Satsop River Riprap Removal Restoration Project

Report Prepared for:

Grays Harbor County

By:

WATERSHED SCIENCE & ENGINEERING

GEOENGINEERS

June 28, 2013

Acknowledgments

We would like to thank the following individuals who participated in this investigation:

- Russ Esses, Grays Harbor County Project Manager
- Terry Willis, Landowner and former Grays Harbor County Commissioner
- Wes Cormier, Commissioner, Grays Harbor County
- Greg Willis, Landowner
- Bill Goeres, Landowner
- Karl Goeres, Landowner
- Joel Rett, Port of Grays Harbor County
- Larry Willis, Landowner
- Michelle Cramer, WDFW

The following consultant staff participated in the project:

- **Watershed Science & Engineering**:

  Larry Karpack, Project Manager, Hydrology and Hydraulics

  Jeff Johnson, Hydraulics and Geomorphology

  Bob Elliot, Numerical Modeling, QA/QC

  Shaina Sabatine, Numerical Modeling, Hydraulics, GIS

  Erika Ottenbreit, GIS

- **GeoEngineers**:

  Joe Callaghan, Environmental Permitting Review

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Satsop River Riprap Removal and Restoration Project

Introduction

Grays Harbor County (County) is considering alternatives for removal of a riprap revetment on the left (east) bank of the Satsop River at a site approximately one mile downstream of State Highway 12. The intended goal of the riprap removal is to allow the river to migrate more freely within its channel migration zone, to restore floodplain function, and to reduce erosive forces on the west bank of the river and protect agricultural lands downstream of the project site.

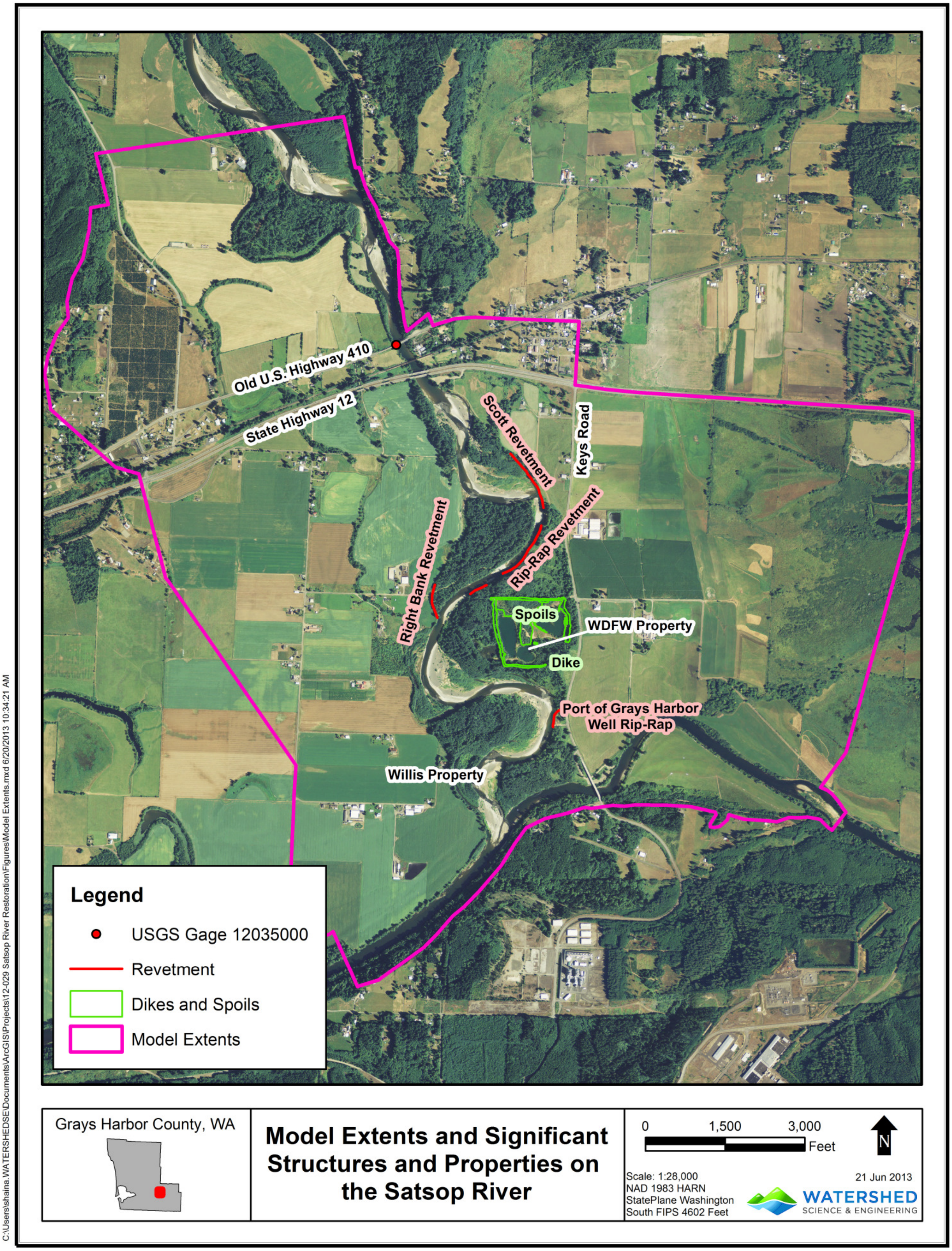
The County retained Watershed Science & Engineering (WSE) to conduct a river engineering and geomorphic evaluation to predict how the river might respond to removal of the riprap and what project alternatives warrant further consideration. The scope for the current work included the following tasks:

1. Project Coordination and Outreach
2. Hydrologic, Hydraulic, and Geomorphic Modeling and Analysis
3. Alternative Development and Selection
4. Permitting and Land Issues Strategy
5. Preliminary Engineering Design and Implementation Plan

WSE's work under Tasks 1-3 is described in detail below. Tasks 4 and 5 were not completed, as noted below, because the technical analyses conducted showed that removal of the riprap revetment is not recommended and therefore these tasks were not needed. However, additional efforts were conducted to evaluate a range of broader (reach-scale) project alternatives and provide recommendations for future work.

Project Setting

The Satsop River in the study reach (SR 12 to the Chehalis River) is constrained by several anthropogenic features including the Highway 12 Bridge and several riprap revetments. Figure 1 shows the project reach and key floodplain features including the primary left (east) bank riprap revetment (the focus of this project) and other revetments within the study reach. Within the fixed bounds provided by the revetments, the Satsop River has historically migrated aggressively in some locations, shifting laterally hundreds of feet in a few years, eroding tens of acres of farmland, and threatening homes and public and private infrastructure (Keys Road, WDFW boat ramp, Port of Grays Harbor well). In particular, the lateral movement of the river since 1997 appears to be more aggressive and widespread than what was seen between the 1940s and 1996. Channel migration, at least in the reach just downstream of SR 12, appears to have been exacerbated by significant sediment deposition during the March 1997 flood event. In addition to risks from lateral migration, the study reach is also prone to significant flooding from both the Satsop and Chehalis Rivers. Assuming that historical channel migration, bank erosion, and flooding continue, the study reach will continue to evolve over time. While future evolution is difficult to predict the current situation poses significant risks to Keys Road, the Port well site, and properties along the river.


Old U.S. Highway 410
State Highway 12
Scott Revetment
Keys Road
Rip-Rap Revetment
Right Bank Revetment
Spoils
WDFW Property
Dike
Port of Grays Harbor
Well Rip-Rap
Willis Property
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USGS Gage 12035000
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Dikes and Spoils
Model Extents
Grays Harbor County, WA
Model Extents and Significant Structures and Properties on the Satsop River
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Figure 1

Project Coordination

WSE coordinated with County staff and project Stakeholders throughout the project. This included the following meetings or coordination activities:

Project Kickoff Meeting – January 10, 2013 – met with Grays Harbor County staff and stakeholders to define project goals and objectives, refine scope of work, confirm schedule milestones, and identify deliverables. The kick-off meeting also provided attendees the opportunity to share information, data, concerns, or constraints they feel are important to the project.

WDFW Meeting – February 13, 2013 – met with Michelle Cramer of Washington Department of Fish and Wildlife (WDFW) to inform her of the current work and obtain WDFW files related to the previous USACE project.

Field Reconnaissance – February 13, 2013 – met with Terry Willis and toured the project reach from upstream of SR 12 to the confluence of the Satsop River with the Chehalis River. Collected field information and anecdotal information on flooding for calibration and validation of the hydraulic model.

Preliminary Results Review – March 20, 2013 – WSE staff coordinated a web based teleconference with County staff to discuss preliminary modeling results and findings. As a follow up to this teleconference WSE prepared and sent baseline model output examples to the County on 4/1/2013.

Presentation of Preliminary Results to Basin Stakeholders – April 9, 2013 – WSE and GeoEngineers staff met with County staff, Flood Authority members, and stakeholders to present findings of the preliminary modeling and analysis and discuss potential project alternatives.

Technical Share Sessions with Regulatory Agencies – May 15, 2013 – WSE and GeoEngineers staff met with County staff and stakeholders to discuss potential project alternatives and determine permitting issues related to these.

Flood Authority Meeting – May 16, 2013 – WSE staff met with the Chehalis River Basin Flood Authority to present the findings of the current project regarding removal of the riprap revetment and discuss additional project alternatives that warrant consideration in a future project.

Stakeholder Briefing – June 12, 2013 - WSE met with several landowners to get feedback on the meetings which took place in May, review the final alternatives matrix and discuss their thoughts for next steps. This meeting was followed up by discussions with County and Port of Grays Harbor staff.

