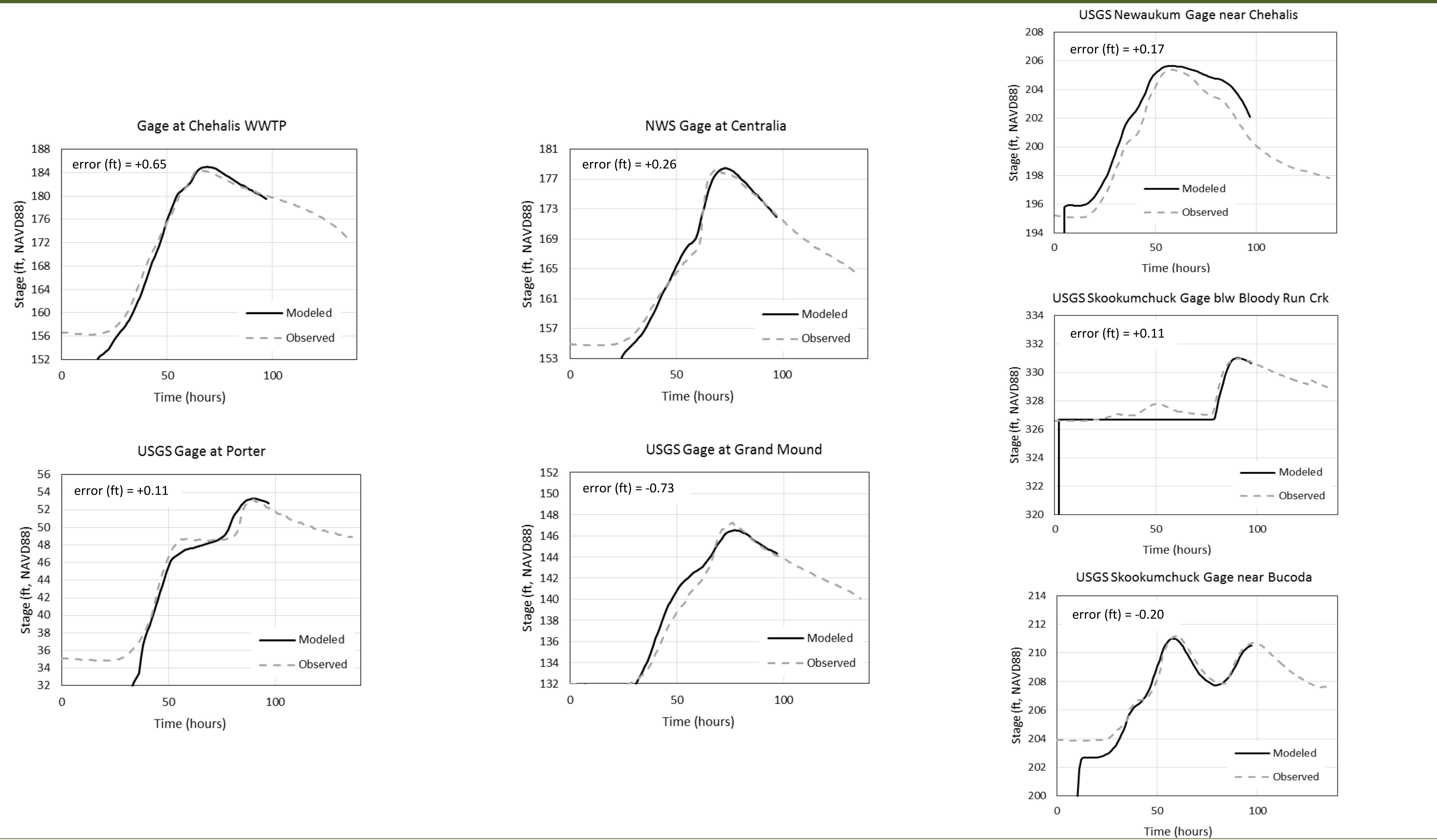
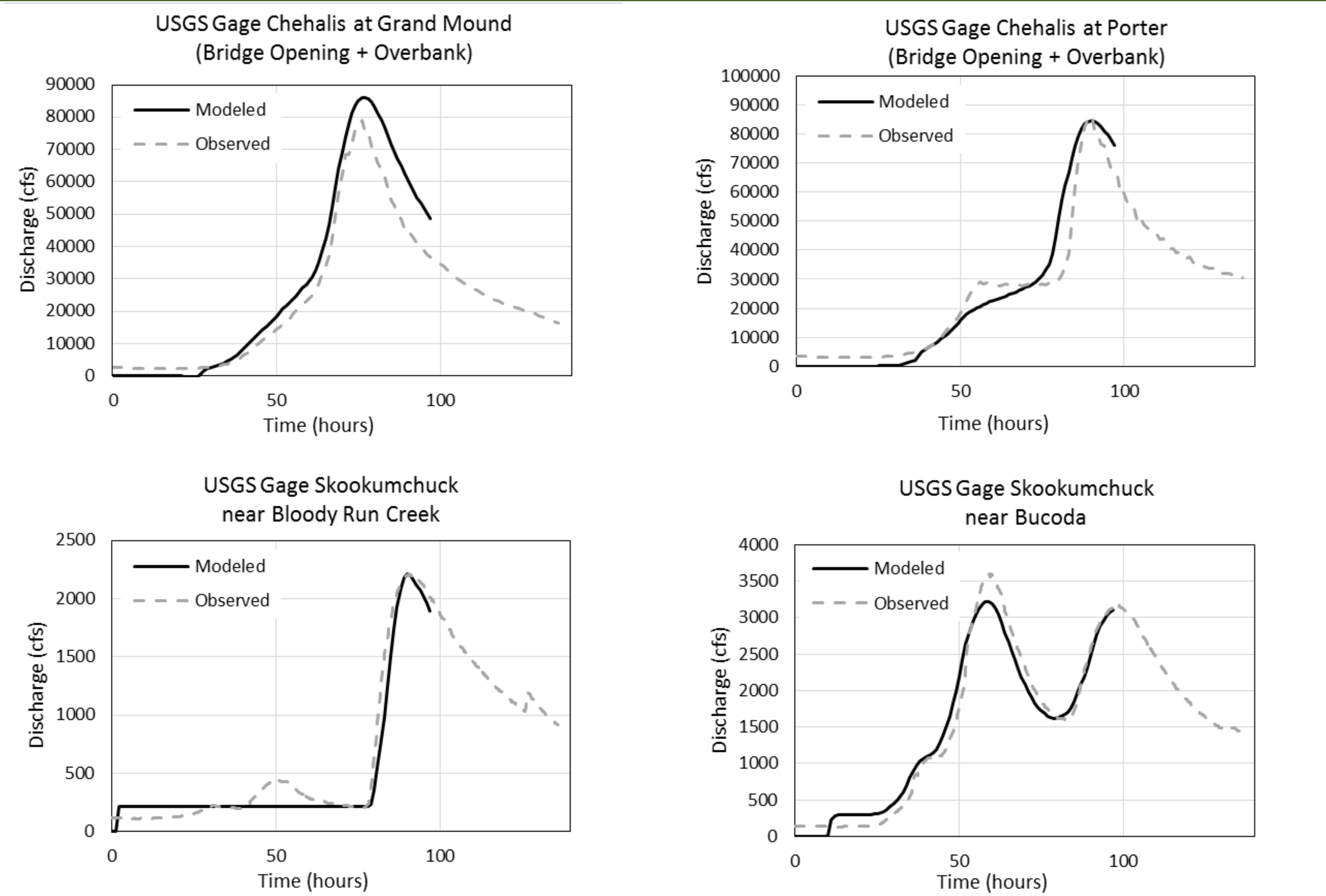


