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Detailed Hydrodynamic Assessment of Preferred Restoration Alternatives at Leque Island and zis a ba Sites, Stillaguamish Estuary

Phase III Report

Adi Nugraha
TP Khangaonkar

May 2018

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Pacific Northwest National Laboratory
Seattle, Washington 98109

Executive Summary

Since 2005, Pacific Northwest National Laboratory (PNNL) has supported Ducks Unlimited Inc. (DU) by providing hydrodynamic analyses of the Stillaguamish River estuary in connection with the feasibility assessment for the Leque Island Restoration project. Hydrodynamic feasibility analysis addresses the capability of the proposed actions to restore tidal functions such as allowing periodic inundation, providing suitable currents, water depth, and desired habitat/salinity levels, and examining sediment impacts, including the potential for excessive erosion or sedimentation that would require maintenance. During Phase I of the Leque Island Restoration assessment, a hydrodynamic model of the site, including Skagit Bay, Port Susan Bay, and the interconnecting region of Leque Island, was developed. The model was used to simulate tidal inundation, tidal currents, and salinity intrusion in the study area for the existing conditions and evaluated potential hydrodynamic changes following future restoration in Leque Island (Battelle 2007). In 2014, DU in collaboration with Washington State Department of Fish and Wildlife, and the Stillaguamish Tribe of Indians (Stillaguamish Tribe) initiated a Phase-II investigation. The objective was to evaluate cumulative effects of restoration at two separate sites near the river mouth. PNNL updated the Phase-I model with new bathymetry and examined several restoration alternatives at the Leque Island as well as an adjacent project site called zis a ba. All scenarios provided estuarine response consistent with planned designs (Whiting and Khangaonkar 2015). As anticipated, increases in bed shear and velocities were noted at certain locations for all alternatives. The study also showed that the Leque Island and zis a ba project sites functioned independently of one another. Subsequently, the project team of DU, the Washington State Department of Fish and Wildlife, and the Stillaguamish Tribe selected their preferred restoration alternative designs at the Leque Island and zis a ba sites.

This study represents Phase III of the project during which the performance of the selected preferred restoration alternative at the Leque Island and zis a ba sites was examined through a final detailed hydrodynamic feasibility analysis. Prior concept-level restoration designs were updated to reflect detailed dimensions associated with proposed coastal restoration and construction actions involving dike removal and channel excavations. While assessing the potential hydraulic and sediment transport responses at the restoration areas and main river channels, the study also helps inform site-specific questions related to impacts of the selected restoration actions on neighboring infrastructure such as dikes, outfalls, and pipelines with respect to inundation, sedimentation, and erosion. The approach was to use the existing model of Port Susan Bay from Phase II, further update it with new bathymetry information available through the Stillaguamish Tribe and the U.S. Geological Survey, refine the grid in localized regions as needed to incorporate the proposed tidal channels and spur dikes or berms, and conduct model application to simulate the response of the *Preferred Restoration Alternative Scenario* to varying river-flow and tidal conditions. The preferred restoration designs also included the creation of a network of tidal channels at both sites to facilitate efficient drainage

The refined and updated model was first applied to existing conditions prior to restoration representing the *Baseline Scenario*. The predicted results were compared with observed data collected in Port Susan Bay near the mouth of the Stillaguamish River estuary in October 2005 as a validation step. The baseline simulation successfully reproduced coastal hydrodynamics in the intertidal region of interest in Port Susan Bay near the mouth of the Stillaguamish River that is tidally dominated with large variations in water-surface levels ($\approx$3 m range) and salinity (0 to 25 ppt). The baseline simulation also showed that the water levels in the Stillaguamish River distributaries entering Port Susan Bay (Hatt Slough and Old Stillaguamish River Channel [OSRC]) are sensitive to the respective distributary channel characteristics (thalweg depth and widths) over the tidal flats in Port Susan Bay. The salinity levels and intrusion upriver near the project sites at Leque Island and zis a ba on OSRC were sensitive to the fraction of fresh water split between Old Stillaguamish River and Hatt Slough.

Following this validation, the model was applied to test the response of the preferred alternative scenarios for typical estuarine flow conditions and high-flow (bank-full) conditions. Examination of the simulation results for the typical estuarine conditions of October 2005 shows that that Preferred Restoration Alternative Scenario at Leque Island and zis a ba results in immediate tidal response and restoration of estuarine functions in the Leque Island and zis a ba project sites with inundation and drainage of restoration sites each tidal cycle. The designed tidal channels functioned well serving as conduits during the flood as well as drainage of the sites during ebb. This result was consistent with results from prior assessments. The performance of the restoration sites was examined already in detail in Phase-II investigation and re-confirmed here with the detailed representation. The emphasis of this effort therefore was to examine closely the effect of the proposed action on the surrounding channels consisting of the Old Stillaguamish River, West Pass, and South Pass, which surround the restoration sites.

The results conclusively demonstrate that proposed Preferred Restoration Alternatives at Leque Island and zis a ba sites will likely not cause a significant change in the hydrodynamic behavior of the estuary. The project sizes and the locations are such that their impact on the overall estuarine exchange through the Old Stillaguamish Estuary Channels is relatively small. As a result, oceanographic properties of interest such as water surface elevations, velocities, salinity, and bed shear stress, are not significantly altered in the restored condition relative to the Baseline or existing conditions.

The results show mean water surface elevation in the estuarine channels for the Preferred Restoration Alternative Scenario is predicted to be ≈ 0.01 m lower relative to the Baseline Scenario. This indicates that there is a small decrease in pressure gradient relative to baseline conditions as the tidal prism is now distributed over the restored area. During incoming tide, flow through South Pass, instead of being restricted to the West Pass and Old Stillaguamish River, is partly distributed over the restored areas of Leque Island and zis a ba resulting in the small reduction in water surface elevations. This also results in similar small change to salinity levels. The results indicate that proposed restoration will likely decrease the amount of seawater intrusion into the Old Stillaguamish River, West Pass and South Pass channels. As a result, predicted salinities in the Preferred Alternative Scenario are ≈ 0.5 ppt lower than in the Baseline Scenario.

Examination of tidally averaged velocities and flows shows that outflow of freshwater from OSRC primarily occurs through the South Pass during ebb which also carries the majority of net outflow to Port Susan Bay and remains relatively unchanged in the Preferred Restoration Alternative Scenario. Results indicate that proposed restoration action will not result in significant changes in velocities at most locations however, an increase in peak velocity of up to ≈ 0.12 m/s during spring tide is predicted in South Pass at selected locations near the mouths of the tidal drainage channels for the Preferred Restoration Alternative Scenario.

At the Leque Island and zis a ba restoration sites, bed shear stress is predicted to be highest near the entrances of the tidal drainage channels. It is expected that the mouths of these tidal channels entrances will likely evolve until an equilibrium cross section is reached. The potential for erosion and flooding related damage was further examined using the bank-full river flow condition for the Baseline and Preferred Alternative Scenarios. Besides experiencing lower salinities during high river flow, the Leque Island and zis a ba sites also experienced increases in velocity magnitudes and bed shear stresses, especially in the main river channels relative to typical estuarine conditions. However predicted changes under Preferred Restoration Alternative Scenario relative to Baseline conditions are still small. During the high-flow condition, under Preferred Restoration Alternative Scenario, bed shear stresses in West Pass and South Pass are higher. In Old Stillaguamish River bend around zis a ba, decrease in bed shear is noticeable associated with reduced flow due to the fraction that is diverted through the tidal channels over east zis a ba site. However, these changes in bed shear are negligible relative to the typical magnitude of

bed shear stress under Baseline conditions which is significantly higher than that needed for movement of silt and sand, and therefore unlikely to cause increased scour or deposition.

Results do not show a further increase or reduction in water-surface levels or inundation as a result of restoration related change relative to the baseline for high-flow conditions.

Restoration projects such as these involve removal of dikes that allow tidal water to move up the previously diked off regions. During periods of high flow, high tides, and stormy conditions, the upland properties previously protected by the dikes may be at increased risk from increased proximity to open waters. To assess the potential for flooding of properties adjacent to project sites, an estimate of extreme high-water level was prepared. The maximum potential water level near the project site was estimated with consideration of the extreme high tide, wind-induced storm surge, significant wave height, and future sea level rise based on numerical model results and coastal engineering calculations. The maximum water level projections for a 100-year return period were 4.6 m and 3.9 m (above mean sea level, or 5.9 m and 5.2 m above NAVD88) for the Port Susan Bay and Leque Island sites, respectively. The differences are primarily from the different fetch lengths and associated differences in significant wave heights. Those extreme values were estimated under assumptions that the 100-year maximum wind was blowing following typical Pacific storms with the peak speed of 29.49 m/s in the same direction and the storm event would occur at the same time as the extreme high tide. It should be noted that the wind-induced surge was simulated under normal spring tide condition. These results helped validate the decision by the project team to retain the dike section along the southern back of West Pass to serve as a wave overtopping inundation barrier for City of Stanwood properties north of the project site.

Overall, simulation results indicate that the Preferred Restoration Alternative Scenario provides an estuarine response consistent with the planned design. The preferred restoration actions would result in relatively small changes in water surface elevations and salinity in the OSRC surrounding the restoration sites. Because of changes in the tidal prism from increased storage and drainage from the restoration sites, changes in velocity magnitude and associated bed shear stresses are predicted. At most locations in the surrounding river channels, under typical flow conditions, there is a small reduction in bed shear stress and a small increase in bed shear stress near the mouths of tidal drainage channels from the restoration sites. These changes in bed shear are negligible relative to the typical magnitude of bed shear stress under Baseline conditions which is significantly higher than that needed for movement of silt and sand. The overall conclusion based on the result is that tidal estuarine functions will be successfully restored at the Leque Island and zis a ba sites through the proposed actions and should lead to an increase in available tidal marsh area in the system. Also, impacts to existing circulation and estuarine characteristics would be relatively small.

Acknowledgement

Acronyms

CTD	Conductivity-Temperature-Depth
DU	Ducks Unlimited, Inc.
FVCOM	Finite Volume Coastal Ocean Model
LIDAR	Light Detection and Ranging
ME	Mean Error
MSL	Mean Sea Level
NAVD 88	North American Vertical Datum of 1988
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
OSRC	Old Stillaguamish River Channel
PNNL	Pacific Northwest National Laboratory
RM	river mile
RMSE	Root Mean Square Error
SPM	*Shore Protection Manual*
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
WDFW	Washington Department of Fish and Wildlife

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1.0   Introduction

1.1   Background

Puget Sound is a complex system of estuaries, basins, deltas, and habitats and home of large populations of birds, marine mammals, and fish. Puget Sound supports an enormous community of fishermen, hunters, nature enthusiasts, etc. Over the last 150 years, economic development in Puget Sound has resulted in significant losses of fish and wildlife habitat and alteration of habitat sustaining processes. A series of engineering activities such as construction of dikes for irrigation practices that took place over a period of approximately 100 years, has been recognized as one of the major causes of those habitat changes and losses. In addition, the condition of these historic perimeter dikes in many Puget Sound estuaries has deteriorated and has become a concern from a maintenance and economic perspective. Government agencies such as the Washington State Department of Fish and Wildlife (WDFW), the U.S. Army Corp of Engineers (USACE), and the National Oceanic and Atmospheric Administration (NOAA) along with sovereign Indian nations are actively evaluating near-shore tidal restoration as a potential long-term solution to the flooding and dike maintenance issue while also providing ecological benefits of restored tidal marsh habitat with the goal of recovering the salmon fishery in Puget Sound.

This study examines the feasibility of restoring historical tidal marsh habitat near the mouth of the Old Stillaguamish River Channel (OSRC). In collaboration with the WDFW and Stillaguamish Tribe, Ducks Unlimited Inc. (DU) has led an assessment of restoration at two project sites: 1) Leque Island and 2) zis a ba. That effort is the subject of this report (see Figure 1.1).
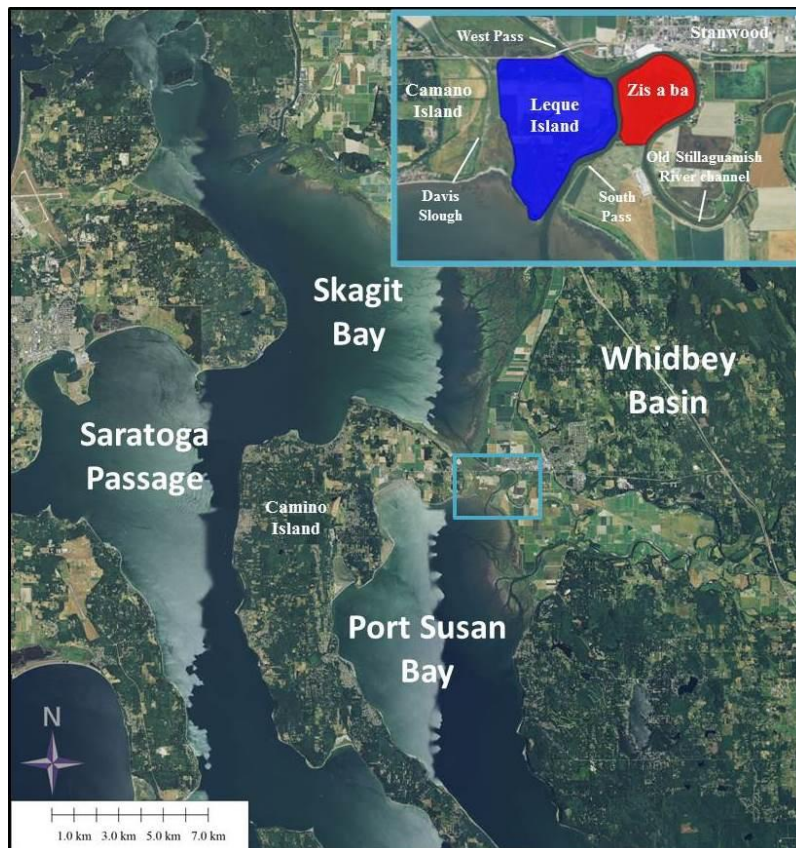
Figure 1.1. Location of the Leque Island and zis z ba Sites in Whidbey Basin

The goal of the restoration project is to provide estuary-rearing habitat for juvenile salmon, especially Stillaguamish and Skagit chinook populations that are protected under the Endangered Species Act. Since 2005, Pacific Northwest National Laboratory (PNNL) has assisted DU through various phases of feasibility assessment and hydrodynamic analysis to ensure that proposed dike and shoreline modification actions would provide the desired hydrodynamic response in terms of inundation frequency, water depth, currents, salinity, and result in conditions suitable for rearing juvenile salmon.

During Phase I of the project, PNNL developed a hydrodynamic model of Skagit Bay, Port Susan Bay, and the interconnecting region of Leque Island, the site and project originally proposed by DU for restoration (Yang et al. 2007). The model was used to simulate tidal inundation, tidal currents, and salinity intrusion in the study area for the existing condition and to evaluate potential hydrodynamic changes following future restoration in Leque Island. Hydrodynamic feasibility includes examination of capability of the proposed restoration to provide desirable restoration of tidal functions and sediment supply but without causing harmful impacts such as flooding or excessive erosion or sedimentation requiring maintenance. Only one restoration alternative was considered in the Phase-I hydrodynamic assessment—restoration of nearly 50% of the island (115 ac) south of Highway 532 by removing dikes or dike setbacks along South Pass and Davis Slough. The Phase-I effort showed that the proposed restoration action would successfully restore tidal function subject to daily inundation and salinity intrusion during high tides and would become a tidal flat during low tides. Erosion impacts were small, and currents over the restored site were within acceptable levels.

In Phase-II of the Leque Island Restoration project, DU in collaboration with WDFW and the Stillaguamish Tribe selected eight new restoration scenarios for feasibility assessment, with full restoration of Leque Island included. In addition to Leque Island restoration, these scenarios included restoration actions at an adjacent site named "zis a ba" (formerly known as Matterand). As in Phase I, PNNL supported DU by providing hydrodynamic modeling of the proposed scenarios. All scenarios included dike modifications such as existing dike removal, removal of previously damaged and repaired sections to create breaches, and construction of new setback dikes. The effects of proposed restoration actions on physical oceanographic parameters such as water surface elevations, currents, salinity, and bed shear stress were examined relative to existing conditions as part of this assessment. The proposed restoration scenarios also were subjected to high-flow conditions critical for assessing erosion impacts and long duration runs using a year-long record from 2003 when the highest number of flood flow events in recent years occurred. Based on Phase-II results (Whiting and Khangaonkar 2015), the indications were that proposed changes for most scenarios would provide an estuarine response consistent with the planned design. The results also showed that restored project sites at Leque Island and zis a ba provided an estuarine response independent of one another. The results from the scenarios were used by the DU project team, WDFW, and the Stillaguamish Tribe to select the preferred restoration actions with due consideration to feedback obtained at public meetings from approximately 30 local stakeholders.

This study—titled *Detailed Hydrodynamic Assessment of the Preferred Restoration Alternatives at Leque Island and zis a ba Sites, Stillaguamish Estuary*—is Phase-III of the Leque Island Restoration Feasibility Assessment. In this effort, PNNL further updated the model bathymetry using new data collected by the Stillaguamish Tribe and the U.S. Geological Survey (USGS). The configuration of the preferred restoration designs at the Leque Island and zis a ba sites were updated from the conceptual levels in Phase II to design and pre-construction level detail, and the updated information was incorporated into the modeling framework through further refinement. The model then was applied with a focus on site-specific questions related to impacts of the selected alternatives on neighboring infrastructure such as dikes, outfalls, and pipelines with respect to inundation, sedimentation, and erosion. The results were examined relative to the baseline at specified locations of interest. Also included in this study is an assessment of wave and storm-induced exposure to extreme high-water surface elevations from Port Susan Bay.

1.2　Study Area

Leque Island and zis a ba are former tidal marshlands that are located in the Old Stillaguamish River Delta between Skagit Bay and Port Susan Bay near the mouth of the Stillaguamish River estuary (Figure 1.1). The OSRC splits into two distributary channels along the eastern shoreline of Leque Island. West Pass of the Stillaguamish River on the northeast side of Leque Island is the main connection between Skagit Bay and Port Susan Bay. West Pass flows northwest around Leque Island into Skagit Bay. South Pass flows into Port Susan Bay along the southeast shoreline of Leque Island. The 90-ac zis a ba site is located northeast of Leque Island separated by South Pass. The Old Stillaguamish River mainstream bends around the east and north sides of zis a ba, separating zis a ba from the City of Stanwood to the north, while South Pass separates zis a ba from Leque Island to the west.