Technical Analyses

Considering the objectives identified in the project scope and at the project kickoff meeting WSE undertook detailed technical analyses to evaluate the potential riprap removal. Hydrologic data were developed to quantify peak flows in the study reach and to provide input to the hydraulic modeling. A two dimensional (2D) hydraulic model was created to provide key hydraulic parameters including velocities and depths of flow under baseline conditions. Aerial photographs were reviewed to understand historical channel migration and bank erosion in the project reach and to provide information for future predictions. It should be noted that an earlier study by the US Army Corps evaluated restoration options including the potential for riprap removal. The current project makes use of the data developed for the Corps study, although because the river channel has shifted dramatically within the project reach a new analysis is required to evaluate potential impacts of the riprap removal.

Hydrologic Data Development

Hydrologic data is required for input to the hydraulic model being developed for this study. Peak flows and flow hydrographs are needed for the Satsop River and for the Chehalis River. Peak flows on the Satsop River were estimated based on frequency analysis of the data from USGS gage 12035000 Satsop River near Satsop, WA. Data are available at this gage from Water Year (WY) 1930 through WY 2012, a period of 83 years. The highest observed discharges in the period of record occurred in March 1997 (63,200 cfs), December 1999 (54,500 cfs) and December 1994 (50,600 cfs). Recent high flows include the event of January 2009 (45,500 cfs) and November 2012 (28,900 cfs). Peak flows on the Chehalis River were estimated previously by WEST Consultants (2012) based on frequency analysis of the USGS gage at Porter (gage 12031000). Peak flow quantiles are summarized in Table 1.

Table 1: Hydrologic Data

Location	Peak Discharge (cfs) for Return Period (years)				
	2-year	10-year	25-year	100-year	500-year
Satsop River near Satsop	26,000	41,400	48,400	58,000	68,300
Chehalis River at Porter	29,650	51,680	67,600	89,500	125,150

Hydrograph inputs for calibration of the hydraulic model were developed for the recent high flow events of January 2009 and November 2012. Data for the Satsop River were taken directly from the USGS gage near Satsop. For the Chehalis River, data were developed using the HEC-RAS unsteady model previously developed by WSE for the Chehalis River Basin Flood Authority (WSE, 2012). Data for these events from the USGS gage at Porter were input into the HEC-RAS model and routed downstream to the upstream end of the developed 2D model as described below. In addition, tailwater elevations on the Chehalis River at the downstream boundary of the 2D hydraulic model were extracted from the HEC-RAS output.

Design flood events corresponding to the 2-, 10-, 25-, 100-, and 500-year floods were also developed. These were created by extracting historical flow data from the USGS gages and scaling the data such that the peak flow for the design event matched the corresponding quantile listed in Table 1. For example, the 25-year design flood was developed by extracting the USGS data for the January 2009 event and scaling the data such that the Satsop River peak flow in the design event was 48,400 cfs. Since the observed peak flow for the 2009 flood was 45,500 cfs all data were scaled up by 1.06 (e.g. 48,400/45,500 = 1.06). Other design events were created using a similar process.

Hydraulic Modeling and Analysis

WSE developed a 2D hydraulic model of the Satsop River using the July 2012 release of the Bureau of Reclamation's Sedimentation and River Hydraulics – 2D model (SRH-2D). The model was created to facilitate analysis of hydraulic conditions under current (baseline) conditions and to allow evaluation of potential future project alternatives. The model was used to simulate several flood events including the recent observed floods of November 2012 and January 2009. Additional model runs were made to evaluate conditions during design flood events corresponding to the 2- through 500-year events. Hydrologic data for input to the model were developed as described in the preceding section. Details of the development and application of the hydraulic model are described below.

Model scope/domain

The SRH-2D model extends from about one mile upstream of State Highway 12 down to the Satsop River's confluence with the Chehalis River (about four miles). The model includes approximately two miles of the Chehalis River to allow simulation of interactions between the Chehalis River and the downstream end of the Satsop River. The upstream model boundary on the Satsop River was chosen to allow the model to appropriately simulate flow that splits from the main channel and flows through side channels and remnant channels in the right (west) overbank upstream of State Highway 12 (and ultimately through relief bridges under the railroad and Highway 12). The upstream and downstream model boundaries on the Chehalis River were chosen to be far enough away from the Satsop confluence to allow the 2D model to simulate the complex interactions at the confluence and also to correspond to cross section locations from the previously developed HEC-RAS model (WSE, 2012) so that hydraulic data could be extracted from that model to serve as boundary conditions in the 2D model. Figure 1 shows the model extents.

Model development

The 2D model requires detailed topographic information representing the entire channel and floodplain within the model extents. The following sets of data were available to create the most accurate and up to date topographic surface:

- LiDAR topographic coverage (2012)
- Aerial Photograph (2011)
- Surveyed cross sections along the Satsop River spaced 500-1000 feet apart (or closer at bends) collected in November 2011 by Pacific Geomatic Services for the Flood Authority
- Surveyed cross sections along the Chehalis River spaced 1000-2000 feet apart collected in November 2011 by Minister Glaeser Surveying for the Flood Authority

A detailed topographic surface was created by combining interpolated bathymetric in-channel surfaces for both the Satsop and Chehalis Rivers with the 2012 LiDAR coverage. Checks against the field survey showed that the LiDAR provided an accurate representation of elevations of channel banks, floodplains, and large in-channel gravel bars, vegetated bars, and islands. In-channel bathymetric (underwater) surfaces were produced by delineating 1-foot elevation contours using the survey and LiDAR data augmented by WSE's engineering judgment regarding typical channel forms. These contours were then interpolated to produce a bathymetric channel surface that adequately represents the survey and LiDAR data and known features and characteristics of these rivers. Figure 2 shows an area of the final topographic surface near State Highway 12 along with some surveyed cross section locations and delineated in-channel contours.

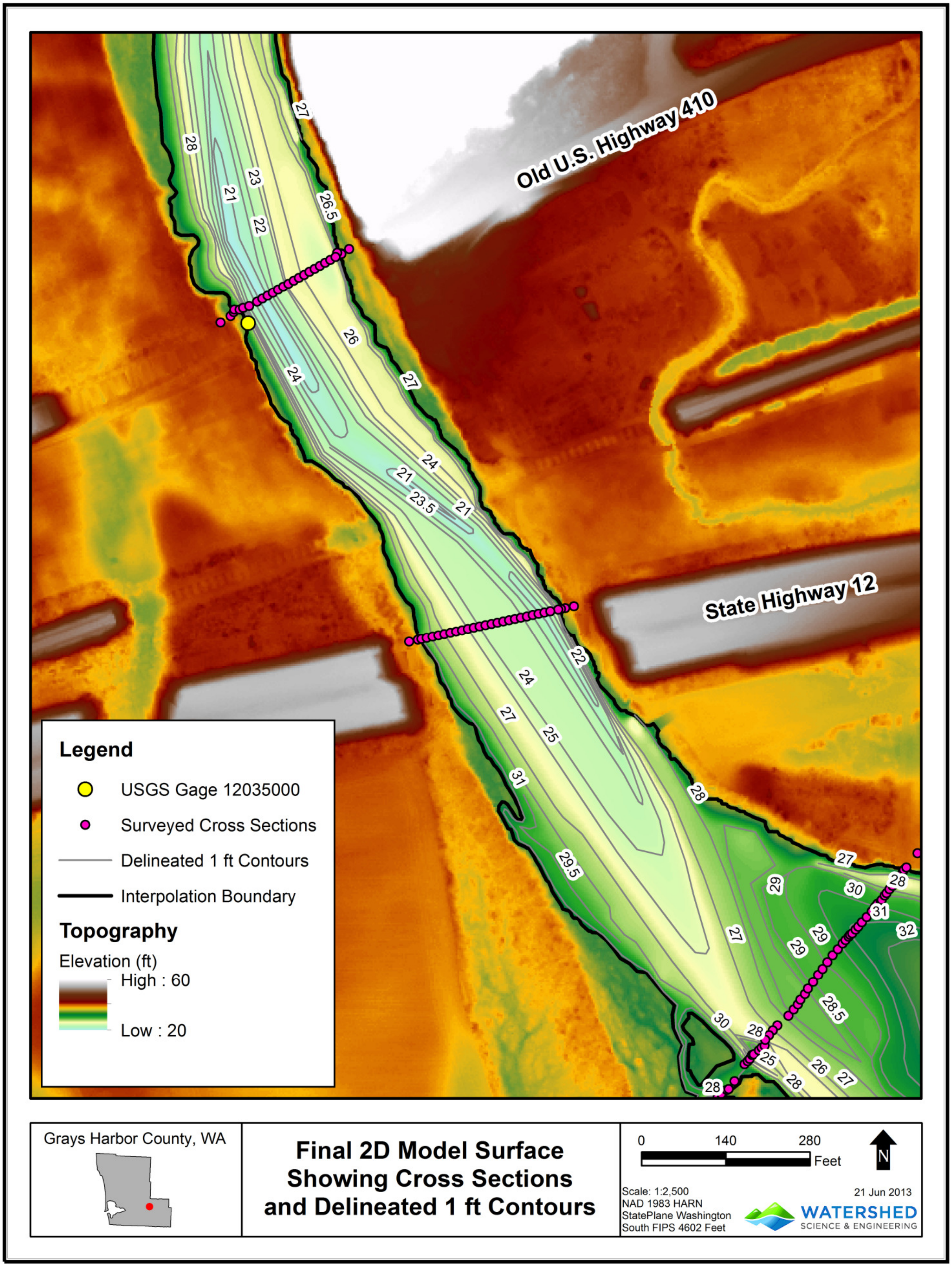
Old U.S. Highway 410
State Highway 12
Legend
USGS Gage 12035000
Surveyed Cross Sections
Delineated 1 ft Contours
Interpolation Boundary
Topography
Elevation (ft)
High : 60
Low : 20
Grays Harbor County, WA
Final 2D Model Surface Showing Cross Sections and Delineated 1 ft Contours
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Figure 2

The 2D model was then set up using Aquaveo's Surface-water Modeling System (SMS) interface. This process involves the development of a "conceptual model" to guide the creation of a "computational mesh". The conceptual model delineates significant in-channel and overbank features using polylines with carefully and regularly placed vertices to pick up elevations of important channel and floodplain features (e.g. bank lines, toe of slopes, levee tops, etc.) These lines form a series of breaklines that are used by SMS to create the model mesh. The model mesh consists of triangular elements (polygons) and nodes at which hydraulic model outputs are computed. The size of these elements are varied as necessary to capture complexity in the floodplain (i.e. smaller elements in complex areas such as the main channel and larger elements in less complex areas such as on the floodplain). Figure 3 displays an area of the final 2D model mesh near State Highway 12. It shows the conceptual model breaklines in this area along with computational nodes and elements of the final mesh.