Figure 10
Comparisons of December 2007 Recorded and Simulated Discharge Hydrographs

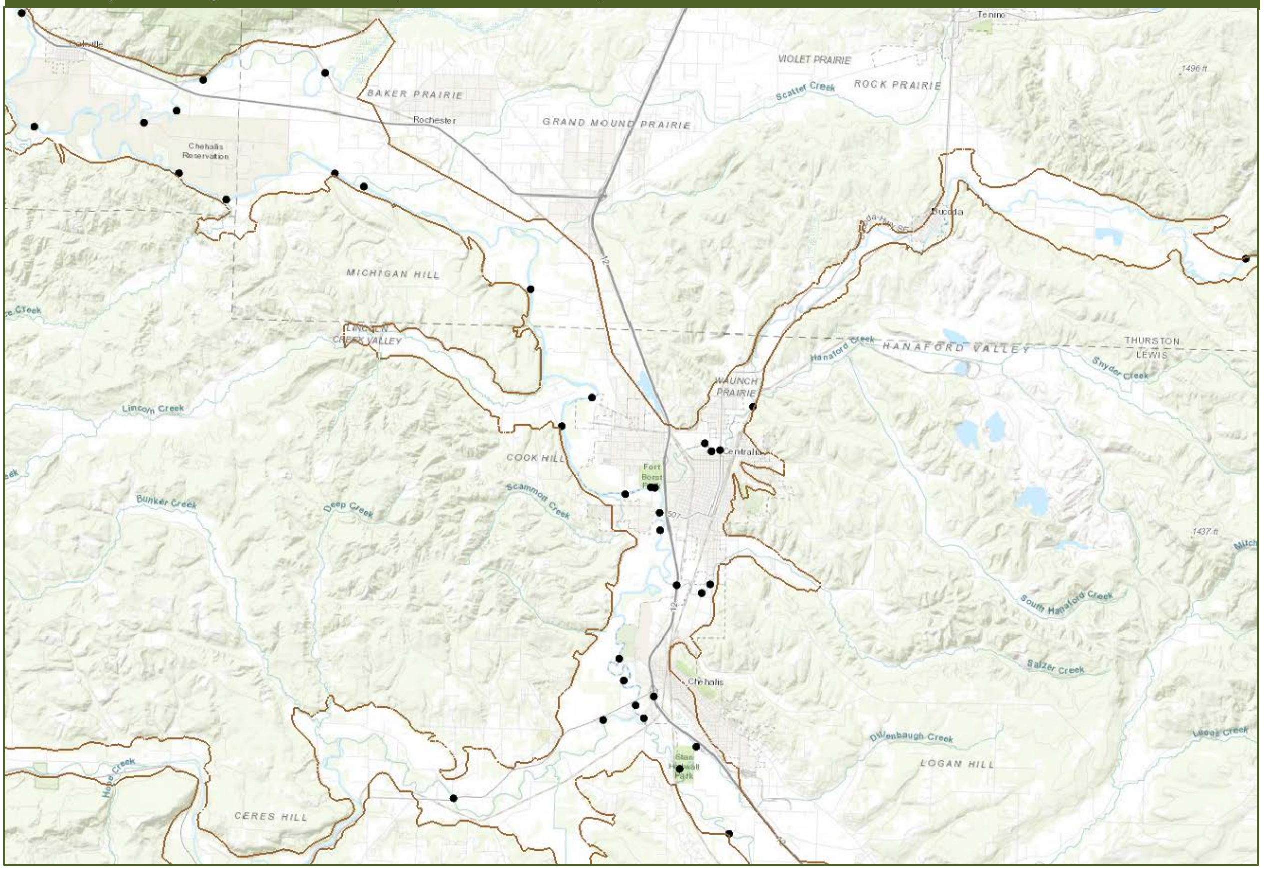


February 1996

The flood of February 1996 was a very large event and prior to 2007 the flood of record on the mainstem Chehalis River. This flood was simulated to verify the model calibration. For the 2009 and 2007 flood event simulations, roughness coefficients were adjusted (within reasonable limits) in order to produce results that reasonably mimicked the HWMs and measured hydrographs. For the February 1996 simulation, no additional adjustments were made for several reasons. First, this simulation is intended to verify (or validate) the prior calibration of the more recent flood events rather than further adjust roughness or other model inputs. Second, this event occurred more than 10 years prior to the other events, and nearly 20 years prior to the topographic and bathymetric data used for the majority of the model. As such, it is assumed to be less reliable, in terms of accurately replicating the measured data.

Observed HWM data at 36 locations along the Chehalis and several tributaries, as shown in Figure 11, were previously added to the HEC-RAS model. These HWM points were extracted from the HEC-RAS input file and compared to the RiverFlow2D results. The average difference of all points was only about -0.2 feet. Of the 36 points, 26 fall within +/-1.0 foot of the measured data (nearly 75 percent), and 32 fall within about +/-1.5 feet (nearly 90 percent). The remaining 4 points include two that are about 2 feet too high and two that have differences exceeding 4 feet. One HWM location at the Black River BNSF bridge computes about 4.5 feet too low, possibly in part due to debris issues or poor representation of the Black River hydrology. Another point on the Chehalis below Oakville computes about 4.8 feet too high. Neither has other nearby HWMs for comparison. And thus it is not possible to say whether these observations are erroneous or not. However, these are the only two outliers of the set of 36 HWMs, indicating that the errors could be due to unusual circumstances (e.g. debris) or due to error in the HWM measurements. Of the 22 observed HWMs in the Twin Cities area, all but two fall within +/-1.0 foot (and the remaining two are within 2.0 feet).

Figure 11
February 1996 High Water Marks (and Model Extent)



Figures 12 and 13 present stage and discharge comparison hydrographs, respectively, at locations that provided continuously measured data throughout the flood event. The stage gages near the Chehalis and Centralia wastewater treatment plants were not operating continuously at this time. And as mentioned previously, discharge hydrographs at Doty and Labree Road (Newaukum) match favorably primarily because they directly provide inflow boundary conditions to the model and are therefore not included in the comparison. Examination of the stage hydrograph results shows a very tight calibration at Doty throughout the event. The upper locations on the Newaukum and Skookumchuck tributaries generally over-predict the stage throughout the flood including at the peak. Downstream at Grand Mound, the simulation likewise over-predicts during the rising limb but then under-predicts at the peak. The differences at the peak are all within about 1 foot. Examining the discharge hydrographs shows a reasonably close match of the peak discharges on both the Chehalis and Skookumchuck Rivers, although the upper Skookumchuck gage near Bloody Run was not operational during the peak. Timing of the simulated peak at the three operating gages however each lag behind the measured peak by several hours, most notably on the Skookumchuck River near Bucoda by about 8 hours which likely influences the downstream lag at Grand Mound and Porter. The stage and discharge hydrograph comparisons for the 1996 flood are nevertheless reasonable overall for a validation event.

