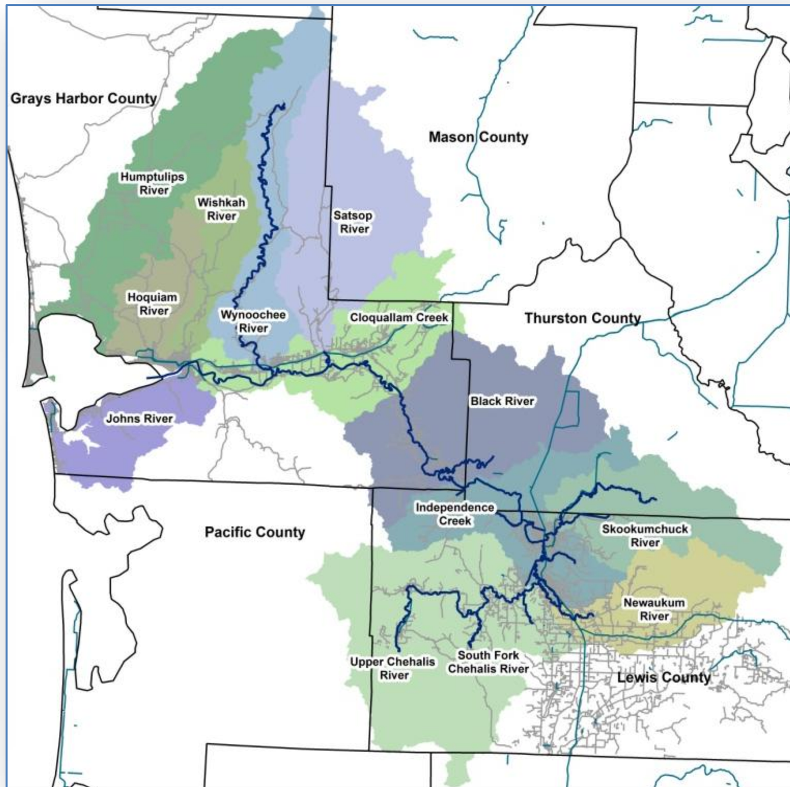
Draft Report - Chehalis River Hydraulic Model Development Project



Prepared by:
WATERSHED Science & Engineering
and
WEST Consultants

Prepared for:
Chehalis River Basin Flood Authority

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Executive Summary

Numerous studies have been undertaken to evaluate flood damage reduction in the Chehalis River basin. These include work for the Federal Emergency Management Agency (FEMA), the US Army Corps of Engineers (Corps), Lewis County, and the Lewis County Public Utility District (PUD). Much of the effort has focused on the development of a hydraulic model for the mainstem of the Chehalis River and application of that model to simulate the "100-year flood". The studies have provided insight into floodplain management issues; however, work to date has focused primarily on the Chehalis River upstream of Grand Mound. The Chehalis River Basin Flood Authority (Flood Authority) recognized a need to extend the work downstream from Grand Mound to the mouth of the Chehalis River at Grays Harbor.

The Washington State Legislature concurred with the Flood Authority regarding the need to study the lower portions of the river. Through a budget proviso in Engrossed Substitute House Bill (ESHB) 2020 the Legislature provided funding to "complete the hydraulic model for the Chehalis River to calculate flood levels, flood damages, and benefits of proposed flood mitigation projects for the lower portions of the river."

The Flood Authority retained WATERSHED Science & Engineering (WSE) and subconsultants WEST Consultants, Pacific Geomatic Services and Minister & Glaeser Surveying to develop a hydraulic model and evaluate flood relief alternatives for the Chehalis River basin. While the primary objective of the Flood Authority project are to develop the hydraulic model, additional tasks identified over the course of the project have been completed to the extent possible considering funding and schedule constraints. These include collection of field survey data, workshops and education regarding basin flood issues, and evaluation and reporting on a wide range of flood relief alternatives.

The hydraulic model developed for this study extends from the mouth of the Chehalis River to upstream of Pe Ell, a distance of more than 108 miles. The model also includes significant portions of key tributaries including the following: 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 (5.8 miles). While the model was developed primarily to evaluate the effects on the main stem Chehalis River of large-scale flood relief projects it can also serve as a tool for the evaluation of hydraulic conditions and flooding on these tributaries. In fact, the model has already been used by WSE to evaluate the effects of potential modifications to the railroad bridge downstream of Bucoda on the Skookumchuck River.

The hydraulic model developed for this study was used to evaluate 15 individual flood relief projects, and the results of those evaluations were reported to the Flood Authority and stakeholders at meetings in April and May 2012. Based on feedback from the Flood Authority the projects were grouped into combinations and additional modeling was conducted. The additional modeling was presented to a broader group of basin stakeholders at meetings in Lacey in May 2012 and in Grand Mound in June 2012. After receiving feedback at those meetings three additional combinations were formulated and evaluated. In total more than 25 potential flood relief projects or combinations of projects were evaluated with the results reported herein. The results have also been provided to the State Office of Financial Management and the Flood Authority for use in defining an appropriate path forward for basin wide flood relief.

The baseline hydraulic model developed for this project represents the best available information on hydraulic conditions in the modeled reaches. However, it must be recognized that the model includes both newly modeled reaches (e.g. Chehalis River between Porter and Aberdeen) and reaches based on older models. Some of the older model reaches were updated with newly collected cross section surveys, while others use cross sections collected as long ago as 2001. Similarly, in some portions of the model floodplain topographic data were updated to reflect new LiDAR data while in other reaches the topographic data dates back to 2002. While it would have been preferable to update the entire model with new field surveyed cross sections and up to date topographic data the model is still a significant improvement over any tool that has been previously available and it should benefit flood relief investigations throughout the basin. As time and resources allow it is recommended that the model be updated to use new topographic and survey data, that the updated model be refined to address any new infrastructure that has been built since the original model development, and that the updated model be calibrated to available flood information.

Chehalis Basin Hydraulic Model Report

Background

Over the past 15 years numerous studies have been undertaken to evaluate flood damage reduction in the Chehalis River basin. These projects include work for the Federal Emergency Management Agency (FEMA), the US Army Corps of Engineers (Corps), Lewis County, the Lewis County Prosecuting Attorney's Office, and the Lewis County Public Utility District (PUD). Much of this recent work has focused on the development of a hydraulic model for the mainstem of the Chehalis River between Doty and Grand Mound and application of that model to simulate the "100-year flood". Work for Lewis County and the PUD focused on application of the FEMA model to evaluate the potential benefits or impacts of various proposed flood damage reduction projects including upstream water storage. Work by the Corps has focused on evaluation of new and heightened levees along the Chehalis River near the cities of Chehalis and Centralia and flood storage at Skookumchuck dam.

The previous studies have provided insight into issues related to floodplain management in the upper basin; however, work to date has focused primarily on the Chehalis River upstream of Grand Mound. The Chehalis River Basin Flood Authority (Flood Authority) recognized the need to extend the hydrologic and hydraulic modeling downstream from Grand Mound to the mouth of the Chehalis River at Grays Harbor and to use the extended model to evaluate the potential impact of upstream flood damage reduction projects on downstream flooding.

The Washington State Legislature concurred with the Flood Authority regarding the need to study the lower portions of the river. Through a budget proviso in Engrossed Substitute House Bill (ESHB) 2020 the Legislature provided funding to "complete the hydraulic model for the Chehalis River to calculate flood levels, flood damages, and benefits of proposed flood mitigation projects for the lower portions of the river." The Office of Financial Management also showed support for this study in an agreement signed with the Flood Authority in early August 2011.

Concurrent with the efforts of the Flood Authority, the U.S. Army Corps of Engineers (Corps) identified a need for additional hydraulic modeling to support "ecosystem restoration" planning in this same area, and procured funding to support this through the Corps' Basinwide General Investigation process. Considering the need for hydraulic modeling to support both ecosystem restoration and flood risk reduction, and a desire to make the best use of available resources, the Flood Authority retained WATERSHED Science & Engineering (WSE) and WEST Consultants (WEST) to work with the Corps, WSDOT, and other basin stakeholders to develop a basinwide hydraulic model and conduct analyses of potential flood damage reduction projects. This report documents model development and application efforts by the WSE team.

Engrossed Substitute House Bill 2020

As noted above, the current study effort is funded through a budget proviso in ESHB 2020. The specific sections of the bill that are relevant to the work of the Flood Authority are found in Section 1033 starting on Page 19 and read as follows:

Catastrophic Flood Relief (20084850)

(1) The appropriations in this section are subject to the following conditions and limitations:

(a) $1,320,000 of the appropriations are provided solely for the Chehalis basin flood control authority or other local flood districts

(i) to study, develop, construct, maintain, operate, and fund flood control measures throughout the basin,

(ii) to complete by December25 2011 the ongoing study of the effect of possible retention structures on fish in the basin, and

(iii) to complete the hydraulic model for the Chehalis river to calculate flood levels, flood damages, and benefits of proposed flood mitigation projects for the lower portions of the river; and

(b) $1,200,000 of the appropriations are provided solely for nonfederal matching funds and state agency costs associated with the United States army corps of engineers flood hazard mitigation projects for the Chehalis river basin. p. 19 ESHB 2020.SL

(2) By July 2012, the office of financial management, in collaboration with the department of transportation and the department of ecology, and affected and interested federal agencies, tribal governments and local governments, must provide a report to the governor and legislature that identifies recommended priority flood hazard mitigation projects in the Chehalis river basin for continued feasibility and design work. The report must:

(a) Address the potential for flood mitigation through upstream water retention facilities, including benefits and impacts to fish and potential mitigation of impacts;

(b) Describe the current alignment and design of the federal flood levees proposed at Centralia and Chehalis, including extent of protection provided to these communities, and any upstream or downstream effects of the levees;

(c) Evaluate alternative projects that could protect the interstate highway and the municipal airport at Centralia and Chehalis, and ensure access to medical and other critical community facilities during flood events;

(d) Discuss other alternatives that could provide flood relief and protection in the basin, such as replacement of highway bridges that constrain flood waters, flood easements on agricultural lands, livestock evacuation facilities and routes, small-scale water diversion and retention, use of riparian habitat and environmental restoration projects to mitigate damages from flood waters, and other projects or programs;

(e) Summarize the benefits and costs of recommended projects, using available information and accepted benefit/cost methods; and

(f) Identify the responsible parties and procedures for making final decisions on funding, construction and governance of recommended flood projects, any related and necessary government agreements, and a schedule for these decisions.

(3) It is the intent of the legislature to fulfill the commitment of section 101, chapter 179, Laws of 2008 and chapter 180, Laws of 2008, by appropriating funds when the federal match requirement is needed.

Flood Authority Contracting

Given the need to develop hydrologic and hydraulic modeling to evaluate ecosystem restoration and flood risk reduction projects the Flood Authority issued a request for qualifications on July 25, 2011. Four responses were received by the August 8, 2011 deadline. Flood Authority staff then worked with technical staff from state, federal, and local agencies to develop screening criteria and review and score the responses. After consultation with the technical team, the Flood Authority's Executive Committee selected three firms to interview and ultimately asked two firms (WATERSHED Science & Engineering and WEST Consultants) to collaborate to complete this project. WSE and WEST revised their proposals into a joint effort with WSE as the prime and overall technical lead and WEST as their key subconsultant. This collaboration provided the Flood Authority with the technical and management expertise they wanted and addressed the Flood Authority's desire to leverage available resources, as WEST was already under contract to the Corps of Engineers to develop modeling for portions of the basin as part of the General Investigation.

The Executive Committee approved the WSE contract and recommended to the Lewis County Board of County Commissioners (BOCC) (as the lead agency for the Flood Authority) that this contract be adopted. On September 6th the BOCC entered into a contract with WATERSHED Science & Engineering (WSE) and subconsultants WEST Consultants (WEST), Pacific Geomatic Services (PGS) and Minister Glaeser Surveying (MGS) to develop a hydraulic model and evaluate flood relief alternatives for the Chehalis River basin. While the primary objective of the Flood Authority's project was to develop a hydraulic model, other, secondary objectives identified over the course of the project have been addressed to the extent possible considering funding and schedule constraints.

Scope of Work

The Scope of Work for the hydraulic model development project was finalized in October 2011. The scope was prepared by WSE in coordination with the Flood Authority to define the tasks necessary to address the ESHB 2020. The scope was amended in January 2012 to include hydraulic modeling and analysis of key tributaries. Key tasks in the final scope are summarized below:

Task 1 - Overall Project Management, Stakeholder Involvement, Regular Communication with Flood Authority

WSE is responsible to the Flood Authority for the overall management of the model development project including administering the contract and providing monthly invoicing and progress reports. This task also includes presentations at key milestones and as necessary to keep the Flood Authority fully informed about the status of the work.

Task 2 - Initial Basin Reconnaissance

The project team conducted targeted field reconnaissance of the basin, contacted key stakeholder groups, coordinated with the State technical team, and gathered information (including topographic and survey data).

Task 3 - Conduct Adequacy Review of Existing Floodplain Topographic and LiDAR Data

This task was deferred. No work was conducted under this task.

Task 4 - Detailed Work Plan Development

A detailed Work Plan was developed to guide the Chehalis River hydraulic model development project. The Work Plan included schedule milestones, scope information and estimated costs for each task. The draft Work Plan was distributed by the Flood Authority to interested agencies and Tribes for review and comment.

Task 5 - Refine Hydraulic Model to reflect Flood Authority Interest

WEST Consultants is currently under contract to the Corps to develop a hydraulic model of the Chehalis River (Pe Ell to Montesano with the exception of Grand Mound to Porter) under the Basin-wide General Investigation (GI). The Corps project includes collection of bathymetric survey data for model cross sections in several reaches and the development of hydrologic data for the basin. Based on stakeholder input, the Flood Authority tasked the WSE project team with modifying, enhancing, or refining the Corps hydrologic and hydraulic modeling. The following sub-tasks were completed:

Task 5a - Obtain new channel survey data for the Chehalis River between Grand Mound (RM 60.6) and Porter (RM 33) - The Twin Cities hydraulic model includes cross sections in this reach but the exact location of those cross sections was not known. A portion of the reach, from RM 41 to Grand Mound, was surveyed by Minister Glaeser in 2001 for the Corps but that survey data is now more than 10 years old and not likely to be representative of current channel conditions. Given these considerations and knowing that a reliable model of this reach is critical for meeting ESHB 2020 requirements, additional survey data collection to support model development for this reach (Task 5b) was needed.

Task 5b - Refine model of Chehalis River between Lewis/Thurston County line and Porter - This reach was included in the earlier Twin Cities hydraulic model. The Corps GI study contract did not call for additional model refinement, however, considering the date of the cross section and topographic information in the model the accuracy and reliability of the simulations in this reach is a concern. This task included developing a new hydraulic model using the new cross section data described in Task 5a and the 2002 PSLC LiDAR data and then validating the model against available observations.

Task 5c - Extend Corps Hydraulic Model downstream from Montesano to Aberdeen - the GI Study contract included development of a hydraulic model for the Chehalis River upstream of the confluence with the Wynoochee River at Montesano. The Chehalis River reach downstream of the Wynoochee River is significantly tidally influenced and more hydraulically complex due to significant side channels and backwater channels in the floodplain. Under this task the HEC-RAS model was extended to Aberdeen including collecting additional channel and overbank survey data. Model development for this reach also required additional hydrologic analysis to provide data for hydraulic model calibration and validation.

Task 5d - Refine hydraulic model of main stem Chehalis River - as noted previously WEST is concurrently working with the Corps to develop a hydraulic model of the mainstem Chehalis River from Montesano to Pe Ell. However, that model was not sufficiently detailed in some locations to meet the needs of the Flood Authority and stakeholders. The Corps model (including the Twin Cities portion of the model) was updated under this task to facilitate Flood Authority investigations.

Task 6 - Extend Hydraulic Modeling (Including Survey, Hydrology and Hydraulics)
The work currently being done by the Corps has been leveraged extensively to meet the Flood Authority's needs for hydraulic modeling in the lower Chehalis River. However, the following sub-tasks were included in the detailed work plan to address specific considerations in the model development:

Task 6a - Expand or refine Corps hydrology analysis – The Corps hydrologic data for the basin were refined and additional hydrologic data were developed as needed to address the needs of the Flood Authority and stakeholders.

Task 6b - Refine/revise/extend hydraulic modeling of tributaries - as noted previously the Twin Cities hydraulic model included several tributaries, but these were not always sufficiently modeled to meet the needs of the Flood Authority. Additional modeling efforts were undertaken on the Satsop River, Black River, Skookumchuck River, and Newaukum River.

Task 6c - Review and refine Twin Cities model – Cross sections orientations in the Twin Cities portion of the Chehalis River model were reviewed and modified where appropriate. Storage area connections and other model assumptions were also evaluated and modified as necessary to improve model calibration.

Task 6d - Re-cut cross sections using "best available" LiDAR – After modifying the orientation of some cross sections in the Twin Cities model the cross sections were re-cut using the best available LiDAR data described above.

Task 7 - QA/QC Technical Review of WEST Consultants Hydrologic and Hydraulic Modeling
WEST Consultants developed hydrologic and hydraulic data for the Chehalis River basin under contract with the Corps. These baseline analyses were subject to independent technical review by WSE to ensure they adequately meet the needs and objectives of the Flood Authority as defined in the work plan.

Task 8 - Technical Evaluation, Reporting of Flood Relief Alternatives to Flood Authority
A range of possible flood damage reduction projects are under consideration in the basin. These include (1) upstream storage projects on the Upper Chehalis, South Fork Chehalis and Skookumchuck Dams, (2) USACE proposed levee modifications and (3) combinations of storage and levee projects. The following tasks were completed:

Task 8a - Under this sub-task, the proposed upstream retention facility on the main stem Chehalis River above Pe Ell was modeled and evaluated.

Task 8b - Under this sub-task, dozens of other flood relief alternatives in the watershed were modeled and evaluated.

Task 9 - Provide QA/QC Technical Review of WSE Flood Relief Alternatives Analysis
The flood relief alternatives analyses described in Task 8 were subject to independent technical review to ensure the needs and objectives of the Flood Authority were met.

Task 10 - Milestone Meetings / Conference Calls with Flood Authority
The project team coordinated presentations, communications, and information transfer to the Flood Authority at key milestones in the project to ensure that Flood Authority members were kept fully informed.

Task 11 - Comprehensive Project Report
This report has been prepared to document the findings of the hydraulic model investigations.

Other Hydraulic Modeling and Analysis Efforts

Federal, State, and local efforts are currently underway in the Chehalis River Basin to reduce flood damages and restore the ecosystem. The Federal Emergency Management Agency (FEMA) recently prepared a revised Flood Insurance Study (FIS) for Lewis County including the Chehalis River, Hanaford Creek, Lincoln Creek, Salzer Creek, Skookumchuck River, South Fork Chehalis River, and Stearns Creek (FEMA, 2011). The FIS hydraulic model was based on a previously developed UNET model of the Chehalis River and tributaries, which was converted to a HEC-RAS model. The final FIS HEC-RAS model consisted of approximately 150 river miles and 700 river cross-sections. While the model extended downstream to the town of Porter in Grays Harbor County, the portion of the model that was geo-referenced and calibrated ended at Grand Mound.

The Corps is currently conducting a Basinwide General Investigation (GI) including the development of hydrologic and hydraulic modeling for portions of the basin (USACE, 2012). The GI models will be used to establish baseline conditions to evaluate potential aquatic ecosystem restoration measures. Concurrent with the GI effort the Corps and its local partner, Washington State, are reevaluating the authorized Twin Cities flood damage reduction project, which proposed the construction of levees to protect parts of Centralia, Chehalis, and I-5, as well as modifications to Skookumchuck Dam (USACE, 2012). In addition to that effort, WSDOT is evaluating a range of options for protecting I-5 from flooding (WSDOT, 2012).

Relationship of current project to concurrent efforts by USACE and WSDOT

WEST is working under contract to the Corps to develop the baseline hydrologic and hydraulic modeling for the Chehalis River basin (GI Study). That work includes hydraulic modeling for the Chehalis River between Montesano and Porter and between Doty and Pe Ell as well as the lower 51 miles of the Wynoochee River. The Corps project to model the lower Chehalis River between Montesano and Porter is of particular relevance to the Flood Authority. When combined with the FEMA Twin Cities hydraulic model (Porter to Doty) and the Flood Authority model being developed by WSE (Montesano to Aberdeen) the result is a comprehensive hydraulic model extending from Aberdeen upstream as far as the proposed retention facility site on the main stem Chehalis River near Pe Ell, a distance of 108 river miles (plus tributaries).

Basin Characteristics and Flood Issues

Basin Characteristics

The Chehalis River basin is located in southwest Washington, encompassing a drainage area of approximately 2,100 square miles (See Figure 1). The river rises in the Willapa Hills and runs generally east, then north, and then west to its mouth at Grays Harbor. Elevations range from over 3,000 feet in the headwaters to 150 - 200 feet in the Twin Cities area to sea level at the mouth. Major tributaries to the Chehalis River include the South Fork Chehalis, Newaukum, Skookumchuck, Black, Satsop, and Wynoochee Rivers. Communities along the Chehalis River include Doty, Pe Ell, Chehalis, Centralia, Oakville, Montesano, and Aberdeen. Mean annual precipitation in the upper watershed ranges from 45 near Chehalis to more than 120 inches per year in the Willapa Hills upstream of Pe Ell.

Figure 2 and Figure 3 show the schematic of the stream network in the Upper and Lower Chehalis River basins, respectively. The upper portions of tributaries such as the South Fork Chehalis River, the Newaukum River, the Skookumchuck River, the Satsop River and the Wynoochee River are located in steep, mountainous terrain, with steep channel slopes and very narrow floodplains. The lower portions of these tributaries, as well as most of the smaller tributaries that join the Chehalis River lower in the basin are characterized by lower gradient, meandering channels with broad floodplains. These lower reaches offer significant temporary flood storage.

Flood Characteristics

Floods in the Chehalis River Basin typically occur in the November to February time frame. They are driven for the most part by atmospheric river (aka “Pineapple Express”) weather systems, which tap moisture from the tropics and funnel it to locations in western Washington, resulting in heavy precipitation. Significant flood events have occurred frequently in the Chehalis River basin. The annual peak flow record at the Chehalis River gage near Doty indicates that, in the last forty years alone, significant floods (greater than 20,000 cfs) occurred in January 1972, January 1990, November 1990, February 1996, December 2007, and January 2009. The gage on the Chehalis River near Grand Mound shows that the five largest peak flows in the past 85 years, all of which exceeded 50,000 cfs, have occurred since 1986 (December 2007, February 1996, January 1990, November 1986, January 2009). Significant widespread flooding and damage was associated with each of these events.

For the purposes of the current project only extreme, basin wide, floods were evaluated. These are large throughout the basin, have high flows on the mainstem Chehalis River (as measured at Grand Mound), and have a range in contributions from the major tributaries. The basin wide floods evaluated for this study were not selected to capture individual tributary design flood events, extreme high tide events, or anomalous conditions (e.g. dam break flood, etc). The modeled floods include the historical events of February 1996, December 2007, and January 2009, as well as a hypothetical basin wide flood event, developed by WEST for the Corps GI study. The characteristics of each of these events are described below:

February 1996 Event – This was a large frontal storm with very broad rainfall distribution throughout the Chehalis River basin and beyond (from north of Seattle to southern Oregon). The 24-hour rainfall totals throughout the basin generally ranged from 10+ year to 100+ year recurrence. It was extremely cold in the month prior to the storm and there may have been some snow accumulations in mid elevations. The resulting flood was the second largest in the historic record at many basin streamflow gages including Grand Mound (82 year record), Porter (63 year record), and Doty (71 year record) and the 4th largest in the historic record on the South Fork Chehalis (71 years aggregate record). It is still the largest flood in the observed record on the Skookumchuck River (71 years aggregate record) and Newaukum River (71 year record).

December 2007 Event – This event was a classic atmospheric river (pineapple express) type event with a fairly narrow path of extreme rainfall. The highest rainfall center was concentrated in the Willapa Hills in the Upper Chehalis River Basin (main stem and South Fork). Unlike 1996, the December 2007 storm was focused in the Chehalis Basin and parts of the Olympic mountain range, and was much smaller south of the Chehalis Basin. Additionally, there was not much low level snow immediately prior to the event. The 2007 storm set records for 24-hour precipitation in the upper basin, although the heaviest precipitation was actually limited to about 12 hours or less at many locations. The resulting flood was the largest in the historic record at Grand Mound (82 years), Porter (63 years), Doty (71 years), and the South Fork Chehalis (71 years aggregate record). It was the third largest storm in the 71 year record on the Newaukum River. On the Skookumchuck, however, it was only the 55th largest storm in the 71 years aggregate record due in part to less rainfall seen in that portion of the basin and in part due to incidental storage at Skookumchuck Dam. The peak discharge on the Chehalis River at Doty (USGS estimate 63,100 cfs) was more than double the next highest flood in the 72 year record (28,900 cfs in 1996) and was approximately 67% greater than the current estimate of the 100-year flood. In contrast, at Grand Mound the USGS estimated flow was only about 6% higher than the next highest event (1996).

January 2009 Event – This event was focused primarily in the eastern and northern portions of the Chehalis River Basin although significant rain still fell in the upper watershed. Flooding, or near flooding, of Interstate 5 was caused by high flows on the Newaukum system which peaked well in advance (12 hours or more) of the arrival of the peak Chehalis River flow from the upper basin. The January 2009 event also caused very high flows in many lower basin tributaries (Satsop, Black…etc.). The resulting flood was the 5th largest in the 82 year historic record at Grand Mound and the 7th largest in 71 years at Doty. The January 2009 event was the second largest observed flood on the South Fork Chehalis (after 2007) and Newaukum Rivers (after 1996) and the third largest on the Skookumchuck (after 1996 and 1953). At Porter on the Chehalis River, the 2009 flood was the 3rd largest in the 63 year record reflecting large contributions from lower basin tributaries. The January 2009 event was the third largest event in the historic record on the Wynoochee (in 39 years since the construction of the dam) and the 5th largest event on the Satsop (in 82 years). Considering the flow at Porter and on the lower basin tributaries the January 2009 event is estimated to be the second largest event in the historic record downstream of Montesano.

100-year Design Event – The 100-year design event developed by WEST is described fully in the Corps GI Report (USACE, 2012). On the recent floods in the basin, the design event is most similar to February 1996 with broadly distributed extreme precipitation. The analysis targeted matching the 100-year discharge at Grand Mound and then distributed tributary inflows based on statistical analyses of observed flows on the tributaries versus mainstem flows (with regard to both magnitude and timing of flows). The design event sought to match both instantaneous peaks and longer durations (from 1 to 15 days).

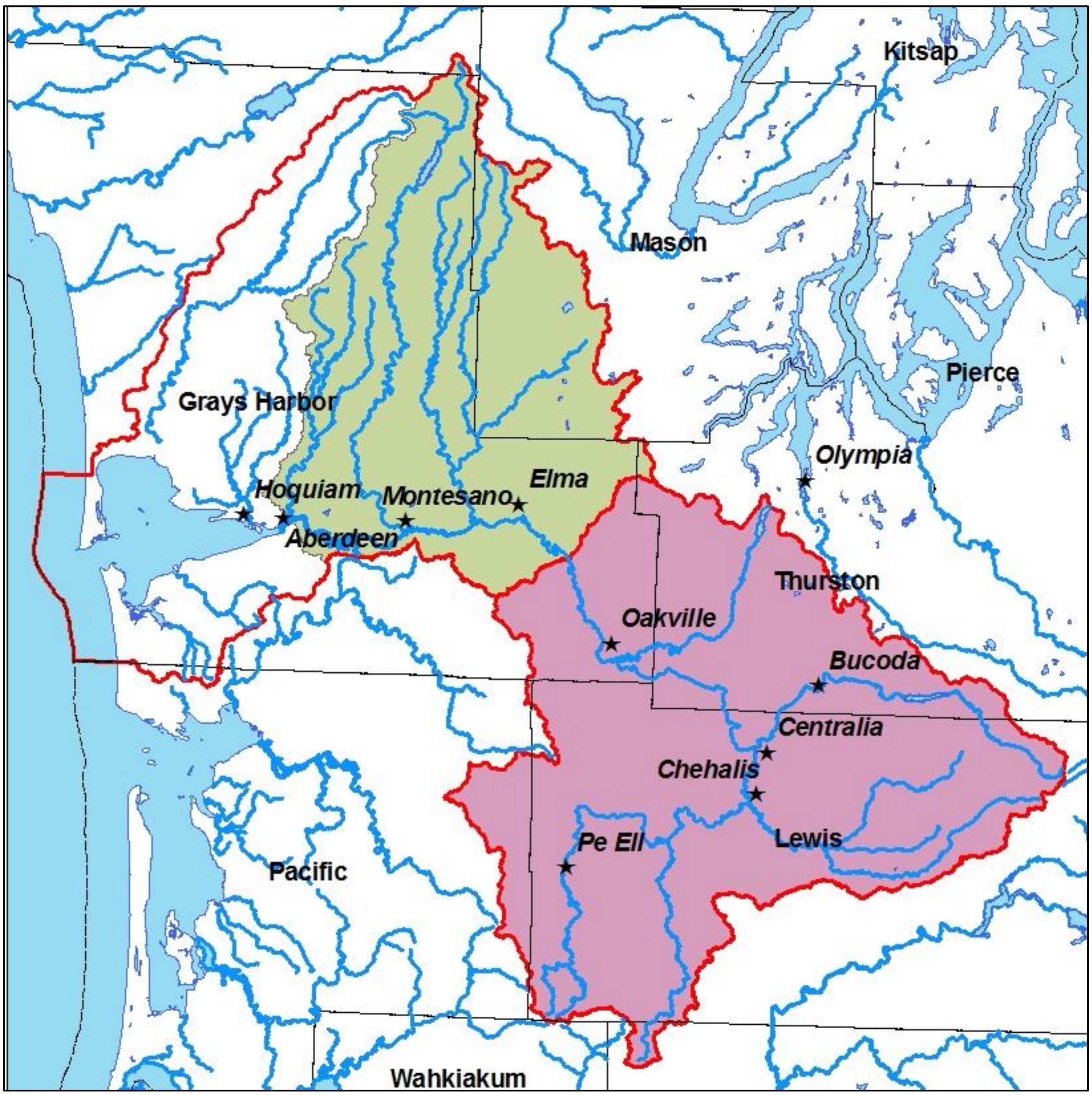

Figure 1. Study Area within the Watershed Boundaries of WRIAs 22 and 23

Figure 2. Upper Chehalis River Basin (WRIA 23)

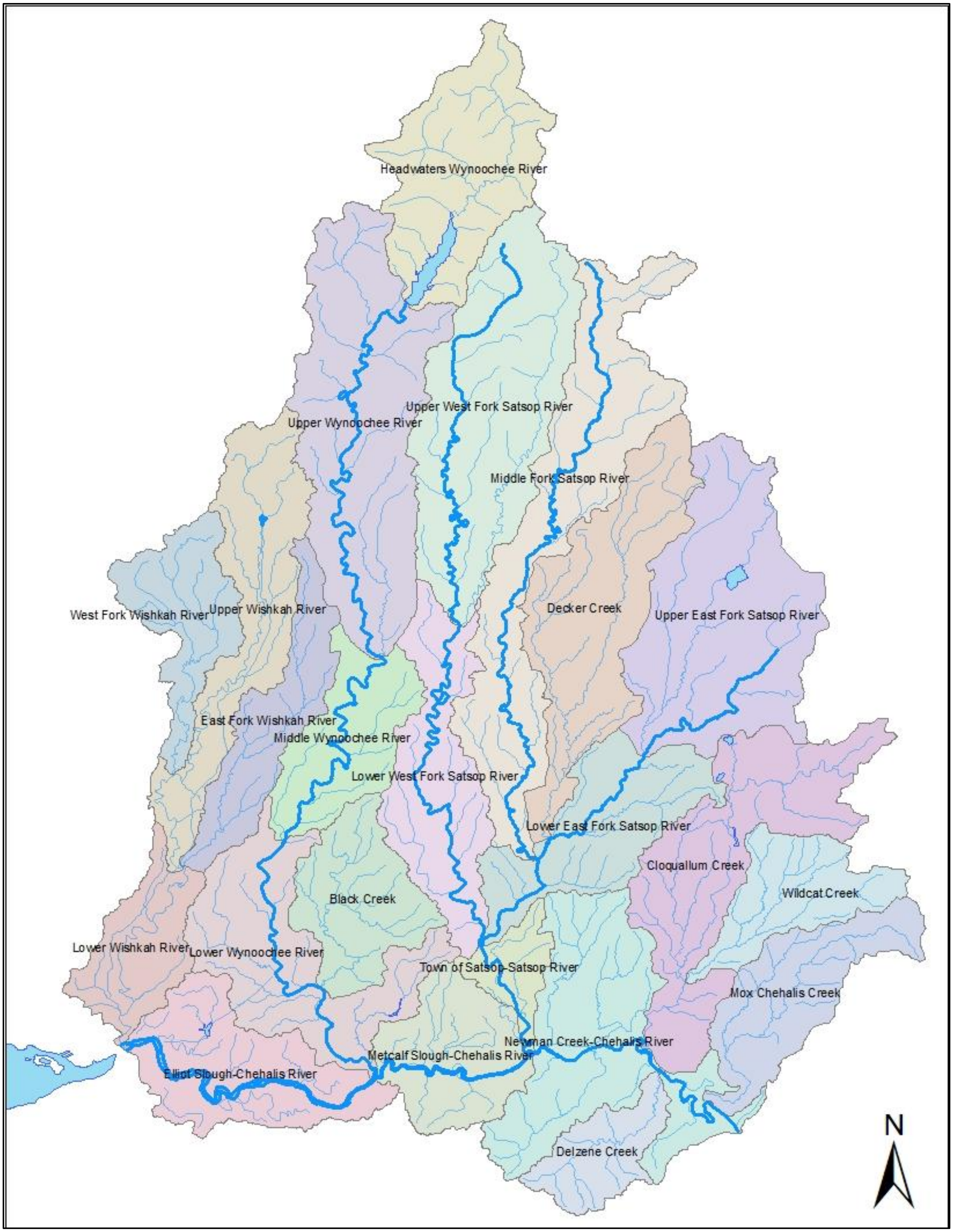

Figure 3. Lower Chehalis River Basin (WRIA 22)

Model Development

Basic Data and Information

Existing Hydraulic Models

As described previously, numerous hydraulic studies have been completed in the Chehalis River basin. Many of these have developed and applied hydraulic models to analyze rivers and streams within the basin. These models, and data used in their development, have been incorporated into the current modeling effort wherever feasible.