Runtime and hydraulic parameters were then defined for the model. Runtime parameters define how long the simulation will be and how often computations are performed at the nodes. Hydraulic parameters define how the model distributes flow through the domain. The key hydraulic parameter is Manning's *n*, which is defined at each element to specify how "rough" the surface is. Manning's *n* can depend on many things including the general land cover, the size of the bed material in the channel, presence and density of vegetation, and other factors. The Manning's *n* parameter is the main parameter used to calibrate the hydraulic model to match observed flood conditions.

The model also requires definition of boundary conditions (flows over a period of time at each river inlet, water surface elevations over a period of time at the river outlet, and ground slopes at any area water leaves the model boundary over the floodplain) before a simulation can be started. The inflow for the Satsop River was based on the USGS gage but scaled up to account for water that splits and flows onto the floodplain before reaching and thus bypassing the gage. In this way the flow data from the USGS gage was used as a calibration measure (in addition to the stage information). The inflow for the Chehalis River was based on USGS gage 12031000 at Porter, WA, routed to the 2D model boundary using the previously constructed 1D HEC-RAS model as described previously. The water surface elevation at the outlet of the Chehalis was directly based on the HEC-RAS model result at the same location on this reach.

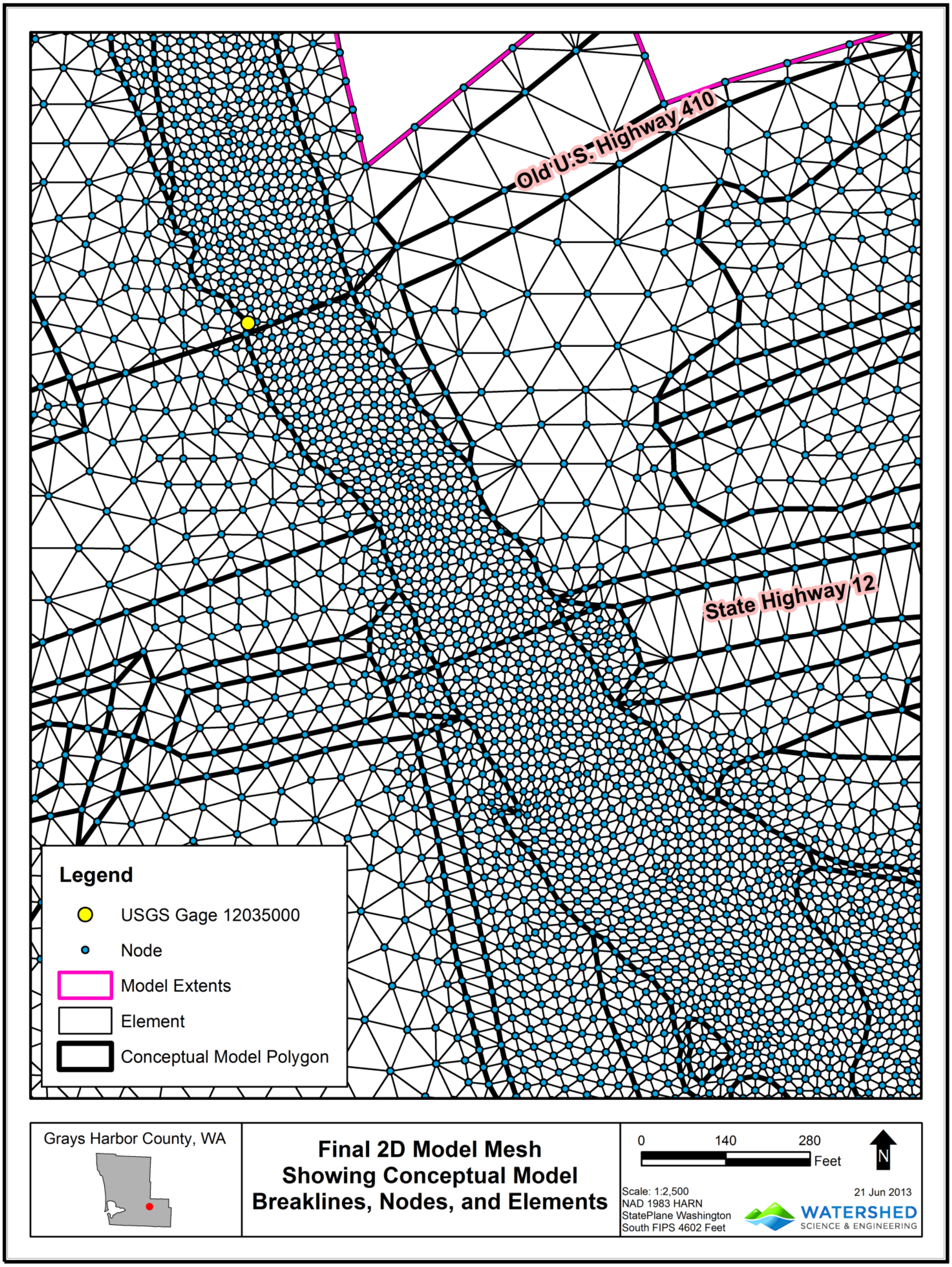

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Figure 3

Calibration

Two recent floods, in January 2009 and November 2012, were used as calibration events for the hydraulic model. Anecdotal observations for these flood events were obtained from property owners including approximate high water marks, indications of the extent and depth of the floodwaters, and whether or not flow overtopped specific structures such as Key's Road. The model was calibrated to match these anecdotal water surface elevations and observations as well as the measured flow and stage information from USGS gage 12035000 located on the right bank under the bridge on old U.S. Highway 410. In-channel Manning's *n* values were adjusted until the model matched the observed water surface elevations to a reasonable degree. Final calibrated channel *n* values range from 0.015 in less rough areas to 0.04 in rough areas with significant vegetation (like vegetated bars). Overbank n values range from 0.02 on roads to 0.1 in heavily forested areas.

A 2D model that simulates water surface elevations at calibration points within +/- 0.5 feet of the observed values is generally considered to be well-calibrated. Simulated water levels from the Satsop River model were found to be within +/- 0.5 ft of all observations for both the November 2012 and January 2009 events. Figures 4 and 5 show the measured and simulated water surface elevations at the USGS gage on the Satsop River for both of these events. While it might be possible to further refine the calibration it was not considered to be warranted to spend any more time to do so, as differences of up to 0.5 feet as remain in this modeling can often be attributed to various factors including:

1. Waves that cause fluctuations in actual water levels especially at higher flows
2. Localized topographic or hydraulic conditions finer than the resolution of the model
3. Errors in flow estimates (the USGS considers flow estimates within +/- 5 percent of actual flows to be excellent)
4. Uncertainty inherent in identifying high water marks along the channel after a flood event or from historical photos.

Figure 4: Comparison of measured and simulated water surface elevation for the November 2012 event.