Figure 12
Comparisons of February 1996 Recorded and Simulated Stage Hydrographs

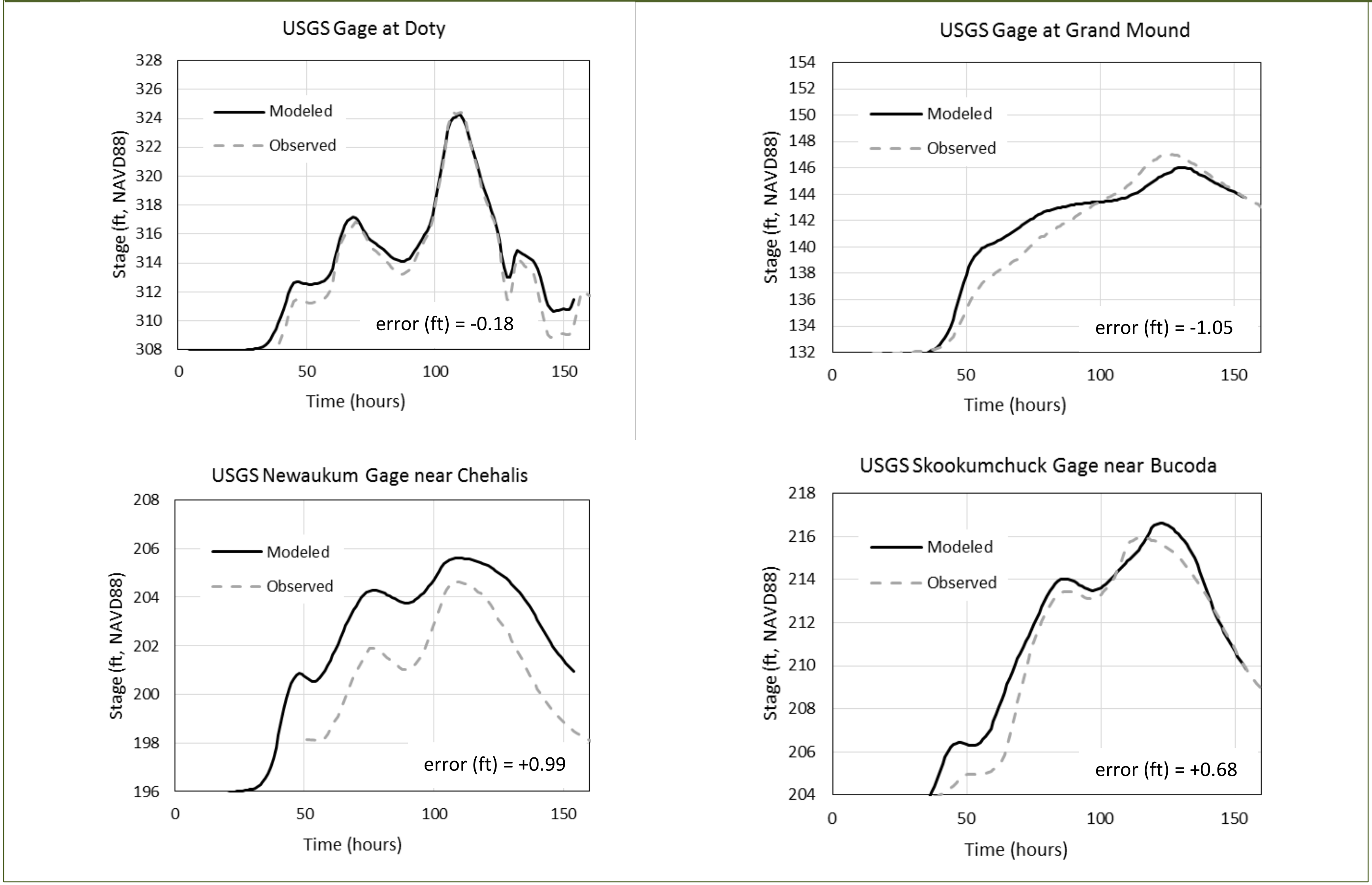
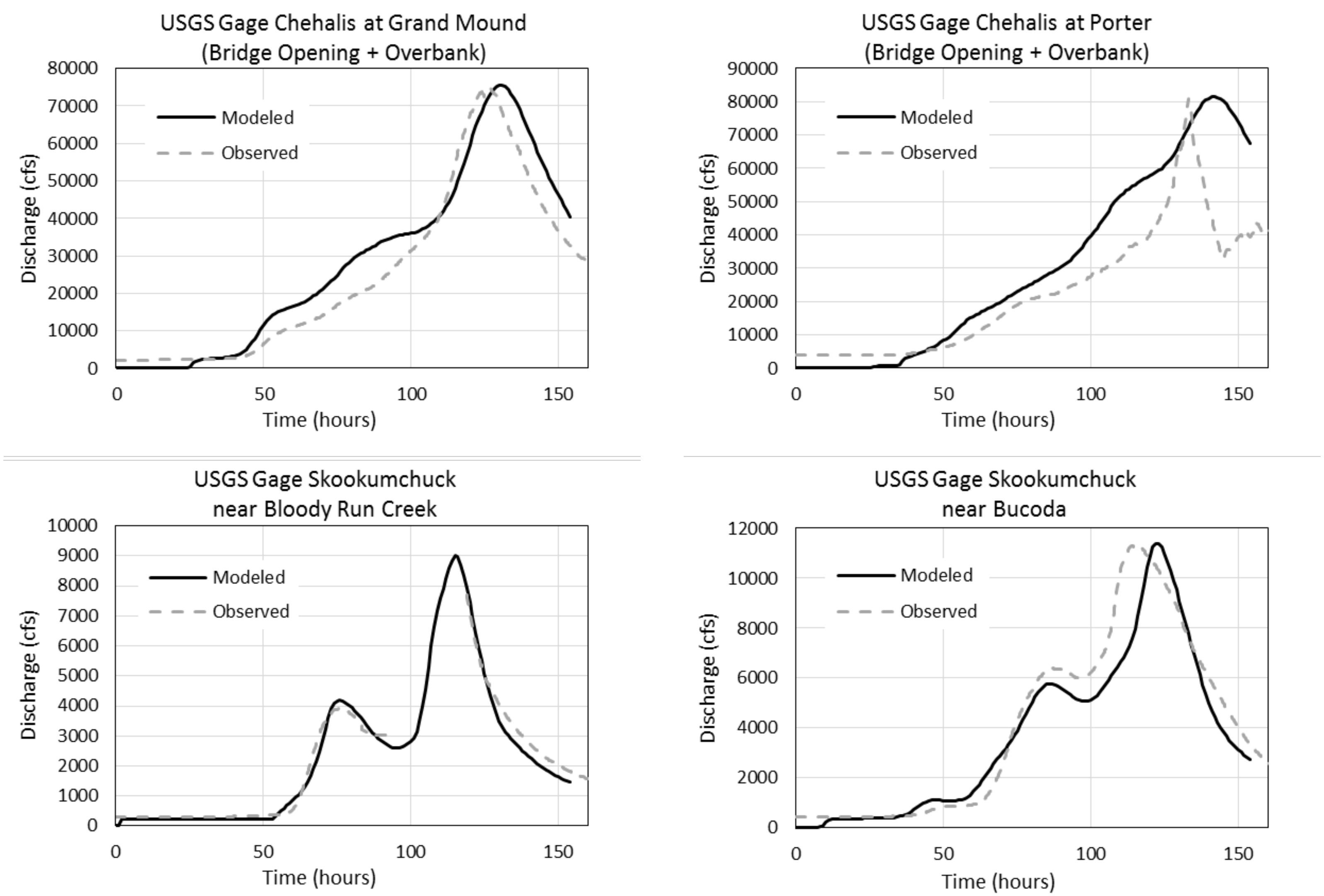