The original Chehalis River Basin Flood Insurance Study (FIS) completed for FEMA (c. 1982) included steady state hydraulic modeling (HEC-2) of portions of the Chehalis River, Black River, Newaukum River, Hanaford Creek, and South Fork Chehalis River. That effort was superseded by a study conducted by Pacific International Engineering (PIE) for the Corps in 2001. The PIE work included development of a UNET unsteady state hydraulic model including the main stem Chehalis River between Porter and Doty plus portions of significant tributaries including the Black River, Lincoln Creek, Skookumchuck River, Hanaford Creek, Salzer Creek, Newaukum River, Dillenbaugh Creek, Stearns Creek, and the South Fork Chehalis River. That model was used in the Corps 2003 General Reevaluation Report (GRR) study of the Chehalis River basin.

FEMA recently completed a revised Flood Insurance Study for Lewis County including the Chehalis River, Hanaford Creek, Lincoln Creek, Salzer Creek, Skookumchuck River, South Fork Chehalis River, and Sterns Creek (FEMA, 2011). For the hydraulic modeling, the previously developed UNET model of the Chehalis River and tributaries used in the USACE 2003 GRR study was converted to a model using the USACE Hydrologic Engineering Center (HEC)'s River Analysis System (HEC-RAS) software (HEC, 2010). The complete HEC-RAS model used in the study consists of approximately 150 river miles and 700 river cross-sections, and extends to Porter in Grays Harbor County.

The current modeling effort for the Flood Authority began with the existing FEMA Twin Cities Model as its basis. The model was extended both upstream and downstream and up some of the tributaries as described below. New cross sections were surveyed for portions of the model and topographic data were replaced with more recent data wherever possible. Model branches for the Satsop and Wynoochee Rivers were also added as follows:

The Corps previously developed a HEC-RAS model of the lower Satsop River, from its mouth to Highway 12 (approximately 2 miles) in 2004 as part of a gravel pit restoration project (WEST, 2004). Cross section data used in that model were based upon 2002 channel survey and 2002 LiDAR. That Satsop River model was incorporated into the Flood Authority Model as a branch, although it is recognized that the channel cross sections in that model have changed considerably since 2002.

WEST, under contract to the Corps of Engineers, recently completed a hydraulic model of the Wynoochee River (USACE, 2012). That model extends 51 miles upstream from the confluence with the Chehalis River near Montesano, to the Wynoochee Dam based on 2009 survey and LiDAR. The Wynoochee River model was incorporated into the Flood Authority model as a branch.

Topographic Data

Topographic data from various sources were used in the development of the Chehalis River hydraulic model. Digital elevation models (DEMs) were used to provide information on the overbank geometry, to evaluate hydraulic connections in the model, and to analyze the areas and depths of inundation under the different flood scenarios. The topographic data sets are primarily based on LiDAR flown within the last 10 years, with the exception of USACE contours, which come from aerial photogrammetric survey completed in 1999. Because the topographic data were collected at different times, and for different purposes, there are many areas where two or more DEMs overlap. In such cases, the most recent DEM was used for the hydraulic modeling and analysis. The following list details topographic datasets used in this study (See Figure 4):

South West Washington 2009 – A one meter resolution LiDAR grid flown for FEMA and the Oregon LiDAR Consortium in 2009, which covers the Wynoochee River Basin and the lower 13 miles of the Chehalis River Floodplain. Data was accessed through the Puget Sound LiDAR Consortium website.

Centralia 2006 – LiDAR coverage of City of Centralia flown in 2006 including the lower portions of Hanaford, Salzer and Lincoln Creek, and the Skookumchuck River. Additionally covers the Chehalis River from River mile 67.86 to 61.05 and the Skookumchuck Overflow Reach.

Lewis County 2005-2006 – LiDAR coverage from 2005 and 2006 including the upper portions of the Newaukum, South Fork Chehalis, and Chehalis River, as well as the upper portions of Lincoln, Salzer, Newaukum, Dillenbaugh, and Sterns Creek. Data provided by Lewis County.

PSLC 2002 – LiDAR coverage for the Puget Sound Lowlands from 2002, accessed from Puget Sound LiDAR Consortium website, covers a large portion of south west Thurston County including the upper 15 miles of the Skookumchuck River, and extends down the Lower Chehalis River from mile 61 to its mouth.

USACE 1999 – Topographic survey collected by the USACE in 1999 covers portions of the Chehalis and Newaukum River, and Dillenbaugh Creek near Centralia and Chehalis, and the upper Chehalis River between river mile 95 and 104.

NOAA Bathymetric data is available for Grays Harbor and portions of the Lower Chehalis River, although the date these were collected and the accuracy specification of the data are unknown. These data were used for in-channel portions of the three most downstream cross sections of the Lower Chehalis River, which extend into Grays Harbor.

Several new LiDAR data sets are currently in development. LiDAR for the main Chehalis river valley upstream of Montesano to Grand Mound and in various parts of Lewis County are being developed through a joint effort between FEMA and Lewis County. The LiDAR flights were completed in January and February 2012 but data are not available for use in the Flood Authority project. It is anticipated that these data will become available in summer 2012. New LIDAR for Thurston County was also collected in June and July 2011 but the post processed, quality controlled data did not become available until June 2012. These new LiDAR data sets are expected to provide much better resolution in areas of the basin, especially in regions that are currently only covered by the 1999 Corps photogrammetry or the PSLC 2002 LiDAR data. The new data will reflect channel and floodplain changes that have occurred since the previous data collection efforts and provide a good representation of current topographic conditions.

This is particularly important for the Satsop River channel, which is very dynamic, and for potions of the Chehalis River between Grand Mound and Montesano.

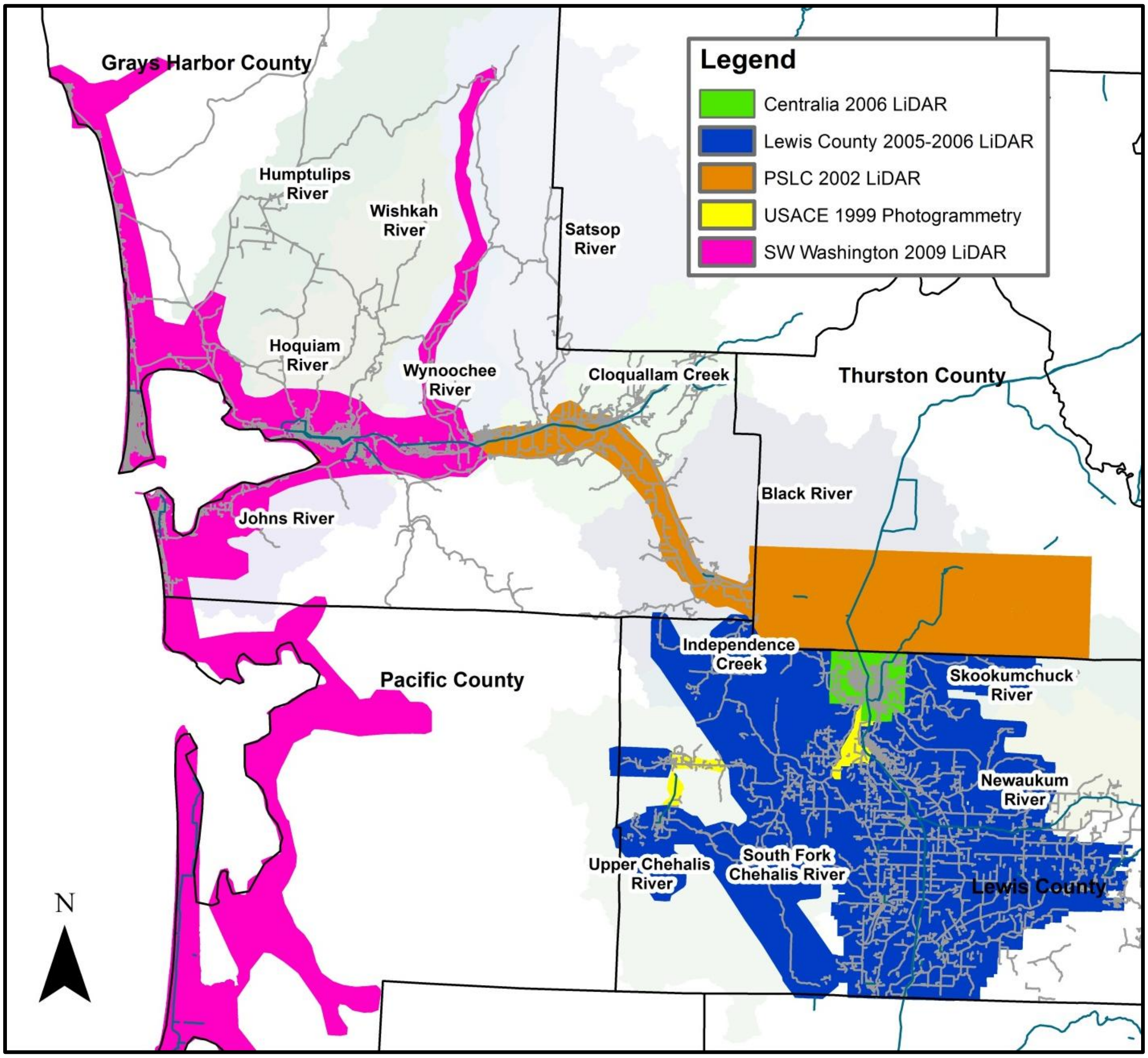

Figure 4. Chehalis Topographic Coverage Boundaries over WRIA 22 and 23

New Cross Section Surveys

New cross section surveys were collected to support the upstream and downstream extensions of the model and to provide current bathymetric data in areas that were previously modeled. Pacific Geomatic Services (PGS) collected forty five (45) cross sections within the Chehalis River channel between the mouth of the river and river mile 12, plus a depth profile along Preacher's slough, a main overflow path in the lower Chehalis floodplain. PGS also collected twenty-one (21) cross sections within the Skookumchuck River channel between river mile 9.8 and 12 and twenty (20) cross sections within the Satsop River between Highway 12 and the Chehalis River. These data were collected in November and December 2011

Minister Glaeser surveyed 70 sections within the Chehalis River between Pe Ell and Doty, 84 sections between Grand Mound and Porter, and 60 sections between Porter and Montesano.

WSDOT Additional Survey of I-5 and Airport Levee

In April 2012 WSDOT completed topographic survey to detail portions of I-5, the Chehalis-Centralia Airport levees, and the Highway 6 / I-5 overpass near the city of Chehalis, WA. These data were used to refine connections in the model including airport levee overtopping, I-5 overflows, Market Street overtopping, and Dillenbaugh creek breakout flow at I-5.

Hydrology (from USACE study)

Hydrologic data for the current modeling effort is being obtained from the concurrent Corps GI study (USACE, 2012). For that study WEST was tasked with developing basin wide flood flow hydrographs at return periods ranging from 1.5 to 500-years and seasonal low flow data. In addition, hydraulic model inputs were developed for three calibration events; February 1996, December 2007, and January 2009. The data developed for the Corps study are being used without modification for the current study, providing consistency between the two modeling efforts.

In addition to the Corps hydrologic data a downstream boundary condition at Aberdeen was required. Observed data is not currently collected at Aberdeen; therefore, a correction factor was applied to NOAA tide predictions at Aberdeen based on a comparison of observed and predicted tides at Westport. Applied corrections could be either positive or negative and ranged as high as 3 feet or more. Transposition of the differences between Westport and Aberdeen included a half hour offset to account for the difference in peak tide timing between the predicted tides at the two stations.

Model Configuration

As documented above, the final Chehalis River Basin baseline hydraulic model developed for the Flood Authority leveraged concurrent modeling efforts being conducted for the Corps, and utilized new survey to further refine and extend the earlier FEMA Twin Cities model. Table 1 lists the agency that funded development of each segment of the model, the surveyor and date for new cross section surveys, and the firm responsible for the development of the hydraulic model. Additional details for the model development are provided below.

Table 1. Chehalis River Model Reach Summary

	Reach	Client	Cross Section Survey	Model Development
Chehalis River	Pe Ell to Doty	USACE	MGS, 2011	WEST
	Doty to Grand Mound	FEMA	USACE, 2000	NHC, WEST, WSE[1]
	Grand Mound to Porter	FA	MGS, 2011	PIE, WEST
	Porter to Montesano	USACE	MGS, 2011	WEST/WSE
	Montesano to Mouth	FA	PGS, 2011	WSE
Tributaries	Satsop	USACE	USACE 2001, PGS, 2012[2]	WEST/WSE
	Wynoochee	USACE	USACE, 2009	WEST
	Skookumchuck	FA	PGS, 2012	WEST/WSE[3]
	Newaukum	FA	USACE, 2001	WSE
	Black	FA	MGS, 2011	WEST/WSE

[1]The original HEC-RAS model was developed by NHC for FEMA based on an earlier PIE UNET model. WEST georeferenced and re-cut cross sections in the model under the Flood Authority contract. WSE made final refinements and revisions to the model to improve the calibration and better reflect physical features in the Twin Cities area.

[2]New surveyed geometry was used for a comparison of channel changes but was not incorporated into the final model.

[3]WEST georeferenced the Skookumchuck model. WSE incorporated new survey and added a bypass reach in Bucoda (RM 9.8)

Upstream Extension (Pe Ell to Doty - WEST for USACE)

WEST extended the Chehalis River model upstream of Doty to Pe Ell as part of the Corps GI study. Channel geometry data in the model were based on new MGS field surveys. Overbank topography was based on 1999 USACE contours and 2005-2006 Lewis County LiDAR where available.

Twin Cities (Doty to Grand Mound)

The model between Doty and Grand Mound is based on the FEMA Twin Cities model. Although reach refinement was not originally scoped for this portion of the model, the Twin Cities model reach was ultimately refined considerably by WSE and WEST to resolve legacy issues such as overlapping cross sections and inaccurate reach lengths at tributary junctions that were discovered during model integration. The model was also revised by WSE to better reflect physical features in the Twin Cities area (railroads, road grades, Interstate 5, culverts, etc.) and to better calibrate to observed high water marks from February 1996 and December 2007.

Grand Mound to Porter (WEST for USACE and Flood Authority)

Although the Chehalis between Grand Mound and Porter was included in the earlier Twin Cities modeling, previous efforts by the Corps and/or FEMA did not include georeferencing or otherwise refining the model in the reach downstream of Grand Mound. Under the Corps GI Study effort WEST reconfigured this reach using new channel survey data collected by MGS under Task 5b of the Flood

Authority Contract. The new model development used topographic data from the 2002 PSLC LiDAR data set.

Porter to Montesano (WEST for USACE and WSE for Flood Authority)

Extension of the model downstream of Porter to Montesano was completed by WEST as part of the USACE GI study. New MGS survey collected under contract to the Corps was used in channel, with 2002 PSLC LiDAR for overbank areas. This reach of the model was subsequently refined by WSE to better match observed water marks near the South Elma and Porter Creek roads provided by lower basin landowners in June 2012.

Montesano to Aberdeen (WSE for Flood Authority)

No previous hydraulic modeling was found for the lower 12 miles of the Chehalis River between Montesano and Grays Harbor. WSE developed the model geometry for this reach based on new PGS channel survey and 2009 LiDAR data. Unsteady capabilities within HEC-RAS allowed the incorporation of a time varying tidal boundary condition at the downstream end of the model. The model was calibrated to data for the USGS stage gage at Montesano.

Tributaries

Modeling of four tributaries to the Chehalis River: the Skookumchuck, Black, Newaukum and Satsop Rivers, was expanded or refined under Task 6. In addition, a branch representing the Wynoochee River was incorporated into the basin wide model. The intent of work on the tributaries was to evaluate existing models and refine/replace/extend them as necessary to meet the needs of the Flood Authority and basin stakeholders.

Satsop (WSE for Flood Authority)

Grays Harbor County indicated that a hydraulic model of the Satsop/Chehalis River confluence area would be very useful in light of upcoming project proposals on the Satsop River. Using a model developed by WEST as part of a Corps of Engineers floodplain restoration project in 2004 the lower Satsop River, from SR 12 to its mouth, was included as a branch in the Chehalis River hydraulic model. The 2004 model was based on cross sections that were field surveyed in 2002 and overbank data from the PSLC 2002 LiDAR data set. Unfortunately, there has been significant lateral movement of the Satsop River channel since the previous surveys were obtained and therefore the model is somewhat outdated. However, until new LiDAR data are available for the overbank floodplain it is not possible to refine the lower Satsop River branch.

In lieu of an updated model, WSE assessed how changes to the Satsop River channel since the earlier Corps project affect the accuracy of the existing model. Twenty (20) cross sections were surveyed along the Satsop River and the new cross section surveys were graphically compared to the earlier survey data using Excel. Comparisons of the channel location (as estimated from the LiDAR data at the time of the earlier survey and a recent aerial photograph) were also made. The results of these comparisons determined that the Satsop channel has shifted considerably, although it is not possible to conclude based on the survey data alone whether the Satsop channel has gained or lost conveyance capacity since 2001. The evaluations are summarized in an earlier WSE memorandum; "Satsop River Channel and Cross Section Comparisons" (WSE, 2012a).

Skookumchuck (WSE for Flood Authority)

The Twin Cities Skookumchuck model reach (from RM 6.42 to 21.77) was georeferenced by WEST, including an update of channel overbank elevations based on 2002 PSLC LiDAR. WSE then refined the model in the vicinity of Bucoda (RM 9.8 - 12) using channel survey collected by PGS, and calibrated the model using high water elevations from the January 2009 flood event. Refinement of the Skookumchuck River model reach included the addition of a "Bucoda Bypass" reach, which allows a much more accurate representation of the split-flow flooding that occurs through the town of Bucoda.

The refined Skookumchuck model was then utilized to determine the impact of bridge constrictions on flood levels within the town of Bucoda. This analysis is documented in an earlier WSE memo - "Skookumchuck River Model Update and Bucoda Flood Reduction Alternative Investigation" (WSE, 2012b).

Newaukum (WSE for Flood Authority)

The Twin Cities model included portions of the Newaukum River from its mouth upstream to approximately River Mile 4.1 at Labree Road, as well as the lower 3.45 miles of Dillenbaugh Creek, which receives overflows from the Newaukum River both upstream and downstream of Labree Road. Modeling conducted for the Corps of Engineers in the 1990s by PIE using UNET, and more recently in 2001 by Northwest Hydraulic Consultants (NHC) using HEC-RAS, covered the entire main stem of the Newaukum River including upstream of Labree Road to RM 10.63 (just below the North Fork confluence). NHC's modeling used data from various sources but primarily the UNET model developed by PIE. Neither the PIE nor the NHC model was geo-referenced (e.g. tied to a fixed horizontal coordinate system); however, AutoCAD files from PIE are available to show the location and alignment of the model cross-sections.

WSE geo-referenced, refined, and extended the existing model of the Newaukum River, upstream of Labree Road from RM 4.11 to RM 10.63, and incorporated this extension into the Flood Authority model. The floodplain portions of all cross-sections were re-cut using 2002 LiDAR data obtained from the Puget Sound LiDAR Consortium (PSLC) and merged with channel cross section data from the NHC model. Cross-sections in the NHC model that were not shown on the PIE AutoCAD drawings were located along the channel based on their reach lengths, then extended appropriately across the floodplain and cut from the LiDAR data.

The work performed by WSE is fully documented in "Newaukum River Model Extension and Refinement" (WSE, 2011c).

Black (WEST for Flood Authority)

Georeferencing of the Black River model was updated by WEST using 2001 cross section surveys obtained from W. & H. Pacific. Storage area locations, volumes, and connections were updated using the 2002 LiDAR data. The revised/refined model was calibrated to high water mark information for the confluence area obtained from Glen Connelly of the Chehalis Tribe.

Model Review

The HEC-RAS Hydraulic Model developed by the WSE/WEST Project team was subject to detailed review by the State Technical Team (comprised of staff from WSDOT, WADOE, and WDFW), by the Corps, and by WSDOT. The goal of these independent reviews was to ensure that the model was technically well developed and to facilitate acceptance by other stakeholders working in the basin. In particular, having the model reviewed and accepted by WSDOT and the Corps was instrumental in those agencies acceptance of the model for future hydraulic investigations. The fact that WSDOT, the Corps, and the Flood Authority are all working from the same baseline hydraulic model should make future discussions of flood relief alternatives more productive.

State Technical Team

WSE and WEST presented a preliminary version of the Chehalis River hydraulic model to a group of State technical staff at a coordination meeting at WEST's offices on February 23, 2012. Following that meeting the model and available documentation were provided to the State team for review and comment. Three State reviewers provided detailed written comments on the model: Paul Pickett (DOE), Casey Kramer (WSDOT), and Guy Hoyle-Dodson (DOE). These comments were well formed and generally helpful in identifying areas in the hydraulic model that required additional consideration and/or refinement. The comments were reviewed and discussed by the WSE-WEST team and a number of modifications were made to the model to address concerns. In some cases, no changes to the model were necessary, either because the model was already configured appropriately or because the comments raised questions beyond the scope of the current study. General responses to the reviewer's comments were provided in a memorandum entitled "Response to State team comments on Chehalis River Hydraulic Model" (WSE, 2012d). These responses were discussed further with the individual reviewers to ensure that the model could be refined appropriately. Brief summaries of the comments and responses are provided below:

RE: Paul Pickett comment letter of 3/30/2012:

Mr. Pickett's comments focused primarily on the hydrologic data proposed for use in the evaluation of flood relief alternatives. He noted that flood events in a basin as large and complex as the Chehalis Basin can come in many different forms and that a comprehensive analysis of flood relief alternatives would require a range of design events to be simulated. In our response we provided data showing that the largest flood events observed in the Chehalis basin have similar enough characteristics to make the proposed design event modeling approach reasonable for the current effort. We also noted that the hydrology for this project was done as part of the concurrent Corps project and using the same hydrology maintains consistency between the modeling efforts.

To evaluate basin hydrology data from the top 10 annual peaks at the Grand Mound gage were compared to the corresponding peaks at major upstream gages. The key findings of this analysis are as follows:

1) A large flow (herein defined as among the top 10 highest peaks recorded) on the Chehalis at Grand Mound has never happened without a correspondingly large flow on the Chehalis River at Doty.
2) A large flow at Doty is a reliable (although not perfect) indicator of a large flow at Grand Mound.
3) A large flow on the Chehalis at Grand Mound can happen with or without a significant flow contribution from the Skookumchuck River.
4) A large flow on the Skookumchuck is not a very good indicator of large flows at Grand Mound.
5) Peak flows on the Newaukum and South Fork are similarly correlated to the flows at Grand Mound, less so than the Doty flows but more so than the Skookumchuck flows.

The hydrologic analyses indicated that the Corps approach provides a reasonable representation of large flood events in the Chehalis River basin. However, as we agreed with Mr. Pickett that there is significant variability in storm timing and magnitude in the Chehalis River basin, the work plan for the project was modified to include analysis of three historical floods (1996, 2007, and 2009) in addition to the 100-year design event modeling.

RE: Guy Hoyle-Dodson comment letter of 4/1/2012:

Mr. Hoyle Dodson's comments on the HEC-RAS model were particularly comprehensive including comments on general modeling approaches as well as a number of specific areas of concern or question. While many of these related to the new model reaches being developed for this study, a large number were specifically related to the "Twin Cities" portion of the model previously developed by others. That said, and in an effort to make the model as robust and useful as possible, we reviewed all of the comments and attempted to address all of them in refining the model. We also provide responses to Mr. Hoyle- Dodson's comments in our detailed response letter (WSE 2012d).

RE: Casey Kramer comment letter of 4/2/2012:

Mr. Kramer's comments were discussed between Mr. Kramer, WSE, WEST, and NHC staff in a meeting at WSE's office on March 27, 2012. A plan of action was agreed upon for updating the model to address the comments. It should be noted that Mr. Kramer's model comments focused on the Twin Cities portion of the model constructed by others and not actually part of the current model development effort. However, to ensure that future analyses conducted with the model are as useful as possible modifications were made to the model to better simulate the area upstream of Mellen Street and along the lower reaches of Dillenbaugh Creek where it passes under I-5. These are detailed in WSE's April 2012 comment response letter and discussed further below.

USACE

As noted previously, the Corps has a concurrent project to develop a hydraulic model of the Chehalis River for use in ecosystem investigations (USACE 2012a). The work being conducted by the WSE/WEST team under contract with the Flood Authority is highly integrated with WEST's work for the Corps. Specific deliverables developed by WEST, including the hydrology and hydraulic modeling, have been submitted and subject to the Corps rigorous ITR process. The comprehensive model generated by the WSE project team has also been provided to the Corps for review and comment. It is our understanding that the Corps review is currently on hold pending allocation of funding. Any comments provided by the Corps will be responded to and reflected in future refinements to the model as appropriate.

WSDOT

In addition to the comment letter from Casey Kramer described above, WSDOT and its consultant Northwest Hydraulic Consultants (NHC) provided additional review of the Chehalis River hydraulic model after initial refinements were made. This work included direct coordination between NHC and WSE to refine portions of the model in the Twin Cities area, a re-release of the existing conditions geometry on May 2, 2012, and a technical team meeting at WSDOT headquarters on May 9, 2012. WSDOT is currently applying the model to evaluate a range of possible alternatives for protecting the Interstate 5 from flooding. As such, they have great interest in ensuring that the model is well formulated and appropriate for modeling, particularly in this area. Model issues raised by NHC and WSDOT were addressed in revisions to the existing conditions model that was subsequently distributed to WSDOT and the other members of the State tech team. That revised existing conditions model forms the basis for the alternatives analyses described below.

Final Model Refinements

As described above, the Chehalis River HEC-RAS model was developed through an open and participatory process involving the Flood Authority, the Corps, WSDOT, and other members of the State tech team. The model was widely distributed facilitating review by basin stakeholders and key agencies. The intent of this process was that the model would provide a broadly accepted and shared tool for making future decisions regarding flood relief in the basin. A number of general and specific refinements were made to the model in response to the detailed reviews. Several of these warrant additional detailed descriptions as provided below:

WSDOT 2012 Survey (WSE and WEST)

Considering their desire to have as accurate a calibration as possible in the Twin Cities area, to facilitate detailed planning and design of I-5 flood protection projects, WSDOT collected additional field topographic survey in April 2012 for Interstate 5 and the Chehalis-Centralia Airport levee for use in updating the model. The original data for these features were derived from the remote sensed topographic data sets (LiDAR and/or photogrammetric mapping). As such, the accuracy of the data was generally limited to plus or minus 1 foot (although the data are often more accurate for "hard" surfaces in open terrain (roads, railroads, etc)). The new survey data were used to update the model, thus improving its ability to accurately simulate existing conditions flooding.

Dillenbaugh Creek Area (WSE)

To better approximate December 2007 flood conditions near the Dillenbaugh Creek/Chehalis Junction, two lateral weirs (0.120 and 0.092) were added along Dillenbaugh to model flow entering the north- and southbound lanes of I-5 and flowing under the Highway 6 overpass. Weir elevations were based on the April 2012 survey completed by WSDOT. Additionally, the weir coefficient (C_d) for Main Street was reduced from 2.0 to 1.5 to approximate losses as water exiting Dillenbaugh flows through vegetation and around buildings on its path to Storage Area #303.

A section of the I-5 weir (LS 74.41) was then lowered (as discussed during the March 27th meeting with WSDOT and NHC) to simulate the portion of I-5 that does not have a jersey barrier along its east side, and the failure of the centerline jersey barrier that occurred during the Dec 2007 flood event. With these changes the maximum simulated depth of flow over I-5 in between SR-6 and NW West Street was about 2.0 ft, which may be somewhat high based on photographs from the 2007 flood. Additional model refinement might reduce the peak stages over the freeway in this area but it is not clear that there is enough information to definitively state how high the flow may have gotten and/or the direction and magnitude of breakout flows from Dillenbaugh Creek during the event. As such, no additional model refinement was completed.

Bridges and Revised Calibration (WSE)

Following the incorporation of the revised I-5 and airport levee survey data and the refinements to the modeling of Dillenbaugh Creek the model calibration in the Twin Cities area was reviewed. This review showed that model calibration at several locations, particularly just upstream of Mellen Street and in the reach between the airport levee and the Newaukum River confluence, could be improved. The model configuration was refined by adjusting ineffective flow limits and modifying "n" values to improve calibration. While the model changes were generally minor, improvements in calibration by up to 0.5 feet were attained at some locations. The revised calibration focused on the December 2007 flood event due to the fact that this event was significantly larger in the Twin Cities area and there were more observed high water marks distributed throughout the Twin Cities than for any other event. However, the other calibration events, February 1996 and January 2009 were also simulated to verify that the revisions also improved model calibration for those events.

MTB Project (NHC for WSDOT)

WSDOT has received permit approvals and obtained funding to construct a series of improvements collectively known as the Mellen to Blakeslee Bridge (MTB) Junction Project. The $155 million project, which broke ground in late May, will provide access to medical and other critical community facilities in Centralia during flood events up to the 2007 flood level. The first stage of the projects is expected to be completed in spring 2013; the second will begin in the summer of 2013 and finish late in 2014 or early 2015. The project includes connecting Louisiana Avenue and Airport Road, constructing a "shared use" path for pedestrians and cyclists, and re-constructing the Mellen Street interchange. Another element of the project is the addition of collector-distributor (CD) lanes alongside of the freeway between Mellen Street and Blakeslee Junction. The CD lanes will allow drivers to pass from Centralia to Chehalis without using I-5.

Because the MTB project is being actively implemented at present, it was decided that the Chehalis River existing conditions hydraulic model should be updated to include this project. NHC used the existing conditions geometry distributed by WSE on May 2, 2012 and updated it to reflect the planned MTB project. The modified geometry produced by NHC forms the "Baseline" geometry being used by all parties for purposes of evaluation of impacts and benefits of flood relief alternatives.

Lower Basin Model Refinements (WSE)

In coordination with the Flood Authority, the Ruckelshaus Center, and the Washington Dairy Federation, a series of meetings and workshops were held in Porter and Montesano in June 2012 to discuss specific flooding problems in the lower Chehalis River basin. During those workshops additional calibration information was obtained including high water marks for the December 2007 flood and anecdotal information about flooding during the January 2009 and February 1996 events. Using these new data the lower Chehalis River model calibration was refined, specifically with respect to the modeling of the Porter Creek Road and Wakefield Road (South Elma) bridges and approach fills. Ineffective flow limits and Manning's roughness values in the model were adjusted to reflect observations and to allow a better match to the high water mark data. The model was also modified in a manner that facilitates evaluation of several lower basin flood relief alternatives that were discussed at the workshops, specifically modifications to the overflow bridges on Porter Creek Road and/or Wakefield Road. The model refinements were incorporated into all earlier versions of the model and all previously modeled alternatives were re-simulated.

Final Model Calibration Summary

The Flood Authority Chehalis River HEC-RAS model was calibrated to the February 1996 and January 2009 storm events, with the storm event of December 2007 used for model validation. The calibration and validation data used were the observed stage and discharge hydrographs and rating curves at Doty on the Chehalis River, RM 101.549, Grand Mound on the Chehalis River, RM 59.909, Porter on the Chehalis River, RM 33.22, the Newaukum River near Chehalis, RM 4.11, the Skookumchuck River below Bloody Run, RM 20.7, the Skookumchuck River near Bucoda, RM 6.4, and the Skookumchuck River at Centralia, RM 2.41.