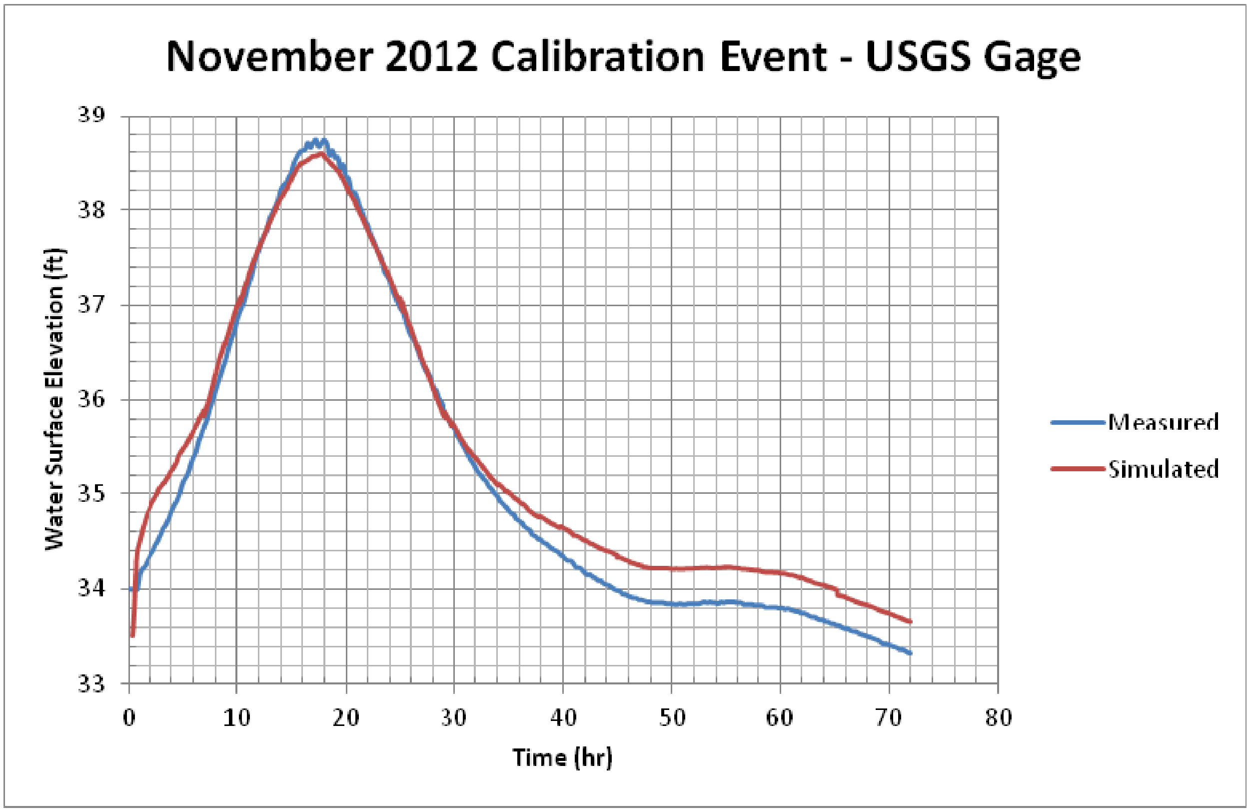
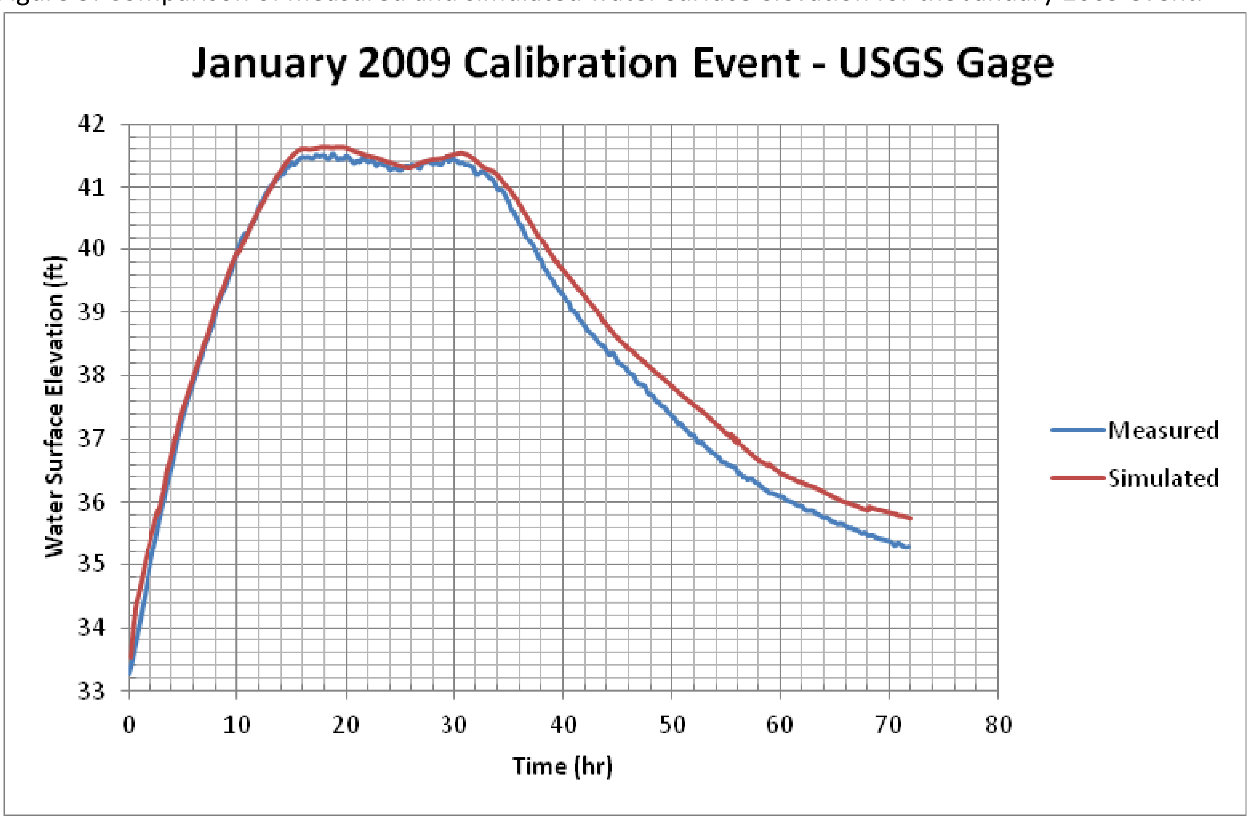


Figure 5: Comparison of measured and simulated water surface elevation for the January 2009 event.



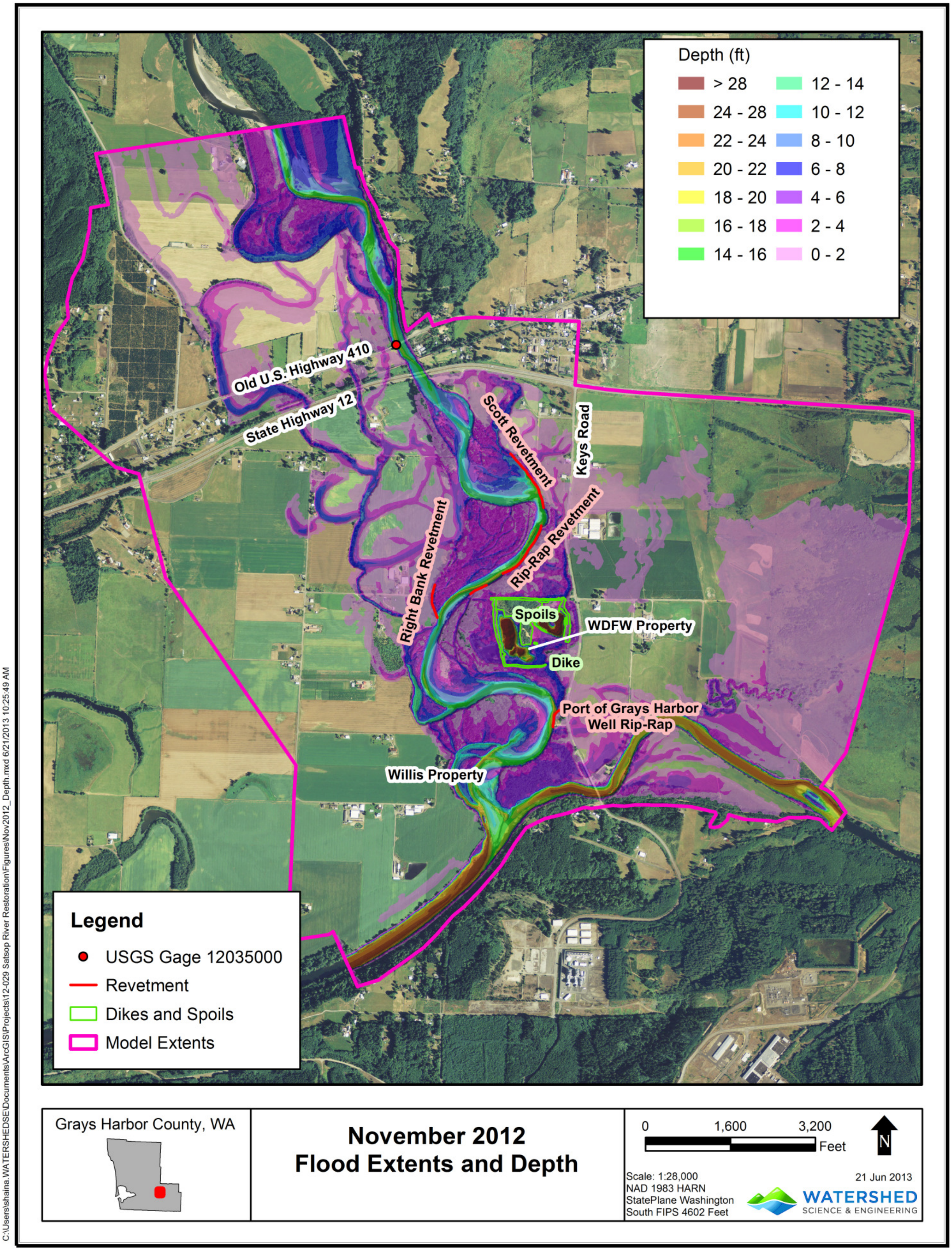
Model Application and Results

The model was used to simulate flow patterns and key hydraulic outputs (velocity patterns and flood levels) throughout the project reach for the November 2012 and January 2009 events as well as for several design flood events including the 2-year, 10-year, 25-year, 100-year, and 500-year floods. Example model outputs for the baseline conditions are shown in Figures 6 through 8.

Figure 6 shows the area of inundation and depth of flow at the peak of the November 2012 event (with approximately 28,900 cfs main channel flow at the Satsop River gage). The modeling for this event shows there is approximately 2,800 cfs on the left overbank, 7,800 cfs on the right overbank, and about 20,000 cfs in the channel near the downstream end of the revetment. The model and anecdotal information show that Key's Road is overtopped in several locations including about half a mile south of State Highway 12 near the Goeres farm, and near the Port of Grays Harbor Well site.

Figure 7 shows the area of inundation and depth of flow at the peak of the January 2009 event (with approximately 45,500 cfs main channel flow at the Satsop River gage). The modeling for this event shows there is approximately 9,600 cfs on the left overbank, 20,000 cfs on the right overbank, and 19,000 cfs in the channel near the downstream end of the revetment. Overtopping of Key's Road during the January 2009 event was much more significant, in terms of length and depth of overtopping, than in the November 2012 event.