Figure 13
Comparisons of February 1996 Recorded and Simulated Discharge Hydrographs



Model Application

The calibrated Riverflow2D hydraulic model was used to simulate hydraulic conditions throughout the Chehalis River basin corresponding to the 10- and 100- year flood events. Inflows for these events were taken from the existing HEC-RAS model and reflect the hydrologic analysis conducted by WEST Consultants for the Corps of Engineers (USACE, 2014). Maximum modeled water surface elevations at key locations throughout the model domain are listed in Table 5. These are the same locations that have previously been reported for the HEC-RAS modeling (e.g. WSE, 2012). Simulated maximum water surface elevations for the December 2007 flood event are also shown in Table 5 for comparison. Figures 14 and 15 show simulated maximum flow depths for the 10- and 100- year events, respectively, in and around the Twin Cities area.

Table 5

Maximum modeled water surface elevations at various locations

LOCATION	10-YEAR MAX. WSEL (FT NAVD88)	100-YEAR MAX. WSEL (FT NAVD88)	DEC. 2007 MAX. WSEL (FT NAVD88)
Near Doty	311.9	319.5	325.6
Curtis Store (on S Fork Chehalis)	229.5	231.9	237.7
Downstream of South Fork	214.3	220.1	225.5
Near Adna	195.3	198.1	199.2
Labree Road Bridge (on Newaukum R)	205.5	206.2	206.1
Newaukum Confluence	182.8	185.9	186.9
Dillenbaugh Creek at I-5	181.6	186.0	187.0
South End of Airport riverward of levee	177.9	181.8	183.2
South End of Airport landward of levee	Dry	179.9	182.9
North End of Airport riverward of levee	174.5	179.4	181.9
North End of Airport landward of levee	Dry	179.5	182.0
Mellen St Bridge	171.5	176.7	178.4
Mellen St just east of I-5	Dry	176.1	178.1
Skookumchuck Confluence	170.0	174.9	176.6
Upstream of Galvin Road	163.2	167.2	168.9
Grand Mound (Prather Road Bridge)	144.1	146.3	147.0
Near Rochester	121.3	124.1	124.6
Anderson Road	108.5	110.6	110.8
Black River Confluence	91.0	94.2	94.5
Sickman Ford Bridge	79.2	82.5	82.6
Porter Creek Road Bridge	50.8	53.2	53.3