Model calibration was achieved by adjusting channel and overbank values of the Manning's n bottom roughness coefficient, flow roughness factors, and the placement of ineffective flow areas, until good agreement was found between the computed and observed stage and flow hydrographs and computed and observed rating curves at the gages listed above.

Results

The following discussion provides an overview / summary of calibration results for each of the calibration events (February 1996, and January 2009) and the validation event (December 2007) – a more comprehensive discussion of model calibration can be found in the GI Study report (USACE 2012a).

February 1996 Calibration

Table 2 shows the comparison between modeled and observed peak flows at various locations on the Chehalis, Newaukum, and Skookumchuck Rivers for the February 1996 event. For illustration, plots of simulated and observed stage and flow hydrographs at Grand Mound are included in Figures 5 and 6.

Table 2. Summary of model calibration for flow for February 1996 event

Location	Computed Peak Flow (cfs)	Observed Peak Flow (cfs)	Difference in Peak Flow Magnitude (%)	Difference in Event Volume (%)	Peak Time Difference (hours)*
Chehalis River at Doty	28,055	28,900	-2.9	-0.3	0
Chehalis River at Grand Mound	74,485	74,800	-1	15.3	5
Chehalis River at Porter	82,420	80,700	2.1	39.3	10
Newaukum River near Chehalis	11,960	13,300	-10.1	-0.3	2.5
Skookumchuck River below Bloody Run	9,053	N/A	N/A	N/A	N/A
Skookumchuck River near Bucoda	11,635	11,300	3	-5.7	-2

*A negative time difference denotes the simulated peak occurring before the observed peak

Though the estimated inflows produce hydrograph volumes that are high compared to the observed data, the flow magnitudes are within 10 percent and the timing of the peak flows are within a few hours of observed data - with the exception of the simulated peak at Porter, which is 10 hours early. Further investigation suggests that this is likely an anomaly within the gaged data at Porter (USACE 2012a).

In general, the flow hydrograph calibrations look reasonable. At gages where the majority of the upstream contributing flow is gaged (Chehalis at Doty, Newaukum near Chehalis, Skookumchuck below Bloody Run and near Bucoda), the calibration of the flow hydrographs appear relatively tight. At the gages where the majority of the contributing flow is ungaged (Chehalis River at Grand Mound and Porter), the simulated flows tend to be high compared to the observed. This in turn yields stage hydrograph calibrations that look reasonable for the Chehalis River at Doty and the Skookumchuck gages. The stage hydrographs for the Chehalis River at Grand Mound and Porter are slightly high, which is to be expected due to the high simulated flow peaks.

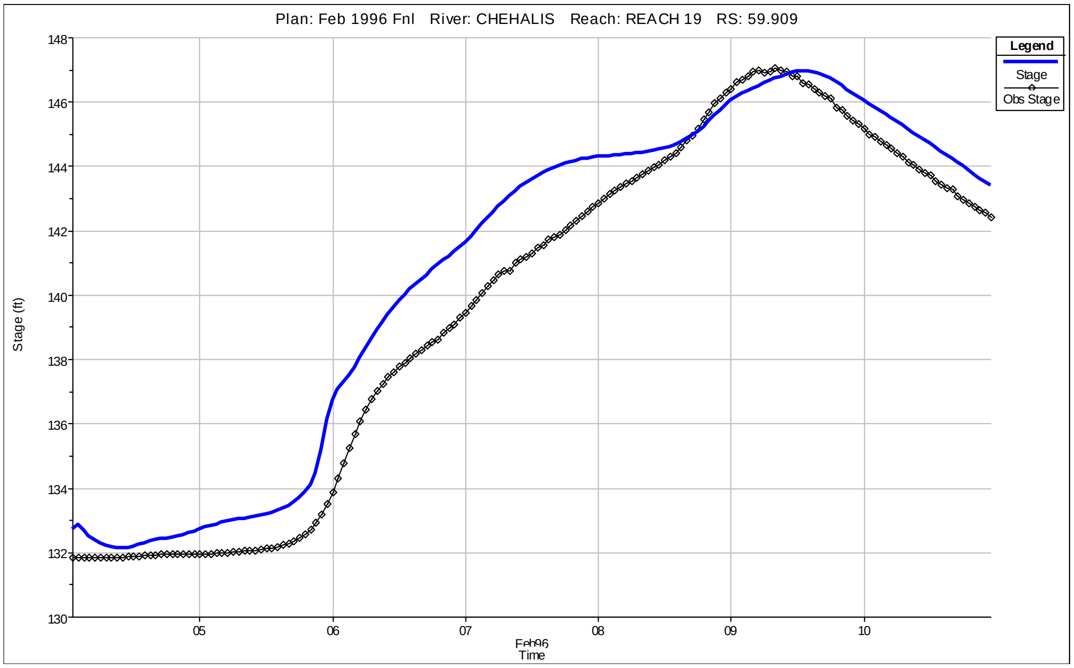

Figure 5. Stage hydrographs for Chehalis River at Grand Mound– February 1996

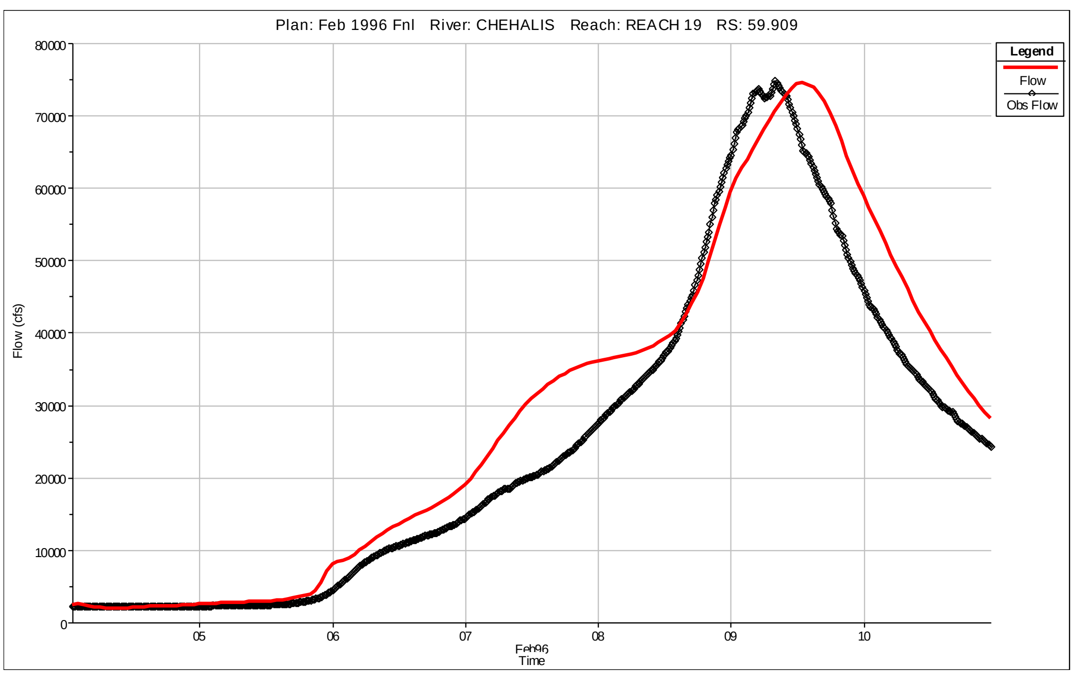

Figure 6. Flow hydrographs for Chehalis River at Grand Mound– February 1996

In addition to the stream gage data that were available for calibration, high water mark data are also available in specific locations throughout the basin. A comparison of simulated water surface elevations to recorded high water marks for the February 1996 event is shown in Table 3.

Table 3. Summary of high water mark data – February 1996

River	HEC-RAS River Station (RM)	Simulated Water Surface Elevation (feet NAVD88)	Observed High Water Mark (feet NAVD88)	Difference (feet NAVD88)
Black River	9.09	112.56	113	-0.44
Black River	4.62	101.04	100.95	0.09
Black River	3.44	97.43	97.48	-0.05
Black River	2.5	95.1	96.12	-1.02
Chehalis River	81.03	199.93	199.37	0.56
Chehalis River	76.1	186.01	185.93	0.08
Chehalis River	75.09	184.77	185.75	-0.98
Chehalis River	74.82	183.66	184.9	-1.24
Chehalis River	74.02	182.3	183.4	-1.1
Chehalis River	72.8	181.57	181.9	-0.33
Chehalis River	67.86	178.8	179.61	-0.81
Chehalis River	67.43	177.26	177.7	-0.44
Chehalis River	66.88	175.59	176.54	-0.95
Chehalis River	66.73	175.2	175.61	-0.41
Chehalis River	66.36	172.71	173.12	-0.41
Chehalis River	64.2	162.69	164.53	-1.84
Chehalis River	63.2	158.19	158.9	-0.71
Chehalis River	61.96	155.27	156.73	-1.46
Chehalis River	59.909	146.95	147	-0.05
Chehalis River	54.476	123.75	124.43	-0.68
Chehalis River	54.045	120.08	120.11	-0.03
Chehalis River	51.158	104.04	106.36	-2.32
Chehalis River	50.022	100.89	99.72	1.17
Chehalis River	45.217	88.17	87.21	0.96
Chehalis River	42.283	77.79	71.2	6.59
Dillenbaugh Creek	1.25	185.95	187.1	-1.15
Dillenbaugh Creek	0.09	183.79	185.41	-1.62
Newaukum River	4.11	204.59	206.69	-2.1
Newaukum River	1.66	186.84	187.9	-1.06
Salzer Creek	1.56	180.32	180.4	-0.08
Salzer Creek	1.28	180.32	180.4	-0.08
Salzer Creek	0.36	179.92	180.12	-0.2
Skookumchuck River	20.7	334.58	333.98	0.6
Skookumchuck River	6.4	216.29	216.2	0.09
Skookumchuck River	3.84	201.42	201.66	-0.24
Skookumchuck River	2.42	191.47	190.69	0.78
Skookumchuck River	2.21	189.33	188.4	0.93
Skookumchuck River	2	187.99	187.7	0.29

January 2009 Event

Table 4 shows the comparison between modeled and observed peak flows at various locations on the Chehalis, Newaukum, and Skookumchuck Rivers for the January 2009 event. For illustration, a plot of simulated and observed stage and flow hydrographs at Grand Mound are included in Figures 7 and 8.

Table 4. Summary of model calibration for flow for January 2009 event

Location	Computed Peak Flow (cfs)	Observed Peak Flow (cfs)	Difference in Peak Flow (%)	Difference in Event Volume (%)	Peak Time Difference (hours)*
Chehalis River at Doty	19,602	20,100	-2.5	-0.2	0.0
Chehalis River at Grand Mound	57,928	50,700	14.3	17.3	0.5
Chehalis River at Porter	66,992	68,100	-1.6	6.9	-0.5
Newaukum River near Chehalis	12,629	13,000	-1.7	6.5	1.0
Skookumchuck River below Bloody Run	7,018	6,900	1.7	3.5	-0.75
Skookumchuck River near Bucoda	9,962	10,500	-5.1	-4.2	1.0

*A negative time difference denotes the simulated peak occurring before the observed peak

Flow volumes in the Chehalis River tend to be slightly higher than observed data, especially in the lower Chehalis River. The majority of the contributing area between the gage at Doty and the gage at Grand Mound is ungaged; therefore, the majority of the contributing flow between Doty and Grand Mound is estimated using procedures discussed the GI Report (USACE 2012a). These results suggest that the inflow estimates between Doty and Grand Mound are high. Although the estimated inflows produce hydrograph volumes that are high compared to the observed data, the flow magnitudes are generally within 10 percent.

At the Newaukum River and Skookumchuck River gages, both the simulated flow volumes and peak flow magnitudes are within 10 percent of the observed volumes and magnitudes for the 2009 event. Simulated and observed peak times also agree well; all differences are within one hour.

In general, the flow hydrograph calibrations look reasonable. For observed flow hydrographs where the majority of the upstream contributing flow is gaged (Chehalis at Doty, Newaukum near Chehalis, Skookumchuck below Bloody Run and near Bucoda), the calibration of the flow hydrographs appear relatively tight. At the gages where the majority of the contributing flow is ungaged (Chehalis River at Grand Mound and Porter), the simulated flows tend to be high compared to the observed, as noted previously. This in turn yields stage hydrograph calibrations that look reasonable for the Chehalis River at Doty and the Skookumchuck gages. The stage hydrographs for the Chehalis River at Grand Mound and Porter are slightly high which is to be expected due to the high simulated flow peaks.

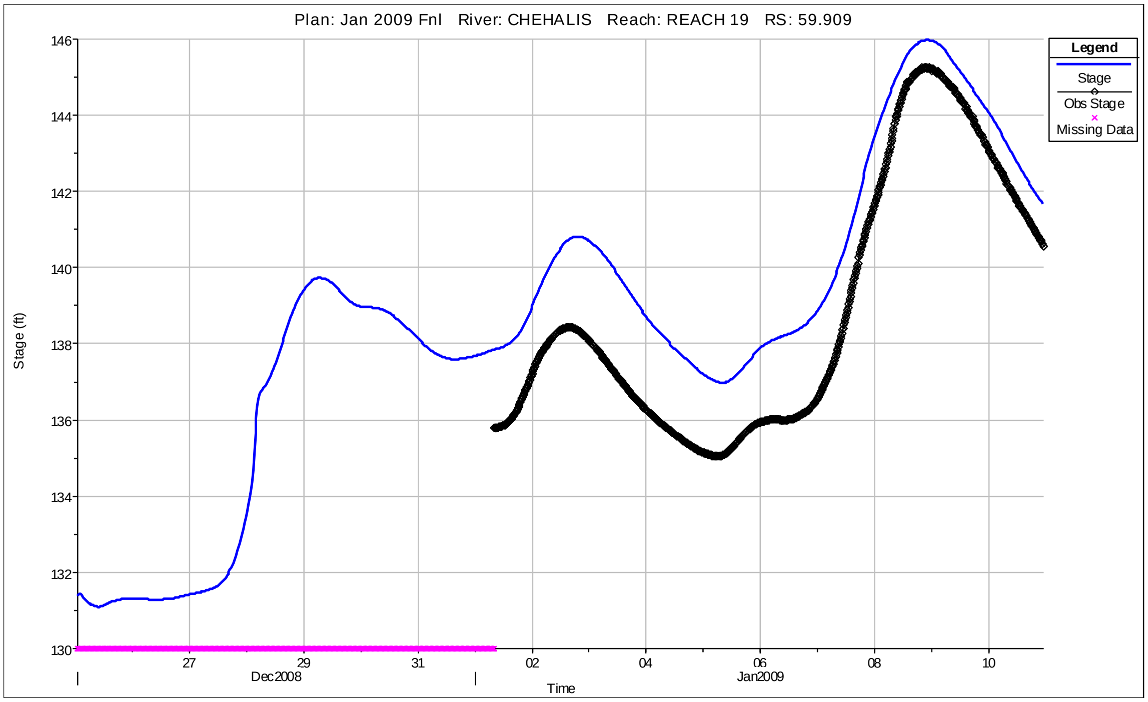

Figure 7. Stage hydrographs for Chehalis River at Grand Mound– January 2009

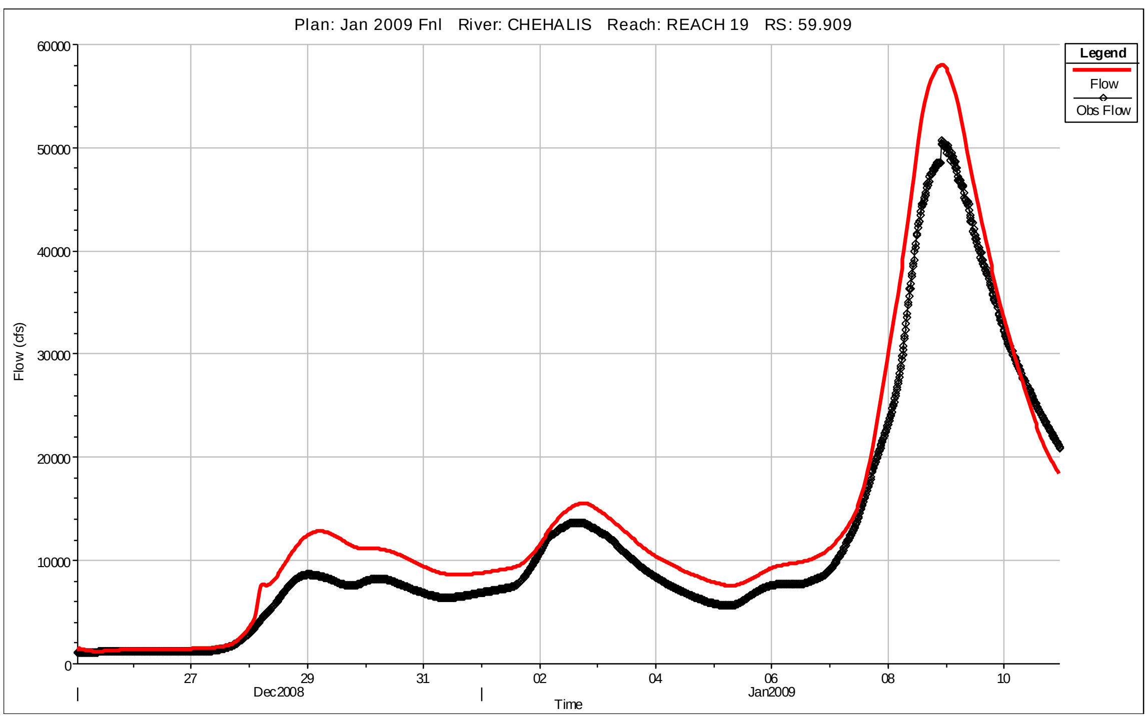

Figure 8. Flow hydrographs for Chehalis River at Grand Mound– January 2009

In addition to the stream gage data that were available for calibration, high water mark data are also available in specific locations throughout the basin. A comparison of simulated water surface elevations to recorded high water marks for the January 2009 event is shown in Table 5.

Table 5 Summary of high water mark data – January 2009

River	HEC-RAS River Station (RM)	Simulated Water Surface Elevation (feet NAVD88)	Observed High Water Mark (feet NAVD88)	Difference (feet NAVD88)
Chehalis River	85.99	213.22	211.1	2.12
Chehalis River	74.57	181.43	181.95	-0.52
Chehalis River	72.58	180.01	179.3	0.71
Chehalis River	64.25	161.51	163.11	-1.6
Chehalis River	64.2	161.33	163.11	-1.78
Dillenbaugh Creek	1	185.67	185.4	0.27
Dillenbaugh Creek	0.792	185.64	185.4	0.24
Dillenbaugh Creek	0.155	183.45	182.4	1.05
Dillenbaugh Creek	0.142	183.39	182.4	0.99
Newaukum River	1.3	185.26	185.4	-0.14
Salzer Creek	2.32	178.06	181.7	-3.64
Salzer Creek	2.25	177.98	181.7	-3.72
Salzer Creek	2.05	177.39	181.2	-3.81
Salzer Creek	1.15	177.26	176.4	0.86
Skookumchuck River	4	201.43	199.8	1.63
Skookumchuck River	2.41	190.54	190.46	0.08

December 2007 Event

Table 6 shows the comparison between modeled and observed peak flows at various locations on the Chehalis, Newaukum, and Skookumchuck Rivers for the January 2009 event. For illustration, a plot of simulated and observed stage and flow hydrographs at Grand Mound are included in Figures 9 and 10.

Table 6. Summary of model validation for flow for December 2007 event

Location	Computed Peak Flow (cfs)	Observed Peak Flow (cfs)	Difference in Peak Flow Magnitude (%)	Difference in Event Volume (%)	Peak Time Difference (hours)*
Chehalis River at Doty	62,215	63,100**	-1.4**	-0.1	0.0**
Chehalis River at Grand Mound	82,690	79,100	4.5	28.3	3.0
Chehalis River at Porter	84,790	102,000	-16.9	2.7	3.0
Newaukum River near Chehalis	12,458	12,900	-3.4	0.5	1.0
Skookumchuck River below Bloody Run	2,223	2,210	0.6	2.0	0.25
Skookumchuck River near Bucoda	3,494	3,600	2.9	0.9	-2.25

* A negative time difference denotes the simulated peak occurring before the observed peak

** Stream gage record ends near peak, values for comparison may be missing.

As seen in the table, most of the simulated and observed flow magnitude and volume differences are within 10 percent. The notable exceptions are the flow volume in the Chehalis River at Grand Mound and the peak flow magnitude in the Chehalis River at Porter. Similar to the 2009 calibration event, the simulated flow volume at Grand Mound is high compared to the observed volume. However, to "correct" this issue, the inflows upstream of Grand Mound would have to be dramatically reduced, and the inflows between Grand Mound and Porter would have to increase by about a multiple of three. We felt that this distribution of inflows would be unrealistic.

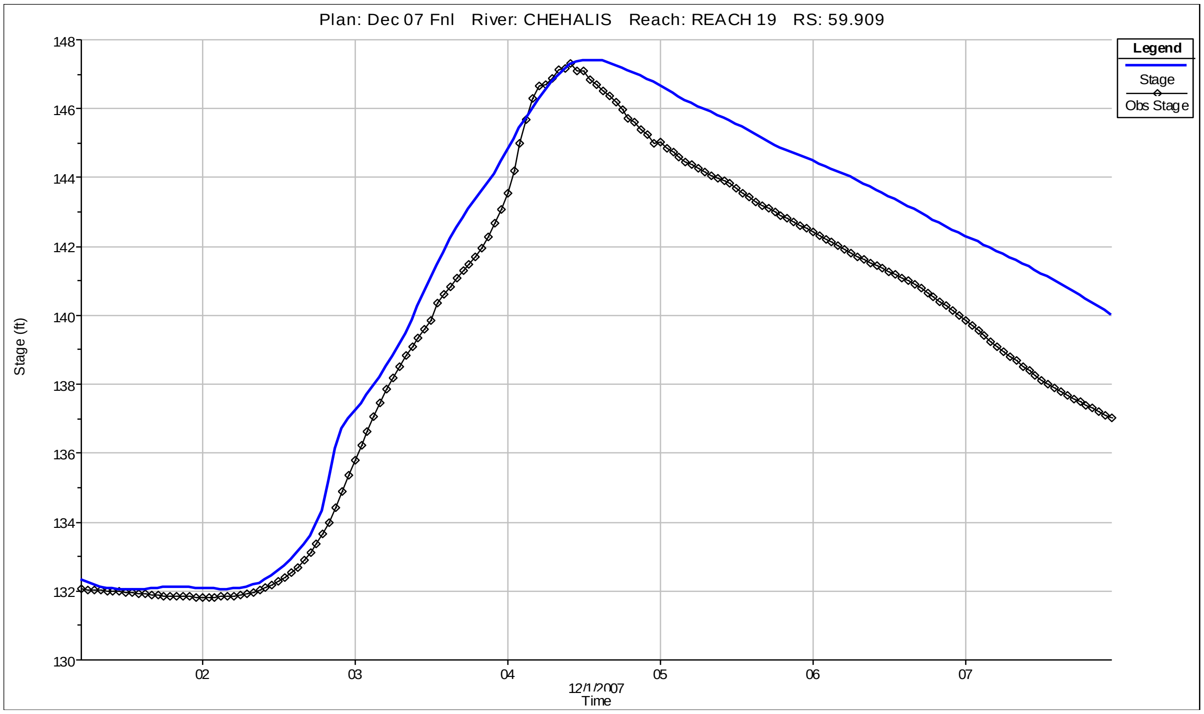

Figure 9. Stage hydrographs for Chehalis River at Grand Mound– December 2007

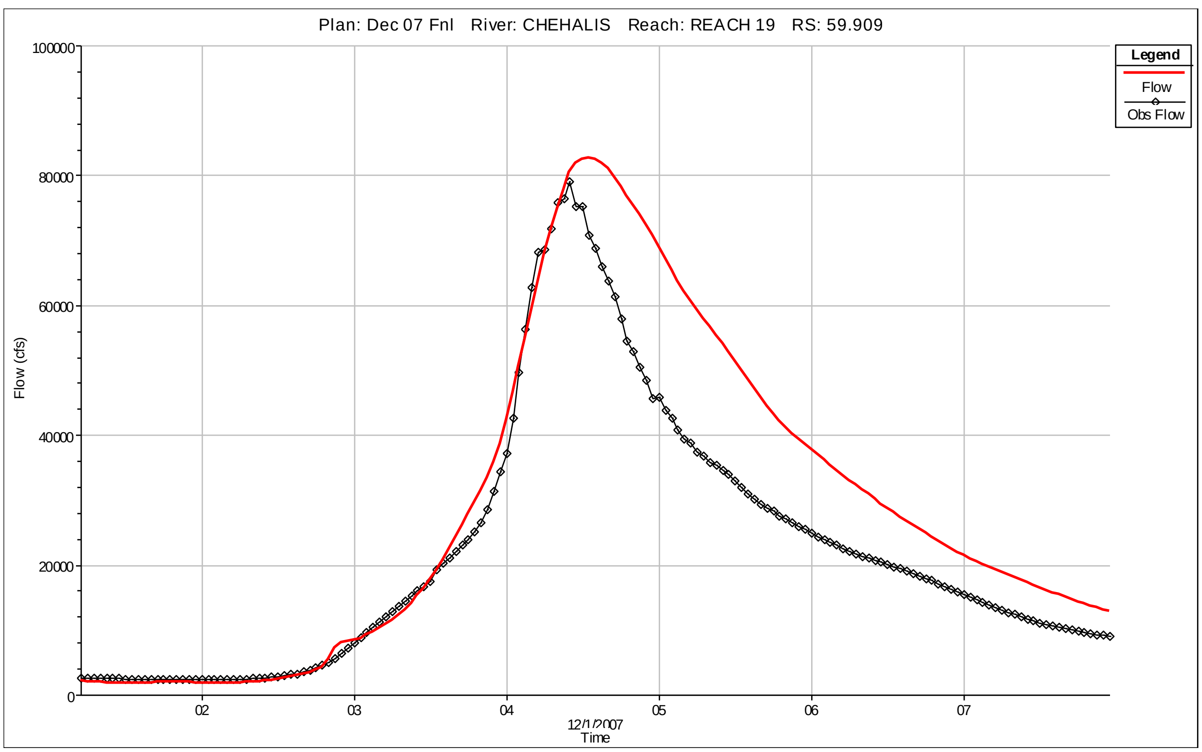

Figure 10. Flow hydrographs for Chehalis River at Grand Mound– December 2007

In addition to the stream gage data that were available for calibration, high water mark data are also available in specific locations throughout the basin. A comparison of simulated water surface elevations to recorded high water marks for the December 2007 event is shown in Table 7.

Table 7. Summary of high water mark data – December 2007

River	HEC-RAS River Station (RM)	Simulated Water Surface Elevation (feet NAVD88)	Observed High Water Mark (feet NAVD88)	Difference (feet NAVD88)
Black River	7.07	107.65	104.26	3.39
Black River	5.64	102.96	103.92	-0.96
Chehalis River	86.01	223.05	223.2	-0.15
Chehalis River	84.3	210.19	212.1	-1.91
Chehalis River	78.97	195.25	196.4	-1.15
Chehalis River	77.959	193.89	194	-0.11
Chehalis River	77.65	192.61	193.2	-0.59
Chehalis River	77.39	188.92	188.2	0.72
Chehalis River	75.2	186.62	187.65	-1.03
Chehalis River	74.73	185.03	185.48	-0.45
Chehalis River	74.25	183.9	184	-0.1
Chehalis River	74.02	183.65	184.1	-0.45
Chehalis River	73.73	183.37	183.1	0.27
Chehalis River	72.8	182.83	182.9	-0.07
Chehalis River	72.22	182.34	182.4	-0.06
Chehalis River	69.22	181.34	181.6	-0.26
Chehalis River	68.67	181.23	181.3	-0.07
Chehalis River	67.86	180.67	179.8	0.87
Chehalis River	66.95	176.5	175.5	1.00
Chehalis River	65.8	171.65	171.93	-0.28
Chehalis River	64.9	168.29	168.2	0.09
Chehalis River	61.96	155.75	157.9	-2.15
Chehalis River	61.7	155.75	153.13	2.62
Chehalis River	60.22	150.29	151.8	-1.51
Chehalis River	54.045	120.44	117.83	2.61
Chehalis River	53.264	115.33	115.42	-0.09
Chehalis River	52.947	113.98	114.72	-0.74
Chehalis River	51.499	106.03	111.34	-5.31
Dillenbaugh Creek	0.321	186.32	187	-0.68
Dillenbaugh Creek	0	185.03	185.48	-0.45
Newaukum River	0.1	186.97	187.65	-0.68
Salzer Creek	3.4	182.02	181.5	0.52
Salzer Creek	2.22	182.01	181.8	0.21
Salzer Creek	1.32	182.01	181.9	0.11
Salzer Creek	1.05	182.01	182.1	-0.09
Salzer Creek	0.65	182.01	181.8	0.21
Skookumchuck River	0.49	177.44	177.5	-0.06

Areas of concern

The development and calibration of the HEC-RAS hydraulic model developed for this project has followed the highest technical standards for a project such as this. The use of new channel and overbank topographic and bathymetric survey data to refine the model clearly improves the model's ability to capture physical conditions in the basin. Detailed calibration of the model to three large floods including numerous high water marks and flow and stage hydrographs improves our confidence in the model's ability to accurately simulate large flood events. Technical review of the model by three respected consulting firms, the Corps, WSDOT, WDFW, WADOE, and others helps ensure that the model is appropriately configured and well defined. However, despite all of these considerations, it must be remembered that any model is simply a representation of the actual system being investigated and any model is subject to uncertainty and error. In the case of the Chehalis River basin, the most significant issues leading to uncertainty in the results include the hydrologic data used to develop inputs to the model, potential anomalies during past flood events, and whether the hypothetical design flow events are adequately representative of the wide range of potential conditions. Each of these is discussed briefly below:

USGS Gage data

The USGS maintains a number of key streamflow gages in the Chehalis River basin. The USGS is the preeminent agency for streamflow gaging in the United States and data collected by the USGS is generally the best information available for gaining an understanding basin hydrology. Data from these gages is essential to developing inputs to basin wide hydraulic modeling. However, it must be acknowledged that accurately estimating flows from extreme events is particularly difficult and the inherent uncertainties (errors) in gage data need to be considered when evaluating and using hydraulic model results. Several key streamflow gages in the Chehalis River basin, including the Chehalis River at Grand Mound, Chehalis River at Porter, and Newaukum River at Labree Road are subject to flows bypassing the gages during extreme flood events. Since the rating curves for these gages are generally developed using stage-discharge measurements made when flow is contained within the main channel (i.e. with no overbank bypass flows) it is unlikely that the extensions of these rating curves reflect the bypass flows. It is not clear, but discussions with the USGS and our review of the USGS data indicate that modifications to streamflow data to directly account for bypass flows are not made. As such, the data for periods when flows are bypassing the gage site are especially uncertain.

In addition to general difficulties in estimating high flows and particular concerns with gages that have bypass flows the data for several gages for the December 2007 flood are particularly difficult to use due to problems with the gages. The USGS gage at Doty was inoperable at the time of the peak of the December 2007 flood. The gage on the South Fork Chehalis River at Wildwood, while operable throughout the event had such large changes in bed level due to sediment movement during the event that the data is not felt to be useful at the peak of the flood. Because these gages measure runoff from the area where the storm was centered, and the mainstem and South Fork Chehalis were likely the source for 60% or more of the flow seen in the Twin Cities during the December flood, accurate modeling of that event is particularly problematic. However, considering the large number of calibration points throughout the basin, the availability of a continuous flow hydrograph at Grand Mound, and the work done by the USGS, the Corps, and FEMA/NHC to accurately re-create flood flow hydrographs for the upper basin for the December 2007 flood, we are confident that modeling and analysis of that flood is still appropriate for the current project. We would simply caveat the results that there is probably greater uncertainty in the flow values during that event than in other, less severe events.

Doty Flows – debris jams, volumes

Residents in the Upper Chehalis River, upstream of the South Fork confluence, have suggested that debris jams and or damming of the river caused by failed bridges during the December 2007 flood event were significant factors in the magnitude of the observed flows. The USGS has reviewed this issue and has determined that their estimate of the flood peak at Doty is reasonable. However there remains significant uncertainty in the flows reported for all gages in the upper basin during that flood event due to the fact that the discharges were higher than any previously seen and that there were significant debris and sediment issues throughout the watershed. The analyses documented herein include simulations of three extreme flood events, in addition to the December 2007 flood, and as such the conclusions reached regarding flood relief alternatives should hold regardless of the uncertainty in the hydrologic data for that particular flood.