Figure 8 shows the velocity magnitude and direction in the area of the failed revetment when approximately 16,800 cfs is flowing past the USGS gage. Simulated velocities are highest in this area when the in-channel flow is around this value. Velocities as high as 16 ft/s are seen flowing around the bend and into the left bank near the upstream end of the failed revetment. As will be discussed below, velocities of this magnitude would be expected to lead to additional bank erosion, which could exacerbate the existing riprap failure. Figure 9 shows a field photo of the existing failure along the primary riprap revetment while Figure 10 shows a failure of the riprap near the Port of Grays Harbor well site.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4 - 6
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Old U.S. Highway 410
State Highway 12
Scott Revetment
Keys Road
Rip-Rap Revetment
Right Bank Revetment
Spoils
WDFW Property
Dike
Port of Grays Harbor
Well Rip-Rap
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Legend
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Dikes and Spoils
Model Extents
Grays Harbor County, WA
November 2012
Flood Extents and Depth
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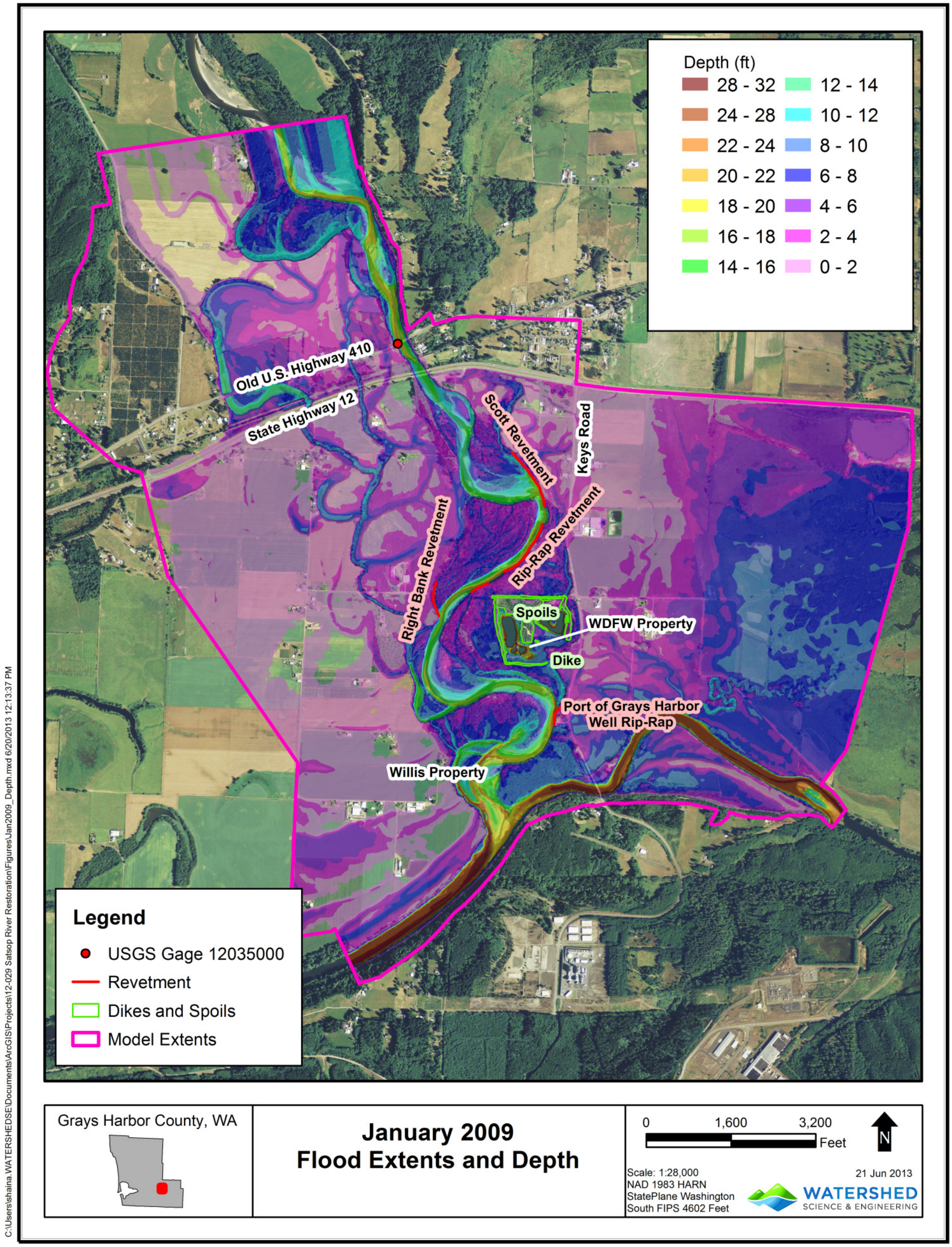
Figure 6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Grays Harbor County, WA
January 2009
Flood Extents and Depth
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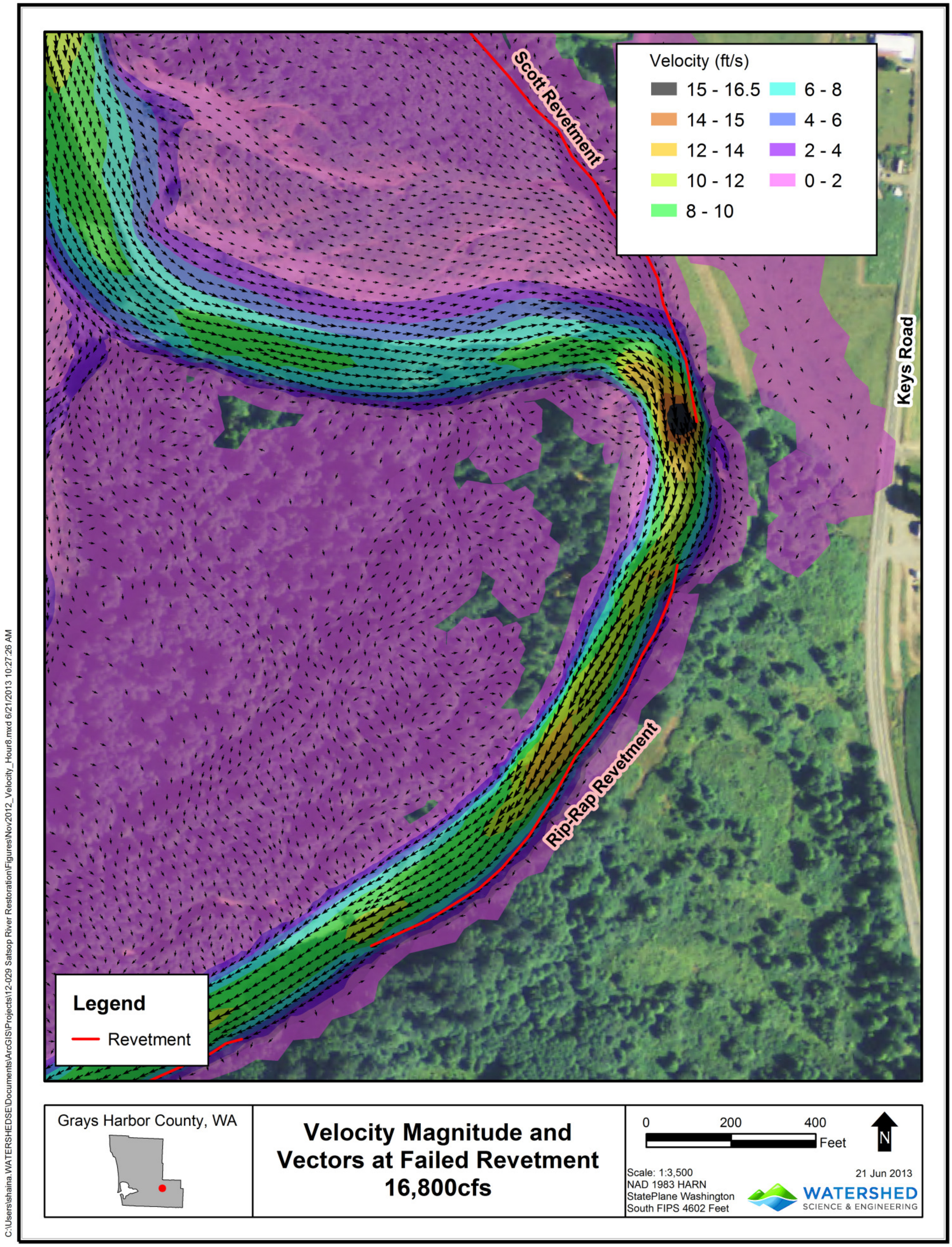
Figure 7


Velocity (ft/s)
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14 - 15
12 - 14
10 - 12
8 - 10
6 - 8
4 - 6
2 - 4
0 - 2
Scott Revetment
Keys Road
Rip-Rap Revetment
Legend
Revetment
Grays Harbor County, WA
Velocity Magnitude and Vectors at Failed Revetment 16,800cfs
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Figure 8

Figure 9: Riprap failure at upstream end of primary left bank revetment (photo date: February 13, 2013).

Figure 10: Riprap failure at upstream end of Port of Grays Harbor Well site revetment (photo date: February 13, 2013).

Future Application of the Model

This 2D model provides a tool that can be used for detailed hydraulic evaluation of potential alternatives. It is relatively easy to manipulate the topography to simulate proposed alternatives. Data generated with the model can be used to support professional judgment in predicting the response of the channel and overbank to these alternatives and provide data needed for future design of floodplain restoration projects. In addition to the baseline conditions simulated (described above) the model was modified and used to produce preliminary simulations of one potential alternative, where spoils piles and dikes on the property owned by WDFW were removed. While the results of this modeling are not discussed in detail, the work was undertaken to provide an example of the types of analyses that can be supported by the model.