Figure 14
Modeled Maximum Flow Depth during 10-year Event

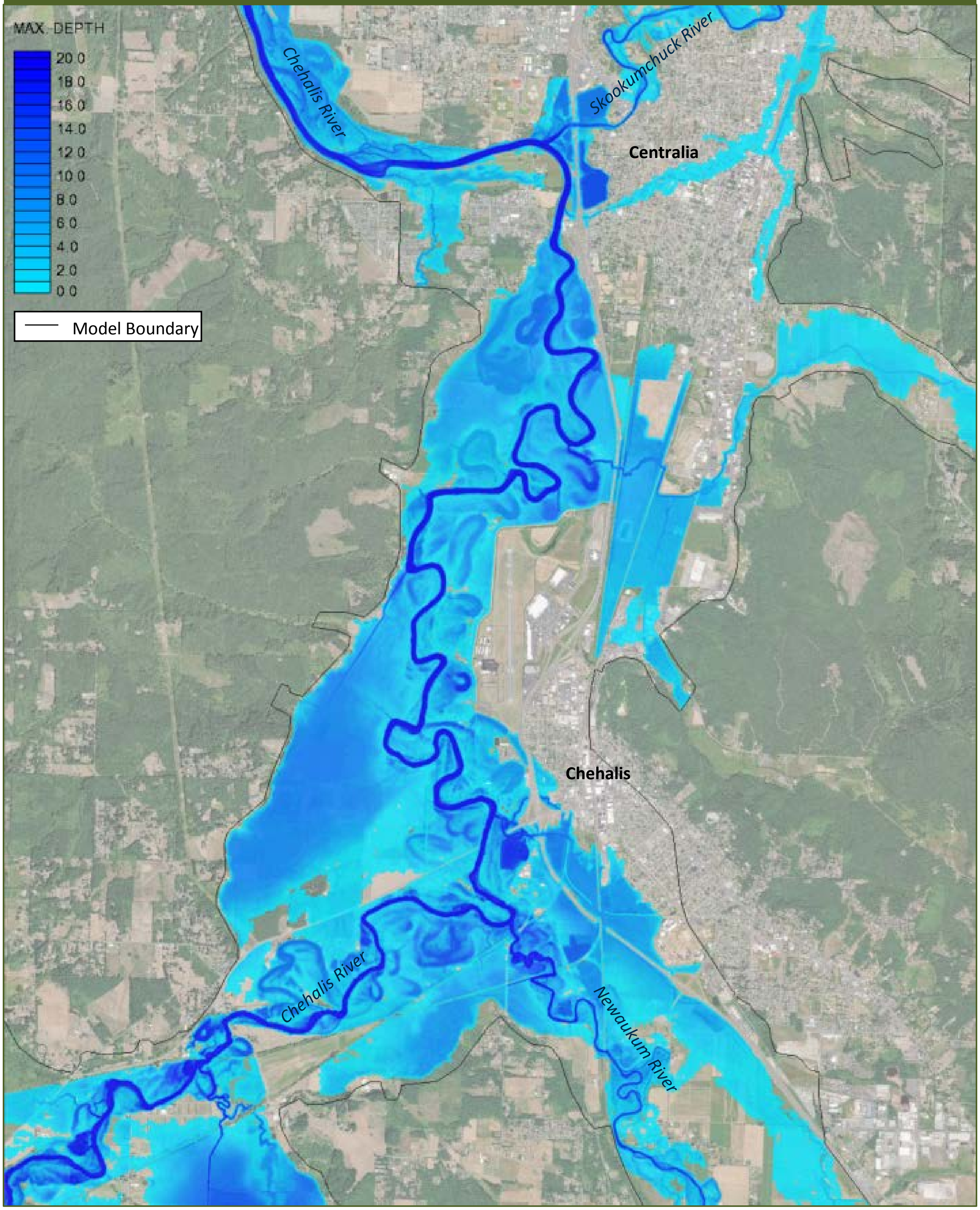
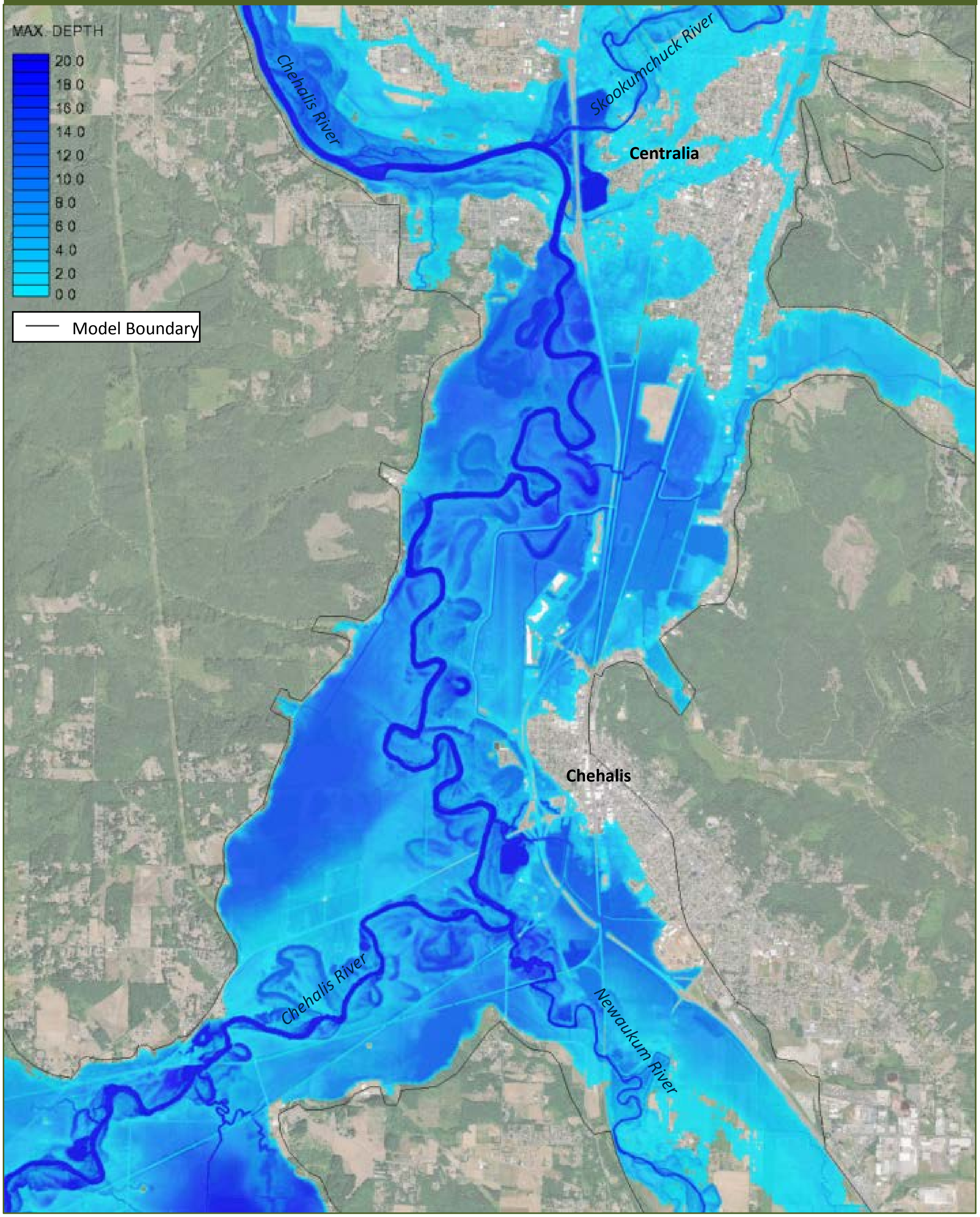