Perimeter dikes on Leque Island were originally built in the 1870s when three local citizens collaborated to purchase the land for farming (Conroy 2004). The land was later owned by other private farmers and eventually was sold to the WDFW in phases between 1974 and 2012. The WDFW currently owns the 294-acre site except for Highway 532, which runs across the northern end of the island. Contract farmers annually plant cereal grains as food for wintering waterfowl, providing bird watching, bird dog training, and pheasant and waterfowl hunting for the public. On the other hand, zis a ba currently is owned by the Stillaguamish Tribe. The tribe purchased the property along the Stillaguamish River in 2012 and named it zis a ba after a former tribal chief.

1.3　Study Objectives and Approach

The overall objective of the Leque Island and zis a ba Restoration Feasibility Modeling Study in Phase III is to evaluate the performance and hydrodynamic response of a selected preferred restoration design to ensure feasibility of successful restoration of tidal marsh habitat suitable for rearing juvenile salmon. While assessing the potential hydraulic and sediment transport impacts to the restoration areas and main river channel, the evaluation focuses also on site-specific questions related to impacts of the preferred alternative design on neighboring infrastructure such as dikes, outfalls, and pipelines with respect to inundation, sedimentation, and erosion.

The approach was to use the hydrodynamic model of Port Susan Bay and Skagit Bay developed during Phase II of the project (Whiting and Khangaonkar 2015), suitably updated with new bathymetry information available through the Stillaguamish Tribe and USGS, to first simulate existing (pre-restoration conditions) to serve as the baseline for comparison with the preferred restoration conditions. The preferred restoration condition consists of modified bathymetry and topography of the study area. In particular, perimeter dikes at the Leque Island and zis a ba sites would be removed or breached to allow restoration of tidal processes and periodic inundation and dewatering during ebb and flood. To facilitate drainage of the site during ebb, tidal channels were incorporated per designs developed by Hood (2015) from allometric analysis of tidal channel planform relative to marsh areas coupled with LIDAR data, the number, location and size (i.e., width and length) of tidal channels for Leque Island were computed. At the zis a ba site, in addition to tidal drainage channels, placement of a berm in the middle of the site was proposed resulting in a division of the site into two sub-basins. The berm placement was driven by the need to protect an underground wastewater outfall line. Figure 1.2 is a schematic representation of the dike and tidal channel configuration for (a) Baseline Scenario corresponding to existing pre-restoration condition and (b) Preferred Restoration Alternative Scenario corresponding to post restoration condition as evaluated in this report.
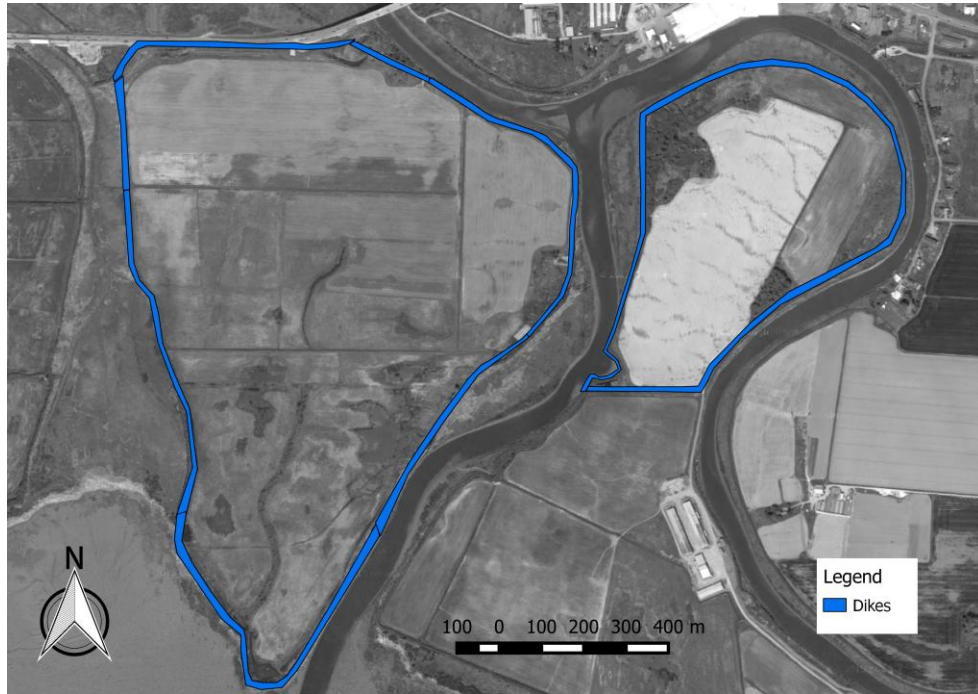
(a) Baseline Scenario
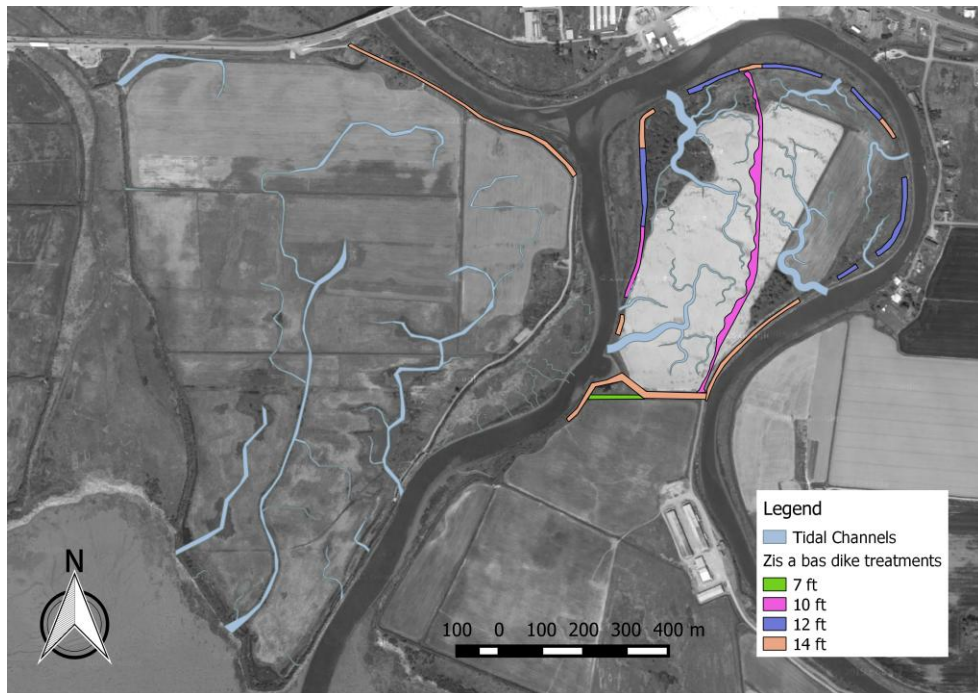
(b) Preferred Alternative Scenario

Figure 1.2. Schematic Representation of (a) the Baseline Scenario and (b) the Preferred Restoration Alternative Scenario

As highlighted in Figure 1.2, the Baseline Scenario includes the perimeter dike intact that prevents tidal access to the region behind the dike. Under Preferred Alternative Scenario, the perimeter dike has been removed, lowered, or breached. At both sites, a portion of the original dike has been retained to provide a river training benefit and protection from wave induced inundation and overtopping. The locations of the tidal drainage channels are indicated. Also included in this study is an assessment of wave- and storm-induced exposure to extreme high-water surface elevations from Port Susan Bay. The Leque Island restoration site has an exposure to the southerly fetch from Port Susan Bay. Storm-induced waves and extreme tidal elevations have previously affected the delta and urban infrastructure in the restoration site. The objective was to assess the potential for inundation of properties north of the project site to help evaluate the need for retaining the spur dike on the northeast boundary of Leque Island along the southern shore of the West Pass of the Old Stillaguamish River.

In summary, the scenarios evaluated in this study are briefly described below, while more detailed descriptions of the modifications at the study sites are provided in Table 1.1.

- The *Baseline Scenario* refers to the existing conditions, which will maintain the current river system by permanently repairing failed dikes on Leque Island.

- The *Preferred Restoration Alternative Scenario* involves full restoration of Leque Island, removing all dikes on the southern side of the island, and retaining a spur dike along the northeastern border of the island.

Table 1.1. Descriptions of the Proposed Restoration Scenarios at the Leque Island and zis a ba Sites

Description	Leque Island	zis a ba
Baseline	Existing Conditions	Existing Conditions
Preferred Alternative – Full restoration at Leque Island and zis a ba sites	Partial removal of existing dike (retaining northeastern spur dike), creation of tidal channels, filling existing ditch and borrow area	Partial removal of existing dike, lowering the perimeter dike elevation, creation of tidal channels, construction of a berm, filling existing ditch and borrow area

2.0 Hydrodynamic Model Setup and Validation

2.1 Model Setup

In this section, refinement and validation of the three-dimensional hydrodynamic model of Skagit Bay, Port Susan Bay, and the interconnecting region of Leque Island are described. The hydrodynamic model is based on the Finite Volume Coastal Ocean Model (FVCOM) developed by University of Massachusetts (Chen et al. 2003). FVCOM solves the three-dimensional momentum, continuity, temperature, salinity, and density equations in an integral form by computing fluxes between non-overlapping, horizontal, and triangular control volumes. It uses a finite volume approach that provides flexibility in handling complex shorelines. The model employs the Mellor Yamada level 2.5 turbulent closure scheme for vertical mixing and the Smagorinsky scheme for horizontal mixing.

A sigma-stretched coordinate system was used in the vertical direction, and five uniformly distributed vertical layers were used. The model was set up in the Universal Transverse Mercator North American Datum 83 (Zone 10) coordinates in the horizontal plane with reference to NAVD88 in the vertical direction.

2.2 Model Bathymetry Update and Grid Refinement

2.2.1 Model Bathymetry

Model bathymetry was created from different data sources. As in the Phase-II effort, the primary source of bathymetry and topography in the intertidal regions was LIDAR data from the Puget Sound LIDAR Consortium. The existing bathymetry was updated using LIDAR data obtained by The Nature Conservancy in 2012. The Snohomish County Surface Water Management Division provided channel cross-section data for Hatt Slough and the OSRC including the West Pass and South Pass reaches. In this effort, we further updated the bathymetry using most recent LIDAR data from detailed surveys conducted near the zis a ba project site by the Stillaguamish Tribe.

Figure 2.1 shows the topography of Leque Island study area based on available LIDAR data and the Snohomish County channel cross-section survey track lines. In the main waterbody of the Skagit Bay and Port Susan Bay region, bathymetry data were obtained from the University of Washington Puget Sound Digital Elevation Model. The data have a spatial resolution 30-ft by 30-ft.

All bathymetry data were referenced to NAVD 88. In the study area, MSL is 1.33 m above the NAVD 88 datum, and the corresponding Mean Lower Low Water level is about 0.638 m below the NAVD 88 datum. Model bathymetry finally was linearly interpolated into the model grid.
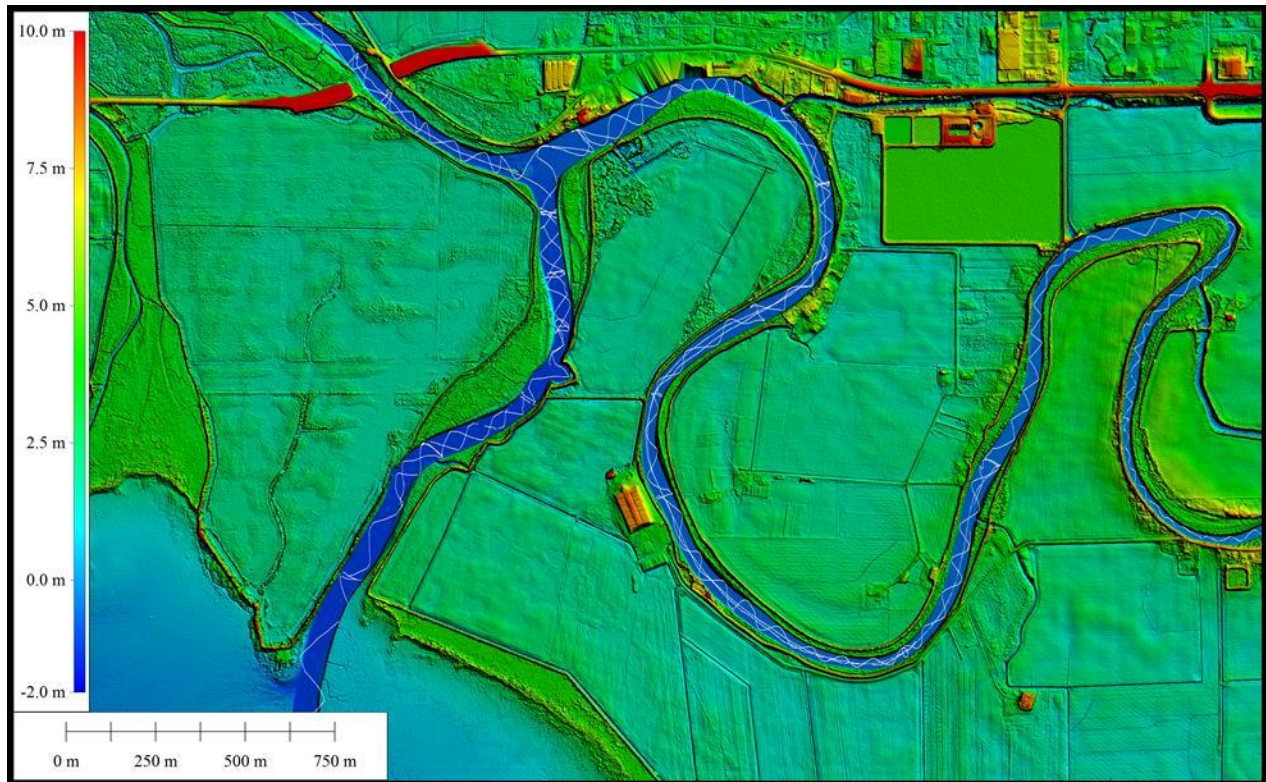
Figure 2.1. LIDAR Topography and Stillaguamish River Channel Survey Data used in Developing Bathymetry of the Leque Island and zis a ba Regions of the Model Domain

2.2.2   Model Grid

The unstructured finite volume grid for this study was based on the existing model grid from the Phase-II effort. The model grid covers Skagit Bay, Port Susan Bay, and includes the West Pass of the Stillaguamish River that connects Port Susan Bay to Skagit Bay. The model also includes Davis Slough, which is the second channel between Port Susan Bay and Skagit. A fine grid is used for the Leque Island and zis a ba regions of the domain to represent the geometry of the dikes, topography, and bathymetry.

In Phase III, two different grids were generated: 1) the baseline grid and 2) the preferred alternative grid. For the baseline, the model grid retained the Phase-II grid for the inner part of Leque Island and zis a ba sites, but was refined along West Pass, South Pass, and the lower Stillaguamish River (Figure 2.2). The inner part is defined as the area of the Leque Island interior to the dikes that is not under tidal inundation. This refinement effort was aimed at understanding in detail the erosion and deposition areas along the Stillaguamish River channels outside of the proposed restoration sites under existing conditions. The model baseline grid consists of 35,630 elements and 19,380 nodes in the horizontal plane. This model grid was used for validation simulations and for generating baseline conditions for comparison with the preferred alternative simulations.
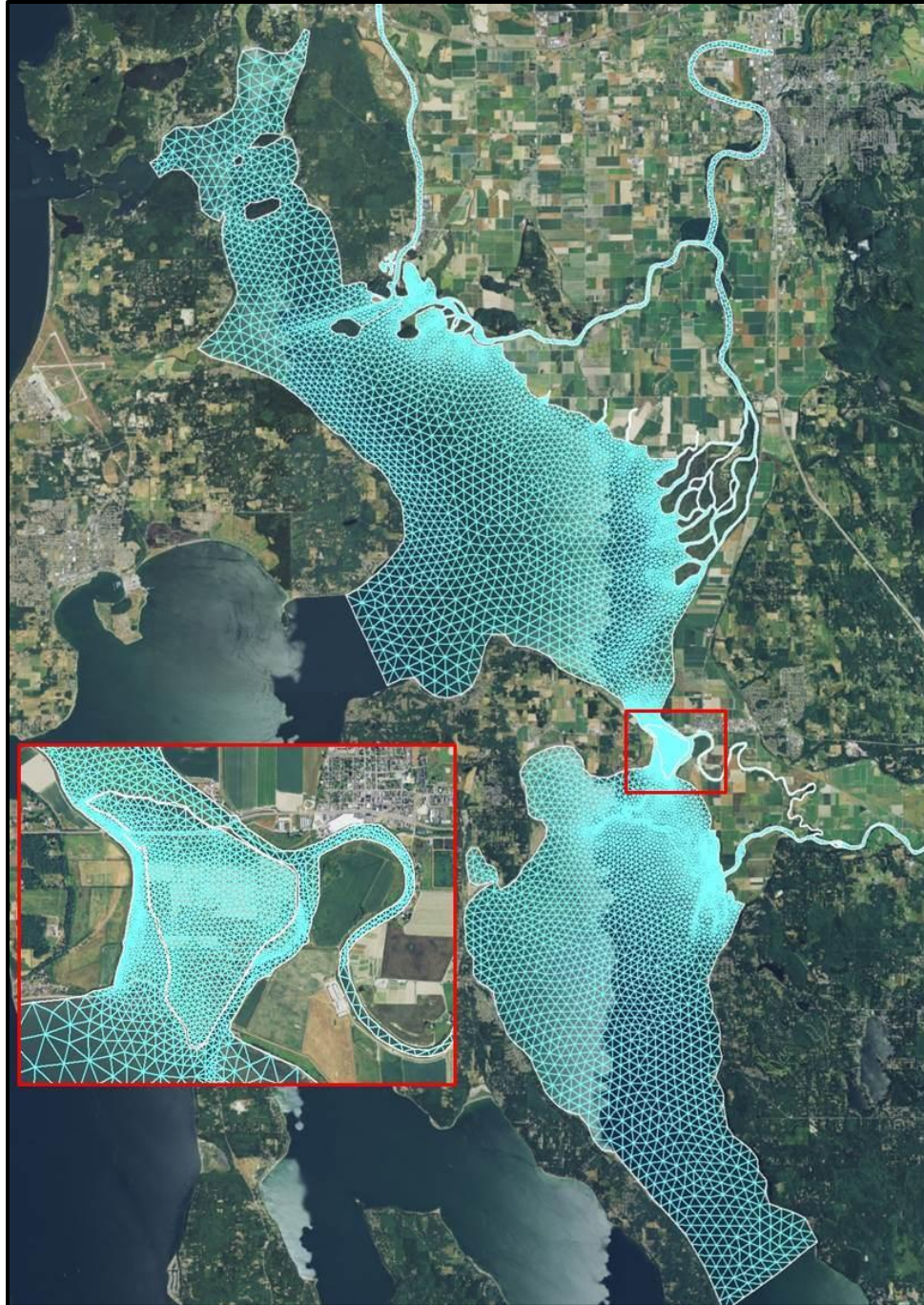
Figure 2.2. Baseline Model Grid of the Skagit and Stillaguamish River Estuaries including Skagit Bay, Port Susan Bay, and the Leque Island and zis a ba Sites. The inset shows detail near the Leque Island and zis a ba project sites.