Geomorphology and Channel Stability

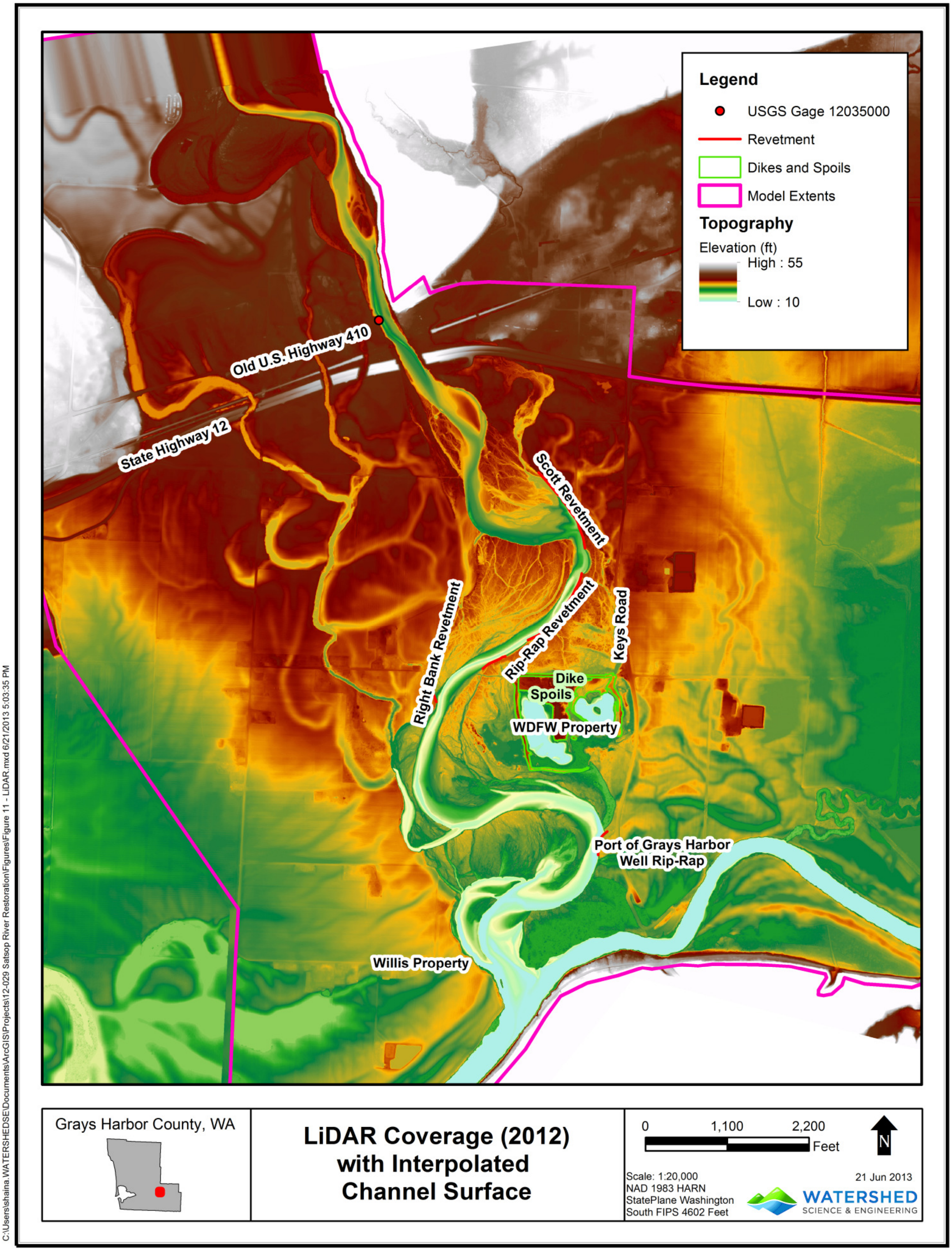
The Satsop River through the project reach flows across a large alluvial fan that is formed from sediment deposited by the Satsop River onto the floodplain of the Chehalis River. Prior to the construction of roads, rock riprap revetments, and earthen berms, the Satsop River was free to meander from one side of this fan to the other as revealed by the numerous remnant channel scars visible in historical aerial photographs and LiDAR imagery (see Figure 11). The freedom to move back and forth across the fan is now limited by the infrastructure along the study reach. The 2500-foot long riprap revetment that is the primary focus of this investigation has prevented migration of one reach of the river since about 1972 when the revetment was constructed and the river was essentially locked in place along it. This is shown in Figure 12, which documents historical river planform alignments delineated from aerial photographs. Prior to 1972 the river was actively migrating towards Keys Road at an average rate of about 20 feet per year; since the installation of the revetment the channel has not migrated any further at this location.

One objective of the current work was to determine whether removing all or part of the primary revetment would reduce bank erosion on the right bank downstream from the project. As shown in Figure 12, the river downstream is actively migrating which has resulted in the loss of high quality farmland and has the potential to erode more in the future.

WSE’s investigation concluded that bank erosion downstream from the revetment would not be reduced if all or a portion of the revetment is removed. Rather we concluded that bank erosion would most likely increase if the revetment were removed or significantly cut back. The planform in this reach of the river behaves much like the end of a fire hose, in that it meanders freely downstream of the point it is held in place. The further up the reach the river is held in place, the longer the uncontrolled section becomes and the larger the potential for meandering.

Bank erosion downstream from the revetment is also greatly influenced by the growth of existing gravel bars. As a bar grows, it will tend to “push” the river toward the opposite bank causing it to erode. The bars downstream from the revetment will continue to recruit material and therefore will continue to play a significant role in the lateral migration of the river channel.

Based upon these findings, we recommend that the riprap not be removed at this time.


Legend
USGS Gage 12035000
Revetment
Dikes and Spoils
Model Extents
Topography
Elevation (ft)
High : 55
Low : 10
Old U.S. Highway 410
State Highway 12
Scott Revetment
Rip-Rap Revetment
Right Bank Revetment
Keys Road
Dike
Spoils
WDFW Property
Port of Grays Harbor
Well Rip-Rap
Willis Property
Grays Harbor County, WA
LiDAR Coverage (2012) with Interpolated Channel Surface
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NAD 1983 HARN
StatePlane Washington
South FIPS 4602 Feet
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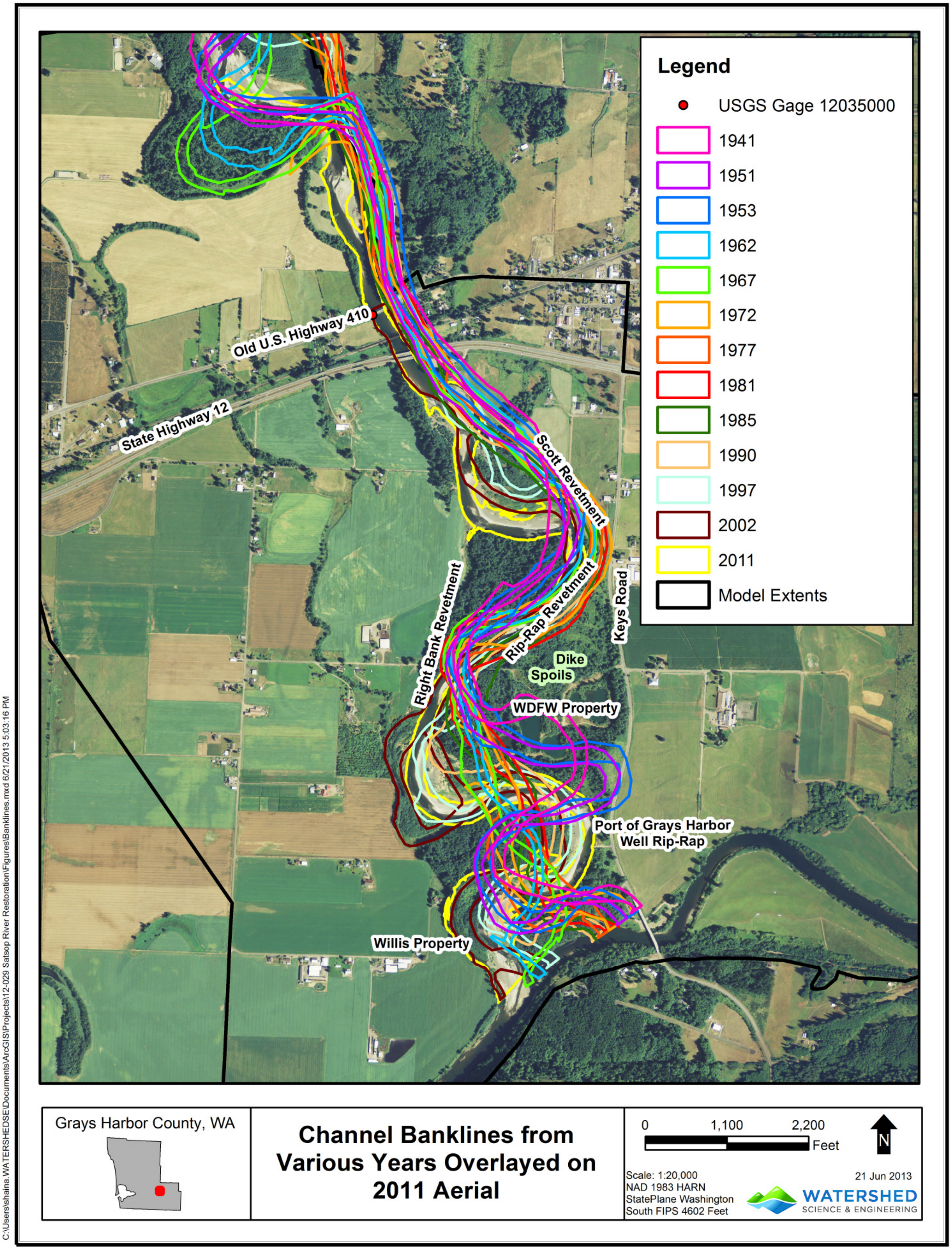
Figure 11