Figure 15
Modeled Maximum Flow Depth during 100-year Event



Conclusions

This memorandum summarizes WSE's development of a RiverFlow2D unsteady flow model of the Chehalis River extending from the proposed dam site above Pe Ell in Lewis County to the Porter Bridge in Grays Harbor County. The model encompasses approximately 75 miles of the Chehalis River and floodplain, as well as significant portions of major tributaries including the South Fork Chehalis, Newaukum, Skookumchuck and Black Rivers. Using inflows from WSE's previously developed HEC-RAS 1D model, the RiverFlow2D model was calibrated to high water marks and observed data at streamflow gages for the flood events of January 2009 and December 2007, and subsequently validated using data from the earlier February 1996 flood event. Calibrating and verifying a basin scale hydraulic model to multiple flood events with a very large set of observed data is extremely challenging. While it is often not possible to match all observed data, the general trends seen in comparisons to observed data provide a good indication of the model's overall performance. Within this context, the Chehalis River model calibration is considered good with similar or better results when compared to the earlier HEC-RAS modeling. The 2D model also provides far better spatial refinement and is based upon more accurate governing equations and simulation methods. This lends confidence to use of the 2D model as an improved tool for future evaluation of flood damage reduction and habitat restoration alternatives.

References

Anchor QEA, 2017. Topobathymetric data for the Chehalis watershed, April 15 through May 10, 2017 survey.

Chow, 1959. Open-Channel Hydraulics. Ven Te Chow. McGraw-Hill Publishing Company.

NHC, 2018. 2D Existing Conditions Hydraulic Model of the North and South Forks of the Newaukum River – Summary Memorandum prepared for Natural Systems Design.

USACE (U.S. Army Corps of Engineers), 2014. Chehalis Basin Ecosystem Restoration General Investigation Study Baseline Hydrology and Hydraulics Modeling. Prepared by WEST. January 2014.

USGS, 1989. Guide for Selecting Manning's Roughness Coefficients for Natural Channels and Flood Plains. George J. Arcement, Jr., and Verne R. Schneider. U.S. Geological Survey Water-Supply Paper 2339.

USGS, 2010. Mastin, M.C., Gendaszek, A.S., and Barnas, C.R.. Magnitude and Extent of Flooding at Selected River Reaches in Western Washington, January 2009. U.S. Geological Survey Scientific Investigations Report 2010–5177.

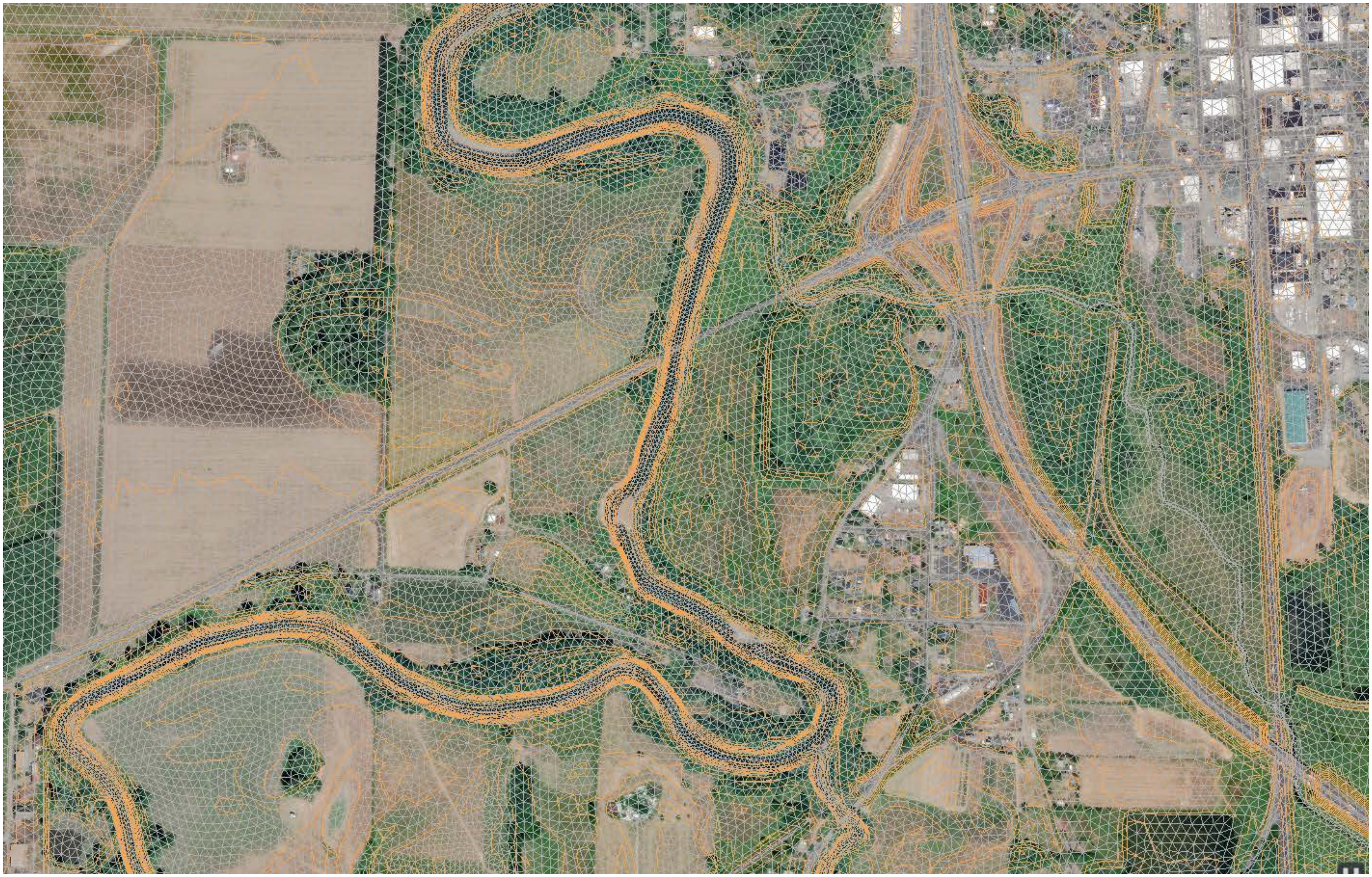
WSE, 2012. Chehalis River Hydraulic Model Development Project. Draft Report. July 23, 2012.