2.3   Model Boundary Conditions

2.4   Tides

Tidal elevations were specified at the following four open boundaries: 1) mouth of Skagit Bay – Crescent Harbor Station, 2) Deception Pass – Yokeko Point Station, 3) Swinomish Channel – Padilla Bay Station, and 4) mouth of Port Susan Bay – Tulalip Station. They were predicted using the X-TIDE program based on National Oceanic Service algorithms. Tidal elevations at the Padilla Bay, Yokeko Point, Crescent Harbor, and Tulalip Stations were predicted for the period from October 10 to 26, 2005. Figure 2.3 shows time histories of tidal elevations at the boundaries with clear spring-neap tidal signatures and large diurnal inequalities at all the four stations.
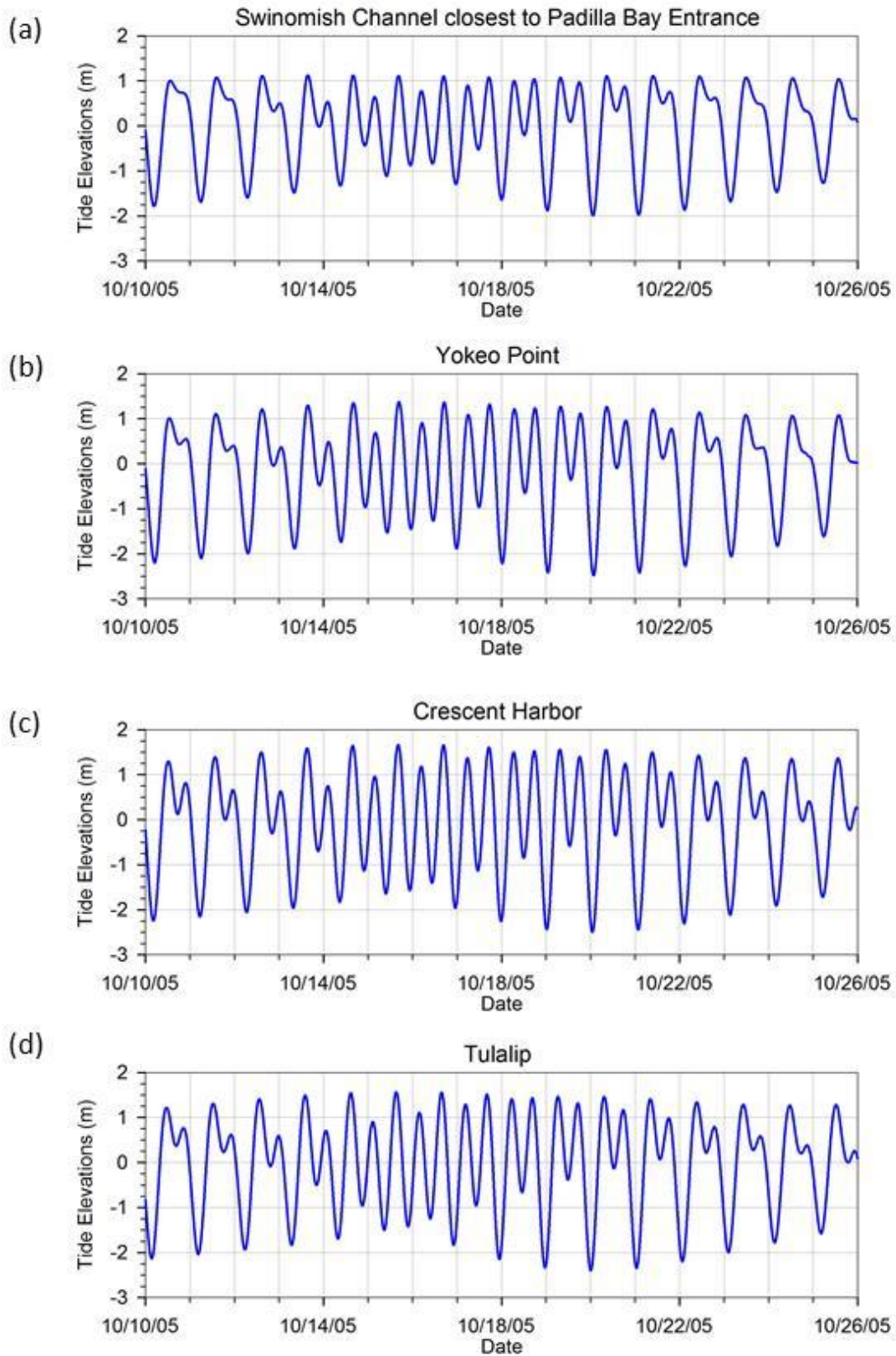
Figure 2.3. Tidal Elevations at the Model Domain Boundaries for October 2005

2.4.1 Salinity and Temperature Profiles

We specified salinity along the Port Susan, Yokeko Point, and Padilla Bay boundaries as a constant value of 30 ppt. This value is based on field data collected at Kayak Point Station. At the Skagit Bay boundary, salinity was set to 25 ppt based on available Skagit Bay data from previous studies. At all boundaries, we set the temperature to 14°C. The temperature effect on density-induced currents was not considered in the simulation. Field data indicated that temperature variations are not significant (<3°C) compared to salinity variation (<20 ppt) during the time of simulation.

2.4.2 Wind

Wind data were obtained from NOAA's National Weather Service site at the Everett/Paine Field Station, which is approximately 30 miles south of the study area. The dominant wind direction is toward the north, and the average wind speed during the period of interest was ≈ 3.4 m/s. Wind force was applied uniformly to the entire model domain and applied at the water-surface as wind stress.

2.4.3 Tributary Inflows

The inflows to the Stillaguamish River system include the Stillaguamish River and the Skagit River. For this study, the total Stillaguamish River flow into Port Susan Bay was estimated by summing the flows from the North and South Forks of the Stillaguamish River. Flow data were obtained from USGS gauge 12167000 near Arlington, Washington, at river mile (RM) 6.5 on the North Fork Stillaguamish and Washington State Department of Ecology gauge 05A105 at RM 33.4 on the South Fork Stillaguamish. The period from October 10 to 26, 2005 during which field data were collected in Port Susan Bay, was selected for the simulation. The average river flow during the plotted period was 2,457 cfs (Figure 2.4).

The Skagit River brings in fresh water to Skagit Bay from the northeastern corner of the estuary through the North Fork and South Fork branches. Skagit River flows were obtained from the USGS gauge 12200500 at Mount Vernon, Washington, at RM 15.7. The Skagit River influences the project site and Port Susan Bay through estuarine flow that occurs from Skagit Bay to Port Susan through the West Pass of the Old Stillaguamish River. Figure 2.5 shows a hydrograph of the Skagit River for the period from October 10 to 26, 2005. The average river flow during the plotted period was 12,331 cfs, with a high-flow event (about 23,000 cfs – daily average) that was observed on October 18, 2005.

2.5 Model Validation Results

In this Phase-III effort, model validation was repeated using the same October 2005 data set used during Phase I (Yang et al. 2008) and Phase II (Whiting and Khangaonkar, 2014). We conducted this validation effort to ensure that model performance in Phase-III was consistent with the level of accuracy achieved in prior efforts. All model parameters for this Phase-III re-validation were kept the same as in the Phase-I calibration and Phase-II validation.

2.5.1 Field Data – October 2005

The model validation includes a comparison of predicted water surface elevation, salinity, and velocity time series results with observed data. Oceanographic data collected by The Nature Conservancy from October 10 to 26, 2005, were used for model validation. These data was collected as part of the hydrodynamic and ecological assessment for the Port Susan Bay restoration project near the mouth of the Stillaguamish River (Yang et al. 2006).
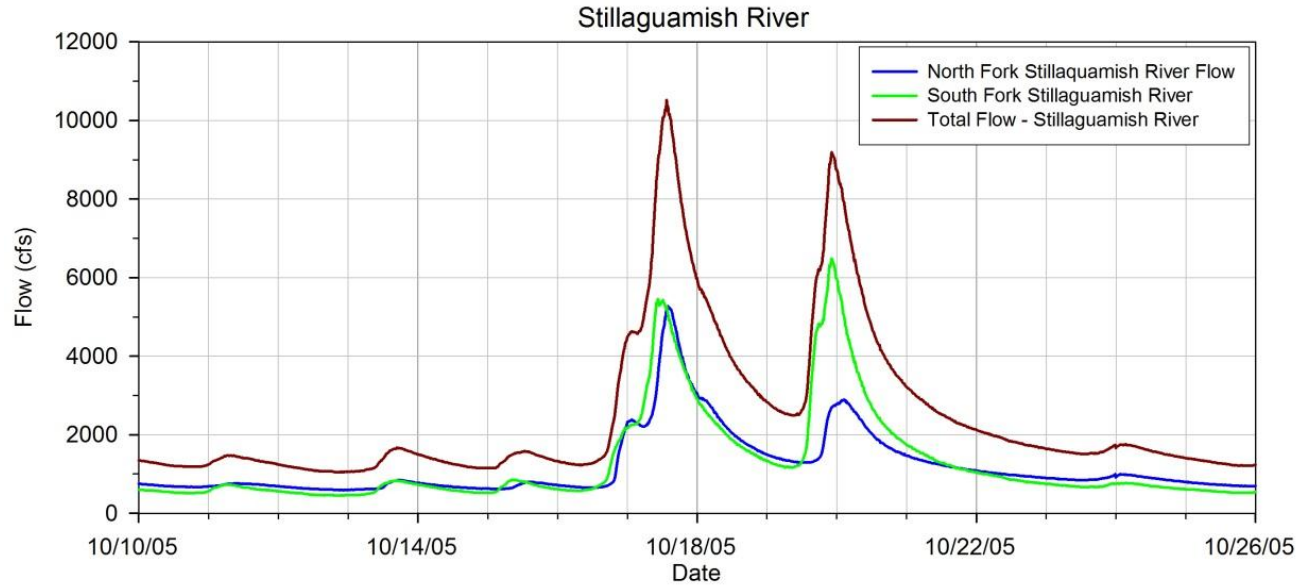
Note:
- North Fork Stillaguamish river flow USGS Arlington gage (RM 6.5)
- South Fork Stillaguamish River flow, Ecology Jordon Rd gage (RM 33.4).

Figure 2.4. Stillaguamish River Flow to Port Susan Bay, October 2005
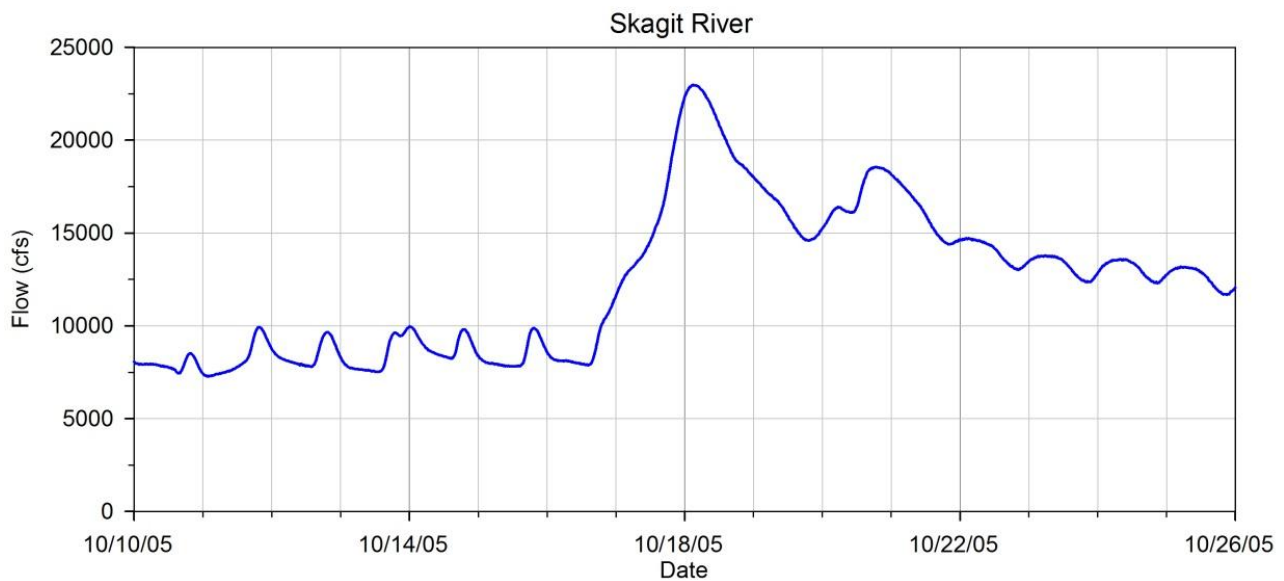
Figure 2.5. Skagit River Flow to Skagit Bay, October 2005

Mooring station locations are shown in Figure 2.6. Two mooring stations were deployed in the main channels of South Pass and Hatt Slough near the mouth of the Stillaguamish River. The South Pass station was equipped with an InterOcean S4 current meter and Star Oddi Conductivity-Temperature-Depth (CTD) instrument for continuous measurements. Hatt Slough Station was equipped with an RD Instruments Acoustic Doppler Current Profiler for continuous measurements of current profiles and a Hydrolab CTD for continuous measurements of tidal elevations, salinity, and temperature.
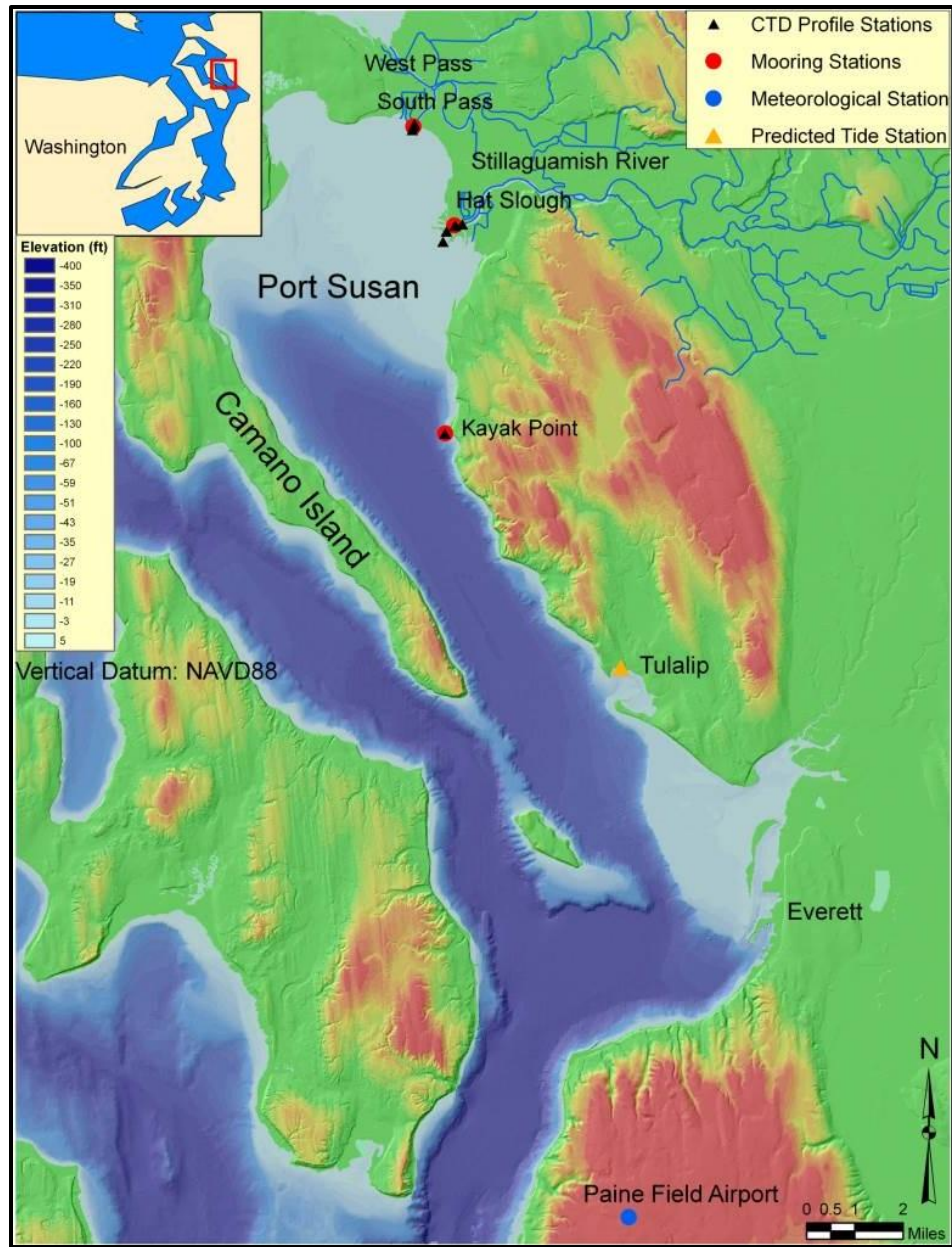
Figure 2.6. Oceanographic Data Collection Stations, Port Susan Bay, October 2005

Two CTDs were deployed at the Kayak Point Station to continuously measure tidal elevations, salinity, and temperature. Instantaneous salinity and temperature profiles also were obtained near the South Pass, Hat Sough, and Kayak Point Stations during deployment and retrieval of the instruments.