Legend
USGS Gage 12035000
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1997
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2011
Model Extents
Old U.S. Highway 410
State Highway 12
Scott Revetment
Rip-Rap Revetment
Right Bank Revetment
Keys Road
Dike
Spoils
WDFW Property
Port of Grays Harbor
Well Rip-Rap
Willis Property
Grays Harbor County, WA
Channel Banklines from Various Years Overlayed on 2011 Aerial
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Scale: 1:20,000
NAD 1983 HARN
StatePlane Washington
South FIPS 4602 Feet
21 Jun 2013
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Figure 12

Alternatives Analysis

The focus of the current project was an evaluation of options for removal of a revetment along the left bank of the Satsop River as a means of restoring connections to the floodplain, allowing additional channel migration, and reducing erosive forces on the right bank of the Satsop River downstream from the revetment. However, as described above, the hydraulic and geomorphic analyses conducted by WSE lead us to conclude that removal of the riprap could actually exacerbate ongoing river bank erosion along the right bank, which would be counter to one of the primary objectives of this project. Considering this conclusion, WSE recommends that the riprap revetment not be removed at present. Instead, we recommend that other actions be considered to achieve the project objectives. Although the current project did not have scope and/or budget to fully evaluate a range of broader alternatives WSE worked with stakeholders in the project reach to define various measures that might be undertaken to achieve the project objectives. The status quo (no action) alternative is described below. Following that, several elements that could be considered to improve conditions in the study reach are discussed. Most of these project elements were elicited from project stakeholders during the stakeholder meeting on April 9, 2013.

No Action Alternative

The Satsop River in the study reach (State Highway 12 to the Chehalis River) is constrained at several locations including the Highway 12 Bridge at its upstream end and several riprap revetments (as shown in the Figure 1). Although the overall condition of the revetments was not investigated in this project, several of them exhibit obvious failures over some portion of their length.

Within the constraints provided by the revetments, the Satsop River has historically migrated aggressively in some locations, laterally shifting hundreds of feet in a few years, eroding acres of farmland, and threatening homes and public and private infrastructure (Keys Road, WDFW boat ramp, Port of Grays Harbor well). In particular, the lateral movement of the river since 1997 appears to be more aggressive and widespread than what was seen between the 1940s and 1996. Channel migration, at least in the reach just downstream of Highway 12, appears to have been exacerbated by significant sediment deposition during the March 1997 flood event.

In addition to risks from lateral migration, the study reach is also prone to significant flooding from both the Satsop and Chehalis Rivers. The "No Action" alternative does not imply that current conditions will continue unchanged. Instead, it means that historical channel migration, bank erosion, and flooding will continue and this reach of the river will continue to evolve over time. While future evolution of the river in the study reach is difficult to predict the current situation poses significant risks to Keys Road, the Port's well site, the Willis property and residence, and the Scott property, among others. Also, as shown in the photographs in Figures 9 and 10, two of the revetments in the study reach have already failed over some portion of their extent due to river forces and these may be subject to additional problems.

Potential Project Elements

A range of project alternatives (elements) were suggested by stakeholders as potentially viable options for addressing concerns in the study reach. These range from those that focus primarily on reducing river bank erosion (installation of barbs), to ones that seek primarily to restore or enhance floodplain function (removal of spoils piles and dikes). Also included are several elements that target repairs to existing flood protection facilities in the study reach. The following general alternatives were identified:

- Removal or modification of main riprap revetment
- Removal or modification of right bank revetment
- Removal or modification of Scott revetment
- Protection of Keys Road
- Protection of Port of Grays Harbor Well
- Channel modifications to achieve project objectives
- Right bank migration control
- Protect right bank properties including Willis property
- Restore WDFW property

Alternatives Matrix

As noted above nine general project elements were identified for consideration. Several alternatives were identified for some of these elements. These are listed in the project alternatives matrix provided in Table 2. The project alternatives matrix lists each alternative, provides a brief description, summarizes potential benefits and impacts of the alternative (qualitatively), identifies implementation issues (permitting, cost, land acquisition), and provides a brief summary of considerations or next steps to further investigate the alternative.

Implementation Issues

The alternatives matrix provides an initial assessment of implementation issues for each of the alternatives. Qualitative assessments (high, medium, low, none) of the permitting complexity, potential cost, and land acquisition requirements are provided. These assessments were prepared by the study team (WSE and GeoEngineers) based on past work on similar projects and our understanding of the scope and complexity of each of the conceptual alternatives. These assessments would be refined in the future as project alternatives are developed and analyzed.

Riprap Project Recommendation

The current project was undertaken to evaluate options for removal of a revetment along the left bank of the Satsop River and to prepare preliminary designs and cost estimates for the removal. However, hydraulic and geomorphic analyses conducted by WSE lead us to conclude that removal of the riprap could:

1. Reduce erosion protection for Key's Road and properties to the east of Key's Road putting these at greater risk
2. Exacerbate ongoing bank erosion along the right bank, which would be counter to one of the primary objectives of this project
3. Allow the river to migrate in an unconstrained manner towards the southeast and capture the off channel ponds on the WDFW property
4. Potentially put the Port of Gray's Harbor well site at greater risk from river erosion

Table 2: Project Alternatives Matrix

Element	Potential Actions	Description of Action	Potential Benefits of Action	Potential Consequences of Action	Implementation Issues	Discussion of Actions
Overview of No Action Alternative						
No Action	The Satsop River in the study reach (SR 12 to the Chehalis River) is constrained at several locations including the Highway 12 bridge at its upstream end and at least 4 riprap revetments (as shown in the Figure 1). Although the overall condition of the revetments has not been investigated, several of them exhibit obvious failures over some portion of their length. Within the constraints provided by the revetments, the Satsop River has historically migrated aggressively in some locations, laterally shifting hundreds of feet in a few years, eroding tens of acres of farmland, and threatening homes and public and private infrastructure (Keys Road, WDFW boat ramp, Port of Grays Harbor well). In particular the lateral movement of the river since 1997 appears to be more aggressive and widespread than what was seen between the 1940s and 1996. Channel migration, at least in the reach just downstream of SR 12, appears to have been exacerbated by significant sediment deposition during the March 1997 flood event. In addition to risks from lateral migration, the study reach is also prone to significant flooding from both the Satsop and Chehalis Rivers. The "No Action" alternative included in each element below should not be taken to imply that current conditions will continue unchanged. Instead it means that historical channel migration, bank erosion, and flooding will continue and the reach will continue to evolve over time. While future evolution of the river in the study reach is difficult to predict the current situation poses significant risks to Keys Road, the Port of Grays Harbor well site, the Willis property and residence, and the Scott property, among others.					
Rip-rap revetment	No Action					
	Complete removal	Remove the entire rip-rap revetment.	Removal of the entire rip-rap revetment will free the river to migrate in this reach and would increase river connectivity with the left bank including portions of the WDFW property. This may reduce flow in the main channel and in the right overbank.	If the entire revetment is removed it is likely that the current river bend along the revetment will shift to the east and southeast, which will threaten Keys Road. Ultimately the bend may migrate far enough to encroach upon the WDFW property and may capture the WDFW ponds. Responses in other parts of the system, including the west bank downstream of the rip-rap revetment, may be seen although these are more difficult to predict. Removal of the revetment will require significant disturbance to the river bank and riparian vegetation.	Permitting Complexity: Moderate Anticipated Cost: High Land Acquisition: None	Risk to Keys Road is high. Would require additional modeling and analysis if pursued.
	Partial Removal	Remove a portion of the revetment (approximately 500-1000 feet) at its southwest end.	Removal of a portion of the revetment will increase the river connectivity with the left bank including portions of the WDFW property. This may reduce flow in the main channel and in the right overbank. The northeast portion of the revetment would be retained (and repaired) to continue to provide protection to Keys Road.	Channel response along the west bank downstream of the rip-rap revetment is difficult to predict. Areas where the revetment is removed will require significant disturbance to the river bank and riparian vegetation.	Permitting Complexity: Moderate Anticipated Cost: Moderate Land Acquisition: None	Requires additional modeling and analysis to evaluate benefits/impacts and to refine design.
	Lower bank elevation or create notches	Lower the bank elevation or create notches (small overflow sections) in the left bank of the river along the revetment but leave the riprap in place to prevent lateral migration of the river.	Lowering the crest of the left bank or creating notches in the bank along the riprap would temporarily increase river connectivity with the left bank floodplain including portions of the WDFW property.	If the revetment is not removed, and the river is held in place at its current location, the river will, over time, deposit sediment along the top of this bank filling any created notches and/or raising the ground elevation of a lowered bank. This action would require disturbance to river bank and riparian vegetation along some or all of the revetment.	Permitting Complexity: Moderate Anticipated Cost: Moderate Land Acquisition: None	Short term impact to riparian corridor may exceed potential benefit. Would require additional modeling and analysis if pursued.
	Partial removal and lower crest	Combine removal of some portion of the rip-rap with lowering of the crest of the remainder of the left bank.	Would gain the benefits of both the partial rip-rap removal and lower bank elevation actions.	Would require significant disturbance to river bank and riparian vegetation. Long term it is uncertain how effective lowering the bank crest will be in reconnecting the floodplain.	Permitting Complexity: Moderate Anticipated Cost: Moderate Land Acquisition: None	See above
	Repair failure near upstream end	Replace and repair riprap at the point near the upstream end of the revetment that has failed. Rebuild bank to pre-failure conditions.	Repair of the recent failure would restore the previous erosion protection to Keys Road and the surrounding properties.	This action would require work in the channel.	Permitting Complexity: High Anticipated Cost: Moderate Land Acquisition: None	Required to restore historical protection to Keys Road. Would require additional modeling and analysis.
Right bank revetment	No action					
	Remove	Complete or partial removal of the riprap revetment along the right bank across from the primary revetment.	Removal of this revetment would likely allow the river to migrate to the west.	This revetment currently deflects and redirects flow to the south and prevents the river from migrating towards the west. Removal of the revetment could lead to substantial loss of farmland.	Permitting Complexity: Moderate Anticipated Cost: Moderate Land Acquisition: None	Little benefit and high potential risks. Would require additional analysis if pursued.
Scott revetment	No action					
	Remove	Complete or partial removal of the riprap revetment along the left bank upstream from the primary revetment.	Removal of this revetment would allow the river to migrate to the east .	This revetment currently deflects and redirects flow to the south and prevents the river from migrating to-the east. Removal of this revetment could allow the river to outflank the downstream revetment, erode substantial farmland, and/or threaten Keys Road.	Permitting Complexity: Moderate Anticipated Cost: Moderate Land Acquisition: None	Little benefit and high potential risks. Would require additional analysis if pursued.
	Relocate or reconfigure	Change the location or orientation of the revetment to better accommodate today's flow conditions.	Reconfiguration of the revetment could improve hydraulic conditions reducing the potential for failure of this revetment or the downstream revetment. This would enhance protection for Keys Road.	This action would require work in the channel which may be difficult to permit.	Permitting Complexity: High Anticipated Cost: High Land Acquisition: Moderate	Likely high cost with limited apparent benefit. Would require additional modeling and analysis if pursued.
Keys Road	No action (Emergency Repairs only)	Status quo				Address problems if they arise.