"Representativeness" of 100-year flood

As discussed above, some reviewers felt that the Chehalis River Basin is too large and flood flows are too variable to model using only one or a few design storm events. Some reviewers suggested that the only way to adequately evaluate flood relief projects would be to develop a calibrated basin-wide hydrologic model and use that model to derive inputs to the hydraulic modeling and analysis. Unfortunately, there is neither time nor budget to undertake such an effort within this project. We concur that the basin hydrology is diverse and that no two storms will look the same. We also acknowledge that the approach of using one theoretical design storm and three historic flood events is not perfect. For this reason it may be necessary to develop additional hydrologic data sets and make additional model runs to evaluate some projects, particularly projects on the tributaries. However, we feel that the approach taken in this study, as modified in consultation with the State tech team, is appropriate to meet the current needs of the Flood Authority. Future modeling efforts with different hydrologic data sets would be straightforward to model once the data were developed. These analyses could be conducted by any qualified hydraulic engineer on behalf of any stakeholder or agency using the HEC-RAS model. Again this highlights the benefit of a cooperatively developed and well vetted model.

Model Geometry versus Current Conditions

Although geometric (cross section) data used in the hydraulic model utilized the best available data sources, that data may not always accurately reflect current conditions. Notable data sets include topography from 1999 (in the Twin Cities floodplain area), 2002 (between Grand Mound and Montesano and along the Skookumchuck River), and 2005 and 2006 in Centralia and Chehalis. On the lower Satsop River, for example, significant channel adjustments have occurred since the 2002 LiDAR used in the current model. However, without updated overbank LiDAR, Satsop channel changes could not be reliably incorporated into the current model.

Although the current effort included new channel survey for a significant portion of the Lower Chehalis River, in-channel and bridge structure data for much of the upper basin and tributaries is from existing model cross sections, which are based on older, often sparse, cross section survey. The representativeness of model geometry should be carefully considered by a qualified hydraulic engineer before the model is utilized for other purposes or projects.

New topographic data will be available soon for much of the basin (Chehalis River corridor from Lewis County line to Montesano) or is already available (Thurston County and portions of Lewis County). The new topographic data could be used to update the hydraulic models thus improving the model's ability to simulate overbank flooding. This effort, however, was beyond the scope and schedule of the current project.

Modeling Tidal Flooding in the Lower Chehalis

Extension of the Lower Chehalis Model from Montesano (RM 12) to Grays Harbor was completed and calibrated for large flood events, and therefore may not provide a good representation of low flow conditions. The model was set up to handle significant riverine flow in conjunction with tidal exchange but it does not attempt to model the effects of solely (or principally) tidal flooding. As such the daily filling and flushing of the intertidal channels and surge plain downstream of Montesano would not be particularly well modeled during times when the river is not flooding. Extension of the Flood Authority model into Grays Harbor was done through the inclusion of a tidal boundary (using observed and/or predicted tide data) to provide a tool for the evaluation of the downstream impact/benefit of upstream flood relief alternatives. The estuary; however, is a dynamic system with a large tidal surge plain and numerous overflow paths and tidal sloughs that behave much differently under low flow conditions, and a different tool (possibly a 2-D model) may be more well suited for low-flow or ecological studies downstream of Montesano.

Alternatives Analysis

Definition of Alternatives

WSE updated the Flood Authority HEC-RAS model in order to examine a number of flood reduction scenarios, including the Dam and Levee alternatives detailed in Task 8, and an additional thirteen alternatives and ten combinations of those alternatives. Descriptions of each model scenario are included below.

Mainstem Chehalis River Dam

Following the severe flood in 2007, the Chehalis Basin Flood Authority began to evaluate whether flood retention structures in the Chehalis River Basin might be part of a solution to basin-wide flooding. This built on early work by the Corps of Engineers and the Lewis County Public Utilities District. After reviewing several sites, the flood retention project site still under consideration is a multi-purpose dam located upstream of Pe Ell on the Upper Chehalis River. The structure would have 80,000 ac-ft of dedicated flood control storage, a structural height of 288 feet, flow augmentation/hydropower storage capacity of 65,000 ac-ft, and an estimated construction cost of $245 million (Phase IIB).

Using the calibrated baseline geometry, WSE modeled the impacts of the dam above Pe Ell by altering model inflow to include the hydrologic effect of the upstream retention facility.

Corps Twin City Levee Project

Beginning in the 1980s the US Army Corps of Engineers began to evaluate a plan to build 11 miles of new levees in the Chehalis River floodway through Chehalis and Centralia. The Corps presented a design to build miles of new levees to the Centralia City Council in 1980. This basic plan was authorized for further analysis, but not funded for construction, by Congress as the Centralia Flood Damage Reduction Project ("Twin Cities project"). Work on the Twin City plan was largely shelved by the Corps in 2011 after the Corps determined that the proposed project would not have protected I-5 during the 2007 flood, would have increased flooding upstream and downstream and, at a cost of over $200 million, would not pass the Corps cost-benefit test.

The Twin Cities Levee project includes:

- Construction of a levee system designed to provide protection along the Chehalis River from approximately river mile (RM) 75 to RM 64 and along most of the lower 2 miles of both Dillenbaugh Creek and Salzer Creek.
- Construction of a levee along the lower approximately 2 miles of Skookumchuck River to the confluence with Coffee Creek that would provide 100-year level of protection.
- Raising the elevation of approximately eight structures that would incur induced damages from increased inundation as a result of the project, located near the Airport, Interstate-5, Skookumchuck River, and Salzer Creek.
- Modification of Skookumchuck Dam to provide for an additional 11,000 acre-feet of flood storage. The project would limit outflows from the dam and attempt to keep the flow in the Skookumchuck River Channel at the Pearl Street Bridge at or below 5,000 cfs.
- Total estimated cost of $205 million.

Mellen Street Bypass

Historically, the bridge at Mellen Street has been suggested by some as a significant cause of flood impacts in the Twin Cities area. However, the Chehalis HEC-RAS model predicts that there would be little benefit from removing the bridge, in part because the natural topography, even without the bridge, acts as a constriction to flood waters. A different alternative would be to construct a high flow bypass from the left edge of the Chehalis River floodplain upstream of Mellen Street (RM 67.7) to downstream of the Skookumchuck River confluence (RM 66.16). The bypass channel would be approximately 700 feet wide and flow depths would be up to 10 feet deep in a flood such as December 2007.

Scheuber Bypass

The Chehalis River downstream of State Highway 603 flows parallel to Highway 6 for approximately 2.5 miles before turning north and flowing under the SR-6 highway bridge near the City of Chehalis. Water overtopping the highway upstream of the Newaukum River confluence enters the Scheuber Bypass reach that reconnects to the Chehalis River downstream of SR-6 near the Chehalis-Centralia Airport, effectively bypassing city of Chehalis. The Scheuber Bypass Alternative would provide culvert or bridge connections under the highway to pass additional flow downstream and into the bypass, with the goal of reducing peak flood levels within the City of Chehalis. A modeled connection was made by placing a large opening within a portion of the lateral structure representing Highway 6 near River mile 77.3.

Dredging/Channel Excavation

In the past, the Corps also evaluated a project to dredge or excavate the mainstem Chehalis River channel downstream of Mellen Street. WSE modeled a dredge/excavation project similar to the Corps investigated project, which would extend from just downstream of Mellen Street to just downstream of Lincoln Creek (RM 67.29 to RM 60.51). The modeled excavation had a 120-foot bottom width trapezoidal channel, and would lower the channel bottom by as much as 15 feet in some locations (tapering into the existing channel at the upstream and downstream ends). According to PIE's Chehalis River Basin Flood Reduction Report (1998), there is a natural rise in the river bottom in this area; the substrate is most likely bedrock that likely would require blasting for removal. Part of the area under consideration for dredging is fairly high quality riparian zone dominated by black cottonwood, red alder, Douglas fir, western red cedar, with an understory of salmonberry, snowberry, and other native shrubs and herbs. The portions of the area considered for dredging have good quality spawning habitat adjacent to it in the Chehalis River, and a high quality riparian zone with seasonally connected side channels. Habitat diversity, species diversity, wetlands and refugia are good quality (USACE 2012b).

Dredging of the Chehalis River would also require some dredging within the lower reaches of the Skookumchuck River. Model cross sections between the mouth of the Skookumchuck River and RM 3.32 were cut to create a 20 foot wide trapezoidal channel in order to tie the Skookumchuck River channel into the lowered Chehalis River channel and provide model stability.

Bridge Removal

Road and bridge restrictions throughout the Chehalis Basin can constrain the flow of the Chehalis River and its tributaries during flood events. Major floods have resulted in bridges overtopping and the inundation of access roads; damage has occurred in areas such as upstream of SR-6, Mellen Street, Galvin Road, the Sickman-Ford Bridge, Porter Creek Road, and Wakefield Road. Modifications of the SR-6 Bridge and Mellen St. Bridge were proposed in the PIE Chehalis River Basin Flood Reduction Report (1998), and projects involving modifications to Sickman-Ford Bridge and Galvin Road were referenced in the Comprehensive Flood Hazard Management Plan for Confederated Tribes of the Chehalis Reservation. In fact, the Chehalis Tribe has evaluated options for changes to the Sickman-Ford Bridge and developed a scope for additional engineering design. Modifications to the Porter Creek Road and Wakefield Road (South Elma Bridge) were suggested as possible flood relief projects during lower basin stakeholder meetings in June 2012.

To better understand the potential for reduced flood impacts, various road and bridge removal projects were modeled using the Chehalis HEC-RAS model, including:

- Removing all bridges and approach fills in the entire model
- Removing the bridge and approach fill of SR-6 alone
- Removing the bridge and approach fills of Mellen Street
- Removing the Bridge and approach fills of Galvin Road
- Removing the bridge and approach fills of Sickman-Ford Bridge
- Removing the bridge and approach fills of Porter Creek Road Bridge
- Removing the bridge and approach fills of Wakefield Road (South Elma) Bridge

Due to time and budget constraints bridge removals were modeled by simply removing the bridge structure, approach fills, and upstream and downstream ineffective flow areas from the model. That is, the entire bridge and approach was removed rather than modified. Obviously, this could create significant concerns for transportation and new bridges and approach roads would likely be necessary in some or all locations to replace the existing structures. The purpose of the current modeling effort was to identify the maximum possible benefit that could be derived from bridge removals so that future analysis efforts could be prioritized to structures that showed some possibility of reducing flooding rather than simply to bridges that have been previously identified as concerns.

I-5 Protection

Flooding in the Chehalis Basin has affected access to I-5, closing it for four days in 1996, four days in 2007, and two days in 2009. The Washington Department of Transportation (DOT) estimated the total loss in economic output to the state economy due to the closure of I-5 in 2007 at $47 million (DOT). The major costs from I-5 closure are freight delays, but closures also impact private operating companies by affecting logistical and scheduling costs, as well as indirect market costs.

The Mellen Street to Blakeslee Junction (MTB) project now underway will provide access to the hospital in Centralia during flood events from downtown Centralia. In addition, the 2011 Washington State Legislature and the Washington State Office of Finance Management (OFM) directed WSDOT to evaluate alternative projects that could protect I-5 and the municipal airport at Centralia and Chehalis.

OFM contracted with WSDOT to perform the work on I-5 alternatives. Project alternatives evaluated include raising I-5 using fill material, raising I-5 using a viaduct, relocating I-5 outside the flood area, and protecting I-5 with walls and levees. The fill, viaduct, and relocation projects had cost estimates ranging from $350 million - $2 billion.

The option modeled by WSE would protect I-5 with walls and levees, which has a projected cost of $80-100 million. This project would involve building earthen levees and structural walls, replacing bridges with bottomless arches at Dillenbaugh and Salzer Creek, and providing stormwater treatment systems.

Localized I-5 Protection and Airport Levee Improvements

The Chehalis HEC-RAS model predicts that even if a water retention project in the upper watershed were constructed, it alone would not protect I-5 from flooding during the 2007 and 2009 flood events. Improvements near the south end of Centralia-Chehalis Airport, north of Salzer Creek and north of the 13th Street interchange would also need to be implemented to protect I-5 from flooding. Over the past few years the Chehalis-Centralia Airport has been working on a project for enhancing the Airport Levee. The airport levee enhancement project is designed to provide protection for the Airport and to a lesser degree I-5.

The airport levee project would involve raising the existing 2.3 miles of earthen levee to an elevation three feet above the 100 year flood level as recently identified by FEMA. This is accomplished by widening the base of the levee and constructing it higher in a way that maintains existing side slopes. In addition to the improvements to the existing levee, the project would elevate Airport Road along the south side of the Airport and replace all utility infrastructure. The cost estimate for this project is approximately $3.2 million, with the roadway improvements responsible for the majority of the cost.

However, to achieve protection of the airport area in a 100-year event, some additional localized flood protection improvements would be needed along I-5 north of Salzer Creek and south by Dillenbaugh Creek. This alternative would include those improvements, designed to a level to eliminate I-5 flooding in an event such as the December 2007 Flood.

Skookumchuck Levees

The Corps Twin Cities Levee Project described previously includes levee segments throughout the Twin Cities area in addition to modifications to operations at Skookumchuck Dam. As documented in the Corps Project Closeout Report (2012b) the Corps has determined that the Twin Cities Project is not viable given federal benefit cost criteria. A modified proposal was developed which would include only the levees along the Skookumchuck River (Corps Levee Reaches 12 through 16) and the levee downstream of the Skookumchuck River confluence (Corps Reach 1). This proposal would not include any modifications to Skookumchuck Dam but would assume that the levees were constructed sufficiently high to prevent overtopping in any of the simulated flood events.

Potential Combinations of Alternatives

Following the initial run of flood reduction projects, WSE was asked to model a number of projects in combination to determine the additive impact on flood levels. The following alternatives were simulated in an initial phase of this work:

1) with mainstem dam and airport levee improvements
2) with WSDOT floodwalls/berms and airport levee improvements
3) with Scheuber bypass, Mellen Street bypass, and airport levee improvements
4) with dam, airport levee improvements, WSDOT floodwalls/berms
5) with dam, airport levee improvements, WSDOT floodwalls/berms, downstream bridge removals
6) with Scheuber bypass, Mellen Street bypass, airport levee improvements, WSDOT floodwalls/berms, downstream bridge removals
7) with Scheuber bypass, Mellen Street bypass, airport levee improvements, small floodwall along I-5 near Dillenbaugh Creek

The results of these alternatives were presented at a workshop held in early June in Grand Mound. The participants at that workshop reviewed the results of the preliminary modeling of the combination alternatives and provided feedback on which of these should be developed and evaluated further. The following alternatives were selected for additional modeling and analysis:

A. Mainstem Dam on the Chehalis River, Airport levee improvements, small floodwall along I-5 near Dillenbaugh Creek, Skookumchuck Levees, Sickman Ford Bridge modification, and Wakefield Road (South Elma) Bridge Modification.

B. Same as Alternative "A" with the addition of WSDOT's proposed I-5 berms and floodwall protection project.

C. WSDOT's I-5 berms and floodwalls, Airport levee improvements, Mellen Street and Scheuber Road Bypasses, Skookumchuck Levees, Sickman Ford Bridge modification, and Wakefield Road (South Elma) Bridge Modification.

Results

Results of the simulation of basin wide flood relief alternatives are presented below. Tabular results are included for every alternative and combination of alternatives listed above. Additional, more detailed analyses have also been prepared for some alternatives. These include inundation mapping for the Twin Cities area, detailed evaluation of flooding of I-5, and bar charts comparing the results at various locations throughout the basin for the December 2007 and 100-year events. These more detailed analyses were completed for several of the individual alternatives and each of the groupings described above. While only the results for combination alternatives A, B, and C are presented herein, many others were presented at workshops or Flood Authority meetings over the course of this project. The additional interim results will be included in the final products submitted by WSE to the Flood Authority.

Tabular Summary

Tables 8, 9, and 10 compare the simulated water surface elevations under each of the modeled alternatives with baseline conditions. Comparisons are made at 26 representative locations distributed throughout the basin. These were focused primarily along the main stem Chehalis River but include points along the South Fork Chehalis, Newaukum, and Skookumchuck Rivers. Table 8 includes data for the December 2007 and 100-year flood events for the individual project elements while Table 9 shows the same alternatives for the February 1996 and January 2009 events. Table 10 compares the effect on water surface elevations of combinations of flood relief elements for all four modeled events. The broad distribution of points provides a basin-wide picture of the effects of each alternative and the data for the four simulated floods allows evaluation of the effects under different types of floods.

Table 8: Comparison of Water Surface Elevation Changes with Flood Relief Alternatives – December 2007 and 100-year Storm Events

Alternatives Analysis Summary for December 2007 Flood Event

Location		Max Water Surface Elevation (feet NAVD) or Change in Flood Water Surface (feet)																
Description	X-section	Dec 07 (ft NAVD)	Dec w/Dam (ft NAVD)	Change (ft NAVD)	Dec w/Lev (ft NAVD)	Change (ft NAVD)	Dec Ph1Lev (ft NAVD)	Change (ft NAVD)	Dec w/Dam&Lev (ft NAVD)	Change (ft NAVD)	Dec MellenBP (ft NAVD)	Change (ft NAVD)	Dec Dredge (ft NAVD)	Change (ft NAVD)	Dec ScheuberBP (ft NAVD)	Change (ft NAVD)	Dec Sc-AP-Mel (ft NAVD)	Change (ft NAVD)
Near Doty	100.95	328.1	315.8	-12.3	328.1	0.0	328.1	0.0	315.8	-12.3	328.1	0.0	328.1	0.0	328.1	0.0	328.1	0.0
Curtis Store (on S Fork Chehalis)	1.81	238.9	232.8	-6.1	238.9	0.0	238.9	0.0	232.8	-6.1	238.9	0.0	238.9	0.0	238.9	0.0	238.9	0.0
Downstream of South Fork	86.42	227.7	222.1	-5.6	227.6	0.0	227.7	0.0	222.1	-5.6	227.7	0.0	227.7	0.0	227.7	0.0	227.7	0.0
Near Adna	80.23	197.9	196.3	-1.6	197.9	0.0	197.9	0.0	196.3	-1.6	197.9	0.0	197.9	0.0	197.9	0.0	197.9	0.0
Labree Road (on Newaukum R)	4.11	204.7	204.7	0.0	204.7	0.0	204.7	0.0	204.7	0.0	204.7	0.0	204.7	0.0	204.7	0.0	204.7	0.0
Newaukum Confluence	75.2	186.6	184.4	-2.2	187.1	0.5	186.6	0.0	184.5	-2.2	186.6	0.0	186.6	0.0	185.1	-1.5	185.6	-1.0
Along Airport Levee	71.49	182.1	179.2	-2.9	183.4	1.3	182.1	0.0	179.7	-2.4	180.4	-1.7	181.5	-0.7	182.1	-0.1	181.2	-0.9
Dillenbaugh Storage Area	SA #301	186.6	184.2	-2.3	187.0	0.5	186.6	0.0	184.4	-2.2	186.6	0.0	186.6	0.0	185.2	-1.4	185.7	-0.9
Airport Storage Area	SA #2	182.2	178.4	-3.7	159.4	-22.8	182.2	0.0	159.4	-22.8	180.6	-1.6	181.5	-0.7	182.1	-0.1	159.4	-22.8
Long Road Storage Area	SA #5	179.1	169.4	-9.7	178.0	-1.1	179.2	0.0	169.4	-9.7	177.7	-1.4	178.5	-0.6	179.1	-0.1	169.4	-9.7
Centralia Storage Area	SA #610	178.5	174.5	-4.0	176.8	-1.7	178.5	0.0	174.5	-3.9	175.8	-2.7	177.2	-1.3	178.4	-0.1	174.7	-3.8
Mellen St	67.43	178.6	175.7	-2.9	178.9	0.3	178.6	0.0	176.0	-2.6	175.4	-3.2	176.9	-1.7	178.6	-0.1	175.5	-3.1
Bucoda (Skookumchuck R)	11.1	244.3	244.3	0.0	244.3	0.0	244.3	0.0	244.3	0.0	244.3	0.0	244.3	0.0	244.3	0.0	244.3	0.0
Pearl Street (Skookumchuck R)	2.43	186.6	186.6	0.0	186.6	0.0	186.6	0.0	186.6	0.0	186.6	0.0	179.6	-7.0	186.6	0.0	186.6	0.0
Skookumchuck Confluence	66.88	176.4	173.4	-3.0	176.4	0.0	176.4	0.0	173.7	-2.7	174.5	-1.9	174.5	-2.0	176.4	-0.1	174.5	-1.9
Upstream of Galvin Road	64.9	168.2	164.6	-3.6	168.2	0.0	168.2	0.0	164.9	-3.3	168.5	0.3	166.6	-1.6	168.1	-0.1	168.6	0.3
Grand Mound (Prather Road)	59.909	147.4	145.7	-1.7	147.4	0.0	147.4	0.0	145.8	-1.5	147.5	0.1	147.4	0.0	147.3	0.0	147.6	0.2
Near Rochester	54.476	124.2	122.0	-2.2	124.2	0.0	124.2	0.0	122.2	-2.0	124.4	0.2	124.2	0.0	124.2	0.0	124.5	0.3
Anderson Road	51.499	106.0	105.3	-0.7	106.0	0.0	106.0	0.0	105.4	-0.6	106.1	0.1	106.0	0.0	106.0	0.0	106.1	0.1
Black River Confluence	46.937	92.9	90.9	-2.0	92.9	0.0	92.9	0.0	91.1	-1.9	93.1	0.2	92.9	0.0	92.9	0.0	93.2	0.3
Sickman Ford Bridge	44.175	85.5	83.0	-2.5	85.5	0.0	85.5	0.0	83.2	-2.3	85.7	0.2	85.5	0.0	85.5	0.0	85.8	0.3
Porter Creek Road	34.497	57.0	54.7	-2.3	57.0	0.0	57.0	0.0	54.9	-2.1	57.2	0.2	57.0	0.0	57.0	0.0	57.3	0.3
Wakefield Road	24.52	40.2	37.7	-2.5	40.3	0.1	40.2	0.0	37.9	-2.3	40.4	0.3	40.2	0.0	40.2	0.1	40.6	0.4
Satsop Confluence	19.89	34.5	33.1	-1.4	34.5	0.0	34.5	0.0	33.2	-1.3	34.6	0.1	34.5	0.0	34.5	0.0	34.7	0.2
Montesano	12.5	17.3	15.6	-1.7	17.4	0.1	17.3	0.0	15.7	-1.6	17.5	0.2	17.2	-0.1	17.3	0.1	17.6	0.4
Cosmopolis	1.99	10.9	10.9	0.0	10.9	0.0	10.9	0.0	10.9	0.0	10.9	0.0	11.0	0.1	10.9	0.0	10.9	0.0

Note: Negative change means that the alternative has lower simulated water levels, positive change indicates the alternative raises water levels.

Alternatives Analysis Summary for 100-year Design Event

Location		Max Water Surface Elevation (feet NAVD) or Change in Flood Water Surface (feet)																
Description	X-section	100 Year (ft NAVD)	100 w/Dam (ft NAVD)	Change (ft NAVD)	100 w/Lev (ft NAVD)	Change (ft NAVD)	100 Ph1Lev (ft NAVD)	Change (ft NAVD)	100 w/Dam&Lev (ft NAVD)	Change (ft NAVD)	100 w/MellenBP (ft NAVD)	Change (ft NAVD)	100 w/Dredge (ft NAVD)	Change (ft NAVD)	100 w/ScheuberBP (ft NAVD)	Change (ft NAVD)	100 w/Sc-AP-Mel (ft NAVD)	Change (ft NAVD)
Near Doty	100.95	323.2	313.0	-10.3	323.2	0.0	323.2	0.0	313.0	-10.3	323.2	0.0	323.2	0.0	323.2	0.0	323.2	0.0
Curtis Store (on S Fork Chehalis)	1.81	233.6	230.2	-3.3	233.6	0.0	233.6	0.0	230.2	-3.3	233.6	0.0	233.6	0.0	233.6	0.0	233.6	0.0
Downstream of South Fork	86.42	223.2	219.1	-4.1	223.2	0.0	223.2	0.0	219.1	-4.1	223.2	0.0	223.2	0.0	223.2	0.0	223.2	0.0
Near Adna	80.23	197.1	195.5	-1.6	197.1	0.0	197.1	0.0	195.5	-1.6	197.1	0.0	197.1	0.0	197.1	-0.1	197.1	-0.1
Labree Road (on Newaukum R)	4.11	204.9	204.9	0.0	204.9	0.0	204.9	0.0	204.9	0.0	204.9	0.0	204.9	0.0	204.9	0.0	204.9	0.0
Newaukum Confluence	75.2	185.7	184.1	-1.6	186.0	0.3	185.7	0.0	184.1	-1.6	185.7	0.0	185.6	-0.1	183.8	-1.9	184.0	-1.7
Along Airport Levee	71.49	180.8	179.1	-1.7	181.7	0.9	180.8	0.0	179.3	-1.4	179.4	-1.4	180.0	-0.8	180.8	0.0	179.9	-0.9
Dillenbaugh Storage Area	SA #301	185.8	184.3	-1.5	186.1	0.2	185.8	0.0	184.3	-1.5	185.8	0.0	185.8	0.0	184.2	-1.6	184.4	-1.4
Airport Storage Area	SA #2	180.8	177.2	-3.6	159.4	-21.4	180.8	0.0	159.4	-21.4	179.4	-1.3	179.9	-0.9	180.8	0.0	159.4	-21.4
Long Road Storage Area	SA #5	177.9	169.4	-8.5	176.7	-1.3	177.9	0.0	169.4	-8.5	169.4	-8.5	176.7	-1.2	177.9	0.0	169.4	-8.5
Centralia Storage Area	SA #610	176.7	174.7	-1.9	176.1	-0.6	176.7	0.0	174.8	-1.8	174.3	-2.3	175.1	-1.6	176.6	0.0	174.3	-2.3
Mellen St	67.43	177.6	175.8	-1.8	177.8	0.2	177.6	0.0	176.0	-1.6	174.3	-3.3	175.5	-2.1	177.6	0.0	174.5	-3.1
Bucoda (Skookumchuck R)	11.1	252.0	252.0	0.0	252.0	0.0	252.0	0.0	252.0	0.0	252.0	0.0	252.0	0.0	252.0	0.0	252.0	0.0
Pearl Street (Skookumchuck R)	2.43	191.7	191.7	0.0	191.7	0.0	191.7	0.0	191.7	0.0	191.7	0.0	189.4	-2.3	191.7	0.0	191.7	0.0
Skookumchuck Confluence	66.88	175.7	174.0	-1.7	175.8	0.1	175.7	0.0	174.2	-1.5	173.8	-1.9	173.5	-2.2	175.7	0.0	173.9	-1.8
Upstream of Galvin Road	64.9	167.3	165.2	-2.1	167.4	0.1	167.3	0.0	165.4	-2.0	167.6	0.2	165.5	-1.8	167.3	0.0	167.8	0.4
Grand Mound (Prather Road)	59.909	147.1	146.2	-0.9	147.1	0.0	147.1	0.0	146.3	-0.8	147.2	0.1	147.1	0.0	147.1	0.0	147.3	0.2
Near Rochester	54.476	124.0	122.8	-1.2	124.1	0.1	124.0	0.0	122.9	-1.1	124.2	0.2	124.0	0.0	124.0	0.0	124.4	0.4
Anderson Road	51.499	106.1	105.7	-0.3	106.1	0.0	106.1	0.0	105.8	-0.3	106.1	0.1	106.1	0.0	106.1	0.0	106.2	0.1
Black River Confluence	46.937	93.0	92.0	-1.1	93.1	0.1	93.0	0.0	92.1	-0.9	93.2	0.2	93.0	0.0	93.0	0.0	93.4	0.4
Sickman Ford Bridge	44.175	85.6	84.3	-1.3	85.7	0.1	85.6	0.0	84.4	-1.2	85.8	0.2	85.6	0.0	85.7	0.0	86.1	0.4
Porter Creek Road	34.497	57.4	56.2	-1.2	57.5	0.1	57.4	0.0	56.3	-1.1	57.5	0.2	57.4	0.0	57.4	0.0	57.8	0.5
Wakefield Road	24.52	41.6	40.1	-1.5	41.7	0.1	41.6	0.0	40.2	-1.4	41.8	0.2	41.6	0.0	41.7	0.1	42.1	0.5
Satsop Confluence	19.89	35.4	34.8	-0.6	35.5	0.1	35.4	0.0	34.9	-0.6	35.5	0.1	35.4	0.0	35.5	0.1	35.7	0.2
Montesano	12.5	18.8	18.1	-0.7	18.9	0.1	18.8	0.0	18.2	-0.7	19.0	0.1	18.9	0.0	18.9	0.1	19.2	0.3
Cosmopolis	1.99	11.0	10.6	-0.4	11.1	0.1	11.0	0.0	10.6	-0.4	11.1	0.1	11.0	0.0	11.1	0.1	11.2	0.2

Note: Negative change means that the alternative has lower simulated water levels, positive change indicates the alternative raises water levels.

Table 8 (continued): Comparison of Water Surface Elevation Changes with Flood Relief Alternatives – December 2007 and 100-year Storm Events

Alternatives Analysis Summary for December 2007 Flood Event

Location			Max Water Surface Elevation (feet NAVD) or Change in Flood Water Surface (feet)													
Description	X-section	Dec 07 (ft NAVD)	Dec WSDOT I5 (ft NAVD)	Change (ft NAVD)	Dec WSDOT-AP (ft NAVD)	Change (ft NAVD)	Dec I5-Dam (ft NAVD)	Change (ft NAVD)	Dec I5-Dam-Br (ft NAVD)	Change (ft NAVD)	Dec I5-2BP-Br (ft NAVD)	Change (ft NAVD)	Dec Twin Cities (ft NAVD)	Change (ft NAVD)	Dec Skook Lev (ft NAVD)	Change (ft NAVD)
Near Doty	100.95	328.1	328.1	0.0	328.1	0.0	315.8	-12.3	315.8	-12.3	328.1	0.0	328.1	0.0	328.1	0.0
Curtis Store (on S Fork Chehalis)	1.81	238.9	238.9	0.0	238.9	0.0	232.8	-6.1	232.8	-6.1	238.9	0.0	238.9	0.0	238.9	0.0
Downstream of South Fork	86.42	227.7	227.7	0.0	227.7	0.0	222.1	-5.6	222.1	-5.6	227.7	0.0	227.7	0.0	227.7	0.0
Near Adna	80.23	197.9	197.9	0.0	197.9	0.0	196.3	-1.6	196.3	-1.6	197.9	0.0	197.9	0.0	197.9	0.0
Labree Road (on Newaukum R)	4.11	204.7	204.7	0.0	204.7	0.0	204.7	0.0	204.7	0.0	204.7	0.0	204.7	0.0	204.7	0.0
Newaukum Confluence	75.2	186.6	186.7	0.1	187.2	0.6	184.5	-2.1	184.5	-2.1	185.6	-1.0	187.7	1.1	186.6	0.0
Along Airport Levee	71.49	182.1	183.0	0.8	183.4	1.2	179.7	-2.4	179.7	-2.4	181.3	-0.8	184.1	2.0	182.2	0.1
Dillenbaugh Storage Area	SA #301	186.6	186.8	0.3	187.3	0.8	184.4	-2.2	184.4	-2.2	185.8	-0.8	173.4	-13.2	186.6	0.0
Airport Storage Area	SA #2	182.2	183.1	0.9	159.4	-22.8	159.4	-22.8	159.4	-22.8	159.4	-22.8	175.0	-7.2	182.3	0.1
Long Road Storage Area	SA #5	179.1	177.9	-1.2	177.9	-1.2	169.4	-9.7	169.4	-9.7	169.4	-9.7	181.9	2.7	181.6	2.5
Centralia Storage Area	SA #610	178.5	176.6	-1.9	176.7	-1.8	174.5	-3.9	174.5	-3.9	174.6	-3.8	181.9	3.4	181.6	3.1
Mellen St	67.43	178.6	178.9	0.2	178.9	0.2	176.0	-2.6	176.0	-2.6	175.5	-3.2	179.4	0.8	179.0	0.4
Bucoda (Skookumchuck R)	11.1	244.3	244.3	0.0	244.3	0.0	244.3	0.0	244.3	0.0	244.3	0.0	245.5	1.3	244.3	0.0
Pearl Street (Skookumchuck R)	2.43	186.6	186.6	0.0	186.6	0.0	186.6	0.0	186.6	0.0	186.6	0.0	187.1	0.5	186.6	0.0
Skookumchuck Confluence	66.88	176.4	176.4	0.0	176.4	0.0	173.7	-2.7	173.7	-2.7	174.5	-2.0	177.1	0.7	176.6	0.2
Upstream of Galvin Road	64.9	168.2	168.2	-0.1	168.2	-0.1	164.9	-3.3	164.8	-3.5	168.1	-0.1	168.5	0.3	168.0	-0.3
Grand Mound (Prather Road)	59.909	147.4	147.3	-0.1	147.3	0.0	145.9	-1.5	146.7	-0.7	148.4	1.0	147.6	0.2	147.3	-0.1
Near Rochester	54.476	124.2	124.1	-0.1	124.2	0.0	122.2	-2.0	122.2	-2.1	124.4	0.2	124.5	0.3	124.1	-0.1
Anderson Road	51.499	106.0	106.0	0.0	106.0	0.0	105.4	-0.6	105.4	-0.6	106.1	0.1	106.1	0.1	106.0	0.0
Black River Confluence	46.937	92.9	92.9	0.0	92.9	0.0	91.1	-1.9	90.9	-2.0	92.9	0.0	93.2	0.3	92.8	-0.1
Sickman Ford Bridge	44.175	85.5	85.4	-0.1	85.5	0.0	83.2	-2.3	82.1	-3.4	84.4	-1.1	85.9	0.4	85.3	-0.1
Porter Creek Road	34.497	57.0	56.9	0.0	57.0	0.0	54.9	-2.1	54.8	-2.2	57.2	0.2	57.4	0.4	58.5	1.5
Wakefield Road	24.52	40.2	40.2	0.0	40.2	0.0	37.9	-2.3	37.8	-2.4	40.7	0.5	40.7	0.5	40.7	0.5
Satsop Confluence	19.89	34.5	34.5	0.0	34.5	0.0	33.2	-1.3	33.2	-1.3	34.7	0.2	34.7	0.2	34.4	-0.1
Montesano	12.5	17.3	17.3	0.0	17.3	0.1	15.7	-1.6	15.7	-1.6	17.7	0.4	17.5	0.2	17.2	-0.1
Cosmopolis	1.99	10.9	10.9	0.0	10.9	0.0	10.9	0.0	10.9	0.0	10.9	0.0	11.0	0.1	10.9	0.0

Note: Negative change means that the alternative has lower simulated water levels, positive change indicates the alternative raises water levels.