2.5.2   Model Validation – Tides

Figure 2.7 shows the comparison of predicted and observed tidal elevations at the Kayak Point, Hatt Slough, and South Pass Stations.
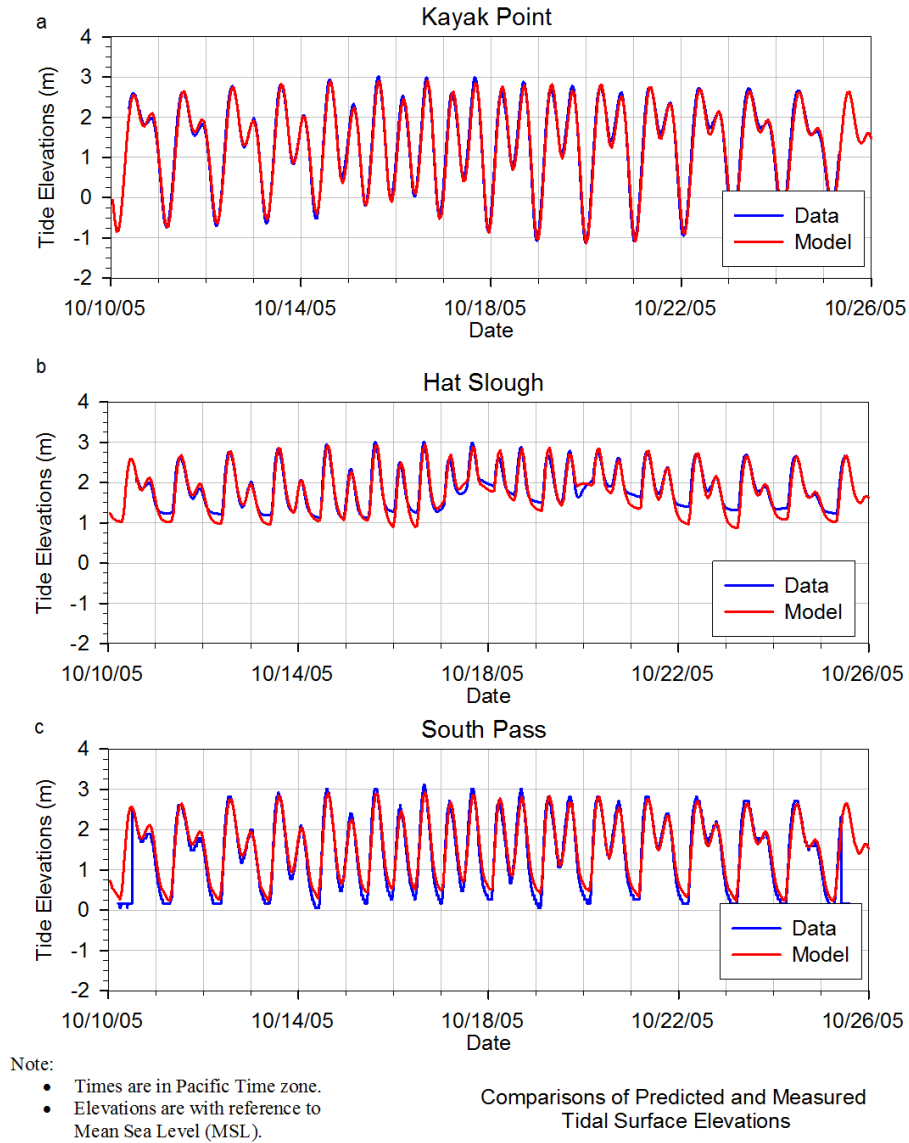
Figure 2.7. Comparison of Predicted Water Surface Elevations and Measured Tides at the Kayak Point, Hatt Slough, and South Pass Stations, Respectively

Predicted water surface elevations are in good agreement with observed monitoring data. The spring-neap tidal cycle and the diurnal inequality were well reproduced in the model. Predicted high and low tidal phases also were matched well with observed data. The predicted tidal range at the Kayak Point Station ranges from -1 m to 3 m as also observed in the Puget Sound coastal region. Weaker tidal elevations were found at South Pass and Hatt Slough. The tidal range at South Pass and Hatt Slough were in the range of 3 m and 2 m, respectively, due to the effects of shallow water depths and river backwater. During the high-flow event from October 17 to 21, 2005, tidal elevations at Hatt Slough and South Pass were further elevated because of the river backwater effect.

Table 2.1 provides validation error statistics comparing measured water surface elevation data to simulated results. Overall root mean square error (RMSE) relative to tidal range is < 10% with a negative bias of 4 cm and average RMSE of 24 cm.

Table 2.1. Model Error Statistics – Water Surface Elevation

Station	ME (m)	RMSE (m)	RME (%)
Tide – Water surface elevation, m			
Kayak Point	-0.05	0.26	6.33
Hatt Slough	-0.07	0.23	11.92
South Pass	0.00	0.24	7.27
Mean	-0.04	0.24	8.51

RMSE = root mean square error, ME = mean error
RME = mean error relative to tidal range (magnitude of change in tidal elevation) at each site

2.5.3   Model Validation – Currents

Predicted velocities were compared to field-observed data at South Pass and Hatt Slough. Velocity data collected at the Hatt Slough and South Pass Stations were decomposed into north and south components for direct comparison to simulated results. Predicted velocities generally matched well with observed data at both the South Pass and Hatt Slough Stations (Figure 2.8). Predicted velocities at the South Pass Station were dominated by the north component, whereas velocities at the Hatt Slough Station were dominated by the east component.

Error statistics comparing measured velocity data to simulated velocity are provided in Table 2.2. The comparison was done for mid-depth layer at both sites. Model predictions match the field data well at a level of accuracy similar to Phase-I and Phase-II calibration efforts. Overall RMSE in the north and south directions is less than 14 cm/s, and the mean absolute error is 7 cm/s, except at the Hatt Slough Station. This represents <10% error relative to the range of current magnitudes in the Stillaguamish River estuary.
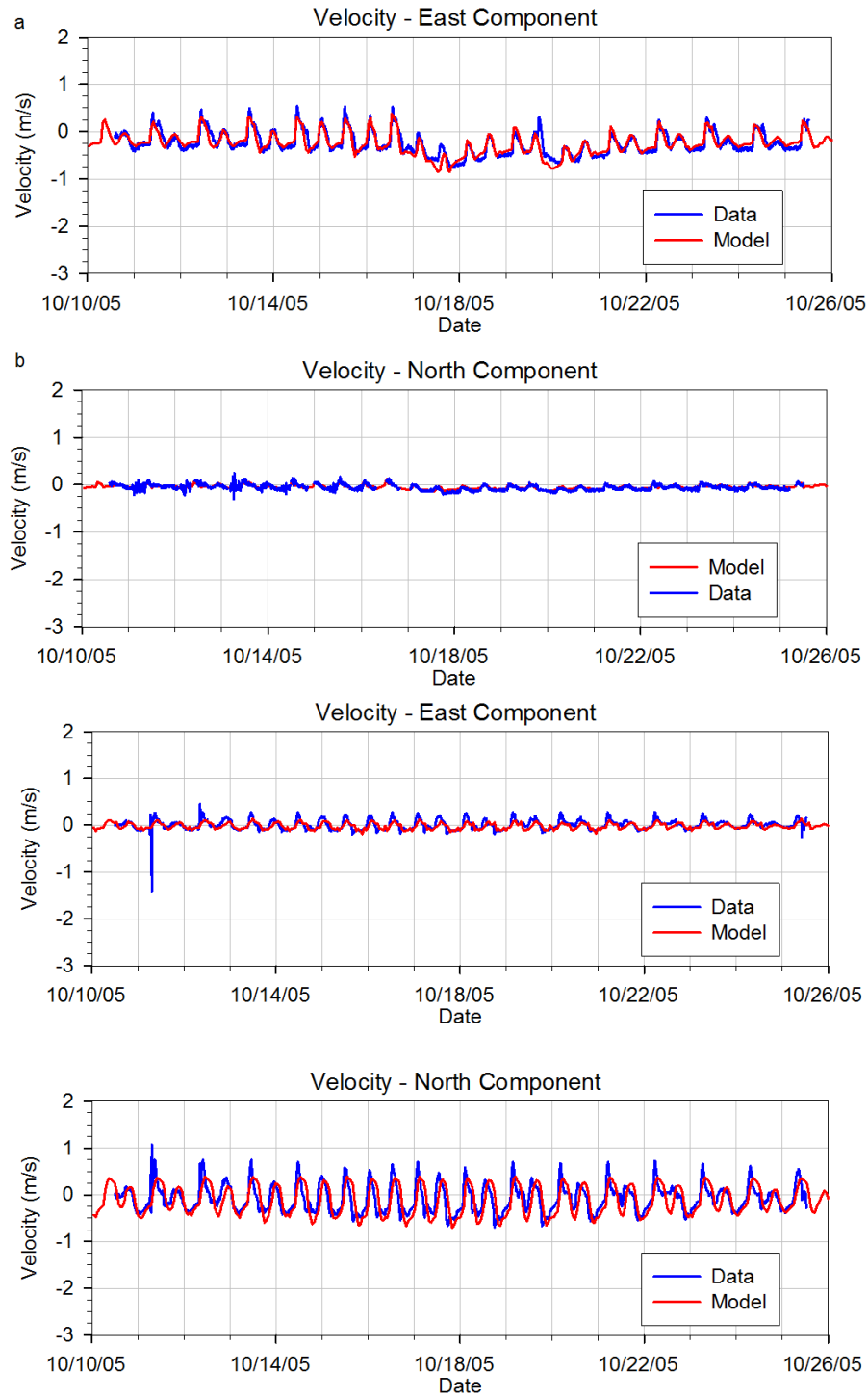
Figure 2.8. Comparison of Predicted And Measured Velocity Components at the Hatt Slough (a) and South Pass (b) Stations, Respectively. Data is from mid-depth of the water column.

2.11

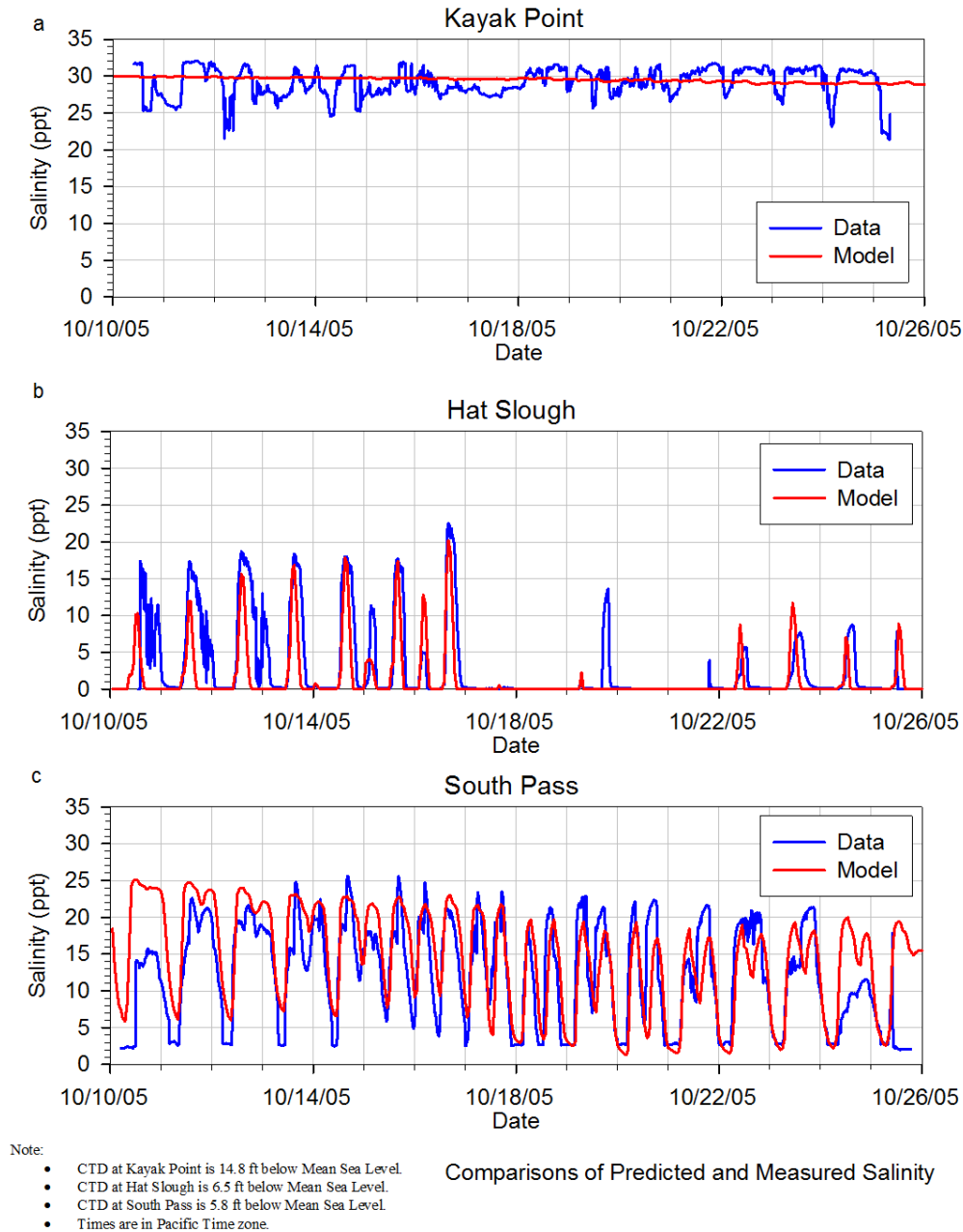**Table 2.2**. Model Error Statistics – Velocity

Station	ME (m/s)	MAE (m/s)	RMSE (m/s)
U – m/s (East Component)			
Hatt Slough	-0.07	0.08	0.11
South Pass	0.01	0.13	0.18
Mean	-0.03	0.11	0.14
V – m/s (North Component)			
Hatt Slough	-0.04	0.19	0.24
South Pass	0.01	0.03	0.04
Mean	-0.01	0.11	0.14
MAE = mean absolute error; RMSE = root mean square error			

2.5.4   Model Validation – Salinity

The predicted salinity time series were compared with data from field monitoring. Figure 2.9 shows the comparison of predicted and observed salinity time histories at the Kayak Point, Hatt Slough, and South Pass Stations. Overall, predicted salinities matched the observed data reasonably well, except at the Kayak Point Station. The predicted salinity at Kayak Point showed little variation because salinity variations there were mainly controlled by the open-boundary condition. At the open boundary, the salinity was specified as constant at 30 ppt. However, salinity at the Hatt Slough Stations showed strong tidal fluctuations, varying from 0 ppt during low tide to 20-25 ppt during high tide in a full tidal cycle. Strong tidal fluctuation influence also was found at the Hatt Slough Station. Sharp salinity intrusion was observed during high tide at the Hatt Slough Station. Some discrepancies between observed data and modeled salinity were detected at the Hatt Slough and South Pass Stations. We believe the source of this error is lack of information on fresh-water river flow distribution between Hatt Slough and the OSRC.

Validation error statistics comparing measured salinity data to simulated results were computed (see Table 2.3). The overall RMSE is 4 ppt with a negative bias of 1.3 ppt and a mean absolute salinity error of 2.7 ppt.

Figure 2.9. Comparison of Predicted and Measured Salinity at the Kayak Point, Hatt Slough, and South Pass Stations, Respectively

Table 2.3. Model Error Statistics – Salinity

Station	ME (ppt)	MAE (ppt)	RMSE (ppt)
Salinity, ppt			
Kayak Point	0.48	1.51	1.83
Hatt Slough	-1.62	2.20	4.46
South Pass	-2.81	4.38	5.71
Mean	-1.31	2.70	4.00
MAE = mean absolute error; RMSE = root mean square error			

3.0 Design of Simulations for the Preferred Restoration Alternative Scenario at Leque Island and zis a ba

3.1 Introduction

After successful refinement of the model grid and validation of the model of the Stillaguamish River Estuary, the model was deemed ready for application to evaluate the feasibility of successfully restoring intertidal estuarine process and marsh habitat at the Leque Island and zis a ba restoration sites currently enclosed by dikes and small channels. Flooding and inundation (restoration area, duration, and frequency), salinity variations, and potential for erosion were the parameters of interest. The risk of flooding nearby properties and spatial coverage of the restored region influenced by the tidal action would be evaluated by combination of plan view maps and inundation frequency response at selected stations. The salinity response to river flows and tidal forcing would be computed to inform the feasibility of habitat restoration and vegetation predictions. The potential for erosion and deposition would be evaluated by examining the bottom velocities and bed shear stress values relative to critical stresses for erosion/deposition that would help determine if restoration actions would lead to a depositional marshland or erosional tidal flat. Furthermore, these evaluations may then be used to assess the feasibility of establishing tidal exchange, potential sedimentation, erosion effects, and fish migration pathways.

Conditions experienced during field data collection in October 2005 that were used previously in model calibration were selected to serve as the typical conditions. In addition, high-river-flow conditions representing maximum potential for sediment erosion, deposition, and geomorphological changes also were developed. Major geomorphologic changes such as river channel erosion and enlargement of steep, incised channels often occur during extreme fluvial events. This scenario was evaluated using bank-full, channel-forming flow and used in combination with the October 2005 tidal conditions. The baseline results were regenerated first followed by the preferred restoration results at Leque Island and zis a ba sites for the two estuarine flow conditions.

3.2 Preferred Restoration Alternative Scenario Design

The model grid for the Preferred Restoration Alternative Scenario was constructed by modifying and refining the baseline model grid used for validation. The grid resolution used for the baseline model grid in river channels was retained; however, the resolution of the grid inside the Leque Island and zis a ba restoration area domains was increased as required according to preferred design. Incorporation of the preferred alternatives design into the model domain included creating a network of drainage channels, dikes, and berms and modifying the model bathymetry for those structures.

At the Leque Island site, selected alternative restoration action includes creation of a network of tidal channels and removal of the majority of the existing dike footprint to restore tidal processes to the entire property. However, a spur dike, which is a linear section of dike adjacent to the West Pass and South Pass bifurcation of the OSRC, is retained. Skagit River System Cooperative has provided predictions and recommendations for the location, number and size (i.e., length) of tidal channels based on allometric analysis of the tidal channel planform relative to marsh area. These proposed tidal channels will allow effective exchange of water, fish, and nutrients between the marsh and Port Susan Bay (Hood 2015). A complete preferred alternative design for the Leque Island site can be found in the preliminary report of the Leque Island Estuary Restoration Project (DU 2016).