Table 2: Project Alternatives Matrix (continued)

Element	Potential Actions	Description of Action	Potential Benefits of Action	Potential Consequences of Action	Implementation Issues	Discussion of Actions
Port of Grays Harbor Well	No action					
	Relocate Well and remove rip-rap	Relocate the Port well to a new site away from the Satsop River.	Relocation of the well would eliminate risks associated with Satsop River bank erosion. It would also allow the existing protective revetment to be removed, allowing channel migration.	The current protective revetment to the west of the well site provides some protection to Keys Road which would be lost if the rip-rap were removed. Channel responses in other parts of the system, including the west bank downstream of the rip-rap revetment, are difficult to predict with any certainty.	Permitting Complexity: Low Anticipated Cost: High Land Acquisition: None	High cost (evaluation is beyond the scope of the current study).
	Repair rip-rap failure	A section of the current riprap has slumped several feet indicating a possible problem with the stability of the protection.	The cause and extent of the current problem would be investigated and a repair designed. The repair would seek to restore the revetment to its original design condition.	The cause and extent of the current problem would be investigated and a repair designed. The repair would seek to restore the revetment to its original design condition and address future channel changes.	Permitting Complexity: Moderate Anticipated Cost: Unknown Land Acquisition: None	Localized problem that should be evaluated, but is beyond the scope of the current study.
	Extend rip-rap to tie in to Keys Road	The river is currently migrating to the east near the upstream end of the revetment. This option would extend the revetment to Keys Road to prevent the river from outflanking the well site.	This option would enhance the protection of the well and Keys Road.	Channel responses in other parts of the system, including the west bank downstream of the rip-rap revetment, may occur if the revetment is modified. However these are difficult to predict with any certainty.	Permitting Complexity: Moderate Anticipated Cost: Moderate Land Acquisition: None	Additional localized enhancement of the well bank protection could be investigated.
Channel modifications	No action					
	Bar scalping	Removal of gravel from specific bars in the study reach.	Targeted gravel removal could temporarily reduce the propensity for the river to migrate which could reduce bank erosion and loss of floodplain property.	This action would require work within the ordinary high water line and may be difficult to permit.	Permitting Complexity: High Anticipated Cost: Low Land Acquisition: None	Additional modeling and analysis could be undertaken to evaluate benefits.
	Initiate avulsions	Cut pilot channels at targeted location in the floodplain to initiate chute cutoffs	Avulsions could temporarily reduce the meandering of the river which could reduce bank erosion and loss of floodplain property.	This action would require work within the ordinary high water line and will be difficult to permit. It will also be difficult to predict, with any certainty, the channel response to an avulsion and as such some properties may be harmed by the action.	Permitting Complexity: High Anticipated Cost: Low Land Acquisition: None	If permitable, this action would likely provide some short term benefit. Longer term response of the river is difficult to predict. Would require additional analysis.
Bank Migration Control	No action					
	Add barbs	Install rock barbs throughout the study reach to contain channel migration to the current planform.	Maintenance of the current planform of the river (minimizing channel migration), if accomplished, would provide the greatest certainty with respect to future flooding and erosion.	Widespread use of barbs to control river migration would be extremely expensive and difficult to permit.	Permitting Complexity: High Anticipated Cost: Very High Land Acquisition: Unknown	High cost and low permitting potential. Would require significant additional modeling and analysis.
	Add Engineered Log Jams (ELJs)	Install engineered log jams throughout the study reach to contain channel migration to the current planform.	Maintenance of the current planform of the river (minimizing channel migration), if accomplished, would provide the greatest certainty with respect to future flooding and erosion.	Widespread use of ELJs to control river migration would be extremely expensive and difficult to design in a manner that would be effective.	Permitting Complexity: High Anticipated Cost: High Land Acquisition: Unknown	High cost and uncertainties in long term performance. Would require significant additional modeling and analysis.
Willis property	No action					
	Purchase land/relocate house	Purchase land and home and allow erosion to continue unabated. Relocate house outside the future meander belt and floodplain of the Satsop River.	Would allow river to migrate freely and enhance public safety. Might eliminate the need for some other actions.	Would require longtime residents to relocate. Future unabated erosion might lead to significant loss of neighboring land and/or an avulsion outside the current channel migration zone	Permitting Complexity: Low Anticipated Cost: Moderate Land Acquisition: High	Option could be evaluated, no additional analysis required.
	Localized bank protection	Design and install bank erosion countermeasures to protect the home from current and future erosion threats.	Would reduce public safety risks and minimize loss of valuable farmland at this location.	Localized bank protection may lead top problems elsewhere in the system. Could be expensive relative to the value of the land. Could be difficult to design in a manner that would be completely effective in the future.	Permitting Complexity: High Anticipated Cost: High Land Acquisition: Unknown	Conceptual design and preliminary cost estimate could be developed.
WDFW Property	No Action					
	Remove dikes and spoils	Remove placed fill on the property to enhance connectivity to the river and improve floodplain conveyance.	Might reduce flow on right bank west of WDFW site which could reduce the likelihood of future bank migration. Removed material could be used to fill in portions of ponds to enhance habitat.	Might allow a headcut to form reaching the Satsop River and leading to a channel avulsion through the property.	Permitting Complexity: Low Anticipated Cost: Moderate Land Acquisition: None	Combine with pond connections as in USACE 2004. Would require significant additional modeling and analysis.
	Connect ponds	Dig shallow channels to connect floodplain ponds to each other and/or to the Satsop River.	Improved hydraulic connectivity could enhance floodplain habitat.	None identified	Permitting Complexity: Low Anticipated Cost: Moderate Land Acquisition: None	Combine with dike and spoils removal as in USACE 2004. Would require significant additional modeling and analysis.
	Remove dikes and spoils and connect ponds	Combine previous two actions (as in USACE 2004 Study Alternative 3B)	Benefits as described for separate actions above.	Potential consequences as described above.	Permitting Complexity: Low Anticipated Cost: Moderate Land Acquisition: None	Perform additional modeling and analysis to evaluate benefits and risks of this alternative.

Considering these conclusions, WSE strongly recommends that the riprap revetment not be removed at this time. Note that the US Army Corps of Engineers reached a similar conclusion, i.e. that removal of the riprap revetment was too risky, in 2004 (WEST, 2004). Consideration should also be given to repairing the existing failure at the upstream end of the revetment to reduce the potential for a channel avulsion and restore protection to Key's Road.

Summary and Conclusions

Grays Harbor County sought an evaluation of alternatives for removal of a riprap revetment on the Satsop River. The objectives of the project include restoring floodplain function while reducing erosive forces on the west bank of the river and protecting agricultural lands downstream of the project site. Considering the hydraulic and geomorphic analyses described above WSE concluded that removal of the riprap could substantially increase risks to infrastructure and property along the study reach. Therefore, removal of the revetment is not recommended. Instead, WSE, in consultation with Grays Harbor County and project stakeholders, developed a matrix of actions that could be considered to help achieve the project objectives. These are summarized in the alternatives matrix in Table 2.

Future work will be required to evaluate potential actions and develop a package of actions that can enhance protection of infrastructure and farmland while improving habitat along the project reach. Several actions, such as removing the spoils piles and dikes on the WDFW property, should provide enhanced floodplain function. Other elements, such as repairing the primary revetment and the Port Well site revetment may be necessary to provide the historical level of protection to Keys Road and private properties to the east of the river. Finally, other elements, such as creating a pilot channel to promote an avulsion across the gravel bar near the Willis residence, should be evaluated to determine if these can be done in a manner that reduces bank erosion without negatively impacting aquatic habitat.

A package of actions, potentially including those mentioned here, should be refined and analyzed to identify a viable project alternative. The baseline analyses conducted for this study have improved our understanding of hydrologic and geomorphic conditions in the project reach, as needed to predict the river's response to potential actions. The hydraulic model developed for this study provides a useful tool for developing the hydraulic data needed to evaluate alternatives. In addition to technical analyses, the next phase of this project will require significant coordination with WDFW, both from a regulatory standpoint and as a major landowner along the study reach. Understanding WDFW's interests for their property is vital to developing a successful future project that can be embraced by all stakeholders.

References

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