Alternatives Analysis Summary for 100-year Design Event

Location			Max Water Surface Elevation (feet NAVD) or Change in Flood Water Surface (feet)													
Description	X-section	100 Year (ft NAVD)	100 WSDOT I5 (ft NAVD)	Change (ft NAVD)	100 WSDOT-AP (ft NAVD)	Change (ft NAVD)	100 I5-Dam (ft NAVD)	Change (ft NAVD)	100 I5-Dam-Br (ft NAVD)	Change (ft NAVD)	100 I5-2BP-Br (ft NAVD)	Change (ft NAVD)	100 Twin Cities (ft NAVD)	Change (ft NAVD)	100 Skook Lev (ft NAVD)	Change (ft NAVD)
Near Doty	100.95	323.2	323.2	0.0	323.2	0.0	313.0	-10.3	313.0	-10.3	323.2	0.0	323.2	0.0	323.2	0.0
Curtis Store (on S Fork Chehalis)	1.81	233.6	233.6	0.0	233.6	0.0	230.2	-3.3	230.2	-3.3	233.6	0.0	233.6	0.0	233.6	0.0
Downstream of South Fork	86.42	223.2	223.2	0.0	223.2	0.0	219.1	-4.1	219.1	-4.1	223.2	0.0	223.2	0.0	223.2	0.0
Near Adna	80.23	197.1	197.1	0.0	197.1	0.0	195.5	-1.6	195.5	-1.6	197.1	-0.1	197.1	0.0	197.1	0.0
Labree Road (on Newaukum R)	4.11	204.9	204.9	0.0	204.9	0.0	204.9	0.0	204.9	0.0	204.9	0.0	204.9	0.0	204.9	0.0
Newaukum Confluence	75.2	185.7	185.7	0.1	186.0	0.3	184.1	-1.6	184.1	-1.6	184.0	-1.7	186.2	0.5	185.7	0.0
Along Airport Levee	71.49	180.8	181.3	0.5	181.6	0.9	179.4	-1.4	179.4	-1.4	179.9	-0.9	182.5	1.7	180.8	0.1
Dillenbaugh Storage Area	SA #301	185.8	185.9	0.1	186.2	0.4	184.3	-1.5	184.3	-1.5	184.4	-1.4	173.7	-12.2	185.8	0.0
Airport Storage Area	SA #2	180.8	181.4	0.6	159.4	-21.4	159.4	-21.4	159.4	-21.4	159.4	-21.4	159.4	-21.4	180.8	0.1
Long Road Storage Area	SA #5	177.9	176.0	-2.0	176.6	-1.3	169.4	-8.5	169.4	-8.5	169.4	-8.5	177.6	-0.3	180.4	2.4
Centralia Storage Area	SA #610	176.7	176.0	-0.6	176.1	-0.6	174.8	-1.8	174.8	-1.8	174.3	-2.3	177.6	0.9	180.4	3.7
Mellen St	67.43	177.6	177.7	0.2	177.8	0.2	176.0	-1.6	176.0	-1.6	174.5	-3.1	178.5	0.9	177.7	0.1
Bucoda (Skookumchuck R)	11.1	252.0	252.0	0.0	252.0	0.0	252.0	0.0	252.0	0.0	252.0	0.0	250.6	-1.4	251.9	0.0
Pearl Street (Skookumchuck R)	2.43	191.7	191.7	0.0	191.7	0.0	191.7	0.0	191.7	0.0	191.7	0.0	190.2	-1.4	192.4	0.7
Skookumchuck Confluence	66.88	175.7	175.7	0.0	175.8	0.1	174.2	-1.5	174.2	-1.5	173.9	-1.8	176.5	0.8	175.8	0.1
Upstream of Galvin Road	64.9	167.3	167.4	0.0	167.4	0.1	165.4	-2.0	165.2	-2.1	167.5	0.1	167.8	0.5	167.1	-0.2
Grand Mound (Prather Road)	59.909	147.1	147.1	0.0	147.1	0.0	146.3	-0.8	147.1	0.0	148.1	1.0	147.4	0.3	147.0	-0.1
Near Rochester	54.476	124.0	124.0	0.0	124.1	0.1	122.9	-1.1	122.9	-1.1	124.3	0.3	124.4	0.4	123.9	-0.1
Anderson Road	51.499	106.1	106.1	0.0	106.1	0.0	105.8	-0.3	105.8	-0.3	106.2	0.1	106.2	0.1	106.0	0.0
Black River Confluence	46.937	93.0	93.0	0.0	93.1	0.1	92.1	-0.9	91.9	-1.1	93.1	0.1	93.4	0.4	92.9	-0.1
Sickman Ford Bridge	44.175	85.6	85.7	0.0	85.7	0.1	84.5	-1.2	83.2	-2.4	84.7	-0.9	86.1	0.4	85.5	-0.1
Porter Creek Road	34.497	57.4	57.4	0.0	57.5	0.1	56.3	-1.1	56.2	-1.2	57.7	0.4	57.8	0.4	59.0	1.7
Wakefield Road	24.52	41.6	41.6	0.0	41.7	0.1	40.2	-1.4	40.2	-1.3	42.0	0.4	41.9	0.3	41.7	0.2
Satsop Confluence	19.89	35.4	35.4	0.0	35.5	0.1	34.9	-0.5	34.9	-0.5	35.7	0.3	35.6	0.2	35.4	0.0
Montesano	12.5	18.8	18.9	0.0	18.9	0.1	18.2	-0.7	18.2	-0.7	19.2	0.3	19.0	0.2	18.8	0.0
Cosmopolis	1.99	11.0	11.0	0.0	11.0	0.0	10.6	-0.4	10.6	-0.4	11.2	0.2	11.1	0.1	11.0	0.0

Note: Negative change means that the alternative has lower simulated water levels, positive change indicates the alternative raises water levels.

Table 9: Comparison of Water Surface Elevation Changes with Flood Relief Alternatives – February 1996 and January 2009 Storm Events

Alternatives Analysis Summary for February 1996 Flood Event

		Max Water Surface Elevation (feet NAVD) or Change in Flood Water Surface (feet)																	
Location		Feb 96	Feb w/Dam	Change	Feb w/Lev	Change	Feb Ph1 Lev	Change	Feb w/Dam&Lev	Change	Feb MellenBP	Change	Feb Dredge	Change	Feb ScheuberBP	Change	Feb Sc-AP-Mel	Change
Description	X-section	(ft NAVD)	(ft NAVD)	(ft NAVD)	(ft NAVD)	(ft NAVD)	(ft NAVD)	(ft NAVD)	(ft NAVD)	(ft NAVD)	(ft NAVD)	(ft NAVD)	(ft NAVD)	(ft NAVD)	(ft NAVD)	(ft NAVD)	(ft NAVD)	(ft NAVD)
Near Doty	100.95	318.1	307.2	-10.9	318.1	0.0	318.1	0.0	307.2	-10.9	318.1	0.0	318.1	0.0	318.1	0.0	318.1	0.0
Curtis Store (on S Fork Chehalis)	1.81	233.1	231.1	-2.1	233.1	0.0	233.1	0.0	231.1	-2.1	233.2	0.0	233.2	0.0	233.2	0.0	233.1	0.0
Downstream of South Fork	86.42	222.4	219.0	-3.5	222.4	0.0	222.4	0.0	219.0	-3.5	222.4	0.0	222.4	0.0	222.4	0.0	222.4	0.0
Near Adna	80.23	196.6	195.0	-1.6	196.6	0.0	196.6	0.0	195.0	-1.6	196.6	0.0	196.6	0.0	196.4	-0.2	196.4	-0.2
Labree Road (on Newaukum R)	4.11	204.6	204.6	0.0	204.6	0.0	204.6	0.0	204.6	0.0	204.6	0.0	204.6	0.0	204.6	0.0	204.6	0.0
Newaukum Confluence	75.2	185.1	183.8	-1.3	185.3	0.2	185.1	0.0	183.9	-1.3	185.1	-0.1	185.1	0.0	183.2	-1.9	183.3	-1.8
Along Airport Levee	71.49	180.3	179.0	-1.3	181.0	0.7	180.3	0.0	179.2	-1.1	179.0	-1.3	179.6	-0.8	180.4	0.0	179.4	-0.9
Dillenbaugh Storage Area	SA #301	185.1	183.8	-1.4	185.4	0.3	185.1	0.0	183.8	-1.3	185.1	-0.1	185.1	0.0	183.4	-1.8	183.5	-1.7
Airport Storage Area	SA #2	180.3	175.9	-4.4	159.4	-20.9	180.3	0.0	159.4	-20.9	178.9	-1.4	179.3	-1.0	180.4	0.0	159.4	-20.9
Long Road Storage Area	SA #5	177.5	169.4	-8.1	175.2	-2.3	177.5	0.0	169.4	-8.1	169.4	-8.1	170.3	-7.2	177.6	0.1	169.4	-8.1
Centralia Storage Area	SA #610	176.1	174.8	-1.3	176.1	-0.1	176.1	0.0	174.9	-1.2	174.1	-2.0	174.7	-1.5	176.2	0.1	174.3	-1.8
Mellen St	67.43	177.3	175.9	-1.4	177.5	0.2	177.3	0.0	176.1	-1.2	174.0	-3.3	175.2	-2.0	177.3	0.0	174.2	-3.0
Bucoda (Skookumchuck R)	11.1	251.4	251.4	0.0	251.4	0.0	251.4	0.0	251.4	0.0	251.4	0.0	251.4	0.0	251.4	0.0	251.4	0.0
Pearl Street (Skookumchuck R)	2.43	191.3	191.3	0.0	191.3	0.0	191.3	0.0	191.3	0.0	191.3	0.0	188.8	-2.5	191.3	0.0	191.3	0.0
Skookumchuck Confluence	66.88	175.5	174.2	-1.3	175.6	0.1	175.5	0.0	174.4	-1.1	173.6	-1.9	173.3	-2.2	175.6	0.1	173.8	-1.7
Upstream of Galvin Road	64.9	167.1	165.4	-1.7	167.3	0.2	167.2	0.0	165.6	-1.6	167.4	0.2	165.3	-1.8	167.2	0.1	167.6	0.5
Grand Mound (Prather Road)	59.909	146.9	146.2	-0.7	147.0	0.1	146.9	0.0	146.3	-0.6	147.0	0.1	146.9	0.0	146.9	0.0	147.2	0.3
Near Rochester	54.476	123.7	122.8	-0.9	123.8	0.1	123.7	0.0	122.9	-0.8	123.8	0.2	123.7	0.0	123.7	0.0	124.0	0.4
Anderson Road	51.499	105.9	105.6	-0.3	105.9	0.0	105.9	0.0	105.7	-0.2	106.0	0.0	105.9	0.0	105.9	0.0	106.0	0.1
Black River Confluence	46.937	92.6	91.8	-0.8	92.7	0.1	92.6	0.0	91.9	-0.7	92.7	0.2	92.6	0.0	92.6	0.1	92.9	0.4
Sickman Ford Bridge	44.175	85.0	84.1	-0.9	85.2	0.2	85.0	0.0	84.2	-0.8	85.2	0.2	85.1	0.0	85.1	0.1	85.5	0.5
Porter Creek Road	34.497	56.7	55.8	-0.9	56.8	0.1	56.7	0.0	55.9	-0.8	56.9	0.2	56.7	0.0	56.7	0.1	57.1	0.4
Wakefield Road	24.52	40.1	39.2	-0.9	40.3	0.2	40.1	0.0	39.3	-0.8	40.3	0.2	40.1	0.0	40.2	0.1	40.7	0.6
Satsop Confluence	19.89	34.7	34.5	-0.2	34.7	0.0	34.7	0.0	34.5	-0.2	34.8	0.1	34.8	0.1	34.8	0.1	34.9	0.2
Montesano	12.5	17.6	17.3	-0.3	17.6	0.0	17.6	0.0	17.3	-0.3	17.7	0.2	17.8	0.2	17.7	0.2	17.9	0.3
Cosmopolis	1.99	9.3	9.2	-0.1	9.3	0.0	9.3	0.0	9.2	-0.1	9.4	0.1	9.4	0.0	9.4	0.1	9.5	0.1

Note: Negative change means that the alternative has lower simulated water levels, positive change indicates the alternative raises water levels.

Alternatives Analysis Summary for January 2009 Flood Event

		Max Water Surface Elevation (feet NAVD) or Change in Flood Water Surface (feet)																	
Location		Jan 09	Jan w/Dam	Change	Jan w/Lev	Change	Jan Ph1 Lev	Change	Jan w/Dam&Lev	Change	Jan w/MellenBP	Change	Jan w/Dredge	Change	Jan w/ScheuberBP	Change	Jan w/Sc-AP-Mel	Change
Description	X-section	(ft NAVD)	(ft NAVD)	(ft NAVD)	(ft NAVD)	(ft NAVD)	(ft NAVD)	(ft NAVD)	(ft NAVD)	(ft NAVD)	(ft NAVD)	(ft NAVD)	(ft NAVD)	(ft NAVD)	(ft NAVD)	(ft NAVD)	(ft NAVD)	(ft NAVD)
Near Doty	100.95	314.4	306.7	-7.7	314.4	0.0	314.4	0.0	306.7	-7.7	314.4	0.0	314.4	0.0	314.4	0.0	314.4	0.0
Curtis Store (on S Fork Chehalis)	1.81	228.1	227.7	-0.5	228.1	0.0	228.1	0.0	227.7	-0.5	228.1	0.0	228.1	0.0	228.1	0.0	228.1	0.0
Downstream of South Fork	86.42	216.9	213.3	-3.7	216.9	0.0	216.9	0.0	213.3	-3.6	216.9	0.0	216.9	0.0	216.9	0.0	216.9	0.0
Near Adna	80.23	193.9	191.7	-2.2	193.9	0.0	193.9	0.0	191.7	-2.2	193.9	0.0	193.9	0.0	193.6	-0.3	193.6	-0.3
Labree Road (on Newaukum R)	4.11	204.7	204.7	0.0	204.7	0.0	204.7	0.0	204.7	0.0	204.7	0.0	204.7	0.0	204.7	0.0	204.7	0.0
Newaukum Confluence	75.2	183.5	182.1	-1.4	183.5	0.0	183.5	0.0	182.1	-1.4	183.4	-0.1	183.4	-0.1	181.8	-1.7	181.5	-2.0
Along Airport Levee	71.49	178.8	177.4	-1.3	178.8	0.1	178.8	0.0	177.4	-1.3	177.7	-1.1	178.1	-0.7	178.9	0.2	177.9	-0.8
Dillenbaugh Storage Area	SA #301	184.1	183.7	-0.4	184.1	0.0	184.1	0.0	183.7	-0.4	184.1	0.0	184.0	0.0	183.8	-0.3	183.7	-0.4
Airport Storage Area	SA #2	172.0	159.4	-12.6	159.4	-12.6	172.0	0.0	159.4	-12.6	167.2	-4.8	169.1	-2.9	174.5	2.6	159.4	-12.6
Long Road Storage Area	SA #5	169.4	169.4	0.0	169.4	0.0	169.4	0.0	169.4	0.0	169.4	0.0	169.4	0.0	169.4	0.0	169.4	0.0
Centralia Storage Area	SA #610	174.5	174.0	-0.5	174.6	0.0	174.5	0.0	174.0	-0.5	172.4	-2.1	172.9	-1.7	174.6	0.1	172.7	-1.9
Mellen St	67.43	175.6	174.5	-1.2	175.7	0.1	175.6	0.0	174.5	-1.2	172.4	-3.2	173.2	-2.5	175.7	0.1	172.6	-3.0
Bucoda (Skookumchuck R)	11.1	250.9	250.9	0.0	250.9	0.0	250.9	0.0	250.9	0.0	250.9	0.0	250.9	0.0	250.9	0.0	250.9	0.0
Pearl Street (Skookumchuck R)	2.43	190.5	190.5	0.0	190.5	0.0	190.5	0.0	190.5	0.0	190.5	0.0	188.1	-2.4	190.5	0.0	190.5	0.0
Skookumchuck Confluence	66.88	173.9	172.9	-1.0	174.0	0.1	173.9	0.0	172.9	-1.0	172.0	-1.9	171.3	-2.6	174.0	0.1	172.2	-1.7
Upstream of Galvin Road	64.9	165.1	164.1	-1.0	165.1	0.0	165.1	0.0	164.1	-1.0	165.3	0.2	163.6	-1.5	165.2	0.1	165.5	0.4
Grand Mound (Prather Road)	59.909	146.0	145.5	-0.5	146.0	0.0	146.0	0.0	145.5	-0.5	146.1	0.1	146.0	0.0	146.1	0.1	146.2	0.2
Near Rochester	54.476	122.5	121.8	-0.7	122.5	0.0	122.5	0.0	121.8	-0.7	122.7	0.2	122.5	0.0	122.6	0.1	122.8	0.3
Anderson Road	51.499	105.5	105.3	-0.3	105.6	0.0	105.5	0.0	105.3	-0.3	105.6	0.0	105.5	0.0	105.6	0.0	105.6	0.1
Black River Confluence	46.937	91.6	91.0	-0.7	91.7	0.0	91.6	0.0	91.0	-0.7	91.8	0.1	91.6	0.0	91.8	0.1	92.0	0.3
Sickman Ford Bridge	44.175	83.8	83.0	-0.9	83.9	0.0	83.8	0.0	83.0	-0.9	84.0	0.2	83.8	0.0	84.0	0.2	84.3	0.4
Porter Creek Road	34.497	55.6	54.8	-0.8	55.7	0.0	55.6	0.0	54.8	-0.8	55.8	0.2	55.6	0.0	55.8	0.2	56.0	0.4
Wakefield Road	24.52	38.8	37.9	-0.9	38.8	0.0	38.8	0.0	37.9	-0.9	39.0	0.2	38.8	0.0	39.0	0.2	39.3	0.5
Satsop Confluence	19.89	33.7	33.4	-0.3	33.7	0.0	33.7	0.0	33.4	-0.3	33.8	0.1	33.7	0.0	33.8	0.2	34.0	0.4
Montesano	12.5	17.7	17.6	-0.1	17.7	0.0	17.7	0.0	17.6	-0.1	17.8	0.0	17.8	0.1	17.7	0.0	17.8	0.0
Cosmopolis	1.99	11.7	11.7	0.0	11.7	0.0	11.7	0.0	11.7	0.0	11.7	0.0	11.7	0.0	11.7	0.0	11.7	0.0

Note: Negative change means that the alternative has lower simulated water levels, positive change indicates the alternative raises water levels.

Table 9 (continued): Comparison of Water Surface Elevation Changes with Flood Relief Alternatives – February 1996 and January 2009 Storm Events

Alternatives Analysis Summary for February 1996 Flood Event

Location			Max Water Surface Elevation (feet NAVD) or Change in Flood Water Surface (feet)													
Description	X-section	Feb 96 (ft NAVD)	Feb WSDOT I5 (ft NAVD)	Change (ft NAVD)	Feb WSDOT-AP (ft NAVD)	Change (ft NAVD)	Feb I5-Dam (ft NAVD)	Change (ft NAVD)	Feb I5-Dam-Br (ft NAVD)	Change (ft NAVD)	Feb I5-2BP-Br (ft NAVD)	Change (ft NAVD)	Feb Twin Cities (ft NAVD)	Change (ft NAVD)	Feb Skook Lev (ft NAVD)	Change (ft NAVD)
Near Doty	100.95	318.1	318.1	0.0	318.1	0.0	307.2	-10.9	307.2	-11.0	318.1	0.0	318.1	0.0	318.1	0.0
Curtis Store (on S Fork Chehalis)	1.81	233.1	233.2	0.0	233.2	0.0	231.1	-2.1	231.1	-2.1	233.2	0.0	233.2	0.0	233.2	0.0
Downstream of South Fork	86.42	222.4	222.4	0.0	222.4	0.0	219.0	-3.5	219.0	-3.5	222.4	0.0	222.4	0.0	222.4	0.0
Near Adna	80.23	196.6	196.6	0.0	196.6	0.0	195.0	-1.6	195.0	-1.6	196.4	-0.2	196.6	0.0	196.6	0.0
Labree Road (on Newaukum R)	4.11	204.6	204.6	0.0	204.6	0.0	204.6	0.0	204.6	0.0	204.6	0.0	204.6	0.0	204.6	0.0
Newaukum Confluence	75.2	185.1	185.1	0.0	185.4	0.3	183.9	-1.3	183.9	-1.3	183.4	-1.8	185.4	0.3	185.1	0.0
Along Airport Levee	71.49	180.3	180.7	0.4	181.0	0.7	179.3	-1.1	179.2	-1.1	179.4	-0.9	181.3	1.0	180.4	0.1
Dillenbaugh Storage Area	SA #301	185.1	185.2	0.1	185.5	0.4	183.8	-1.3	183.8	-1.3	183.5	-1.7	173.4	-11.7	185.2	0.0
Airport Storage Area	SA #2	180.3	180.8	0.5	159.4	-20.9	159.4	-20.9	159.4	-20.9	159.4	-20.9	159.4	-20.9	180.4	0.1
Long Road Storage Area	SA #5	177.5	174.3	-3.2	175.4	-2.1	169.4	-8.1	169.4	-8.1	169.4	-8.1	176.4	-1.1	179.5	2.0
Centralia Storage Area	SA #610	176.1	176.0	-0.1	176.1	-0.1	174.9	-1.2	174.9	-1.2	174.3	-1.8	177.2	1.0	179.5	3.4
Mellen St	67.43	177.3	177.4	0.1	177.5	0.2	176.1	-1.2	176.1	-1.2	174.2	-3.0	177.7	0.4	177.4	0.2
Bucoda (Skookumchuck R)	11.1	251.4	251.4	0.0	251.4	0.0	251.4	0.0	251.4	0.0	251.4	0.0	249.0	-2.4	251.4	0.0
Pearl Street (Skookumchuck R)	2.43	191.3	191.3	0.0	191.3	0.0	191.3	0.0	191.3	0.0	191.3	0.0	190.1	-1.2	191.4	0.2
Skookumchuck Confluence	66.88	175.5	175.6	0.1	175.7	0.2	174.4	-1.1	174.4	-1.1	173.8	-1.7	175.6	0.1	175.6	0.1
Upstream of Galvin Road	64.9	167.1	167.2	0.1	167.3	0.2	165.6	-1.6	165.4	-1.7	167.4	0.2	166.9	-0.3	166.9	-0.3
Grand Mound (Prather Road)	59.909	146.9	146.9	0.0	147.0	0.1	146.3	-0.6	147.1	0.2	148.0	1.1	146.9	-0.1	146.8	-0.1
Near Rochester	54.476	123.7	123.7	0.1	123.8	0.1	122.9	-0.8	122.8	-0.8	124.0	0.3	123.6	0.0	123.6	-0.1
Anderson Road	51.499	105.9	105.9	0.0	105.9	0.0	105.7	-0.2	105.7	-0.2	106.0	0.1	105.9	0.0	105.9	0.0
Black River Confluence	46.937	92.6	92.6	0.1	92.7	0.2	91.9	-0.7	91.7	-0.8	92.7	0.1	92.5	0.0	92.5	-0.1
Sickman Ford Bridge	44.175	85.0	85.1	0.1	85.2	0.2	84.2	-0.8	83.0	-2.0	84.2	-0.9	85.0	0.0	85.0	-0.1
Porter Creek Road	34.497	56.7	56.7	0.1	56.8	0.2	55.9	-0.8	55.8	-0.9	57.0	0.3	56.7	0.0	58.2	1.5
Wakefield Road	24.52	40.1	40.2	0.1	40.3	0.2	39.3	-0.8	39.2	-0.9	40.7	0.6	40.1	0.0	40.7	0.6
Satsop Confluence	19.89	34.7	34.7	0.0	34.7	0.0	34.5	-0.2	34.5	-0.2	34.9	0.2	34.7	0.0	34.7	0.0
Montesano	12.5	17.6	17.6	0.0	17.6	0.0	17.3	-0.3	17.3	-0.3	17.9	0.3	17.7	0.1	17.6	0.0
Cosmopolis	1.99	9.3	9.3	0.0	9.3	0.0	9.2	-0.1	9.2	-0.1	9.5	0.1	9.3	0.0	9.3	0.0

Note: Negative change means that the alternative has lower simulated water levels, positive change indicates the alternative raises water levels.

Alternatives Analysis Summary for January 2009 Flood Event

Location			Max Water Surface Elevation (feet NAVD) or Change in Flood Water Surface (feet)													
Description	X-section	Jan 09 (ft NAVD)	Jan WSDOT I5 (ft NAVD)	Change (ft NAVD)	Jan WSDOT-AP (ft NAVD)	Change (ft NAVD)	Jan I5-Dam (ft NAVD)	Change (ft NAVD)	Jan I5-Dam-Br (ft NAVD)	Change (ft NAVD)	Jan I5-2BP-Br (ft NAVD)	Change (ft NAVD)	Jan Twin Cities (ft NAVD)	Change (ft NAVD)	Jan Skook Lev (ft NAVD)	Change (ft NAVD)
Near Doty	100.95	314.4	314.4	0.0	314.4	0.0	306.7	-7.7	306.7	-7.7	314.4	0.0	314.4	0.0	314.4	0.0
Curtis Store (on S Fork Chehalis)	1.81	228.1	228.1	0.0	228.1	0.0	227.7	-0.5	227.7	-0.5	228.1	0.0	228.1	0.0	228.1	0.0
Downstream of South Fork	86.42	216.9	216.9	0.0	216.9	0.0	213.3	-3.6	213.3	-3.7	216.9	0.0	216.9	0.0	216.9	0.0
Near Adna	80.23	193.9	193.9	0.0	193.9	0.0	191.7	-2.2	191.7	-2.2	193.6	-0.3	193.9	0.0	193.9	0.0
Labree Road (on Newaukum R)	4.11	204.7	204.7	0.0	204.7	0.0	204.7	0.0	204.7	0.0	204.7	0.0	204.7	0.0	204.7	0.0
Newaukum Confluence	75.2	183.5	183.5	0.0	183.5	0.0	182.1	-1.4	182.1	-1.4	181.6	-1.9	183.4	-0.1	183.5	0.0
Along Airport Levee	71.49	178.8	178.8	0.0	178.9	0.1	177.4	-1.3	177.4	-1.3	177.9	-0.8	178.8	0.1	178.8	0.0
Dillenbaugh Storage Area	SA #301	184.1	184.1	0.0	184.1	0.0	183.7	-0.3	183.7	-0.3	183.7	-0.3	173.4	-10.7	184.1	0.0
Airport Storage Area	SA #2	172.0	172.2	0.2	159.4	-12.6	159.4	-12.6	159.4	-12.6	159.4	-12.6	159.4	-12.6	172.0	0.1
Long Road Storage Area	SA #5	169.4	169.4	0.0	169.4	0.0	169.4	0.0	169.4	0.0	169.4	0.0	169.4	0.0	169.4	0.0
Centralia Storage Area	SA #610	174.5	174.5	0.0	174.6	0.0	174.0	-0.5	174.0	-0.5	172.7	-1.9	175.4	0.8	175.5	1.0
Mellen St	67.43	175.6	175.6	0.0	175.7	0.1	174.5	-1.2	174.5	-1.2	172.6	-3.0	175.6	0.0	175.7	0.1
Bucoda (Skookumchuck R)	11.1	250.9	250.9	0.0	250.9	0.0	250.9	0.0	250.9	0.0	250.9	0.0	247.5	-3.3	250.9	0.0
Pearl Street (Skookumchuck R)	2.43	190.5	190.5	0.0	190.5	0.0	190.5	0.0	190.5	0.0	190.5	0.0	188.9	-1.6	190.6	0.1
Skookumchuck Confluence	66.88	173.9	173.9	0.0	174.0	0.1	172.9	-1.0	172.9	-1.0	172.2	-1.7	173.7	-0.2	174.0	0.1
Upstream of Galvin Road	64.9	165.1	165.1	0.0	165.2	0.1	164.1	-1.0	164.0	-1.1	165.4	0.3	164.8	-0.3	165.0	-0.1
Grand Mound (Prather Road)	59.909	146.0	146.0	0.0	146.0	0.0	145.5	-0.5	146.3	0.3	147.1	1.1	145.8	-0.2	146.0	0.0
Near Rochester	54.476	122.5	122.5	0.0	122.5	0.0	121.8	-0.7	121.8	-0.7	122.8	0.3	122.3	-0.2	122.5	0.0
Anderson Road	51.499	105.5	105.5	0.0	105.6	0.0	105.3	-0.3	105.3	-0.2	105.7	0.1	105.5	-0.1	105.5	0.0
Black River Confluence	46.937	91.6	91.6	0.0	91.7	0.0	91.0	-0.7	90.8	-0.8	91.8	0.2	91.4	-0.2	91.6	0.0
Sickman Ford Bridge	44.175	83.8	83.8	0.0	83.9	0.0	83.0	-0.9	82.0	-1.9	83.1	-0.8	83.6	-0.2	83.8	0.0
Porter Creek Road	34.497	55.6	55.6	0.0	55.7	0.0	54.8	-0.8	54.8	-0.9	55.9	0.3	55.4	-0.2	56.7	1.1
Wakefield Road	24.52	38.8	38.8	0.0	38.8	0.0	37.9	-0.9	37.8	-0.9	39.2	0.5	38.6	-0.2	39.4	0.7
Satsop Confluence	19.89	33.7	33.7	0.0	33.7	0.0	33.4	-0.3	33.4	-0.2	34.0	0.4	33.6	0.0	33.6	0.0
Montesano	12.5	17.7	17.7	0.0	17.7	0.0	17.6	-0.1	17.6	-0.1	17.8	0.0	17.8	0.0	17.7	0.0
Cosmopolis	1.99	11.7	11.7	0.0	11.7	0.0	11.7	0.0	11.7	0.0	11.7	0.0	11.7	0.0	11.7	0.0

Note: Negative change means that the alternative has lower simulated water levels, positive change indicates the alternative raises water levels.