Figure 3.1 shows model grid details corresponding to the Preferred Alternative at the Leque Island site. The perimeter dike has been lowered to grade and tidal channels have been incorporated. The design

widths of the tidal channels vary between 5 m and 20 m and the depths vary between 1 m and 2 m. To avoid high computational costs and model stability, we limited model cells to as small as 2.5 m to allow 5-m wide channels to be represented. The number of cells gradually increase with distance as the channel widths increase towards the channel mouths.

Figure 3.2 shows model grid detail corresponding to Preferred Alternative at the zis a ba site. Unlike the Leque Island site, the perimeter dike was lowered to a specified elevation and breached at a number of locations. The Preferred Alternative design includes sustaining a partial section of dike adjacent to the southwest bank of the OSRC. Also, as shown in Figure 3.2, the design includes a north-south oriented berm that divides the site into two drainage basins. More details on the zis a ba restoration design can be found in the *zis a ba Restoration Project Design* (Stillaguamish Tribe of Indians 2016). The design widths of tidal channels vary between 2 m and 26 m and depths vary between 0.5 m at the mouth of the channels and approximately –2 m at the upstream end of the channels.

The model input, parameters and settings were the same as used in the validation and Baseline Scenario simulation. On the PNNL high performance cluster using 384 processors, simulations of selected alternative scenarios took about a day of computer time to simulate two-week periods.
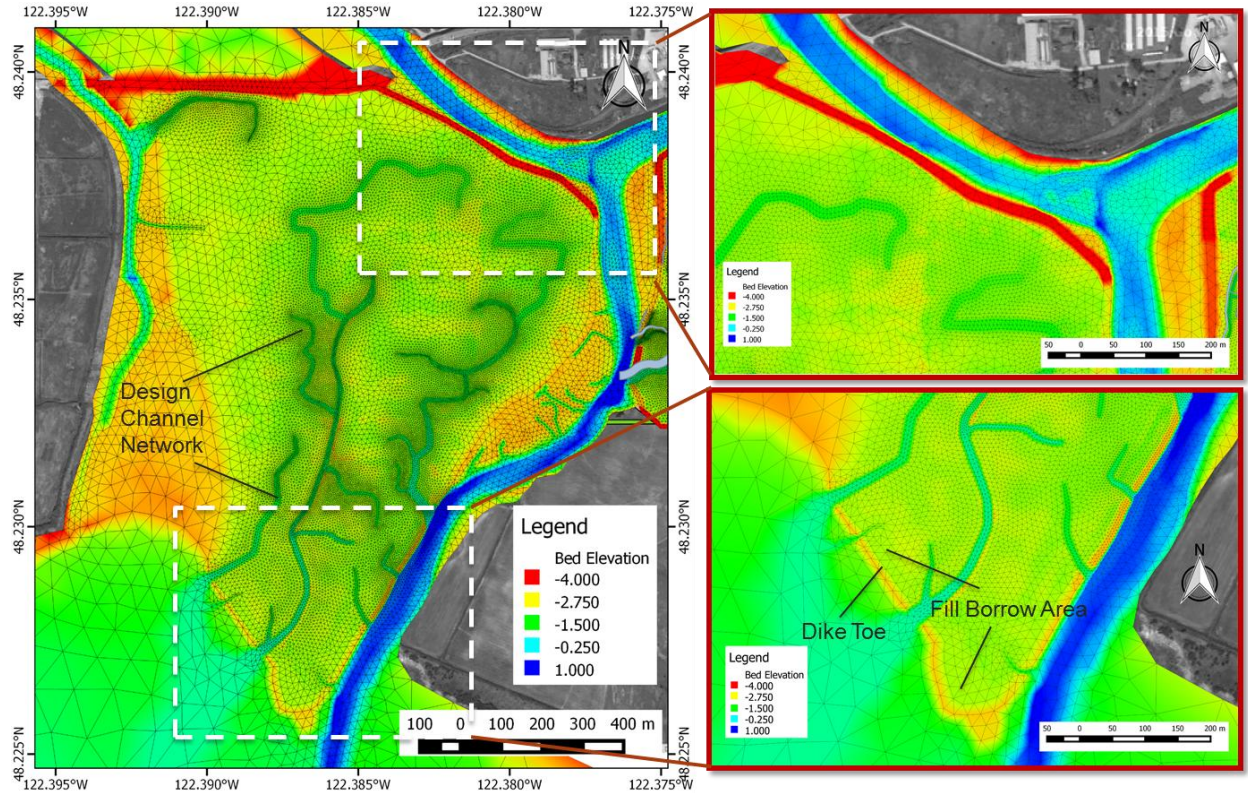
Figure 3.1. Preferred Alternative Model Grid for Leque Island Site
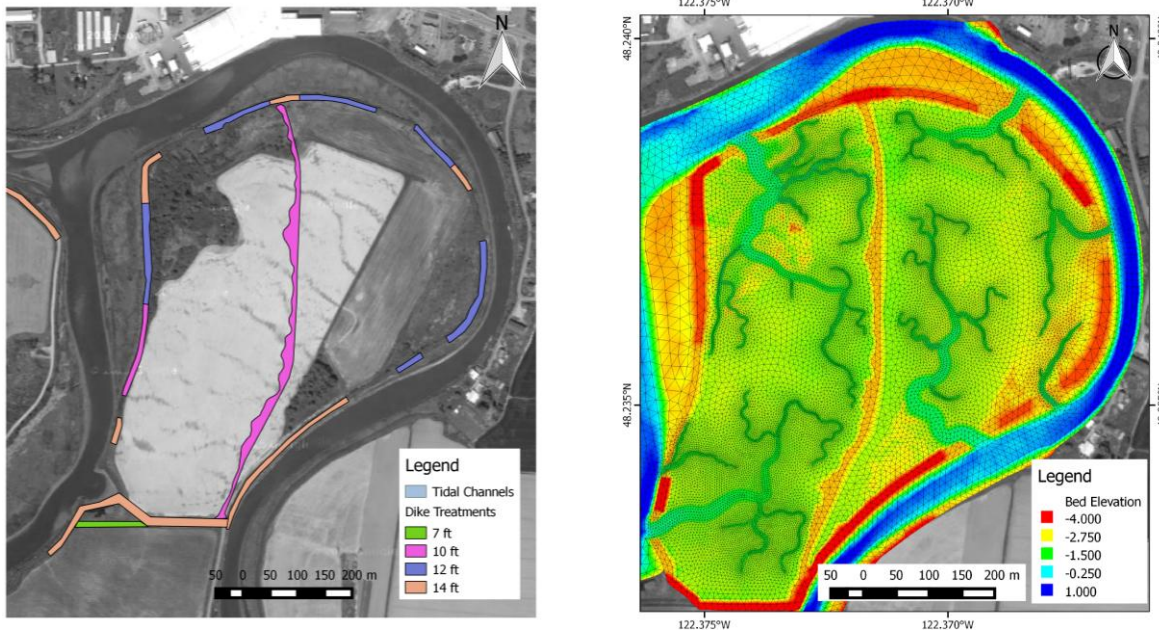
**Figure 3.2**. Preferred Alternative Model Grid for zis a ba Site

3.3   Typical Estuarine Conditions of October 2005

The baseline (existing conditions) and the preferred alternatives at the Leque Island and zis a ba sites were both simulated using same model inputs (i.e., model parameters and forcing) corresponding to typical conditions. We conducted simulations for 2-week periods within October 5 to 26, 2005, window selected to represent the typical estuarine conditions.

The results for each scenario are presented as horizontal plots of surface velocity vector distributions overlaid with salinity contours at peak ebb and flood tides. This presentation allows the salinity values to be examined at the two extremes during flood and slack tide, from which areal extents of the tidal exposure may be assessed. We present the contour plots of maximum bed shear stress during a 2-week simulation period, which allows visual assessment of areas most likely to experience the highest bed shear stresses and potential for sediment erosion. The difference plots of maximum bed shear stress also are presented such that differences between Baseline and Preferred Alternative Scenarios can be examined.

Finally, time series of water surface elevation (m), salinity (ppt), velocity magnitude (m/s), and bed shear at 11 stations requested by DU were plotted over a period of 16 days. Time series plots for the Preferred Restoration Alternative Scenario were provided with baseline results for relative comparison, and evaluated with reference to the desired characteristics for a tidal restoration project. Figure 3.3 shows the locations of the 11 stations where time series plots of water surface elevation, salinity, bottom velocity, and bed shear stress were generated over the complete 2-week simulation. These stations were selected as points of interest based on stakeholder comments. Guidance from the Skagit River System Cooperative (SRSC 2014) provides information about the desired water characteristics after restoration; those characteristics are a depth range between 20 cm and 38 cm and a salinity range between 5 ppt and 15 ppt, which can support fish habitat.

3.3
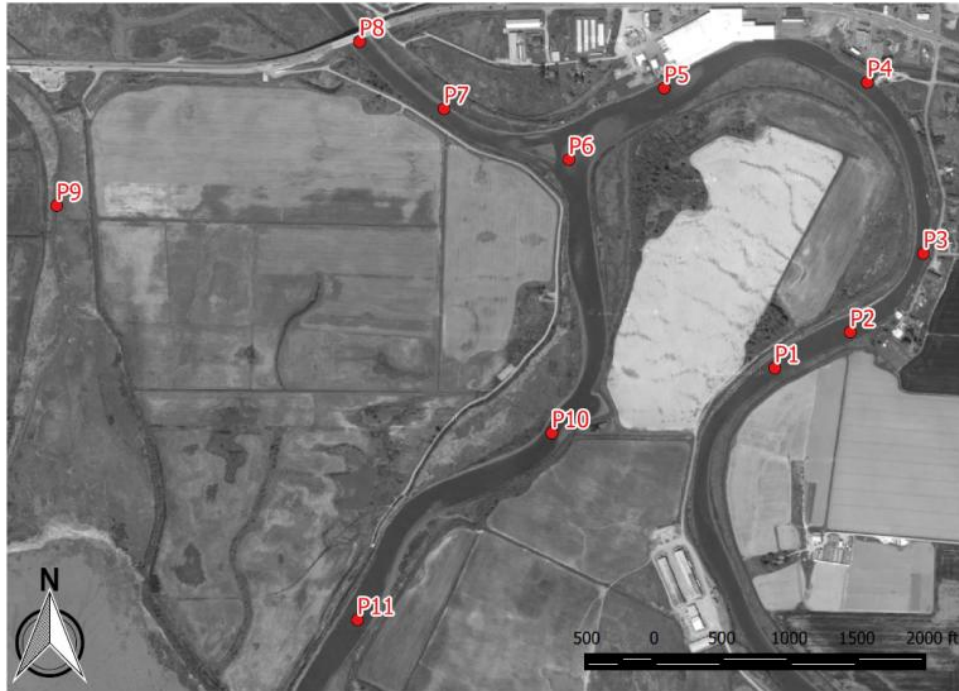
Figure 3.3. Eleven Station Locations on the Leque Island and the zis A ba Sites

Bed shear values are presented in Pascals (Pa) and are examined as the best indicator of expected sediment transport given site-specific variability in bed characteristics and critical shear stress properties controlling erosion potential. An approximate correlation between the size of sediment particles and critical shear stress for erosion are provided in Table 3.1. Assuming non-cohesive sediments, particles will re-suspend and erode when bed shear stress exceeds critical shear stress values (Julien 1998).

Table 3.1. Critical Shear Stress for Different Particle Sizes (from Julien 1998)

Sediment Type	Particle Size (mm)	Critical Shear Stress for Erosion (Pa)
Silt	0.016 - 0.0625	0.065 - 0.11
Sand	0.0625 - 2	0.11 - 1.26

3.4   Simulation of Stillaguamish River High-Flow Conditions

In the Phase-III modeling analysis, performance of the proposed restoration actions during high-river-flow conditions was evaluated primarily to assess potential erosion and deposition concerns. The high flow was defined as the bank-full flow condition of 26,508 cfs. This flow was determined through sensitivity tests reported in the Phase-II modeling report (Whiting and Khangaonkar 2015). The sensitivity test was conducted by increasing daily average flow values in increments of 20,000 cfs of the 16-day period in October 2005. Locations along both the Old Stillaguamish River and Hatt Slough were selected to identify where overtopping seemed most likely to happen. The final flow of 26,508 cfs was selected as the design high-flow value that the river system could sustain before overtopping occurred. Figure 3.4 shows dike elevations along Hatt Slough and the OSRC plotted against maximum surface elevation heights as a function of distance upstream from the river mouths for various flows.
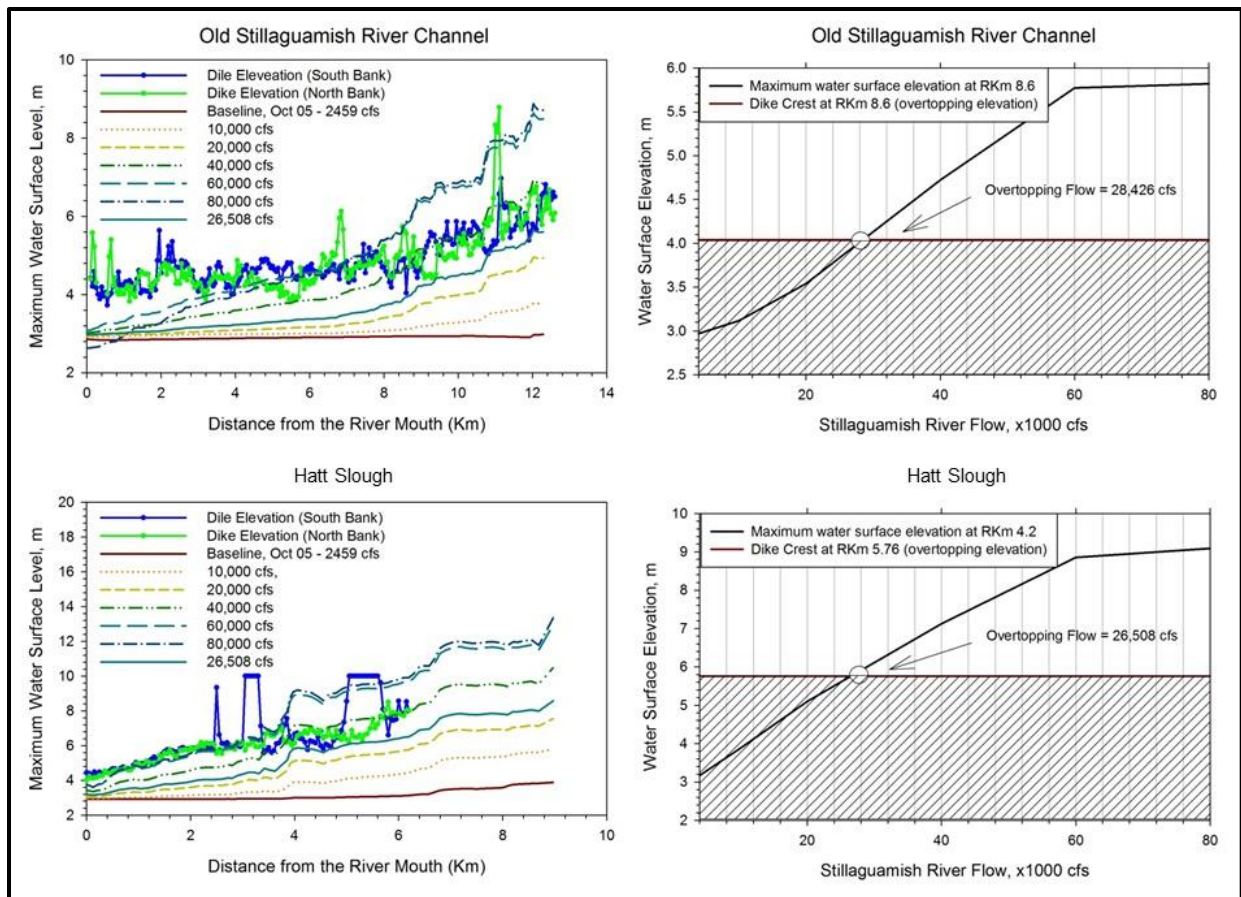
Figure 3.4. Plots used to Determine Bank-Full High-Flow Conditions in the Old Stillaguamish River and Hatt Slough (Whiting and Khangaonkar 2015)

4.0   Hydrodynamic Model Results: Simulation of Restoration Scenarios

4.1   Introduction

In this section, the results of simulations conducted to assist in assessing the feasibility of Preferred Alternative Scenarios at the Leque Island and zis a ba sites near the mouth of the Stillaguamish River are examined and discussed. These simulations cover the Baseline Scenario or existing condition and the Preferred Alternative Scenario described in prior sections of this report. The results examine predicted coastal estuarine responses to the proposed restoration actions relative to existing conditions for typical and high flow conditions. The oceanographic properties of interest are water surface elevation, velocity, salinity, and bed shear stress over the study area. These are provided in the form of horizontal contour plots, and comparisons between Preferred Restoration Alternative Scenario and the Baseline Scenario are provided in the form of difference plots. The results also include time-series and frequency plots for the same variables of interest based on 2-week simulations for each scenario. For the examination and identification of locations of potential high bed shear stress, the maximum and the average of bed shear stress over 2-week simulation periods were extracted and are provided as horizontal contour plots. To better evaluate the relative difference between Preferred Alternative Scenario and the Baseline Scenario, we provide relative difference plots for each of the properties of interest.

Selected plots and figures are presented in this section as part of the discussion. Comprehensive compilations of all plots for all scenarios are included in the following appendices to this report:

- Appendix A: Time series and cumulative frequency – surface elevation, salinity, velocity, and bed shear (October 2005 flow conditions)

- Appendix B: Plan view contours – salinity, velocity, and inundation (October 2005 flow conditions)

- Appendix C: Time series and cumulative frequency – elevation, salinity, velocity, and bed shear (high-flow conditions)

- Appendix D: Plan view contours – salinity, velocity, and inundation (high-flow conditions)

- Appendix E: Plan view contours – bed shear stress (October 2005 flow conditions)

- Appendix F: Plan view contours – bed shear stress (high-flow conditions).