WSE, 2014a. Chehalis Basin Strategy: Reducing Flood Damage and Enhancing Aquatic Species – Peer Review of December 2007 Peak and Hydrograph at Doty Gaging Station. Memorandum prepared by Larry Karpack of Watershed Science & Engineering, to Bob Montgomery of Anchor QEA. January 31, 2014.

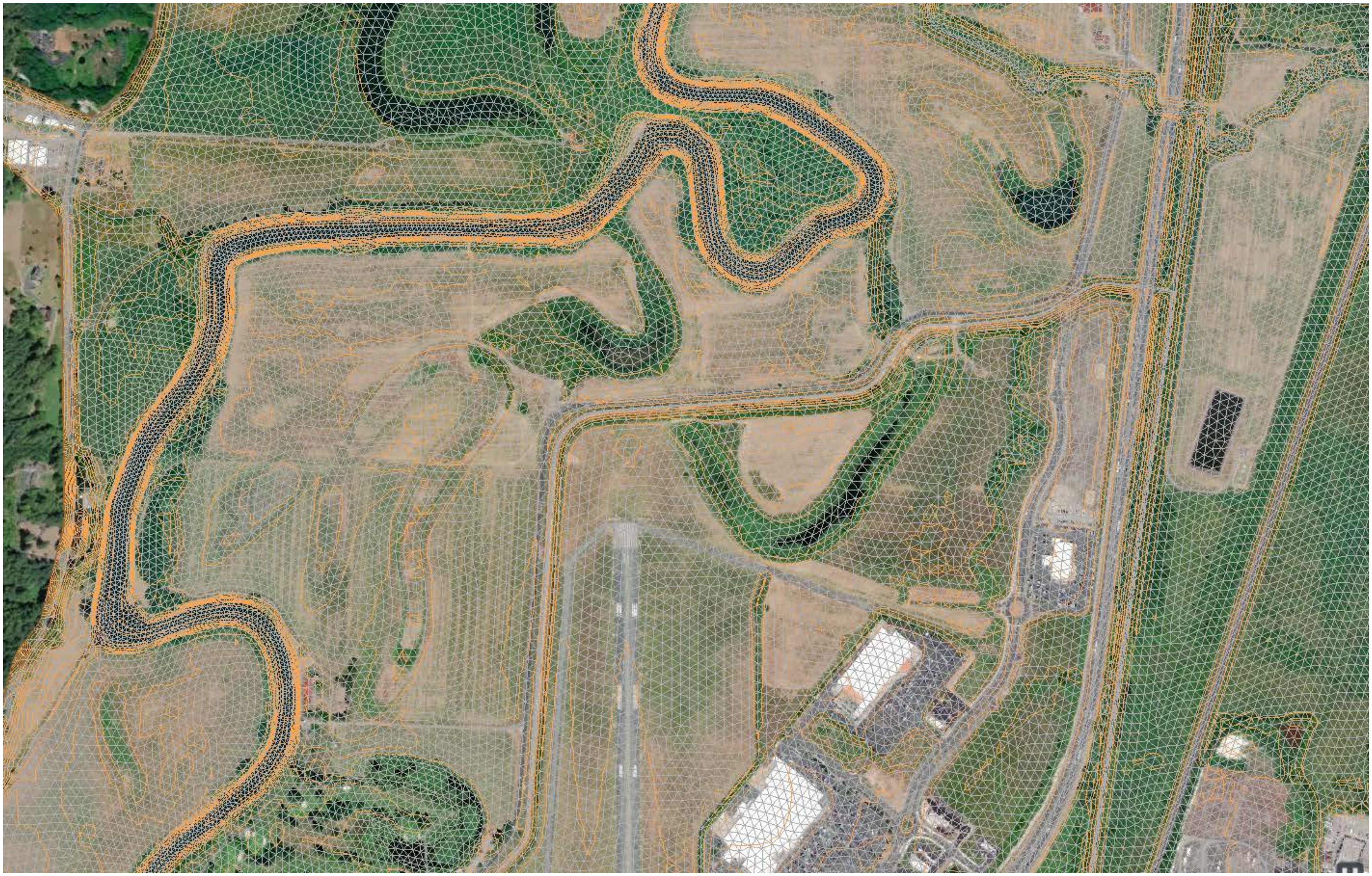
WSE, 2014b. Chehalis Basin Strategy: Reducing Flood Damage and Enhancing Aquatic Species – Development and Calibration of Hydraulic Model. Memorandum prepared by Bob Elliot and Larry Karpack of Watershed Science & Engineering, to Bob Montgomery of Anchor QEA. July 22, 2014.

WSE, 2018. Newaukum River Existing Conditions RiverFlow2D Hydraulic Model Development. Memorandum prepared by Bob Elliot, Tim Tschetter and Larry Karpack of Watershed Science & Engineering, to Bob Montgomery of Anchor QEA. October 16, 2018.

APPENDIX A – REPRESENTATIVE MODEL TERRAIN AND MESH EXAMPLES:



(Highway 6 area near Interstate 5)



(North airport area to Salzer Creek)