Table 10: Comparison of Water Surface Elevation Changes with Flood Relief Alternatives A, B, and C – February 1996, December 2007, January 2009 and 100-year Design Storm Events

		Max Water Surface Elevation (feet NAVD) or Change in Flood Water Surface (feet)													
		February 1996 Flood Event						December 2007 Flood Event							
Location		Baseline	Alt A	Change	Alt B	Change	Alt C	Change	Baseline	Alt A	Change	Alt B	Change	Alt C	Change
Description	X-section	(ft NAVD)	(ft NAVD)	(ft)	(ft NAVD)	(ft)	(ft NAVD)	(ft)	(ft NAVD)	(ft NAVD)	(ft)	(ft NAVD)	(ft)	(ft NAVD)	(ft)
Near Doty	100.95	318.1	307.2	-10.9	307.2	-10.9	318.1	0.0	328.1	315.8	-12.3	315.8	-12.3	328.1	0.0
Curtis Store (on S Fork Chehalis)	1.81	233.1	231.1	-2.1	231.1	-2.1	233.2	0.0	238.9	232.8	-6.1	232.8	-6.1	238.9	0.0
Downstream of South Fork	86.42	222.4	219.0	-3.5	219.0	-3.5	222.4	0.0	227.7	222.1	-5.6	222.1	-5.6	227.7	0.0
Near Adna	80.23	196.6	195.0	-1.6	195.0	-1.6	196.4	-0.2	197.9	196.3	-1.6	196.3	-1.6	197.9	0.0
Labree Road (on Newaukum R)	4.11	204.6	204.6	0.0	204.6	0.0	204.6	0.0	204.7	204.7	0.0	204.7	0.0	204.7	0.0
Newaukum Confluence	75.2	185.1	183.9	-1.3	183.9	-1.2	183.4	-1.8	186.6	184.5	-2.2	184.5	-2.1	185.6	-1.0
Along Airport Levee	71.49	180.3	179.3	-1.1	179.3	-1.0	179.5	-0.8	182.1	179.7	-2.4	179.7	-2.4	181.3	-0.8
Dillenbaugh Storage Area	SA #301	185.1	183.8	-1.3	183.8	-1.3	183.5	-1.7	186.6	184.4	-2.2	184.4	-2.2	185.8	-0.8
Airport Storage Area	SA #2	180.3	159.4	-20.9	159.4	-20.9	159.4	-20.9	182.2	159.4	-22.8	159.4	-22.8	159.4	-22.8
Long Road Storage Area	SA #5	177.5	169.4	-8.1	169.4	-8.1	169.4	-8.1	179.1	169.4	-9.7	169.4	-9.7	169.4	-9.7
Centralia Storage Area	SA #610	176.1	175.9	-0.2	176.1	-0.1	174.7	-1.5	178.5	175.8	-2.7	175.9	-2.6	175.8	-2.7
Mellen St	67.43	177.3	176.2	-1.1	176.2	-1.1	174.7	-2.6	178.6	176.1	-2.5	176.1	-2.5	175.8	-2.8
Bucoda (Skookumchuck R)	11.1	251.4	251.4	0.0	251.4	0.0	251.4	0.0	244.3	244.3	0.0	244.3	0.0	244.3	0.0
Pearl Street (Skookumchuck R)	2.43	191.3	191.4	0.2	191.4	0.2	191.4	0.2	186.6	186.6	0.0	186.6	0.0	186.6	0.0
Skookumchuck Confluence	66.88	175.5	174.5	-1.0	174.5	-1.0	174.3	-1.2	176.4	173.8	-2.7	173.8	-2.6	175.0	-1.4
Upstream of Galvin Road	64.9	167.1	165.5	-1.6	165.5	-1.6	167.5	0.4	168.2	164.8	-3.4	164.9	-3.4	168.4	0.2
Grand Mound (Prather Road)	59.909	146.9	146.3	-0.6	146.3	-0.6	147.2	0.3	147.4	145.8	-1.6	145.8	-1.5	147.5	0.1
Near Rochester	54.476	123.7	122.9	-0.8	122.9	-0.8	124.0	0.4	124.2	122.1	-2.1	122.2	-2.1	124.4	0.2
Anderson Road	51.499	105.9	105.7	-0.2	105.7	-0.2	106.0	0.1	106.0	105.4	-0.7	105.4	-0.6	106.1	0.1
Black River Confluence	46.937	92.6	91.7	-0.9	91.7	-0.9	92.6	0.1	92.9	90.9	-2.0	90.9	-2.0	92.8	-0.1
Sickman Ford Bridge	44.175	85.0	83.0	-2.1	83.0	-2.0	84.1	-0.9	85.5	82.1	-3.4	82.1	-3.4	84.4	-1.1
Porter Creek Road	34.497	56.7	55.9	-0.8	55.9	-0.8	57.1	0.4	57.0	54.8	-2.1	54.9	-2.1	57.2	0.3
Wakefield Road	24.52	40.1	38.4	-1.7	38.5	-1.6	39.6	-0.5	40.2	37.2	-3.0	37.2	-3.0	39.6	-0.6
Satsop Confluence	19.89	34.7	34.5	-0.2	34.5	-0.2	35.0	0.3	34.5	33.2	-1.3	33.2	-1.3	34.7	0.3
Montesano	12.5	17.6	17.4	-0.2	17.4	-0.2	18.0	0.4	17.3	15.7	-1.6	15.7	-1.6	17.7	0.4
Cosmopolis	1.99	9.3	9.2	-0.1	9.2	-0.1	9.5	0.2	10.9	10.9	0.0	10.9	0.0	10.9	0.0

Note: Negative change means that the alternative has lower simulated water levels, positive change indicates the alternative raises water levels.

		Max Water Surface Elevation (feet NAVD) or Change in Flood Water Surface (feet)													
		January 2009 Flood Event						100-Year Design Flood Event							
Location		Jan 09	Alt A	Change	Alt B	Change	Alt C	Change	100-year	Alt A	Change	Alt B	Change	Alt C	Change
Description	X-section	(ft NAVD)	(ft NAVD)	(ft)	(ft NAVD)	(ft)	(ft NAVD)	(ft)	(ft NAVD)	(ft NAVD)	(ft)	(ft NAVD)	(ft)	(ft NAVD)	(ft)
Near Doty	100.95	314.4	306.7	-7.7	306.7	-7.7	314.4	0.0	323.2	313.0	-10.3	313.0	-10.3	323.2	0.0
Curtis Store (on S Fork Chehalis)	1.81	228.1	227.7	-0.5	227.7	-0.5	228.1	0.0	233.6	230.2	-3.3	230.2	-3.3	233.6	0.0
Downstream of South Fork	86.42	216.9	213.3	-3.7	213.3	-3.7	216.9	0.0	223.2	219.1	-4.1	219.1	-4.1	223.2	0.0
Near Adna	80.23	193.9	191.7	-2.2	191.7	-2.2	193.6	-0.3	197.1	195.5	-1.6	195.5	-1.6	197.1	-0.1
Labree Road (on Newaukum R)	4.11	204.7	204.7	0.0	204.7	0.0	204.7	0.0	204.9	204.9	0.0	204.9	0.0	204.9	0.0
Newaukum Confluence	75.2	183.5	182.1	-1.4	182.1	-1.4	181.6	-1.9	185.7	184.1	-1.6	184.1	-1.6	184.0	-1.7
Along Airport Levee	71.49	178.8	177.4	-1.3	177.4	-1.3	178.0	-0.8	180.8	179.4	-1.4	179.4	-1.4	179.9	-0.8
Dillenbaugh Storage Area	SA #301	184.1	183.7	-0.4	183.7	-0.3	183.7	-0.3	185.8	184.3	-1.5	184.3	-1.5	184.4	-1.4
Airport Storage Area	SA #2	172.0	159.4	-12.6	159.4	-12.6	159.4	-12.6	180.8	159.4	-21.4	159.4	-21.4	159.4	-21.4
Long Road Storage Area	SA #5	169.4	169.4	0.0	169.4	0.0	169.4	0.0	177.9	169.4	-8.5	169.4	-8.5	169.4	-8.5
Centralia Storage Area	SA #610	174.5	174.3	-0.2	174.3	-0.2	172.8	-1.7	176.7	175.9	-0.8	176.1	-0.6	175.0	-1.7
Mellen St	67.43	175.6	174.5	-1.1	174.5	-1.1	172.8	-2.8	177.6	176.1	-1.5	176.1	-1.5	174.9	-2.7
Bucoda (Skookumchuck R)	11.1	250.9	250.9	0.0	250.9	0.0	250.9	0.0	252.0	251.9	0.0	251.9	-0.1	251.9	0.0
Pearl Street (Skookumchuck R)	2.43	190.5	190.6	0.1	190.6	0.1	190.6	0.1	191.7	192.4	0.7	192.4	0.7	192.4	0.7
Skookumchuck Confluence	66.88	173.9	173.0	-0.9	173.0	-0.9	172.5	-1.5	175.7	174.3	-1.4	174.3	-1.4	174.4	-1.3
Upstream of Galvin Road	64.9	165.1	164.1	-1.0	164.1	-1.0	165.5	0.4	167.3	165.3	-2.0	165.3	-2.0	167.6	0.3
Grand Mound (Prather Road)	59.909	146.0	145.5	-0.5	145.5	-0.5	146.2	0.2	147.1	146.2	-0.8	146.2	-0.8	147.3	0.2
Near Rochester	54.476	122.5	121.8	-0.7	121.8	-0.7	122.8	0.3	124.0	122.9	-1.1	122.9	-1.1	124.3	0.3
Anderson Road	51.499	105.5	105.3	-0.3	105.3	-0.3	105.6	0.1	106.1	105.8	-0.3	105.8	-0.3	106.2	0.1
Black River Confluence	46.937	91.6	90.8	-0.8	90.8	-0.8	91.8	0.1	93.0	91.9	-1.2	91.9	-1.2	93.1	0.0
Sickman Ford Bridge	44.175	83.8	81.9	-1.9	81.9	-1.9	83.1	-0.8	85.6	83.2	-2.4	83.2	-2.4	84.7	-1.0
Porter Creek Road	34.497	55.6	54.8	-0.8	54.8	-0.8	56.0	0.4	57.4	56.3	-1.1	56.3	-1.1	57.8	0.5
Wakefield Road	24.52	38.8	37.2	-1.5	37.2	-1.5	38.5	-0.3	41.6	39.3	-2.3	39.3	-2.3	40.8	-0.7
Satsop Confluence	19.89	33.7	33.4	-0.2	33.4	-0.2	34.1	0.4	35.4	34.9	-0.5	34.9	-0.5	35.7	0.2
Montesano	12.5	17.7	17.7	-0.1	17.7	-0.1	17.8	0.1	18.8	18.2	-0.7	18.2	-0.7	19.2	0.3
Cosmopolis	1.99	11.7	11.7	0.0	10.6	-0.4	11.7	0.0	11.0	10.6	-0.4	10.6	-0.4	11.2	0.2

Note: Negative change means that the alternative has lower simulated water levels, positive change indicates the alternative raises water levels.

Basin-wide bar charts

Figures 11 through 13 show the effects on water surface elevations of the combination alternatives at the same locations as shown in Table 10. This graphical presentation of results for the four simulated floods facilitates quick comparisons between the alternatives. As can be seen in the bar charts, Alternatives A and B, which include the mainstem dam, result in lower flood water levels throughout the basin for all of the floods. Other proposed elements of these flood relief alternatives have more localized effects. Alternative C, which does not include the main stem dam, would have no effect on water levels upstream of Highway 603 and would have less overall benefit on reaches within the Twin Cities. Downstream water levels would also be generally increased under this alternative with the exception of near the downstream bridge replacement projects.

Twin Cities Inundation Mapping

Figures 14 through 16 show inundation maps for the three basin wide flood relief alternatives (A, B, and C) for the December 2007 flood event. As shown in these figures, the inundated area would be reduced significantly under Alternatives A and B (with the main stem dam). Alternative C, without the dam, tends to increase water levels in some locations while lowering water levels at other locations within the Twin Cities.

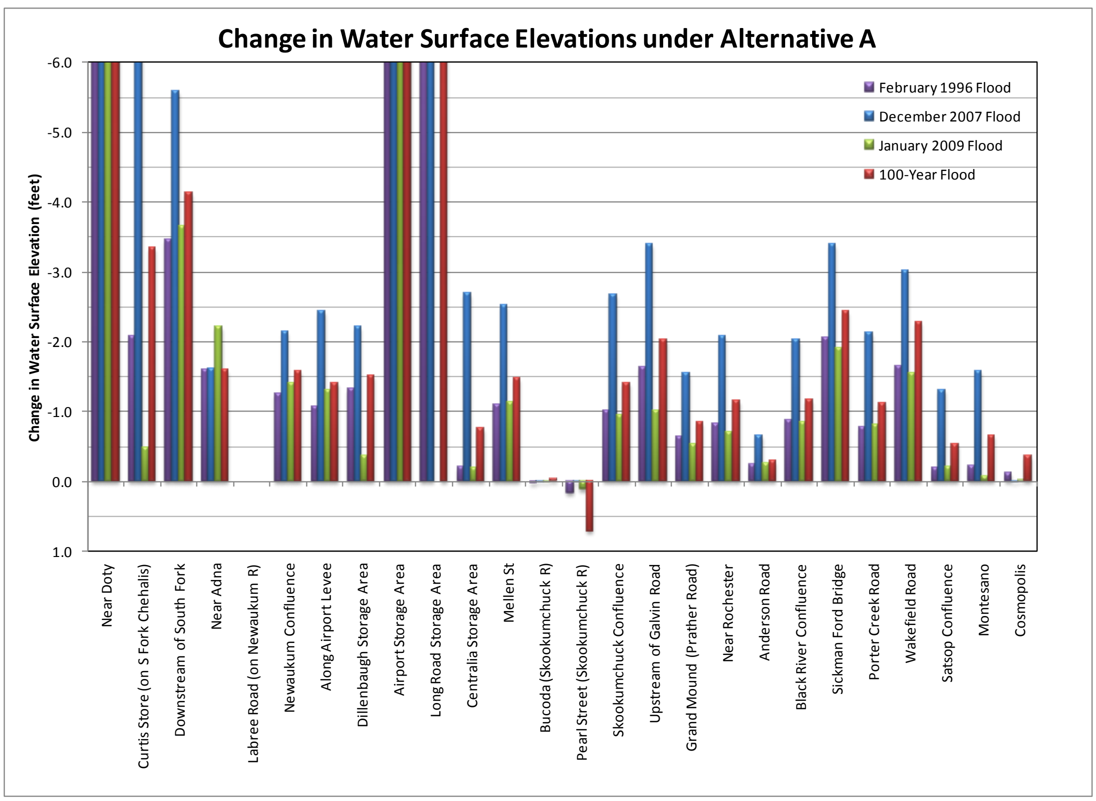

Figure 11. Change in Water Surface Elevation under Alternative A

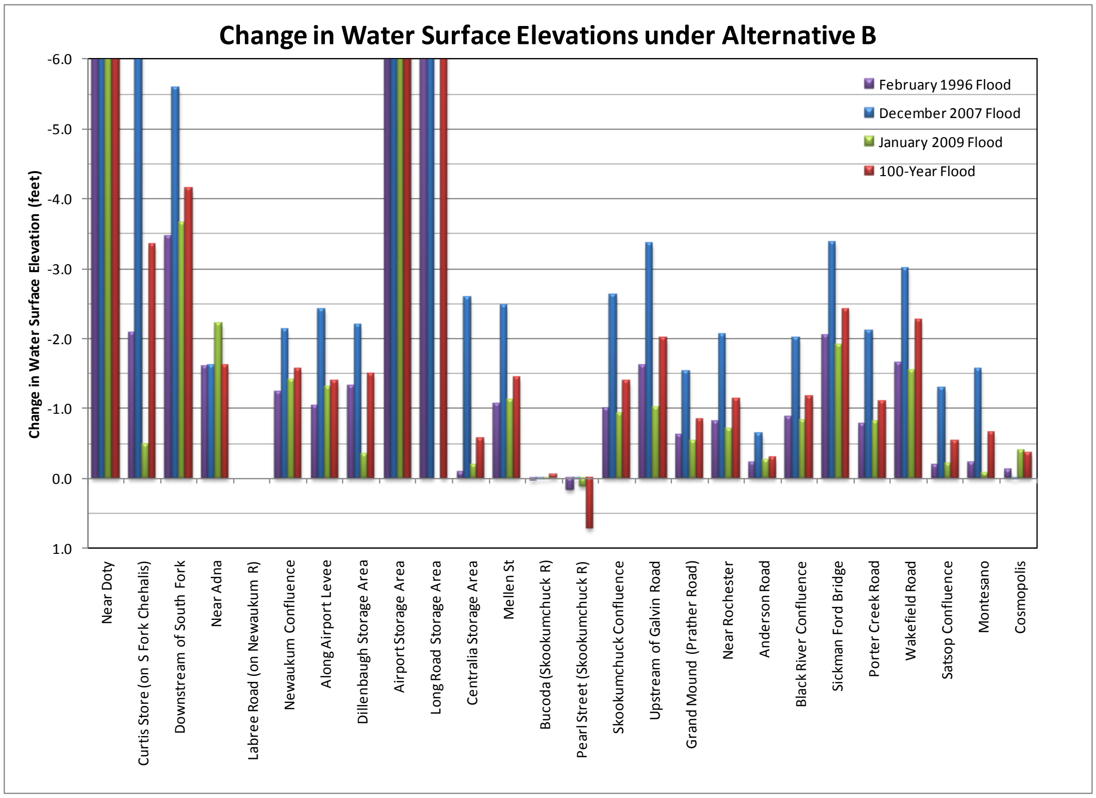

Figure 12. Change in Water Surface Elevation under Alternative B

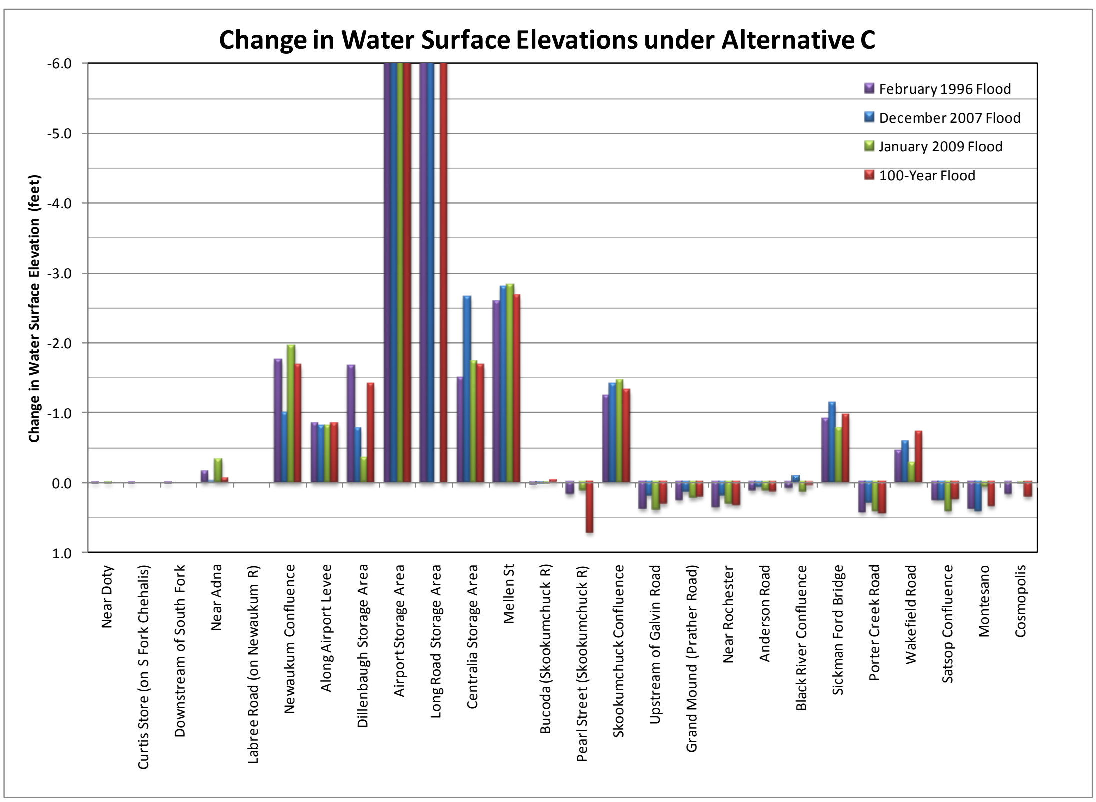

Figure 13. Change in Water Surface Elevation under Alternative C

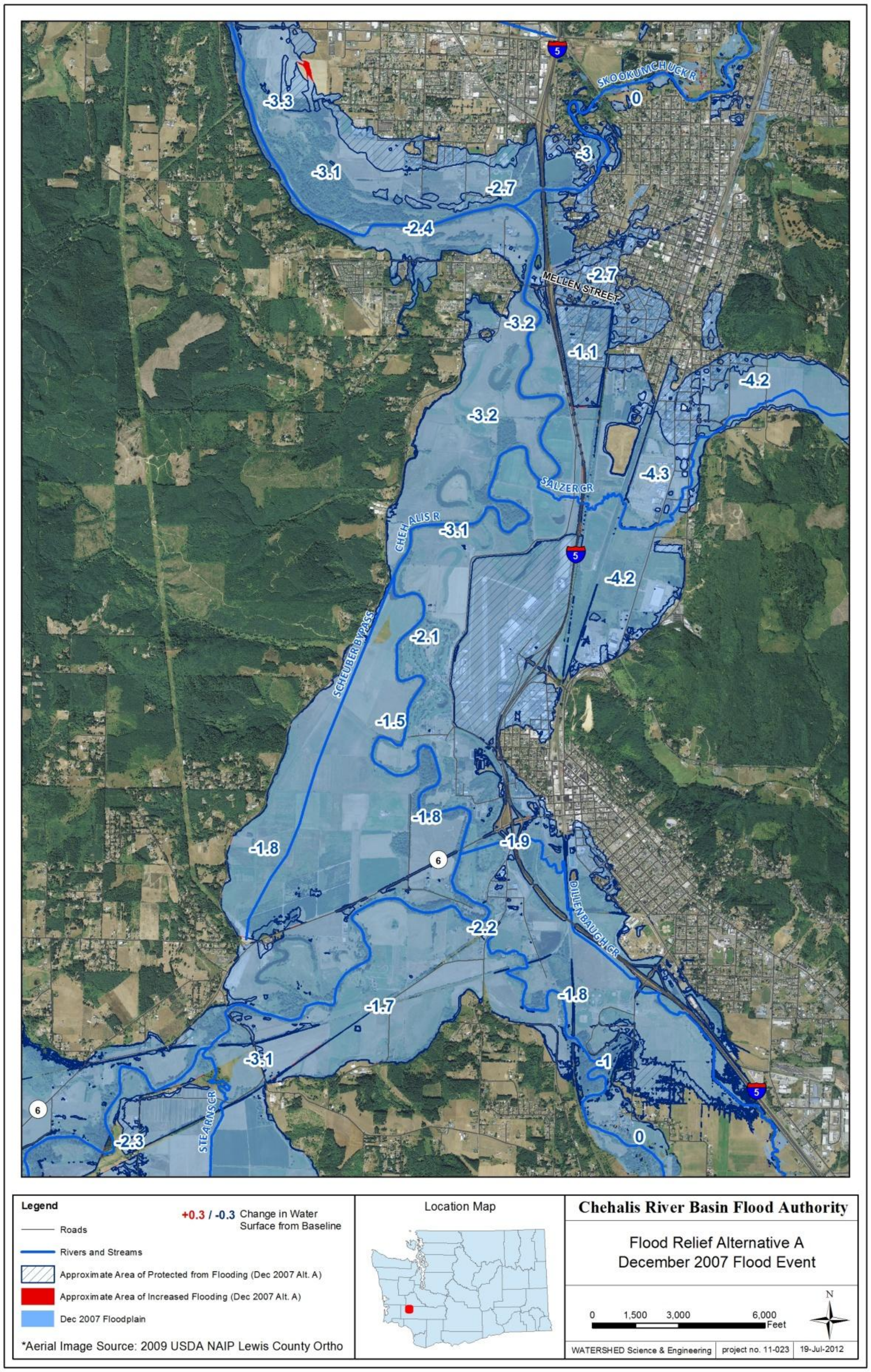

Figure 14. Twin Cities Inundation Map and Flood WSEL Changes for Alternative A

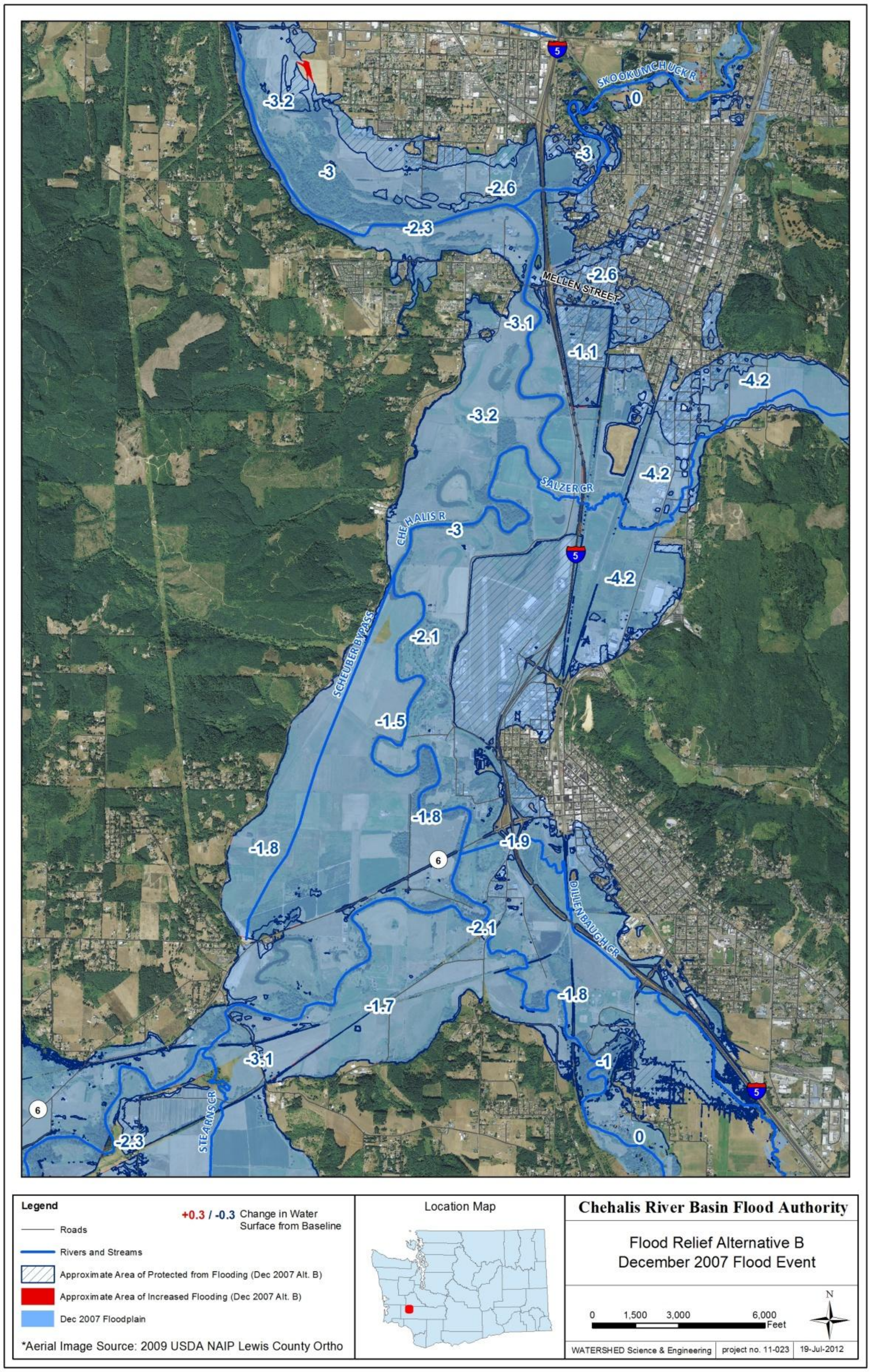

Figure 15. Twin Cities Inundation Map and Flood WSEL Changes for Alternative B

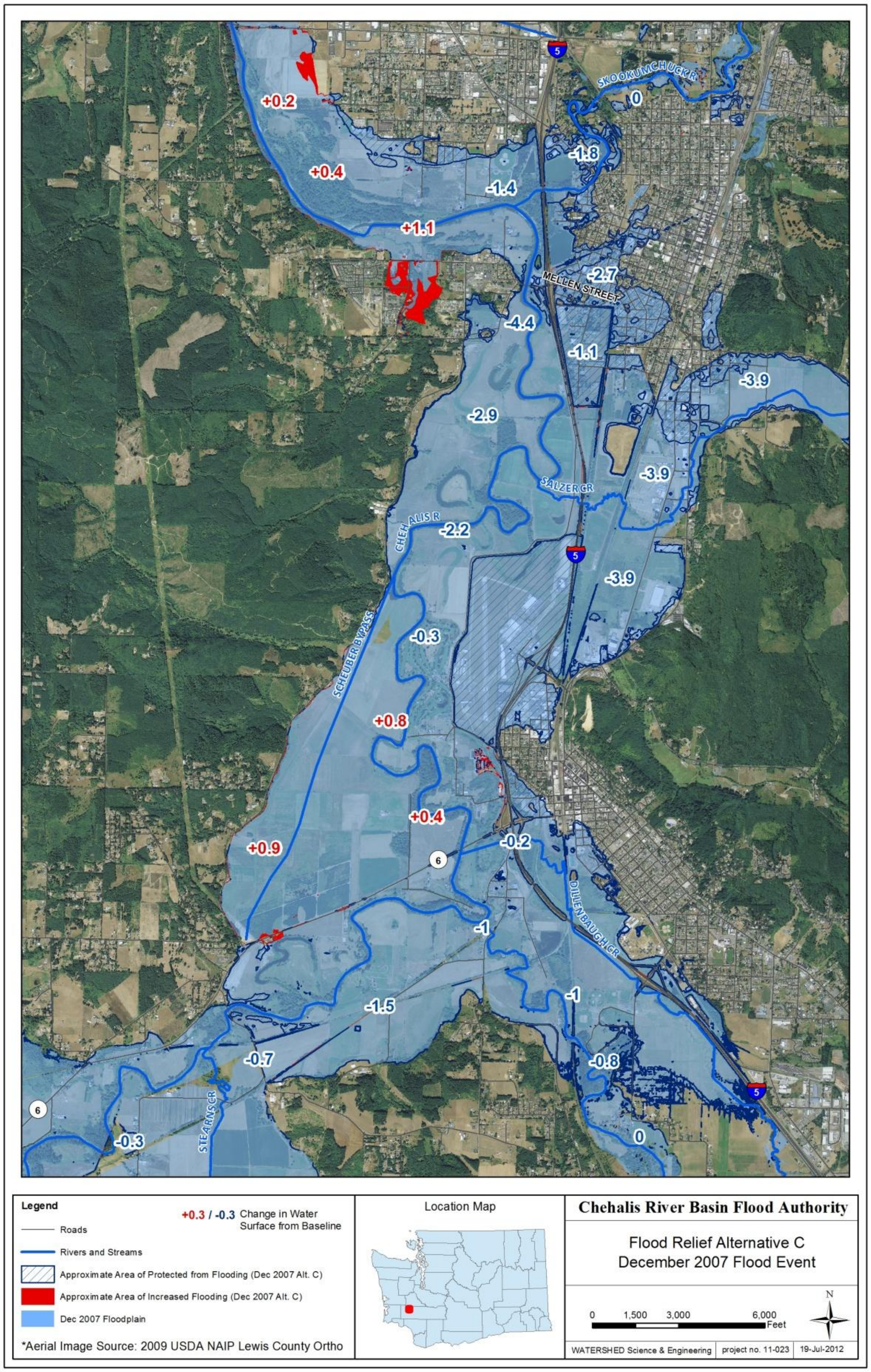

Figure 16. Twin Cities Inundation Map and Flood WSEL Changes for Alternative C

I-5 Protection Summary

Table 11 compares the simulated water surface elevations and minimum roadway elevations for 33 locations along I-5. These locations include each cross section that contacts the interstate as well as the major modeled storage areas. Some of the points are on the west side of the freeway along the main stem Chehalis River, the Newaukum River, and/or Dillenbaugh Creek. Other points are along the east side of the freeway on Dillenbaugh Creek near Chehalis. The road surface elevations for I-5 were taken from the April 2012 field survey by WSDOT, where available, or from LiDAR data where field survey were not available. These data are intended to represent the lowest elevation of the roadway surface, which in many cases is on the shoulder outside the traffic lanes. In some locations the elevations of I-5 are significantly higher than the floodplain because the freeway is elevated where it approaches an overpass.