4.2   Baseline Scenario

The Baseline Scenario represents conditions of the system as it exists today subject to tidal and stream flow forcing. Figure 4.1 shows a close-up of the Baseline Scenario model grid covering Leque Island and zis a ba surrounded by the perimeter dike. This alternative assumes that the existing dike would remain intact and would require permanent repairs on the temporary patches that were installed during failures in 2010. The perimeter dike completely isolates the inner regions at Leque Island and zis a ba and are not influenced by river flow or tides in the Baseline Scenario.
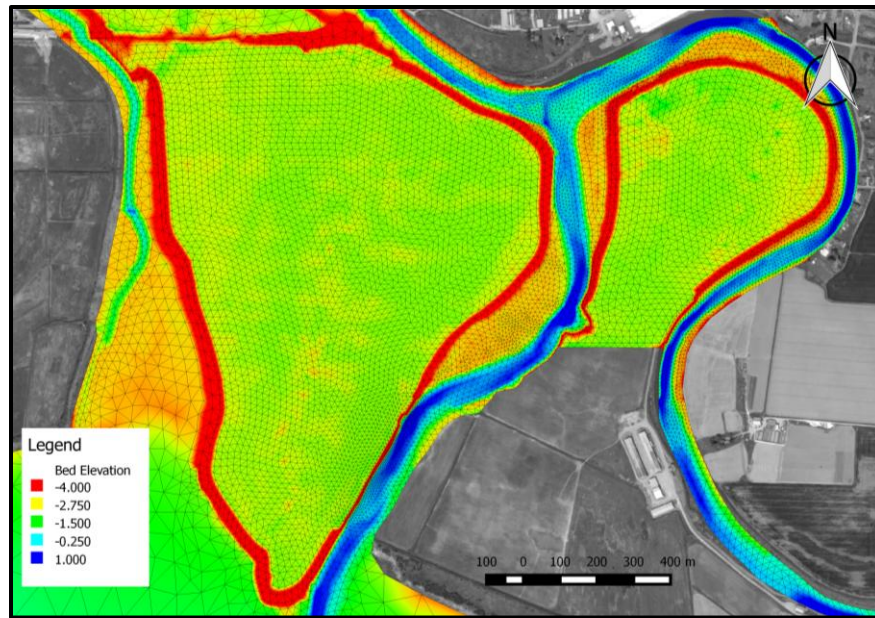
Figure 4.1. Baseline Scenario Model Grid Overlaying the Bed Elevation Map

4.2.1 Typical Estuarine Flow Conditions

Predicted horizontal salinity and velocity distributions in the surface layer corresponding to high tide and low tide on October 24, 2005, for typical estuarine and high-flow conditions are presented. The mouth of the Old Stillaguamish River is strongly influenced by tides. This strong tidal effect is seen clearly in salinity plots that show upstream propagation up the Lower Old Stillaguamish River during incoming flood tide. Tidal exchange between Skagit Bay and Port Susan Bay occurs through West Pass and South Pass channels. Figure 4.2 shows inundation and salinity contour plots at high and low tides, respectively. The intertidal flats in Port Susan and Skagit Bay are fully inundated, reaching elevations above the toes of the perimeter dikes during high tide, and exposed during the ebb tide. The perimeter dike prevents inundation of the Leque Island and zis a ba restoration areas. The improvement of model bed elevation by increasing grid resolution along the main river channel increased the simulated resolution of the wetting and drying intertidal regions during the ebb and flood periods.

Fresh water from the OSRC appears to exit into Port Susan mostly through South Pass. During low tide following ebb, the salinity difference between West Pass and South Pass can be as high as 6 ppt (Figure 4.2, top). The salinity levels and intrusion upriver near the project sites at Leque and zis a ba on the OSRC were sensitive to the fraction of the fresh water split between the Old Stillaguamish River and Hatt Slough. Salinity levels at Davis Slough remain relatively high throughout the tidal cycles as they are controlled primarily by Skagit Bay salinities.

The strongest currents and bed shear were predicted for the high-flow conditions and are discussed in the next subsection.
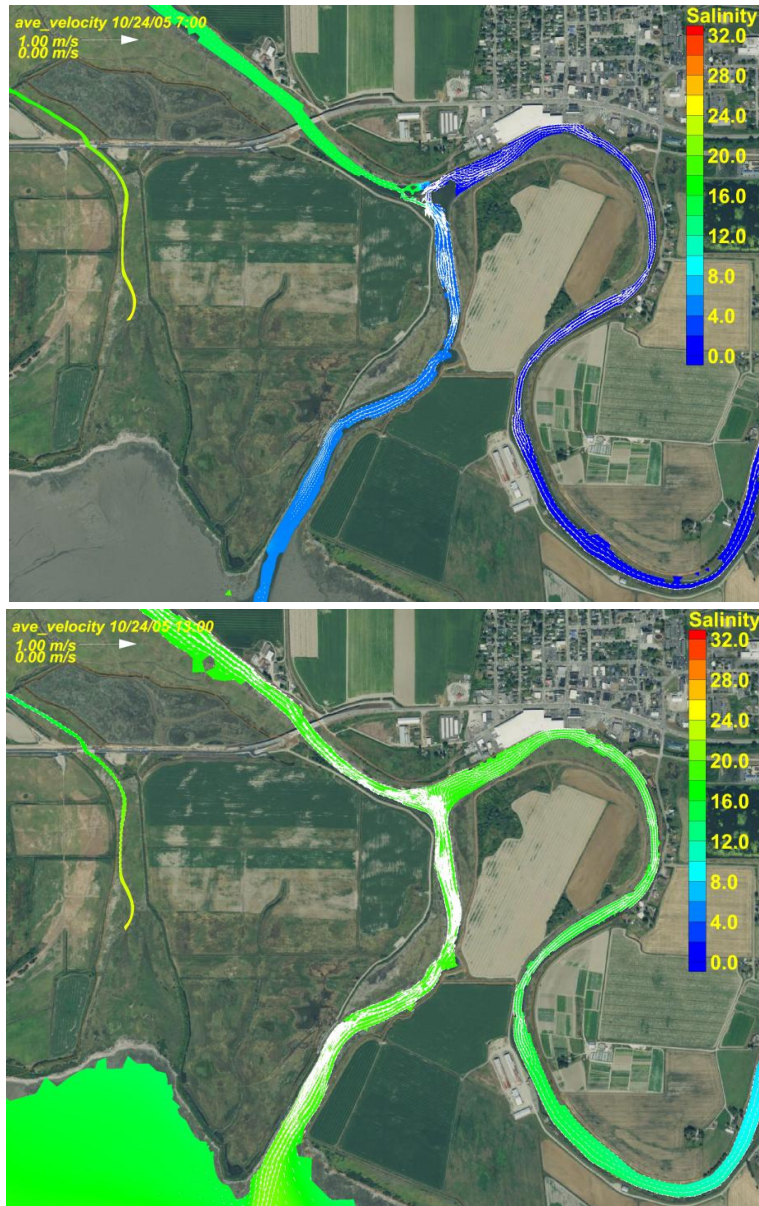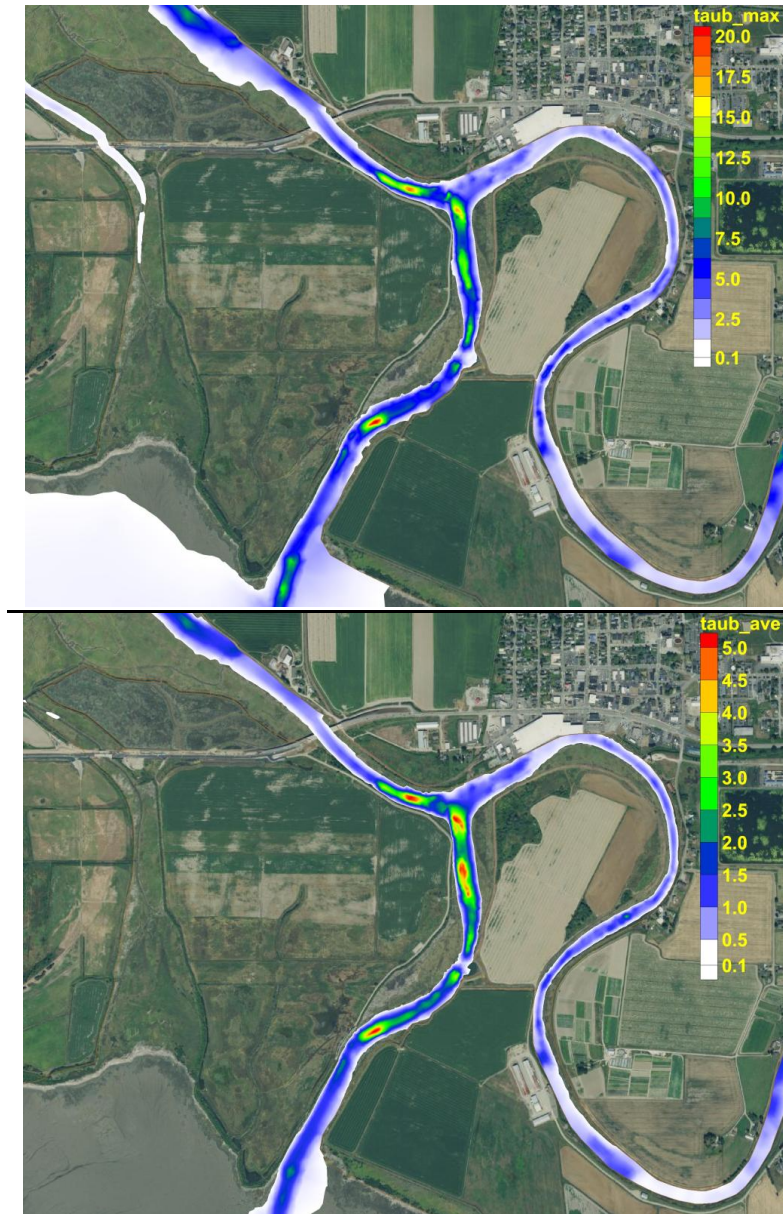
Figure 4.2. Horizontal Distribution of Salinity at Low Tide (07:00) and High Tide (13:00) for the Baseline Scenario on October 24, 2005

4.2.2   High-Flow Conditions

In these high-flow conditions, we focus mainly on examining and identifying regions of high bed shear stress with potential for erosion. Figure 4.3 shows the maximum and average of bed shear stress for the Baseline Scenario at high-flow condition (26,508 cfs) over a 2-week simulation period. As expected, South Pass experiences high bed shear stress as it acts as the main tidal channel connecting Port Susan and Skagit Bay, and provides exchange flow associated with the OSRC. From the plan view of the mean bed shear stress, higher bed shear stresses (>5 Pa) are mostly predicted in South Pass and West Pass reaches immediately downstream of the OSRC channel split at Leque Island.

Figure 4.3. Horizontal Distribution of Maximum (top) and Mean Bed Shear Stress in Pa (bottom) for Baseline Scenario for High-Flow (bank-full) Condition at 26,508 cfs

4.3   Preferred Restoration Alternative Scenario

Figure 4.4 shows the model grid for the Preferred Restoration Alternative Scenario, which involves partial removal of the perimeter dikes and the creation of a network of tidal channels on both the Leque Island and the zis a ba sites. At Leque Island, the grid design considers the removal of dike segments along South Pass and Port Susan but keeps the dike segments along West Pass. Tidal channels at Leque Island are connected directly to South Pass and Port Susan Bay. The Leque Island and zis a ba sites are expected to be inundated and drained through the tidal channels.
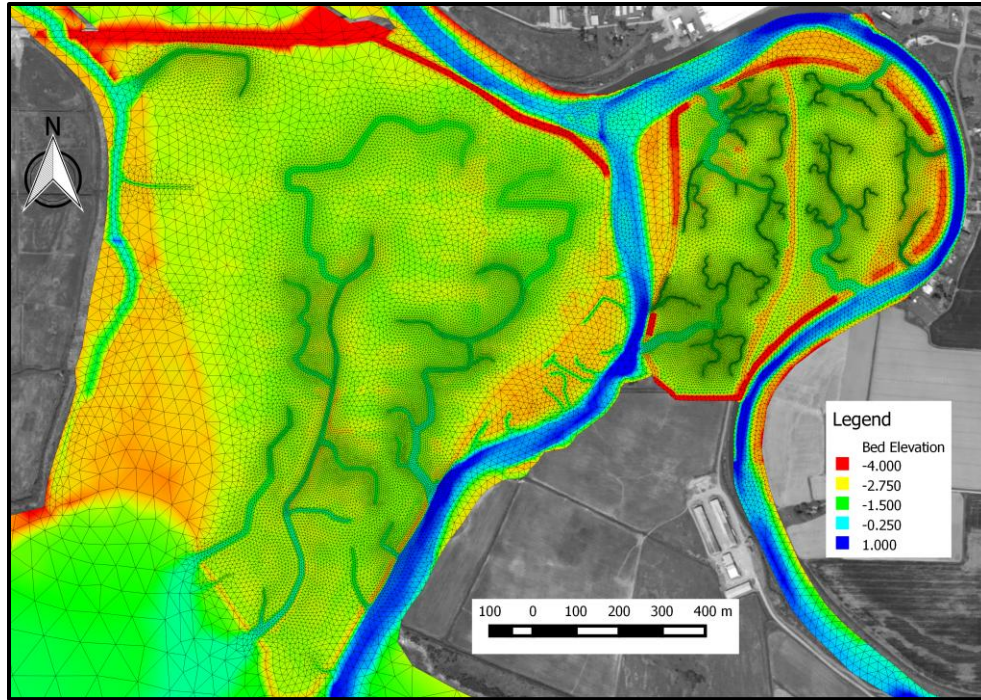
Figure 4.4. Preferred Restoration Alternative Scenario Model Grid Overlaying the Bed Elevation Map

4.3.1   Typical Estuarine Conditions

To facilitate quantitative comparison of the Preferred Alternative Scenarios and the Baseline Scenario, we selected 3 out of 11 stations in the main river channels near the Leque Island and zis a ba sites. Station P1 was selected at the lower OSRC near zis a ba. Station P7 located near the 532 Bridge was selected to represent West Pass at which point the water flux is mainly controlled by Skagit Bay. We selected Station P10 to represent South Pass. (See Figure 3.3 for locations of stations P1, P7, and P10.)

The Preferred Restoration Alternative does not cause any significant changes in water elevations at the West Pass and the lower OSRC stations. Figure 4.5 shows the time series of water surface elevations at stations P1, P7, and P10 for the baseline and preferred alternative scenarios. (The curves are nearly identical and difficult to tell apart.) The mean water surface elevation for the Preferred Restoration Alternative Scenario is ≈ 0.01 m lower relative to the Baseline Scenario.
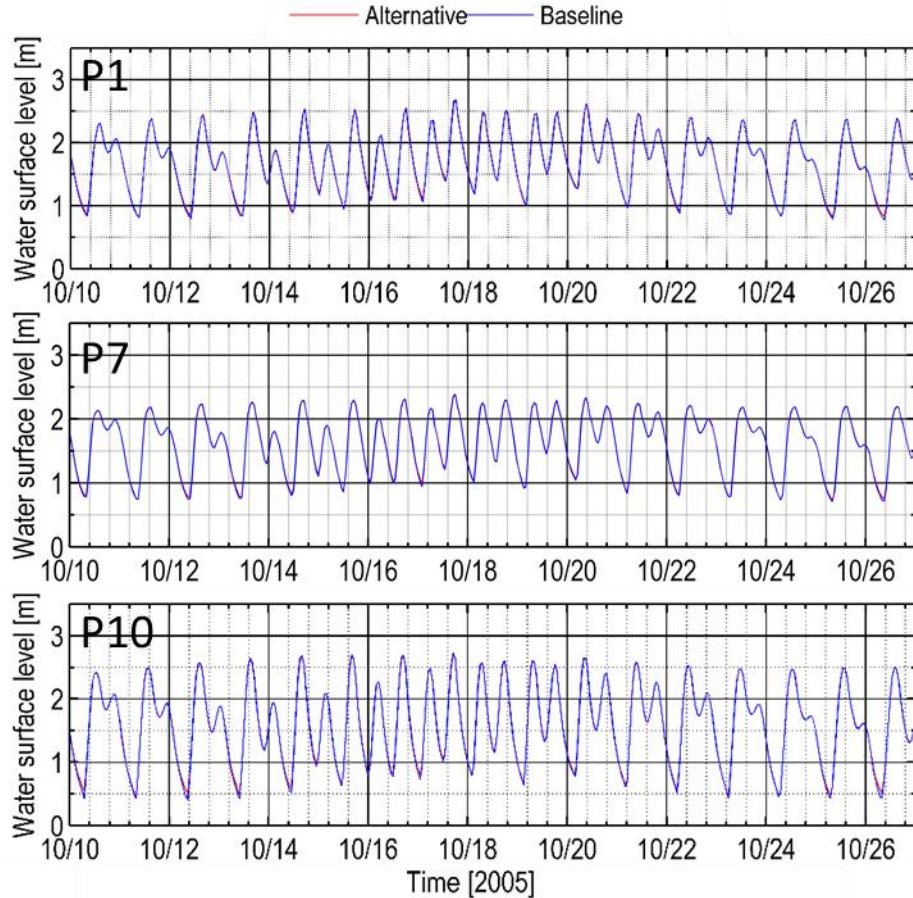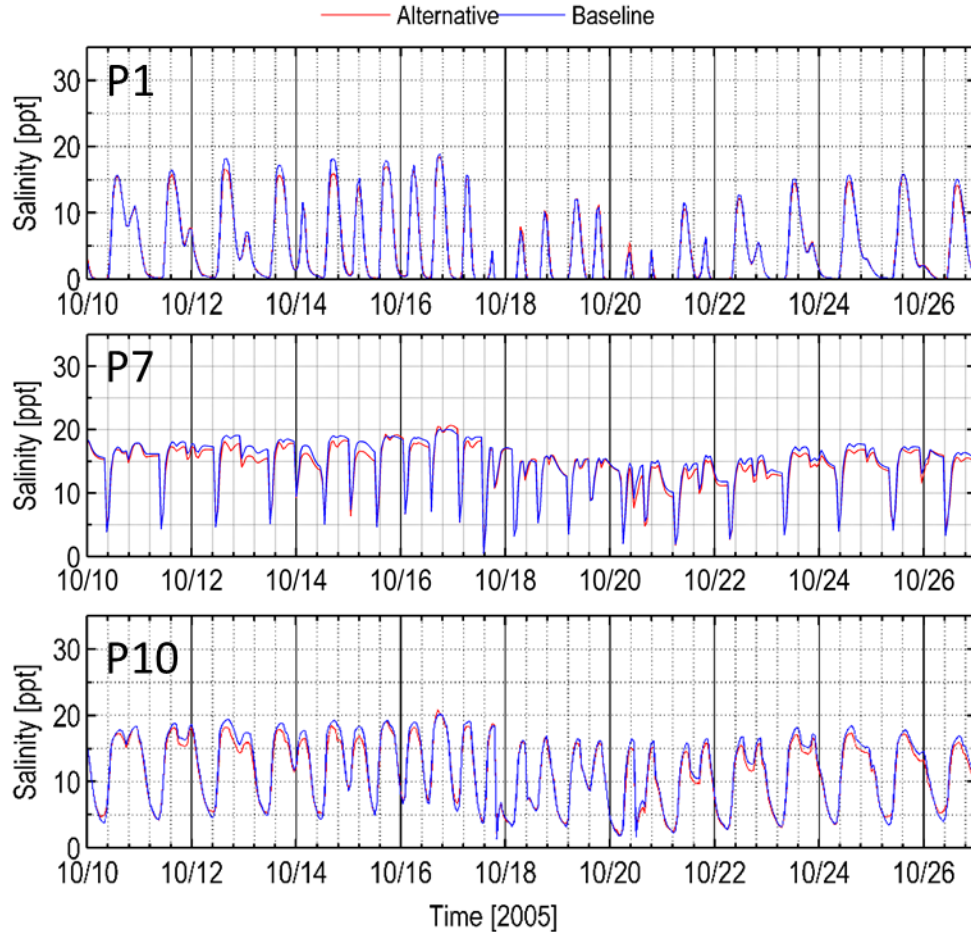
Figure 4.5.   Preferred vs. Baseline Scenarios – Time series of Water Surface Elevation at Station P1, P7, and P10 for Typical Estuarine Condition (October 2005)

However, the results show that the restoration action would alter the predicted salinity at West Pass, South Pass, and the OSRC stations. Salinity is mainly controlled by tidal mixing and upstream fresh-water discharge from the Stillaguamish River. As shown in Figure 4.6, there is notable decrease in salinity levels in South Pass (P10), and the influence extends all the way north into West Pass (P7) during high tide. The plot shows that salinity in the Preferred Alternative Scenario can be up to 2 ppt lower than the Baseline Scenario in West Pass, South Pass, and the lower OSRC stations. The results indicate that proposed restoration will result in a small decrease in the amount of seawater intrusion into the OSRC, West Pass and South Pass channels.