Table 11: Comparison of Effects on I-5 Flooding for Flood Relief Alternatives for December 2007 Event

River	Reach	River Sta	I-5 Elev WSDOT		Description	December 2007 Flood											
							Baseline			Alternative A			Alternative B			Alternative C	
			(NGVD 29)	NAVD 88		WSEL	Change	Result	WSEL	Change	Result	WSEL	Change	Result	WSEL	Change	Result
CHEHALIS	REACH 13	68.98	174.62	178.02	1600 feet N of Salzer Creek culvert	181.4	3.4	Floods	178.2	0.2	Floods	178.3	0.3	Wall	178.7	0.6	Wall
CHEHALIS	REACH 13	69.22	175.65	179.05	280 feet N of Salzer Creek culvert	181.5	2.4	Floods	178.3	-0.8		178.3	-0.7		178.8	-0.3	
CHEHALIS	REACH 11	69.9	175.65	179.05	at Salzer Creek culvert	181.5	2.5	Floods	178.4	-0.7		178.4	-0.6		179.0	-0.1	
CHEHALIS	REACH 11	70.18	175.8	179.2	Between airport levee and Salzer Cr	181.6	2.4	Floods	178.4	-0.8		178.5	-0.8		179.0	-0.2	
Airport Storage Area	SA #2	SA #2		176.3	Low Point From RM 70.25 to RM 73.73	182.2	5.9	Floods	159.4	-16.9		159.4	-16.9		159.4	-16.9	
CHEHALIS	REACH 9	73.73	179.7	183.1	near NW West Street	183.4	0.3	Floods	181.8	-1.3		181.8	-1.3		184.1	1.0	Wall
CHEHALIS	REACH 9	74.02	179.9	183.3	just north of SR6 Interchange	183.7	0.4	Floods	181.9	-1.4		181.9	-1.4		184.2	0.9	Wall
CHEHALIS	REACH 9	74.25	179.5	182.9		183.9	1.0	Floods	182.1	-0.8		182.1	-0.8		184.3	1.4	Wall
CHEHALIS	REACH 9	74.57	183.8	187.2	On southbound off ramp	184.2	-3.0		182.4	-4.8		182.4	-4.8		184.5	-2.8	
DILLENBAUGH CR	REACH 8	0.094	180.46	183.86	dillenbaugh I-5 Weir	185.2	1.3	Floods	183.3	-0.6		183.3	-0.6		184.9	1.1	Wall
DILLENBAUGH CR	REACH 8	0.122	180.46	183.86	dillenbaugh I-5 Weir	186.1	2.2	Floods	183.9	0.1	Floods	184.0	0.1	Wall	185.4	1.6	Wall
DILLENBAUGH CR	REACH 8	0.142	178.16	181.56	low point on I-5 N on-ramp	186.2	4.7	Floods	184.1	2.5	Floods	184.1	2.5	Wall	185.6	4.0	Wall
CHEHALIS	REACH 7	74.95	187.4	190.8	On Chehalis (west) side of I-5. Road superelevated, sloping to low of 186.4 (NAVD) on East side of I-5	185.7	-5.1		183.6	-7.2		183.6	-7.2		185.1	-5.7	
DILLENBAUGH CR	REACH 8	0.155	194.7	198.1	East side of I-5	186.3	-11.8		184.1	-14.0		184.1	-14.0		185.6	-12.5	
CHEHALIS	REACH 7	75.08	204.1	207.5	West side of I-5	186.3	-21.2		184.1	-23.4		184.1	-23.4		185.4	-22.1	
DILLENBAUGH CR	REACH 8	0.219	204.2	207.6	East side of I-5	186.3	-21.3		184.1	-23.5		184.1	-23.5		185.6	-22.0	
CHEHALIS	REACH 7	75.085	204.7	208.1	West side of I-5	186.3	-21.8		184.1	-24.0		184.1	-24.0		185.4	-22.7	
DILLENBAUGH CR	REACH 8	0.239	205.5	208.9	East side of I-5	186.3	-22.6		184.1	-24.8		184.2	-24.8		185.6	-23.3	
NEWAUKUM	REACH 6	0.1	206.07	209.47	West side of I-5	187.0	-22.5		184.7	-24.7		184.8	-24.7		185.9	-23.6	
DILLENBAUGH CR	REACH 8	0.321	208	211.4	East side of I-5	186.3	-25.1		184.2	-27.3		184.2	-27.2		185.6	-25.8	
DILLENBAUGH CR	REACH 8	0.385	209.1	212.5	East side of I-5	186.3	-26.2		184.2	-28.4		184.2	-28.3		185.6	-26.9	
NEWAUKUM	REACH 6	0.553	211.45	214.85	West side of I-5	187.2	-27.6		184.9	-29.9		184.9	-29.9		186.1	-28.8	
DILLENBAUGH CR	REACH 8	0.478	211.4	214.8	East side of I-5	186.4	-28.4		184.2	-30.6		184.2	-30.6		185.7	-29.1	
DILLENBAUGH CR	REACH 8	0.495	211	214.4	East side of I-5	186.4	-28.0		184.3	-30.1		184.3	-30.1		185.7	-28.7	
DILLENBAUGH CR	REACH 8	0.511	211	214.4	East side of I-5	186.5	-27.9		184.3	-30.1		184.3	-30.1		185.8	-28.6	
DILLENBAUGH CR	REACH 8	0.583	207.8	211.2	West side of I-5	186.6	-24.6		184.4	-26.8		184.4	-26.8		185.8	-25.4	
DILLENBAUGH CR	REACH 8	0.623	205.8	209.2	West side of I-5	186.7	-22.5		184.5	-24.8		184.5	-24.7		185.9	-23.3	
DILLENBAUGH CR	REACH 8	0.792	182.4	185.8	West side of I-5	187.6	1.8	Floods	184.9	-0.9		184.9	-0.9		186.3	0.5	Wall
DILLENBAUGH CR	REACH 8	1.00001	181.65	185.05	West side of I-5	187.6	2.6	Floods	184.9	-0.2		184.9	-0.2		186.3	1.3	Wall
DILLENBAUGH CR	REACH 8	1.25	183.2	186.6	West side of I-5	187.6	1.0	Floods	184.9	-1.7		184.9	-1.7		186.3	-0.3	
DILLENBAUGH CR	REACH 8	1.29	183.4	186.8	West side of I-5	187.6	0.8	Floods	184.9	-1.9		184.9	-1.9		186.3	-0.5	
DILLENBAUGH CR	REACH 8	1.32	183.5	186.9	West side of I-5	187.6	0.7	Floods	185.0	-2.0		185.0	-2.0		186.3	-0.6	
DILLENBAUGH CR	REACH 8	1.5	184.8	188.2	West side of I-5	187.6	-0.6		185.0	-3.3		185.0	-3.2		186.3	-1.9	

Discussion of Results

The results presented above show the level of flood water level reduction that can be achieved through individual flood relief projects and combinations of those projects. Data are presented for four flood events to show how each project or alternative performs in each different types of storm events. The data show benefits and potential water surface elevation impact of each project. Given this information, projects can be refined and alternatives can be configured to address specific flood damage problem areas. The data presented herein is limited to water surface elevation comparisons. Information on depths of flooding can be generated using the model output but this level of analysis was beyond the scope of this study. Ultimately, conclusions regarding flood impacts would need to consider changes in water surface elevation in conjunction with actual depths of flooding. In some cases, a small decrease in flood depth could have significant benefits while in other cases even large reductions might not have much effect. The same is true for water level increases – some locations may not be particularly sensitive to increases (for example areas where flooding is already very deep) while other areas might be particularly problematic. That level of analysis and evaluation of the results will need to be undertaken in combination with information on project costs to define a preferred package of flood relief projects for the basin. The model developed for this study will be helpful to generate the hydraulic data needed to inform that effort.

Caveats and further work required

The results and data described herein were developed using the Chehalis River Basin HEC-RAS hydraulic model. As discussed above there are always uncertainties involved in modeling extreme flood events, and the large floods on the Chehalis River are particularly difficult to model accurately due to problems with some flow gages during these events. Significant efforts were made to calibrate the model to all available high water marks and anecdotal information on past flooding. While the modeling is felt to be entirely appropriate for the analyses described herein, use of the model for other purposes should be done with caution.

In particular, caution is necessary when considering very small differences in water surface elevations downstream of the Twin Cities area under some alternatives. The FEMA Twin Cities HEC-RAS model was configured with river reaches on the west side of Interstate 5 (the main flow path) and a network of linked storage areas on the east side of the freeway. The linked storage areas are appropriate for representing the 2-dimensional nature of flow on the east side of the freeway. Unfortunately, RAS routes water differently between storage areas as opposed to river reaches. In some of the alternatives, for example the WSDOT I-5 Protection project, a primary effect of the alternative is that flow from the west to the east across the freeway is reduced, thus reducing the flow in the storage areas and increasing the flow in the main river channel. This change in flow pattern results in more flow attenuation under the alternative than in the existing condition. It is not clear whether this is a real effect of the alternative or simply a modeling effect. As such, the reporting of very small downstream reductions in water surface elevations should be viewed with some skepticism. To be clear the HEC-RAS model is set up in an acceptable manner and provides a good representation of existing conditions. However, under some alternatives (the ones that dramatically alter flow paths in the Twin Cities area) the model may be producing downstream results at very small increments that are not altogether accurate. Unfortunately, there is no simple way to fix this and perhaps no better way to configure the model for the complex flow splits in the Twin Cities area.

It should also be noted that inundation maps prepared to document changes in the extent and depths of flooding under the alternatives were developed using automated mapping techniques, which are appropriate for preliminary evaluations. The maps were also based on the best available topographic data, which in some cases is more than 10 years old. As such, the maps may not be entirely accurate in some locations and should be used with caution. These inundation maps were not intended to replace other flood hazard maps such as those available from FEMA since the preparation of those maps requires significant manual post-processing of the data that is well beyond the scope of this study. Detailed inundation mapping for flood hazard evaluation could be done using the new modeling but that would require additional efforts not currently scoped.

Finally it must be understood that the geometric (cross section) data used in the hydraulic model were derived from available topographic data sources including data from 1999 (in the Twin Cities floodplain area), 2002 (between Grand Mound and Montesano and along the Skookumchuck River), and 2005 and 2006 in Centralia and Chehalis. New topographic data will be available soon for much of the basin (Chehalis River corridor from Lewis County line to Montesano) or is already available (Thurston County and portions of Lewis County). The new topographic data could be used to update the hydraulic models thus improving the model's ability to simulate overbank flooding. That effort, however, is beyond the scope and schedule of the current project.

Summary and Recommendations

The Chehalis River Basin Flood Authority recognized the need for detailed hydraulic modeling and analysis of potential flood relief alternatives in the Chehalis River basin. In particular extending the existing hydraulic modeling downstream to the mouth of the river and using the model to evaluate a broad range of possible flood relief projects. Through a budget proviso in Engrossed Substitute House Bill (ESHB) 2020 the Washington State Legislature provided funding to "complete the hydraulic model for the Chehalis River to calculate flood levels, flood damages, and benefits of proposed flood mitigation projects for the lower portions of the river." WATERSHED Science & Engineering, together with subconsultant WEST Consultants, was retained by the Flood Authority to develop the hydraulic model and apply it to the evaluation of more than 25 potential flood relief projects or combinations of projects. The results of those evaluations are presented above.

Concurrent with the Flood Authority's efforts to evaluate basin wide flood relief alternatives the Corps is conducting hydraulic analyses related to ecosystem restoration planning and WSDOT is designing and evaluating several alternatives to mitigate the effects of flooding to Interstate 5. WSE and WEST worked with those agencies to ensure that the model development work for the Flood Authority leveraged those agencies work and resulted in single baseline hydraulic model that was accepted by all. The comprehensive basin wide model described above has been provided to the Corps for review and is being used by WSDOT for their analyses. The use of a consistent hydraulic analysis tool by all three groups should facilitate agreement on the potential benefits and impacts of various alternatives and as such should improve collaborative efforts to address basin flood problems.

The hydraulic model developed for this study extends from the mouth of the Chehalis River to upstream of Pe Ell, a distance of more than 108 miles. The model also includes significant portions of key tributaries including the following: 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). While the model was developed primarily to evaluate the effects on the main stem Chehalis River of large-scale flood relief projects it can also serve as a tool for the evaluation of hydraulic conditions and flooding on these tributaries. In fact, the model has already been used by WSE to evaluate the effects of potential modifications to the railroad bridge downstream of Bucoda on the Skookumchuck River.

The baseline hydraulic model developed for this study represents the best available information on hydraulic conditions in the modeled reaches. However, it must be recognized that the model includes both newly modeled reaches (e.g. Chehalis River between Porter and Aberdeen) and reaches where existing models were incorporated. In some of the older model reaches new cross sections surveys were collected and used (e.g. Skookumchuck River at Bucoda, Chehalis River between Grand Mound and Porter) while in other reaches (e.g. the Chehalis River between Grand Doty and Grand Mound, South Fork Chehalis) the model is using cross sections collected as long ago as 2001, or in some cases 1989. Similarly, in some portions of the model (e.g. Newaukum River) floodplain topographic data were updated to reflect more recently available LiDAR data while in other reaches (e.g. Satsop River, Black River) the topographic data dates back to 2002, or in some cases earlier. Obviously, it would have been preferable to update the entire model with new field surveyed cross sections and up to date overbank topographic data. Furthermore, it would have been preferable to be able to thoroughly review, refine, and validate all of the exiting model reaches that were incorporated into the final model. However, the efforts are simply beyond the scope and resources of the current project. That said the model is still a significant improvement over any tool that has been previously available and its availability should enhance flood relief investigations throughout the basin.

As time and resources allow it is recommended that the model be updated to use new topographic and survey data, that the updated model be refined to address any new infrastructure that has been built since the original model development, and that the updated model be calibrated to available flood information. It is further recommended that any future application of the model be preceded by an assessment by a qualified hydraulic engineer to see if the model as developed herein is appropriate for the intended use.

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WATERSHED Science & Engineering (2012c). “Newaukum River Model Extension and Refinement” Technical Memorandum, March 13, 2012.

WATERSHED Science & Engineering (2012d). “Response to State Team comments on Chehalis River Hydraulic Model” Technical Memorandum, April 11, 2012.

Appendices

Appendix A

WSE Responses to State Tech Team Comments on Work Plan (Oct 21, 2011)

Reviewer	Comment	Response	Task
Guy Hoyle-Dodson, DOE	The assumption that this tidally influenced flood plain can be even marginally modeled with HEC-RAS is highly optimistic. The matrix solutions in HEC-RAS within the unsteady-state flow simulation is highly unstable in these situations and has difficulty forming a solution.	Both WSE and WEST staff have significant experience applying HEC-RAS in a tidal environment and we do not believe that it's application is as "optimistic" as the reviewer suggests. We can point to numerous instances of HEC-RAS being successfully applied to hydraulic modeling in tidal environments including significant modeling applications on the Green and Snohomish Rivers and Tillamook Bay. We can also cite literature supporting the appropriateness of HEC-RAS in these situations including the FHWA website at http://www.fhwa.dot.gov/engineering/hydraulics/hydrology/hec25c4.cfm and the attached draft paper submitted to the Journal of Hydraulic Engineering (I don't have access to the final version).	Task 5c
Guy Hoyle-Dodson, DOE	The inclusion of tidal influences would require a downstream boundary hydrograph , and measurements.	It is the intent of this study to develop a downstream boundary condition using the NOAA tide gage data available for the Aberdeen station.	Task 5c
Guy Hoyle-Dodson, DOE	Theta Weighting Factor. Theta is a weighting applied to the finite difference approximations when solving the unsteady flow equations. Theoretically Theta can vary from 0.5 to 1.0. However, as practical limit is from 0.6 to 1.0 Theta of 1.0 provides the most stability, but less numerical accuracy. Theta of 0.6 provides the most accuracy, but less numerical stability. The default in HEC-RAS is 1.0. Once you have your model developed, reduce theta towards 0.6, as long as the model stays stable. For rivers with tidal boundaries, in which the rising tide will propagate upstream, the user should always try to use a theta value as close to 0.6 as possible. Tidal waves are very dynamic. In order for the solution to be able to accurately model a tidal surge, theta must be close to 0.6. Thus accuracy is sacrificed for stability.	We don't envision Theta being a big concern The reviewer cites a "textbook" concern but practically speaking we've never had much issue with it nor have we seen it have a tremendous effect on results (except possibly for dam break or other flash flooding type simulations). Usually we are also looking at peak results, whereas Theta is more likely to have an effect on the shape of computed stage/flow hydrographs. But we feel other inputs and uncertainties -- geometry, roughness, boundary conditions -- have a greater effect. The current Twin Cities model already has Theta set to unity, which is the default. For a model this large, plus extended all the way to Grays Harbor, it might be difficult to reduce that down to 0.6 without some instability arising somewhere. Also, if the present model is already calibrated, we probably don't want to change this parameter if it might compromise (however minor) the upstream calibration. Our suggestion would be to initially build a truncated version of the model, from Monteseno downstream, that is both more manageable to run (using inflows taken from the larger model) but can also be used for some sensitivity tests to the lower tidal region of the study. We can modify Theta just for the lower end see if we observe significant change, and do some other sensitivity tests just related to the tidal area. We assume the reviewer is not talking about surface tidal waves, as neither RAS nor any other typical 2D model for rivers simulates those. More likely storm surges, as reflected in the downstream stage hydrograph boundary. HEC-RAS should be able to handle these OK, they don't rise THAT fast or dynamically. And the diffusive effects of using the fully implicit solution (Theta=1) should be minimal.	Task 5c

Reviewer	Comment	Response	Task
Guy Hoyle-Dodson, DOE	It might be easier and more cost effective just to use a 2-D model.	Notwithstanding our opinion that a useful HEC-RAS model can be developed for this reach I share Guy's opinion that a well developed 2-D model would provide a more robust tool for a wide range of purposes. One problem, however, is that we don't have adequate time or budget to do the detailed bathymetric data collection that would be required to support a robust 2-D model. Furthermore, model development costs and run times would also be significantly greater for a detailed 2-D model, pushing them beyond the time and budget resources of the current project. Finally, since the preeminent task in our current work plan is to provide a tool that can be used to evaluate the downstream impact/benefit of upstream flood relief alternatives we need to recognize that modeling for the remainder of the system, from Pe Ell to Montesano, is being performed in HEC-RAS. The intent here is to append the downstream reach to the Corps model to allow the Flood Authority to evaluate basin wide flood relief alternatives in a single tool.	Task 5c
Guy Hoyle-Dodson, DOE	They should ensure that modeling for all tributaries has the QA/QC and level of detail and accuracy that is commensurate with the other modeling being performed for the Corp, otherwise the continuity across the entire model will suffer.	Modeling of the tributaries will be scoped in detail in coordination with the Flood Authority and Stakeholders to ensure their needs are met. There may be benefit in modeling the tributaries at a lower level of detail than the main stem, simply to allow more miles of trib to be modeled. This is still to be determined.	Task 6b
Guy Hoyle-Dodson, DOE	This may require more resources that currently allocated.	The work plan will be tailored to the available funds	Task 5d
Guy Hoyle-Dodson, DOE	Consultant should consider 2-D modeling on the lower reach	See previous response	None
Paul Pickett, DOE	The work plan states that they will be using the hydrologic statistical events developed by the Corps and not adding any more. How will hydrologic statistical events and boundary conditions be developed for the tributary modeling?	WEST's work for the Corps is developing hydrologic data for all major tributaries in the Chehalis basin at up to 78 locations including more than 50 ungaged sites. WEST is also developing flows for the major tributaries for use in the modeling of the main stem Chehalis River. These data will be used for tributary modeling either independently of the main stem or using the main stem model to provide a downstream boundary condition. More detail on WEST's work for the Corps is available in their scope for that project.	Task 6a
Paul Pickett, DOE	One of the issues that has come up in the past has been the timing of storm events and the orientation of the storm events to the basin. Peak flow events from the tributaries won’t occur at the same time. Different scenarios based on historical events would have a sequencing of peak events across the basin and maximum intensity hitting in different locations. How will this be addressed in the modeling?	Assumptions about coincidence of tributary flows, as necessary for modeling the main stem Chehalis River will be implicit in the WEST work for the Corps. Analysis of the fall range of possible spatial precipitation patterns is beyond the scope of either the Corps study or this study and will not be investigated in either study.	Task 6a

Reviewer	Comment	Response	Task
Paul Pickett, DOE	I think Guy is correct that using the HEC-RAS 1-D model could result in significant uncertainty in the results and a 2-D model would be more reliable. I also agree with Hal that it is acceptable, at least as a first-cut analysis. But as part of the study report, the success of using HEC-RAS at the downstream end should be evaluated to determine the limitations and uncertainty of the 1-D model and the benefits of using a 2-D model for an improved analysis in the future. On the other hand, if a 2-D model could be developed with a reasonable amount of additional effort, that would be preferable. Greg Pelletier (Department of Ecology) developed a 2-D hydrodynamic model of Grays Harbor and the Chehalis River from Montesano downstream. He used the "Wetland Dynamic Water Budget Model", which is an Army Corps of Engineers model similar to DYNHYD. Ray Walton is very familiar with it - he "wrote the book" on it, literally. Greg Pelletier says the model input information is available, possibly on the Ecology website. Could the existing WDWBM model be upgraded to serve the purposes of this study? Here are links to Greg's work: • Project page: http://www.ecy.wa.gov/programs/wq/tmdl/ChehalisBasin/GraysHbrTMDL.html • Computer simulation information: http://www.ecy.wa.gov/programs/eap/wrias/tmdl/ghfc/results.html	See previous discussion of 2-D model in response to comments from Guy Hoyle-Dodson. Note that the WDWBM model is not actually a 2-D model. It is a pseudo 2-D link-node model with the 2-D effect gained by branching flows off of and one node in multiple directions. This is structurally the same as the network branching available within HEC-RAS and considering the more sophisticated hydraulic routing available in RAS the RAS model would actually be a better option. Note also that the model developed by Greg Pelletier only has a single branch up the Chehalis River and thus the pseudo 2-D effect is limited to Grays Harbor in an area outside the current project boundary.	Task 5c
Paul Pickett, DOE	Does the workplan include time and funding for review by the state agencies and addressing any comments received?	The work plan will allow time for the Consultant team to discuss technical issues with agency reviewers at key milestones.	none
Paul Pickett, DOE	It would be better to brief state agency technical staff at regular intervals and incorporate their comments during the course of the project (rather than waiting until the draft report is out to brief state agencies and solicit comments)? Is this approach incorporated in the work plan, or could it be?	The work plan will allow time for the Consultant team to discuss technical issues with agency reviewers at key milestones. Note however that the tight timeframe for this project will require great flexibility and responsiveness on the part of the agencies if coordination is to be successful.	none

Reviewer	Comment	Response	Task
Hal Beecher, WDFW	If new channel survey data are obtained, they are presumed to be superior to 2001 data for cross sections. It would be useful to assess how the two data sets compare in maximal conveyance, width, difference between adjacent floodplain elevation and relevant channel bed elevations (probably not pool bottoms) to determine if conveyance in the river is changing or if the two data sets are complementary (two samples from the same population). Such information may shed some light on processes affecting channel conveyance (dynamic equilibrium or not).	The data will be available for these comparisons.	Task 5a
Hal Beecher, WDFW	The plan briefly discusses use of HEC-RAS vs. 2-dimensional modeling. Annear et al. (2002: 265) discussed HEC-RAS and their discussion is supportive of using HEC-RAS: "The model's purpose is to provide information on river stages over a range of flows, particularly for floods." "These situations include mixed flow regime calculations (i.e., hydraulic jumps), bridge hydraulics, and evaluation profiles at river confluences. … It has culvert and bridge routines. The program can model a single river reach, a dendritic system, or a full network (looped systems)." Thus, use of HEC-RAS appears reasonable.	Agreed	Task 5c
Hal Beecher, WDFW	This optional task includes developing hydrographs for "ecologically significant flows at up to 50 locations." Natural resource agencies and interests should be consulted to determine what those flows are and what locations are modeled. A major consideration is stranding of fish as flows recede from a flood. Rate of stage decline should be addressed over the range of flows where overbank flows drop to within the channel.	See previous responses regarding the hydrology. At this point no additional hydrologic data development is planned under this contract.	Task 6a
Casey Kramer, WSDOT	Explain why deferred. Would like a brief discussion summarizing other previous and on-going LiDAR efforts within the project area.	Preliminary checks of the LIDAR data can be made using the area between Montesano and Aberdeen for which both 2009 and 2002 LiDAR data are available. Additional checks can be made using the topographic data collected during the cross section surveys. These checks should suffice for now given that FEMA is planning on collecting new LiDAR data in fall 2011.	Task 3
Casey Kramer, WSDOT	Last sentence in Task 5a seems to support Task 3.	The draft work plan was written prior to the collection of the data discussed above.	Task 5a
Casey Kramer, WSDOT	Refer to which Task you are referring to "topographic data described above".	Task 5a	Task 5b

Reviewer	Comment	Response	Task
Casey Kramer, WSDOT	What are the 50 locations West is looking at?	WEST has a map showing the hydrologic data development locations. This map can be provided upon request.	Task 6a
Casey Kramer, WSDOT	Also interested in China, Salzer, Dillenbaugh, etc. This may be upstream of the proposed work plan.	The available budget is not adequate to allow detailed modeling of the four tributaries already defined in the scope. It is understood that many more tributaries could benefit from hydraulic modeling and analysis. IF additional funds become available additional modeling may be conducted.	Task 6b
Casey Kramer, WSDOT	Explain why deferred.	At the request of the Flood Authority, to make the best use of available funds.	Task 6d
Casey Kramer, WSDOT	Seems like a minimal cost for an important task. Topography/bathymetry is the foundation for a accurate hydraulic model, not knowing the quality of the data could be viewed as a flaw in the modeling results.	See previous comment on checks that will be preformed.	Optional Task 3

Appendix B

WSE Response to State Tech Team Comments on Hydraulic Model (4/17/2012)

WATERSHED
Science & Engineering
110 Prefontaine Place South, Suite 508
Seattle, WA 98104
206-521-3000

Memorandum

To: Chehalis River Basin Flood Authority and State Technical Review Team

From: WATERSHED Science & Engineering (WSE) and WEST Consultants (WEST)

Date: 04/17/2012

Re: **Response to State team comments on Chehalis River Hydraulic Model**

Watershed Science & Engineering (WSE) and WEST Consultants (WEST) have developed an HEC-RAS hydraulic model of the Chehalis River, including portions of several significant tributaries (e.g. the Wynoochee, Satsop, Black, Skookumchuck, and Newaukum Rivers). Following a meeting on February 23rd, the model and available documentation were provided to a group of State technical staff for review and comment. Three State reviewers provided detailed written comments on the model: Paul Pickett (DOE), Casey Kramer (WSDOT), and Guy Hoyle-Dodson (DOE). These comments were well formed and generally helpful in identifying areas in the hydraulic model that required additional consideration and/or refinement. The three comment letters (attached) were reviewed and discussed by the WSE-WEST team and a number of modifications were made to the model to address significant concerns. In some cases, no changes to the model were necessary, either because the model was already configured appropriately or because the comment raised questions beyond the scope of the current study. Our general responses to the reviewer's comments are provided below. These responses will also be discussed further with the individual reviewers to ensure that we are all comfortable moving ahead with the Chehalis River Basin alternatives analysis using the resulting (refined) model.

RE: Paul Pickett comment letter of 3/30/2012:

Mr. Pickett's comments focused primarily on the hydrologic data proposed for use in the evaluation of flood relief alternatives. He noted that flood events in a basin as large and complex as the Chehalis Basin can come in many different forms and that a comprehensive analysis of flood relief alternatives would require a range of design events to be simulated. However, in our response below we provide data showing that the largest flood events (i.e. the top 10 floods) observed in the Chehalis basin in the past 80 years have similar enough characteristics to make the proposed design event modeling approach reasonable for the current effort. Furthermore, we note that the hydrology for the current study was done and widely reviewed as part of the concurrent Corps project and using the same hydrologic methodology as that study will maintain consistency between the modeling efforts. However, in an effort to provide a more robust and useful analysis, we offer a recommendation to use hydrologic data for the calibration events (1996, 2007, and 2009) to augment the design event evaluation.

In addition to comments on the proposed hydrologic data, Mr. Pickett offered a number of suggestions for improving the evaluation and presentation of "Model Quality" metrics. We have reviewed these comments and find them to be well stated and helpful. We will endeavor to provide additional information on model quality including expanded reporting of model uncertainties, as suggested, when reporting the results of the alternatives analysis.

Detailed Response to "Sensitivity to Hydrology"

Mr. Pickett presented a very useful analysis of the high variability in flood coincidence of contributions from major tributaries in the Upper Chehalis River (above the flow gage near Grand Mound). We agree that multiple hydrologic scenarios of inflows from the major tributaries are possible that would result in a similar magnitude of high flow event for the Chehalis River near Grand Mound.

The hydrologic methodology that WEST used to develop the synthetic flood events for their current U.S. Army Corps of Engineers (USACE) study is similar to the one used by the USACE in the 2003 General Reevaluation Study (updated in 2010). The essential feature of the approach was to develop synthetic flood hydrographs at various locations throughout the basin that together would generate 1.5- to 500-year flood events for the Chehalis River near Grand Mound. The flood magnitude (recurrence frequency) of the basin-wide synthetic events is evaluated using the flow gage site on the Chehalis River near Grand Mound. The coincident relationships for peak flows between the Grand Mound gage and upstream gages were determined using all concurrent annual peaks, which provide a systematic and objective method to define the long-term average coincidence between a synthetic peak discharge near Grand Mound and the coincident inflow from an upstream tributary or from the headwaters of the Upper Chehalis River.

In Mr. Pickett's comment letter he plots the correlation between the annual peak discharges near Grand Mound and near Doty with and without inclusion of the December 2007 event. The figure shows that for flows in the Chehalis River near Grand Mound less than about 45,000 cfs, roughly the peak discharge of a 10-year event (Table 1), the two regression curves are relatively close to each other. For flows that exceed about 45,000 cfs, the regression curves depart significantly. Mr. Pickett expressed concern that the higher ratio of flows near Doty to flows near Grand Mound might result in unreasonably large contributions from the upper watershed (above Doty), even though this is only seen in some of the observed flood events.

To evaluate and respond to Mr. Pickett's concern we analyzed data from the top 10 annual peaks at the Grand Mound gage and the corresponding peaks at major upstream gages. Our key finding is that a large flood event near Grand Mound cannot occur if a large event does not occur in the headwaters above Doty. Table 2 summarizes available USGS peak flow data for the Chehalis River basin. This table shows the top 10 flood events recorded by the USGS at the Grand Mound. Of these, two occurred in the 1930s when none of these other major USGS gages in the basin was in operation. Of the remaining eight largest flood events at Grand Mound:

1) All eight had a corresponding flood on the Chehalis at Doty that was in the top 10 of all time at that location.
2) Seven of the eight had a flood on the South Fork Chehalis River that was in the top 10 at that location.
3) Seven of the eight had a flood on the Newaukum River that was in the top 10 at that location.
4) Only four of the eight had a flood on the Skookumchuck River that was in the top 10 at that location.

Furthermore, review of the concurrent USGS gage records for Doty and Grand Mound shows that of the top 10 historical flood events at Doty, eight were also in the top 10 events of all time at Grand Mound. Similarly, of the top 10 events on the South Fork Chehalis River and the Newaukum River 7 were also among the top 10 events at Grand Mound. However, it can be seen that of the top 10 flood events on the Skookumchuck River only four were in the top 10 flood events at Grand Mound. Looking in more detail at the Skookumchuck gage records it can also be seen that the 2nd highest flow of all time on the Skookumchuck was only the 24th highest flow at Grand Mound and the 4th highest flow on the Skookumchuck was only the 23rd highest flow in the USGS record at Grand Mound.

From these data, we can make the following observations:

1) A large flow (herein defined as among the top 10 highest peaks recorded) on the Chehalis at Grand Mound has never happened without a correspondingly large flow on the Chehalis River at Doty.
2) A large flow at Doty is a reliable (although not perfect) indicator of a large flow at Grand Mound.
3) A large flow on the Chehalis at Grand Mound can happen with or without a significant flow contribution from the Skookumchuck River.
4) A large flow on the Skookumchuck is not a very good indicator of large flows at Grand Mound.
5) Peak flows on the Newaukum and South Fork are similarly correlated to the flows at Grand Mound, less so than the Doty flows but more so than the Skookumchuck flows.

Using the top 10 flows at Grand Mound as a representative and sufficiently large sample of basin wide flood events, we see that the average contributions from Doty, South Fork, Newaukum, and Skookumchuck during these events are 45%, 17%, 19%, and 14% of the Grand Mound peak. In his comments Mr. Pickett noted that the preliminary proposed design flow hydrology had ratios of 44%, xx% (South Fork is under review), 17%, and 14%, respectively, for these locations. The proposed design flow ratios appear to be very reasonable given the data in Table 2 and the observations listed above. Figure through Figure show the distributions of flood return periods across the entire basin for the February 1996, December 2007, and January 2009 events. For the January 2009 event, a flood event greater than the 100-year peak discharges occurred in the Skookumchuck and Newaukum Rivers. However, the corresponding flows near Doty and near Grand Mound are only a 12-, and 15-year event, respectively. Thus, while this event is a good example that portions of the basin can see extreme floods while other portions see smaller flood events it also supports the conclusion that a basin-wide extreme flood (as determined using the gage at Grand Mound) is only possible with a large contribution from the Upper Chehalis basin.