The inundation areas at high and low tides at Leque Island and zis a ba are shown in Figure 4.7. During high tide, Leque Island is nearly fully inundated. The tidal channels connecting Leque Island with South Pass and Port Susan bring seawater into the Leque Island site. The tidal channel at the northwest side connecting Davis Slough and Leque Island also contributes to the inundation. During low tide, southern tidal channels at Port Susan and South Pass become primary drainage channels allowing water being transported back to Port Susan. It appears that the restoration area does not drain fully during low tide. Pockets of seawater are shown to remain in the Leque Island. This is due to the fact that model does not account for percolation of wetted areas and cannot resolve fine scale undulations of bathymetry and the associated drainage. It should be noted that the areas that don't drain are isolated low areas, that will be inundated during the next high tide.

Figure 4.6. Preferred vs. Baseline Scenarios – Time series of Salinity at Station P1, P7, and P10 for Typical Estuarine Condition (October 2005)

The outflow of freshwater from OSRC primarily occurs through the South Pass during ebb which also carries the majority of net outflow to Port Susan Bay and remains relatively unchanged in the Preferred Restoration Alternative Scenario. In the existing as well as in restored condition, relatively small outflow of brackish water to Skagit Bay also occurs through West Pass during the flood period.

The predicted horizontal distribution of salinity for the Preferred Restoration Alternative Scenario over the restored area is shown in Figure 4.7. The seawater enters Leque Island site primarily from the tidal channels at Port Susan Bay and South Pass. On the zis a ba site, brackish water (≈14 ppt) inundation occurs through the west side of the island and the presence of the berm separates east side of zis a ba. Inundation of the east side of zis a ba site occurs with brackish water of lower salinity (≈4 ppt) from the Old Stillaguamish River main stem through channels excavated as part of the restoration design.
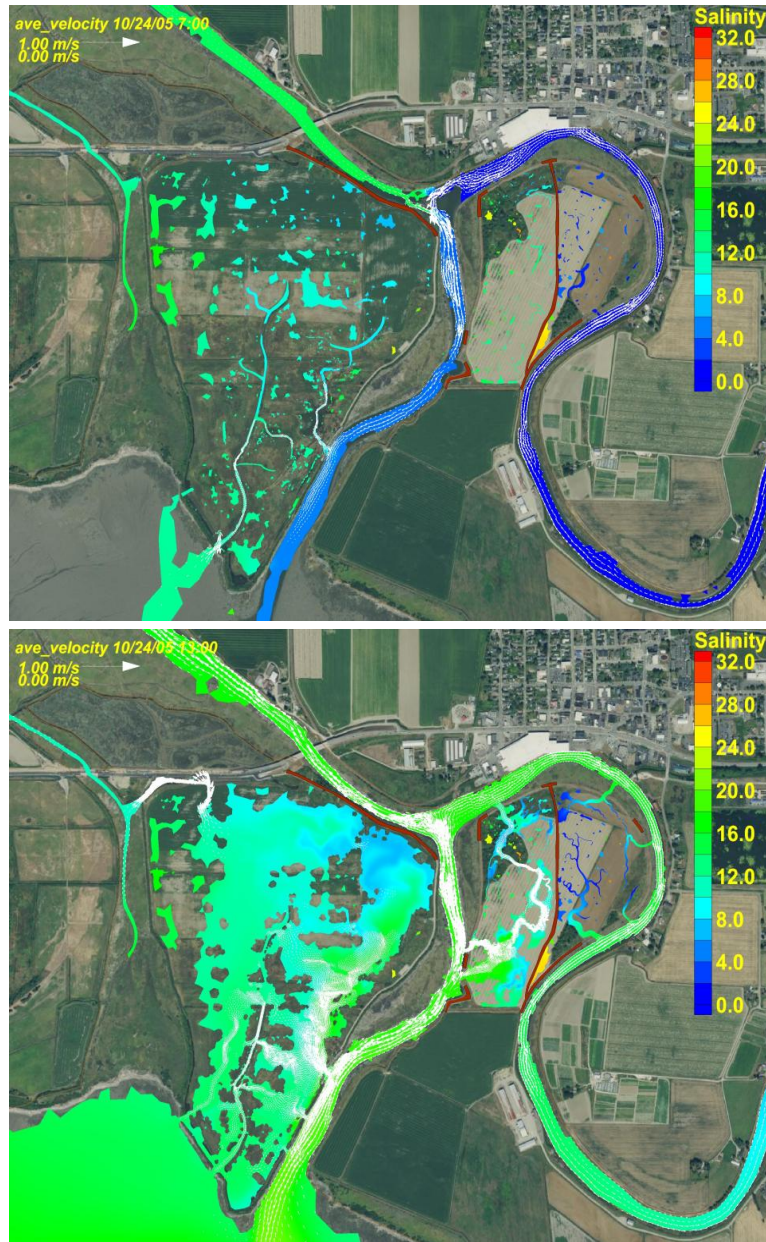
Figure 4.7.   Horizontal Distribution of Salinity at Low Tide (07:00, top) and High Tide (13:00, bottom) for Preferred Restoration Alternative Scenario on October 24, 2005

Figure 4.8 is a difference-plot showing the change in predicted salinity between the Baseline Scenario and the Preferred Restoration Alternative conditions at high and low tides. During low tide following ebb, salinity concentrations are lower ($\approx$ -0.5 ppt) in West Pass relative to the Baseline as also shown in the P7 station time series plot (Figure 4.6) but relatively unaffected in South Pass or OSRC. A similar reduction in salinity is noted in all three channels during high tide following flood indicating an overall reduction in intrusion of saline water from Port Susan. It is noted that this comparison only represents the spring high/low tide condition and that pockets of higher ($\approx$ +0.5 ppt) salinity water may be trapped and intrude upstream during other periods in the tidal cycle as seen in the High Tide panel at the upstream end of OSRC in Figure 4-8.
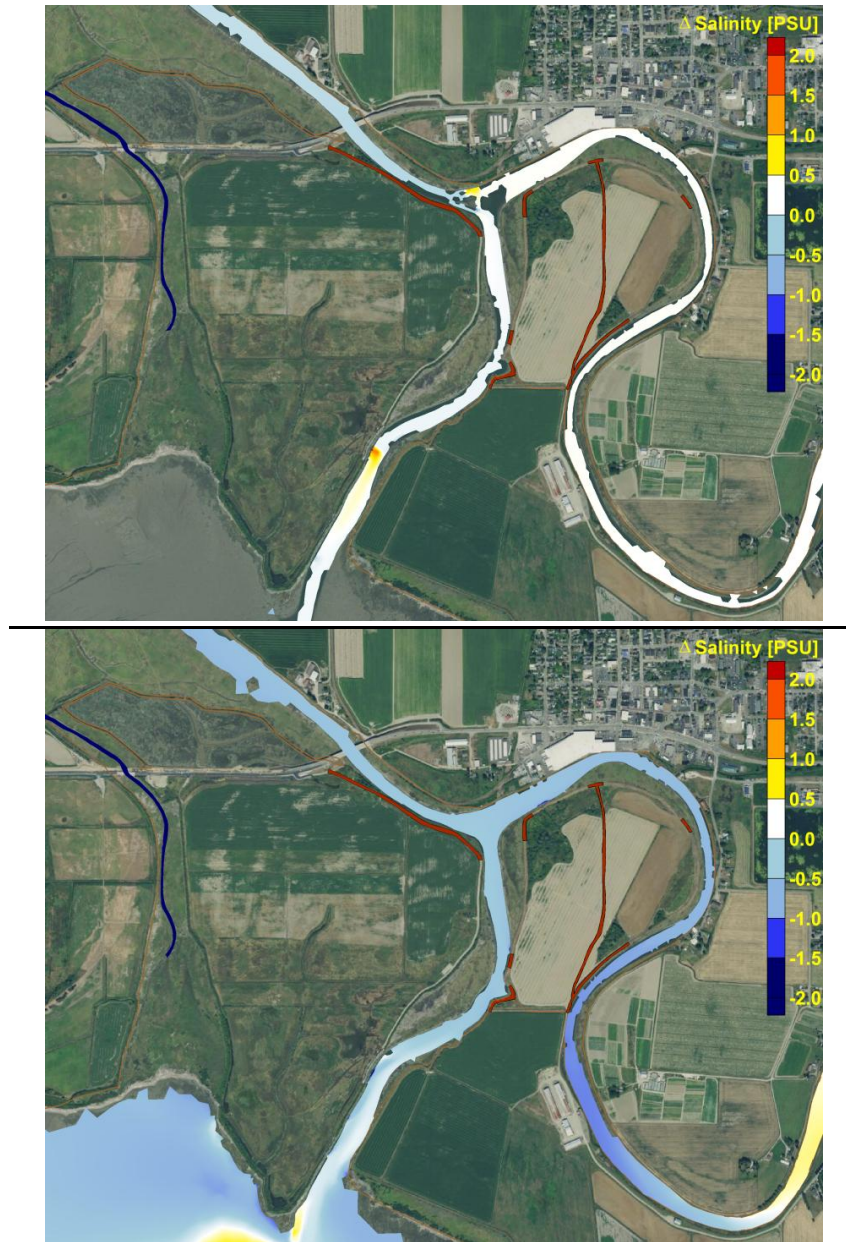
Figure 4.8. Salinity Difference Contours of Preferred Restoration Alternative Scenario Relative to Baseline at Low Tide (07:00, top) and High Tide (13:00, bottom) on October 24, 2005

Time series of predicted water velocity magnitude at the same representative stations around the restoration area are presented in Figure 4.9. Results indicate that the proposed restoration action will not result in significant changes in velocities at P1, P7, and P10 stations. At P1 and P7 the differences are negligible however in South Pass, increase in peak velocity is noticeable during flood as well as ebb. An increase in peak velocity of up to 0.09 m/s during spring tide is predicted in South Pass for the Preferred Restoration Alternative Scenario.
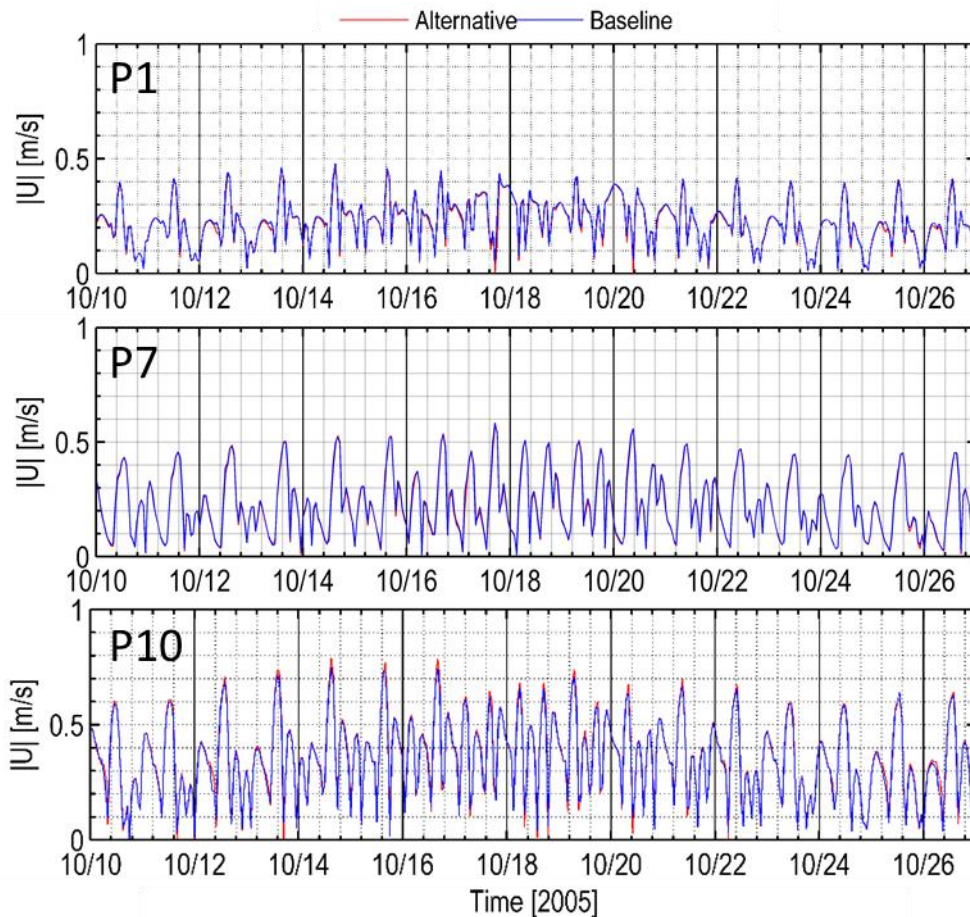
Figure 4.9. Preferred vs. Baseline Scenarios – Time Series of Bottom Velocity Magnitude at Stations P1, P7, and P10 for Typical Estuarine Conditions (October 2005)

Figure 4.10 presents the time series of bed shear stress at the representative stations. Mean bed shear stress at West Pass is predicted to be lower by 0.01 Pa relative to the Baseline Scenario. Mean bed shear stress at South Pass is predicted to increase by 0.04 Pa, with peak increase of 0.8 Pa during spring tide. These results indicate that while West Pass is predicted to experience a slightly lower bed shear stress under the Preferred Restoration Alternative Scenario, South Pass will likely experience higher bed shear stress.