We feel that these additional analyses indicate that the coincident relationships determined from all concurrent annual peaks between the Grand Mound gage and the upstream gages provide a reasonable representation of the large flood events in the Upper Chehalis River basin. However, we agree with Mr. Pickett that a high variability in storm timing and magnitude exists in the Chehalis River basin. To evaluate the sensitivity of storm variability, we recommend that the hydraulic model evaluations of flood relief alternatives be run for both the synthetic hydrographs and for the observed February 1996, December 2007, and January 2009 flood events. While we believe that the design event does a reasonable job of characterizing large, basin wide, floods the addition of the historical flood events provides a range of alternative hydrologic conditions that have been seen in the recent past and are useful for a more robust evaluation of flood relief alternatives.

Table 1. Expected Probability Flood Frequency Natural or Unregulated Peak Discharges (in cfs) at Fully Gaged Active Sites

Recurrence Interval (yrs)		Chehalis River nr Doty	Newaukum River nr Chehalis	Skook. River nr Centralia	Chehalis River nr Grand Mound	Chehalis River at Porter	Satsop River nr Satsop	Wyn. River above Save Ck nr Aberdeen	Wyn. River above Black Ck nr Montesano
		12020000	**12025000**	**12026000***	**12027500**	**12031000**	**12035000**	**12036000**	**12037400**
Annual Peak Recurrence (yrs)	**1.5**	8,155	5,160	3,400	21,519	25,109	21,751	11,300	15,100
	2	9,900	6,206	4,230	25,659	29,651	25,936	13,000	17,700
	5	15,110	8,674	6,390	36,917	42,160	35,644	17,500	23,900
	10	19,412	10,253	7,920	45,352	51,678	41,742	20,700	28,000
	20	24,281	11,732	9,450	54,239	61,840	47,382	24,000	31,900
	50	31,906	13,607	11,500	67,091	76,794	54,432	28,400	37,000
	100	38,775	14,995	13,200	77,844	89,514	59,588	32,100	40,800
	200	46,828	16,370	15,000	89,674	103,733	64,642	36,000	44,800
	500	59,627	18,187	17,400	107,184	125,153	71,242	41,600	50,100

*A substitute for Station 12026150 for unregulated flood flow statistics only

Table 2: Comparison of USGS Recorded Peak Flows for Key Gages in the Chehalis River Basin

Chehalis at Porter				Chehalis near Grand Mound			Skookumchuck at Bucoda				Newaukum				SF Combined (extended w Doty)				Chehalis near Doty			
Date	Flow (cfs)	Rank [1]	% [2]	Date	Flow (cfs)	Rank [1]	Date	Flow (cfs)	Rank [1]	% [2]	Date	Flow (cfs)	Rank [1]	% [2]	Date	Flow (cfs)	Rank [1]	% [2]	Date	Flow (cfs)	Rank [1]	% [2]
12/05/2007	102000	1	129%	12/04/2007	79100	1	12/03/2007	3600	55	5%	12/03/2007	12900	3	16%	12/03/2007	20710	1	26%	12/03/2007	63100	1	80%
02/09/1996	80700	2	108%	02/09/1996	74800	2	02/08/1996	11300	1	15%	02/08/1996	13300	1	18%	02/08/1996	9540	4	13%	02/08/1996	28900	2	39%
01/11/1990	60400	4	88%	01/10/1990	68700	3	01/10/1990	8540	8	12%	01/09/1990	10400	6	15%	01/09/1990	9880	3	14%	01/09/1990	27500	3	40%
11/25/1986	45900	9	89%	11/25/1986	51600	4	02/01/1987	6470	22	13%	11/24/1986	10700	5	21%	11/24/1986	6430	12	12%	11/24/1986	17900	9	35%
01/09/2009	68100	3	134%	01/08/2009	50700	5	01/08/2009	10500	3	21%	01/07/2009	13000	2	26%	01/08/2009	11660	2	23%	01/08/2009	20100	7	40%
01/22/1972	55600	5	113%	01/21/1972	49200	6	01/21/1972	8190	11	17%	01/21/1972	9770	10	20%	01/20/1972	6540	10	13%	01/20/1972	22800	4	46%
Data not available				12/29/1937	48400	7	Data not available															
11/26/1990	43000	11	90%	11/25/1990	48000	8	11/25/1990	8400	9	18%	11/24/1990	10300	7	21%	11/24/1990	7400	7	15%	11/24/1990	20600	6	43%
Data not available				12/21/1933	45700	9	Data not available															
12/05/1975	48100	7	107%	12/05/1975	44800	10	12/04/1975	6110	27	14%	12/04/1975	8020	17	18%	12/04/1975	6590	9	15%	12/04/1975	17400	10	39%
		42	**107%**			**39**			**136**	**14%**			**51**	**19%**			**48**	**17%**			**42**	**45%**
01/27/1971	49600	6	11	01/26/1971	40800	11	12/09/1953	10930	2	24	11/07/2006	11200	4	26	11/06/2006	8130	5	26	02/07/1945	21400	5	32
01/02/1997	46000	8	12	12/30/1996	38700	12	12/11/1955	10150	4	23	12/02/1977	10300	7	17	11/25/1998	7420	6	17	01/18/1986	18100	8	27
01/13/2006	43200	10	15	01/23/1935	38000	13	01/25/1964	9760	5	22	11/26/1998	10000	9	17	01/30/2006	7080	8	15	12/16/2001	16600	11	
02/26/1999	42000	12		02/10/1951	38000	13	02/17/1949	9400	6	17	12/29/1996	9700	11		01/18/1986	6500	11		02/24/1999	16300	12	
12/19/2001	41200	13		01/31/2006	37900	15	12/28/1949	8710	7	36	01/31/2003	8940	12		12/15/1999	6350	13		01/30/2006	16000	13	
01/07/1954	40800	14		01/17/1974	37400	16	12/30/1996	8380	10	12	01/30/2006	8720	13		02/07/1945	5700	14		02/09/1951	15700	14	
01/17/1974	39100	15		02/18/1949	36500	17	12/13/1966	7270	12		01/15/1974	8440	14		12/16/2001	5620	15		12/20/1994	15300	15	
12/23/1955	38900	16		12/03/1977	36500	17	12/22/1964	7200	13		01/26/1971	8390	15		12/20/1994	5500	16		12/03/1982	15200	16	
12/15/1977	38900	16		11/26/1998	36500	17	12/02/1977	7170	14		12/16/1999	8100	16		12/03/1982	5460	17		12/15/1939	15100	17	
01/27/1964	38500	18		01/15/1936	36300	20	11/12/1958	6940	15		01/25/1964	7970	18		12/15/1939	5430	18		11/06/2006	14500	18	
12/17/1999	38100	19		12/21/1994	35900	21	11/20/1960	6680	16		02/23/1986	7960	19		12/09/1987	4960	19		12/09/1987	13800	19	
02/11/1951	36100	20		01/26/1964	35700	22	01/30/2006	6640	17		12/17/2001	7920	20		02/17/1949	4920	20		12/13/1966	13400	20	
12/15/1966	35700	21		12/22/1955	35100	23	01/26/1971	6630	18		12/09/1953	7880	21		12/13/1966	4650	21		02/22/1949	12800	21	
12/22/1994	35600	22		01/06/1954	34700	24	02/08/1955	6530	19		12/04/1982	7820	22		03/19/1997	4530	22		12/09/1956	12600	22	
01/31/1965	34000	23		12/14/1966	34400	25	11/20/1962	6520	20		01/18/2005	7740	23		01/25/1964	4330	23		03/19/1997	12600	22	
02/24/1949	33500	24		11/08/2006	32700	26	02/09/1951	6480	21		01/30/2004	7460	24		12/26/1980	4310	24		11/25/1962	12400	24	
01/26/1982	33300	25		01/20/1986	32100	27	12/11/1946	6320	23		01/14/1975	7400	25		12/30/1970	4250	25		12/15/1999	12400	24	
02/27/1950	32500	26		12/18/2001	31900	28	03/22/1948	6320	23		02/07/1979	7280	26		01/31/2003	4240	26		12/26/1980	12000	26	
01/16/1975	32100	27		12/17/1999	31000	29	11/22/1959	6290	25		12/12/1955	7200	27		11/27/1949	4040	27		12/07/1970	11700	27	
02/23/1961	32000	28		11/21/1962	29800	30	12/19/1941	6190	26		11/20/1962	6960	28		12/09/1956	3940	28		11/27/1949	11400	28	
12/28/1980	32000	28		01/25/1982	27300	31	12/17/2001	6060	28		02/17/1949	6950	29		12/23/1964	3780	29		02/04/1968	11200	29	
11/28/1962	31600	30		02/09/1945	27000	32	02/01/2003	5990	29		01/25/1984	6760	30		12/11/1955	3720	30		12/11/1955	11000	30	
11/23/1959	30100	31		02/22/1961	27000	32	01/16/1974	5950	30		04/01/1931	6750	31		02/09/1951	3690	31		02/02/1947	9980	31	
11/09/2006	29400	32		12/20/1941	26900	34	12/09/1956	5520	31		01/14/1998	6580	32		01/18/2005	3650	32		10/30/1997	9920	32	
01/28/1970	29200	33		01/15/1975	26900	34	01/24/1982	5250	32		12/23/1964	6500	33		10/30/1997	3560	33		11/17/2009	9460	33	
12/19/1979	28600	34		02/26/1950	26300	36	01/08/2007	5240	33		11/20/1960	6460	34		02/03/1963	3460	34		01/25/1964	9450	34	
12/28/1972	28100	35		12/24/1964	26200	37	03/09/1966	5160	34		12/11/1946	6350	35		02/04/1968	3450	35		02/04/1952	9320	35	

Notes: [1] Rank is the rank among the events at each individual gage, highlighted cells show events that were in the top 10 at Grand Mound but not in the top 10 at another gage

[2] % refers to percent of corresponding flow at Grand Mound seen at each of the other gages

[3] The table was truncated to show only events above a 2-year flow at Grand Mound

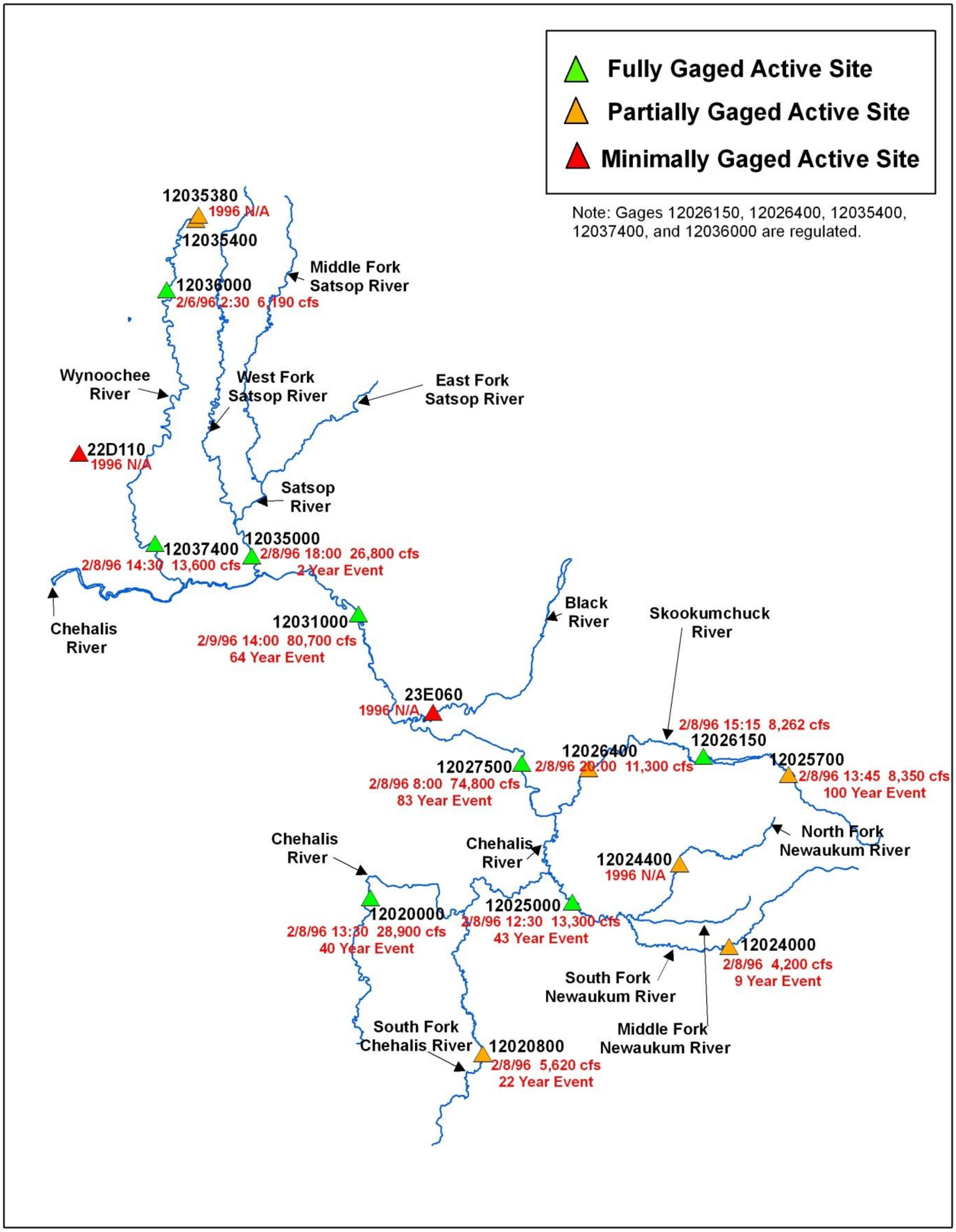

Figure 1. Flood Return Periods at Various Gaged Sites for the February 1996 Event

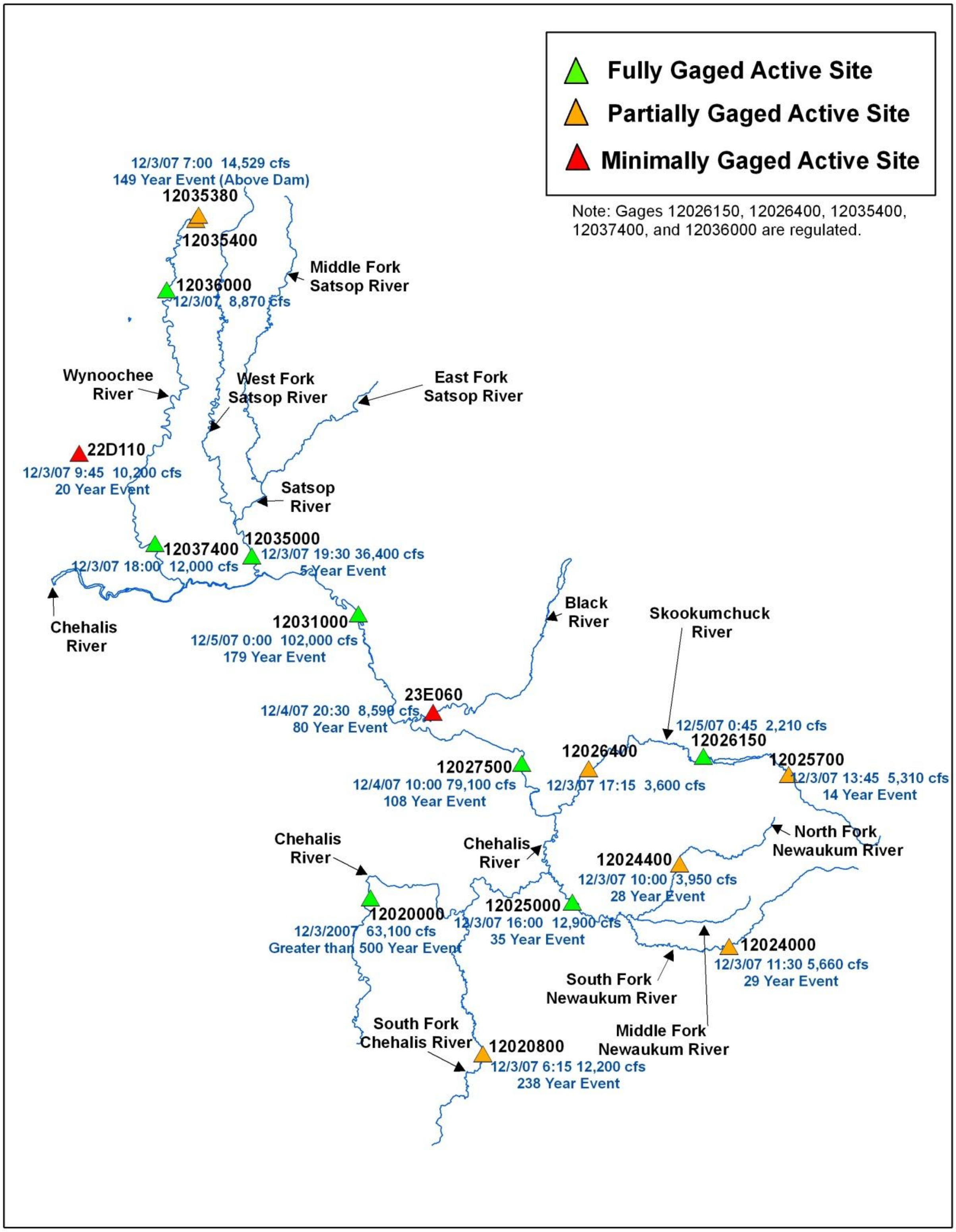

Figure 2. Flood Return Periods at Various Gaged Sites for the December 2007 Event

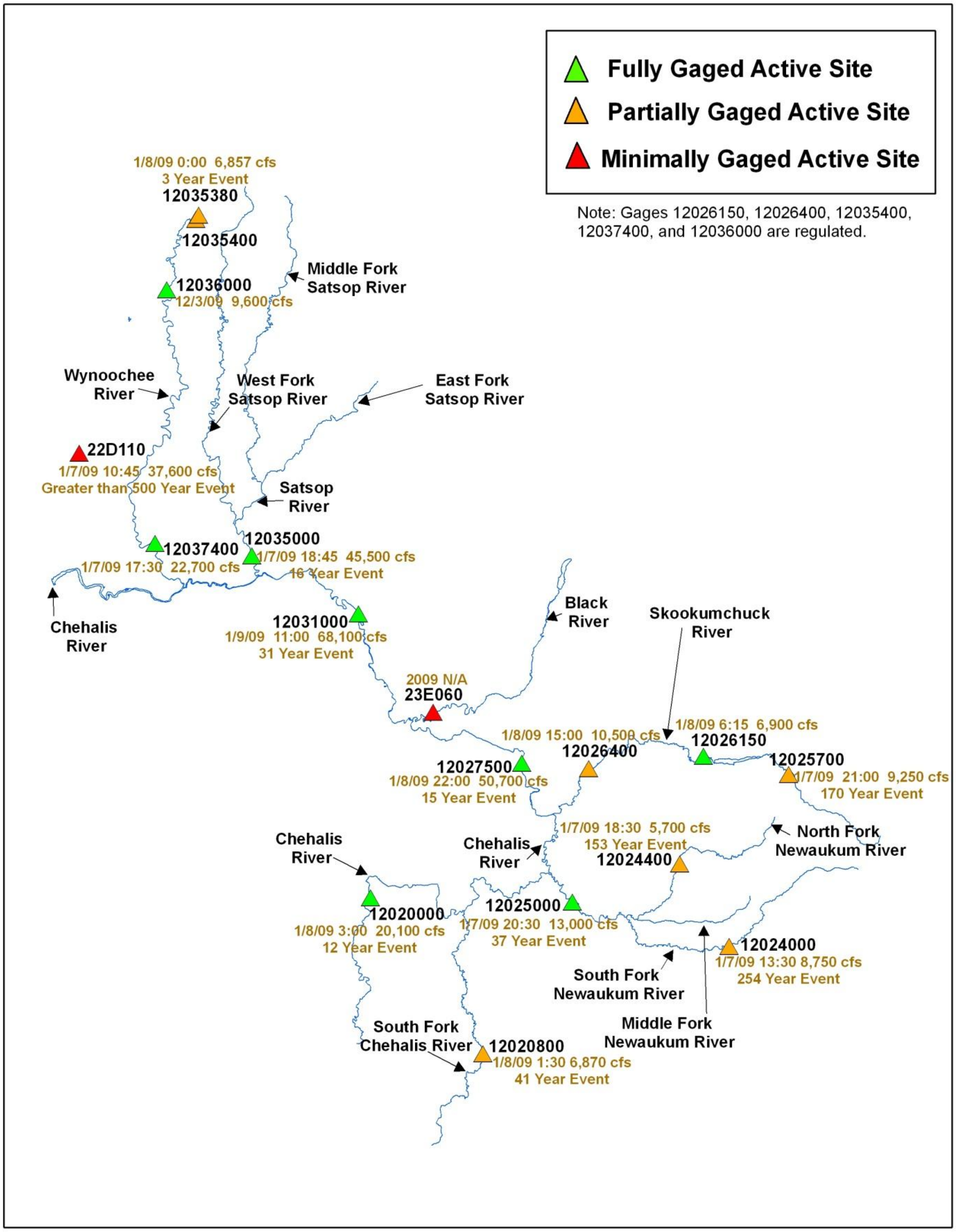

Figure 3. Flood Return Periods at Various Gaged Sites for the January 2009 Event

RE: Guy Hoyle-Dodson comment letter of 4/1/2012:

Mr. Hoyle Dodson's comments on the HEC-RAS model were particularly comprehensive including comments on general modeling approaches as well as a number of specific areas of concern or question. While many of these related to the new portions of the model being developed for this study, a large number were specifically related to the "Twin Cities" portion of the model previously developed by others. That said, and in an effort to make the model as robust and useful as possible, we have reviewed all of the comments and will attempt to address all of them as appropriate in refining the model. In addition to refinements to the model configuration we offer the following responses to key comments made by Guy:

- Regarding contraction and expansion losses, at bridges and elsewhere, note that the momentum equation which is solved under unsteady flow implicitly accounts for losses due to flow transitions. The original modeling by PIE and then by NHC, was carried out using unsteady-flow versions of UNET and HEC-RAS, that did not allow inputs of additional contraction and expansion losses. With the current HEC-RAS version 4.1, the USACE has now added a table to allow modeling of additional losses, for example at bridges with a particularly sharp contraction or expansion zone. For typical bridges, however, these losses are already accounted for in the unsteady (momentum) equation of motion. See HEC-RAS version 4.1 release notes, page 4: http://www.hec.usace.army.mil/software/hec-ras/documents/HEC-RAS_4.1_Release_Notes.pdf
- Regarding reach lengths, it should be noted that this model was developed (by PIE) generally following the 6 cross-section bridge modeling approach commonly called the Normal Bridge methodology in HEC-2 parlance. The two middle cross-sections were cut typically along the top of the roadway. The immediate upstream and downstream cross-sections were then cut close to the roadway but along natural ground (sometimes referred to as full valley sections). These are not intended to be the fully expanded or contracted sections, but are included so that floodplain storage is properly accounted for in the unsteady model. These should have appropriate ineffective areas to keep the majority of the floodplain from conveying flow, and have been checked accordingly. The fully expanded/contracted sections are generally the next downstream/upstream sections from the "full valley" sections, i.e. sections 1 and 6. These are further away from the bridge at a more acceptable distance for the flow transition.
- Regarding divided flow, it was generally assumed that this issue was dealt with appropriately in the original Twin Cities model. The current project did not include scope or budget to review or revise these in the existing FEMA model. That said, we took a quick look at the sections identified, and in some instances examined the amount of flow simulated on the floodplain to see if it would make any significant difference in the simulation results. Revisions were made to ineffective areas at some locations, as noted further below.
- On the Lower Chehalis tidal portion, the divided flow is more complex due to the tidal nature of this reach. Water does not have to exceed the channel bank elevation for flow to be in the side channels, as it comes up the channels from downstream due to the tide. Regarding the two bridges in the tidal reach, the Monte Bridge does not really have any flow contraction or expansion, in part because the upstream reach parallels the highway and does not overtop. The Hwy 101 bridge could have some ineffective areas added upstream and downstream, but it is not going to change the results any this close to the Aberdeen tidal boundary.
- Interpolated cross-sections on the Newaukum River were removed. These were added to reduce reach length and improve model stability, but HEC-RAS is unable to interpolate the

blocked ineffective areas. Upon further review, the interpolations are not necessary for stability.

- Ineffective area limits (station, elevation) were revised at Newaukum cross-sections 9.84, 5.01, 2.97 and 1.03, as suggested. At other locations on the Newaukum, review of topography indicates ineffective area limits are appropriately set; i.e., divided flow would exist based upon upstream conditions.
- Regarding divided flow and ineffective limits on the main stem Chehalis in Reaches 19, 21, 23, and 24: These reaches downstream of Grand Mound tend to have significant remnant channels in some overbank areas. In addition to the general adjustments to ineffective limits discussed previously, in the areas where divided flow was noted and remnant channels are picked up in the cross section geometry, blocked, permanent ineffective areas were used where appropriate to make cut-off remnant channels ineffective.
- Regarding Right Overbank Manning's n values at cross sections 82.61 through 82.57: The overbank n values of 0.08 were a carryover from the Corps modeling. Although the aerial imagery shows what appear to be fields in the overbanks, there are also rows of trees in the right overbank at these cross sections. A Manning's n value of 0.08 does not seem to be overly conservative in this area.
- Regarding lateral structures where bounding channel cross sections have been recommended: HEC-RAS uses a linear interpolation of water surfaces between modeled cross sections to calculate flows over lateral structures. We believe the cross sections currently in the model appropriately estimate the overflows at the level of detail warranted in a regional model and that the addition of cross sections to refine the overflow estimates would not create large changes in water surface elevations in the modeled storage areas and the Chehalis River.
- Regarding Rainbow Falls Inline Weir (Reach 1): We will add a cross section closer to the upstream face of the weir to more accurately model the upstream head on the weir.
- Regarding comments related to the Skookumchuck River: Under the original Flood Authority contract, non-georeferenced areas of the Skookumchuck River model (Reach 14 of the PIE model above RS 6.44) were georeferenced by West, and 2002 LiDAR was used to update overbank geometry. The contract did not include time to investigate (or refine) modeling assumptions made during the original model development. The subsequent tributaries modeling amendment included budget for WSE to update cross section data and refine the model near the town of Bucoda (RS 9.69 to 11.8) While we agree that additional refinement to the remainder of the model would be beneficial, such refinement is generally outside the scope and budget of the current project. That said, the following summarizes the changes made to the Skookumchuck reach of the model to address Mr. Hoyle-Dodson's comments:
    - NHC Reach (River Mile 0.0 to River Mile 6.44) – this reach was refined by Northwest Hydraulic Consultants as part of the Lewis County FEMA study (2010). As such we did not feel that additional model changes, without detailed supporting investigations, were advisable.
    - Intermediate Reach (River Mile 6.44 to 9.39) – this reach, between the NHC reach and the Bucoda reach had some unusual ineffective flow and levee limits in the original PIE model (as georeferenced by WEST). In response to Mr. Hoyle-Dodson's comments and our own review of the topographic information for this reach we adjusted several ineffective and levee boundaries to better simulate expected conditions in this reach.

- Bucoda Reach (River Mile 9.69 to 11.8) – The HEC-RAS configuration in this reach was developed and calibrated by WSE using new cross section surveys and available high water marks. Comments on this reach were reviewed and minor changes were made to levee and ineffective flow limits.
- Upstream Reach (River mile 11.92 to 21.77) – We agree with Mr. Hoyle-Dodson that some of the ineffective limits in the PIE model of this reach appear unusual. However, the hydraulic conditions in this reach are fairly complex with shallow overbank flow in many locations. Without additional high water mark data or detailed field investigations to verify existing conditions we did not feel it was appropriate to make adjustments to the existing model at this time.

RE: Casey Kramer comment letter of 4/2/2012:

Mr. Kramer's comments were discussed between Mr. Kramer, WSE, WEST, and NHC staff in a meeting at WSE's office on March 27, 2012. As a group we agreed upon a plan of action for updating the model to address the comments. It is noted that Mr. Kramer's model comments focused on the Twin Cities portion of the model constructed by others and not actually part of the current model development effort. However, in an effort to ensure that all future analyses conducted with the model are as useful as possible the following modifications were made:

1) USGS Chehalis River Near Grand Mound, WA Gage 12027500

No model modifications were necessary to address questions with the USGS gage. WSE confirmed with the USGS that the Grand Mound gage rating curve was extrapolated from the available discharge measurements, none of which were made at a time when there was any overbank flow or flow over Prather Road. An excel plot of the available USGS discharge measurements was prepared by WSE and discussed at the meeting on March 27th. As concurred by the group, the lack of high flow discharge measurements from which to develop the high flow rating means that the upper end of the current rating curve is subject to greater uncertainty than if actual discharge measurements were available. In our opinion, discharges at higher stages (e.g. near the 100-year event) should only be considered accurate to within plus or minus 15% or so. Thus, the "observed" flow in the December 2007 flood event (79,100 cfs) could actually range between about 67,000 and 91,000 cfs.

2) Chehalis River along I-5 Upstream of Mellen Street

As discussed during the March 27th meeting, several changes were made to the model geometry near the Mellen Street Bridge. The small section of Long Road Dike immediately adjacent to I-5 was lowered and a connection was added between SA501 and SA5. Ineffective limits were added in the left overbank upstream of Mellen Street, at RS 67.86 through 67.59. Ineffective limits through the bridge itself were also modified to further constrict the upstream and downstream cross sections.

These changes had only limited effect on simulated water surface elevations upstream of Mellen Street Bridge. When constrictions were added to the Chehalis River, in the form of ineffective limits (changes to Manning's n and contraction/expansion coefficients were also briefly tested), water surface elevations in the vicinity of Mellen Street increased only about one tenth of a foot. However, more flow did overtop the lateral structures in the right overbank, which resulted in less flow in the Chehalis River.

WSDOT also provided new topographic survey data for I-5 and the airport levee. The lateral structure elevations in the model were revised to reflect the new survey data. The revision to the lateral structures resulted in minor changes to the simulated water levels in the main stem of the Chehalis River.

Considering the results of the model investigations in this area it appears that we would either need to make atypical changes to the modeling of the Mellen Street Bridge (such as arbitrary additional head losses) or increase the flows reaching the bridge in order to "hit" the higher of the high water marks upstream of the bridge. Increasing the flows would lead to problems with matching high water marks at other locations in the model so we do not feel that is a reasonable alternative. Similarly, we don't feel it is wise to insert arbitrary losses into the model simply to meet a few high water marks (bearing in mind that there are other, lower high water marks in the same area that we are already overshooting). Thus, we feel that the modeling in this area has been improved as much as possible and do not propose to make any additional changes.

3) Dillenbaugh Creek and Chehalis River Connections near Main Street and I-5

To better approximate December 2007 flood conditions near the Dillenbaugh Creek/Chehalis Junction, two lateral weirs (0.120 and 0.092) were added along Dillenbaugh to model flow entering the north- and southbound lanes of I-5 and flowing under the Highway 6 overpass. Weir elevations were based on 2012 survey completed by WSDOT. Additionally, the weir coefficient (C_d) for Main Street was reduced from 2.0 to 1.5 to approximate losses as water exiting Dillenbaugh flows through vegetation and around buildings on its path to Storage Area #303.

With these changes the model showed peak flow values of:

- 1870 cfs flowing over the Main Street weir (LS 0.187) between Dillenbaugh Creek and Storage Area #303
- 1710 cfs overtopping of the I-5 weir returning to the Chehalis River (LS 74.41, Chehalis Reach 9) and 30 cfs flowing through the culvert under I-5
- 165 cfs flowing from SA #303 to Dillenbaugh Creek via the northbound lanes of I-5
- 145 cfs flowing from Dillenbaugh Creek to the Chehalis River via the southbound lanes of I-5

A section of the I-5 weir (LS 74.41) was then lowered (as discussed during the March 27th meeting) to simulate the portion of I-5 that does not have a jersey barrier along its east side, and the failure of the centerline jersey barrier that occurred during the Dec 2007 flood event. This resulted in peak flow values of:

- 2378 cfs flowing over the Main Street weir
- 2552 cfs flowing over the I-5 weir or through the culvert back into the Chehalis River
- 176 cfs flowing from Dillenbaugh to SA #303 via the northbound lanes of I-5
- 87 cfs flowing from Dillenbaugh to the Chehalis via the southbound lanes of I-5

The maximum simulated depth of flow over I-5 in between SR-6 and NW West Street was about 2.0 ft, which may be somewhat high based on photographs we have seen from the 2007 flood. Additional model refinement might reduce the peak stages over the freeway in this area but it is not clear that there is enough information to definitively state how high the flow may have gotten and/or the direction and magnitude of breakout flows from Dillenbaugh Creek during the event. As such, no additional refinement to the model calibration was attempted.