4.3.2   High-Flow Conditions

The focus of the high-flow simulation was to evaluate the impact of the proposed restoration action on bed shear stress during channel-forming flow conditions. Examination of time series of water elevations at the Old Stillaguamish River (P1), West Pass (P7), and South Pass (P3) shows that water surface levels are not significantly different in the Preferred Restoration Alternative Scenario relative to those in the Baseline Scenario (see Figure 4.11). This implies that storage volume offered by the restored marshes is not significant with respect to the flood reduction benefit that is often associated with restoration actions in flood plains.
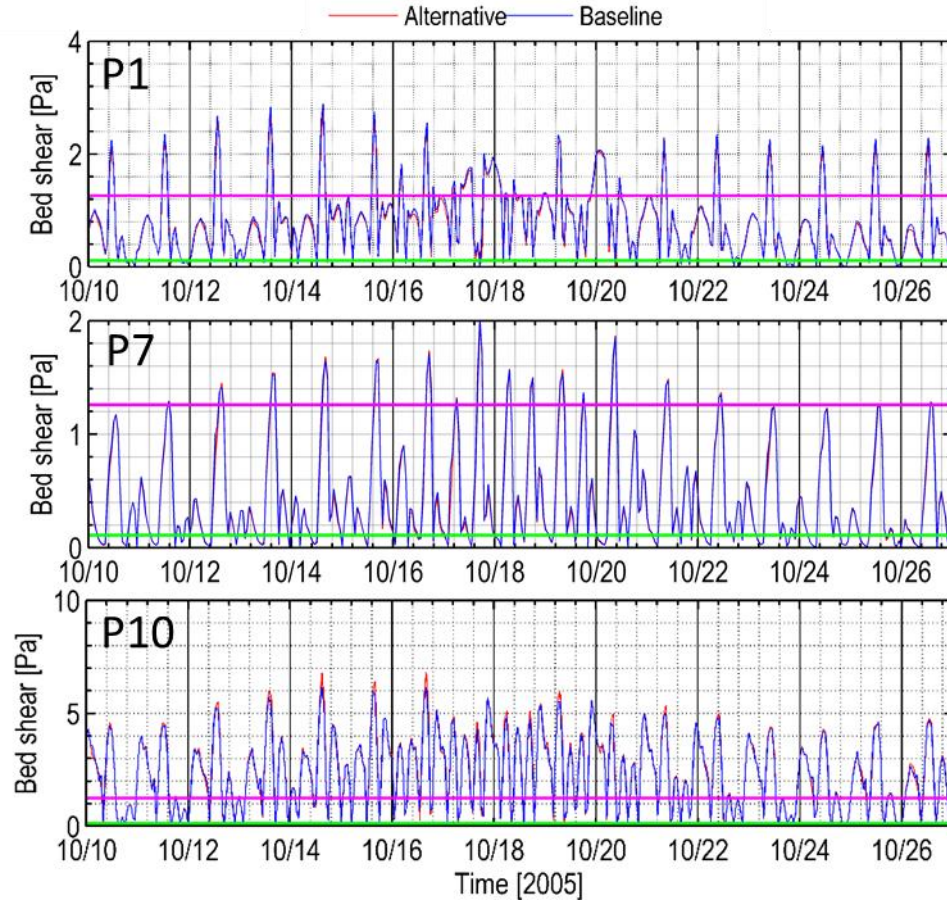
Figure 4.10. Preferred vs. Baseline Scenarios – Time Series Of Bed Shear Stress at Stations P1, P7, and P10 for Typical Estuarine Conditions (October 2005). Critical bed shear for erosion of sand (0.11 Pa) and gravel (1.26 Pa) are marked as green and pink lines.
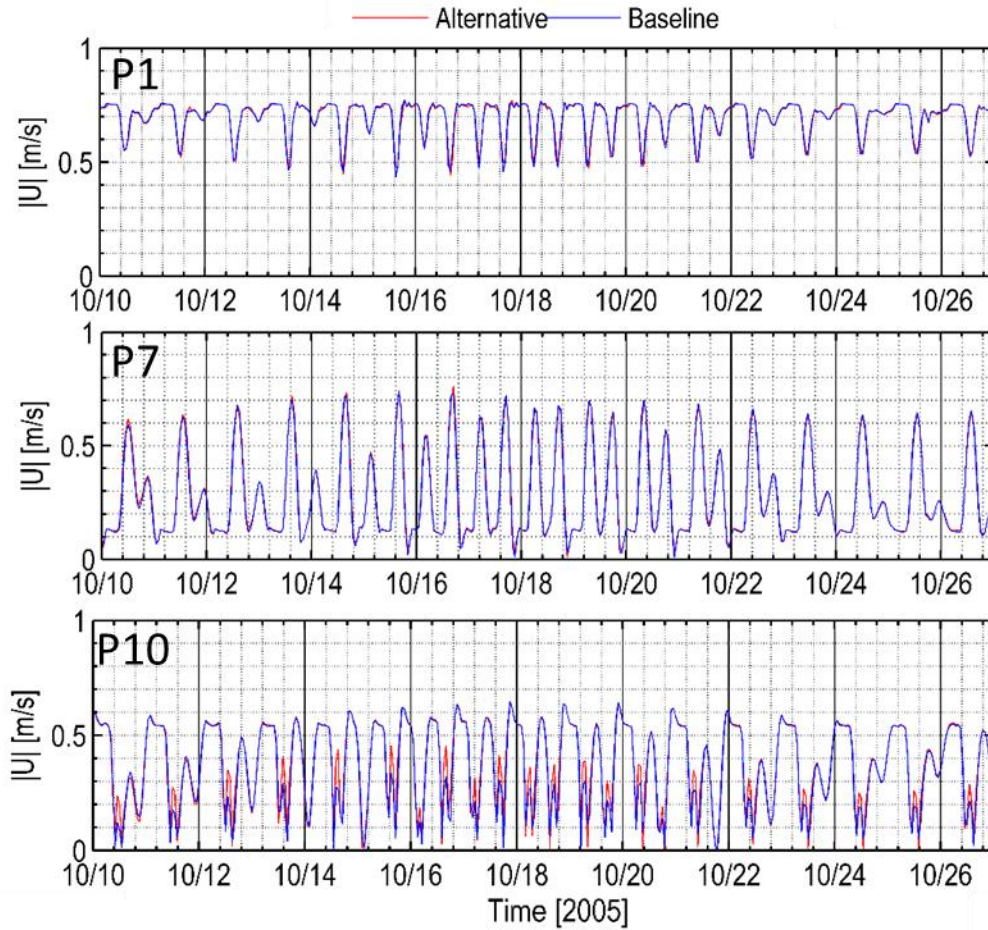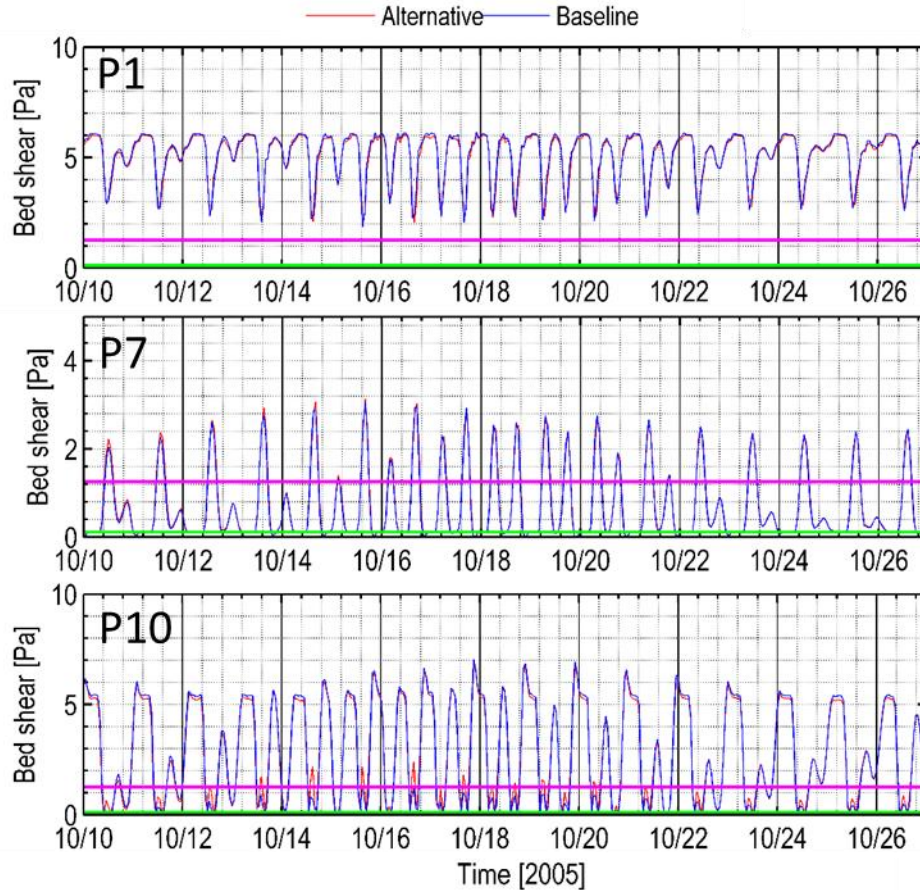
4.11
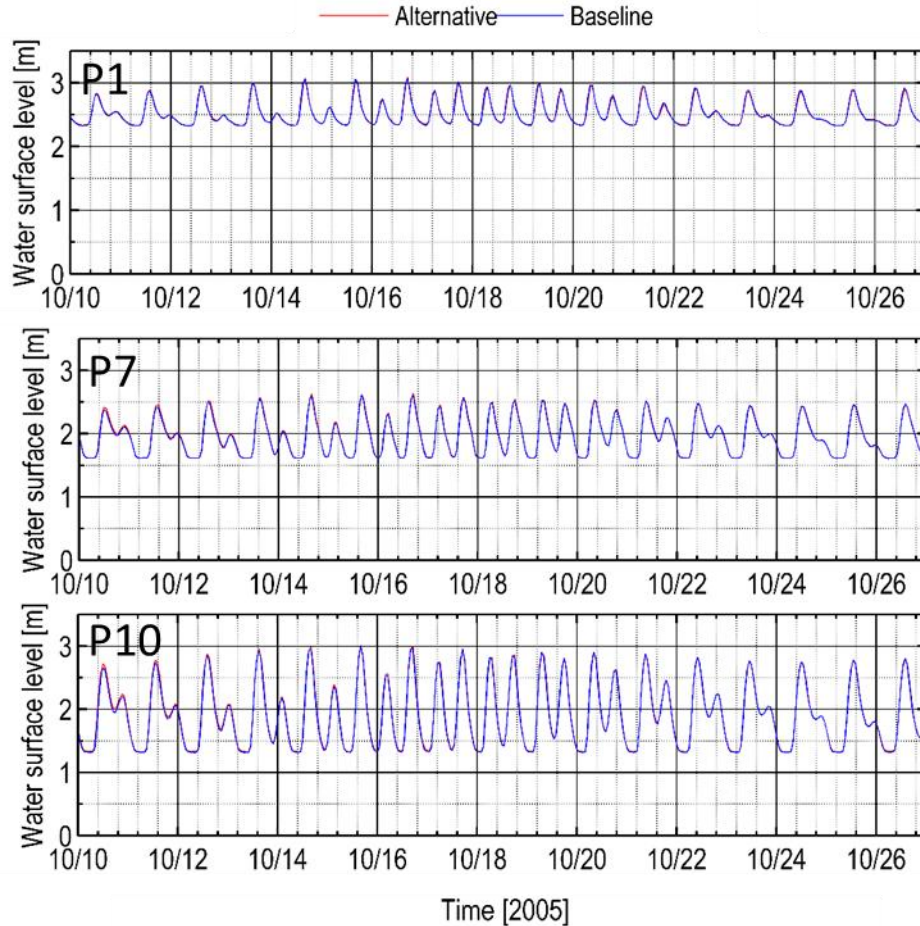
Figure 4.11. Preferred vs. Baseline Scenarios – Time series of Water Elevation at Stations P1, P7, and P10 for Bank-Full Conditions at 26,508 cfs River Flow (tides and wind corresponding to October 2005)

Examination of time series results of predicted velocity magnitudes at Station P1 (ORSC), P7 (West Pass), and P10 (Port Susan) for the Preferred Restoration Alternative Scenario shows that the velocity magnitudes under high flows are relative unchanged compared to the Baseline Scenario. Figure 4.12 shows that velocity magnitudes in West Pass and the lower OSRC in particular remained relatively unchanged under the Preferred Restoration Alternative Scenario relative to Baseline Scenario. In South Pass, velocity magnitudes were predicted to be higher relative to the Baseline Scenario during peak flood period by ≈ 0.12 m/s and relatively no change is seen during ebb when peak velocities are nearly twice as high as those during the flood.

Time series of predicted bed shear stress at the same representative locations during high river flow are shown in Figure 4.13 for Baseline and Preferred Alternative Scenarios. During the high-flow condition, under Preferred Restoration Alternative Scenario, Bed shear stress changes in West Pass and Old Stillaguamish River are relatively small with an average increase of 0.01 Pa. A higher bed shear stress increase of 1.5 Pa is predicted at South Pass station P10 relative to the Baseline Scenario during flood period but relatively no change during peak ebb during which peak bed shear stress values reach as high as 7 Pa. These magnitudes which were above the critical bed shear stress for sand and higher grain sizes in the Baseline were a little higher during the flood tidal period. This could result increased upstream movement of sediment during the flood tide.

4.12

Figure 4.12. Preferred vs. Baseline Scenarios – Time Series of Velocity Magnitude at Stations P1, P7, and P10 for Bank-Full Conditions at 26,508 cfs River Flow (tides and wind corresponding to October 2005)
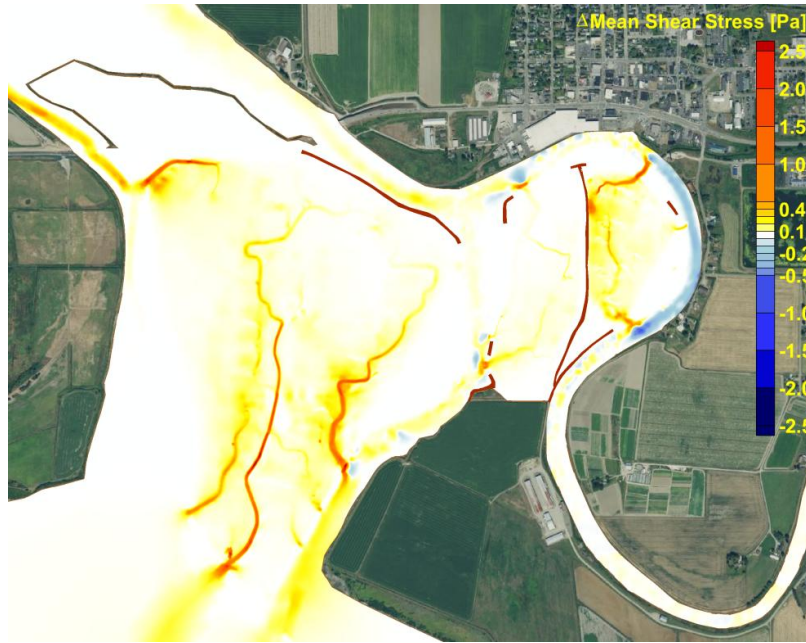
Figure 4.13. Preferred vs. Baseline Scenarios – Time Series of Bed Shear Stress at Stations P1, P7, and P10 for Bank-Full Conditions at 26,508 cfs River Flow (tides and wind corresponding to October 2005). Critical bed shear for erosion of sand (0.11 Pa) and gravel (1.26 Pa) are marked as green and pink lines.

Figure 4.14 shows horizontal distribution of maximum and mean bed shear stress for high-flow (bank-full) condition at 26,508 cfs. The simulated mean bed shear stress result shows that from Twin City Foods downstream to the river channel breach, bed shear stresses higher than 4.5 Pa are noted. This result indicates that predicted bed shear stress is likely higher in the entire OSRC around zis a ba. The tidal channels over the restoration sites at Leque Island and zis a ba are predicted to experience bed shear stresses in the 1.5 Pa to 2.0 Pa range, which are lower than those predicted in the main river channels. However, bed shear stresses in the tidal channels also are above the critical bed shear stress for sand and gravel during high-flow conditions.

Figure 4.15 shows a mean bed shear stress difference plot for the Preferred Restoration Alternative Scenario and the Baseline Scenario. An increase in bed shear stress is predicted at most locations in West Pass and South Pass. A decrease in bed shear stress is noted in OSRC section just east of zis a ba and between the mouths of the tidal channel from zis a bas. This decrease in bed shear is associated with reduction in river channel flow due to the fraction that is diverted over east zis a ba site. The presence of tidal channels could alter the bed shear stress in the West Pass and South Pass channels. An increase of up to 0.3 Pa of bed shear stress relative to the baseline can occur in West Pass and South Pass channels at these locations. This increase is small relative to typical magnitude of bed shear stress which is significantly higher than that needed for movement of silt and sand and will not result in significant increase in scour or channel widening.
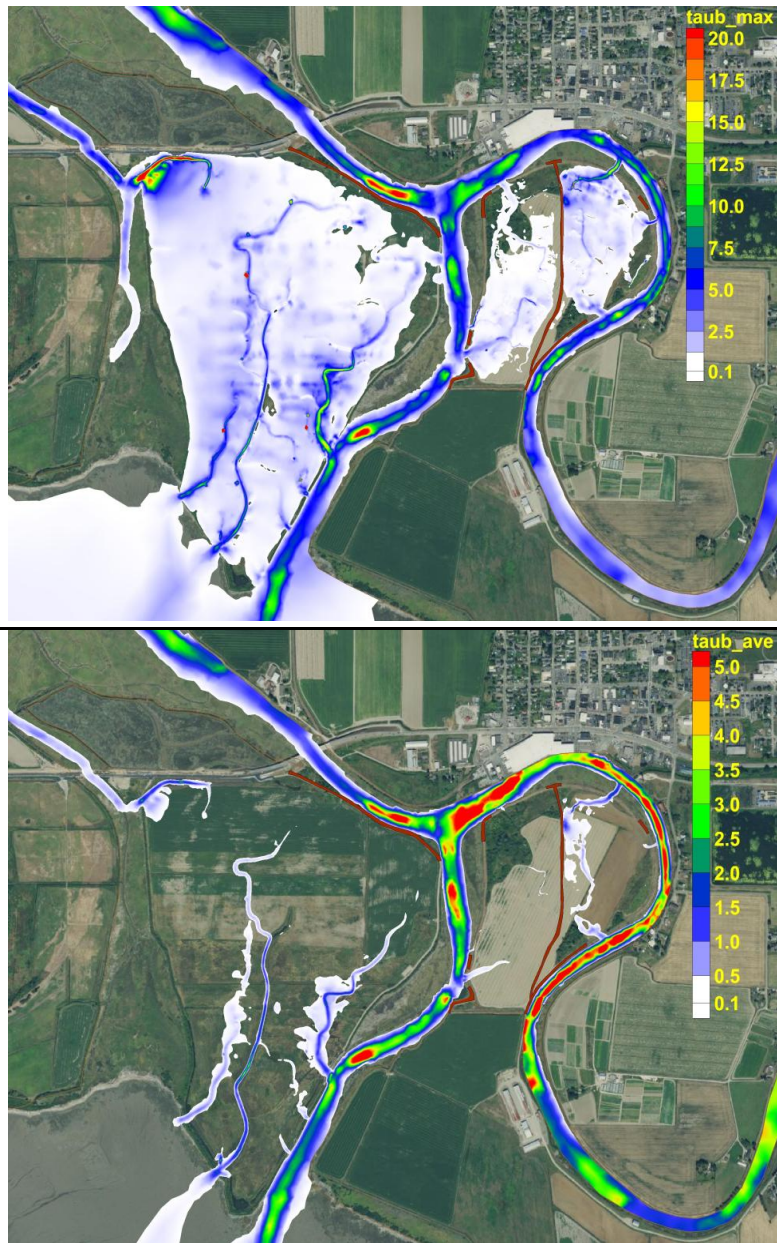
Figure 4.14. Horizontal Distribution of Maximum (top) and Mean Bed Shear Stress (bottom) for Preferred Restoration Alternative Scenario for High-Flow (bank-full) Conditions at 26,508 cfs

Figure 4.15. Mean Difference Bed Shear Stress Contours of Preferred Restoration Alternative Scenario Relative to the Baseline Scenario at the High-Flow (Bank-Full) Condition at 26,508 cfs

Bed shear stress distributions in West Pass during high flow conditions are higher under Preferred Restoration Alternative Scenario relative to Baseline Scenario, which is opposite to predictions for typical estuarine flow condition. Unlike high flow condition, creation of tidal channels and storage across eastern zis a ba leads to a slight increase in bed shear stress along eastern bend of Old Stillaguamish River around zis a ba. Very little change is predicted in the bed shear stress in upstream of Twin Foods facility. Bed shear stresses at the Leque Island and zis a ba restoration sites are predicted to be highest near the mouth of the tidal channels. The entrance to the tidal channels will likely evolve until an equilibrium cross section is reached.

To facilitate quantitative comparison of scenarios, cumulative frequency statistics were generated for bed shear stress at the selected 11 stations.

Table 4.1 provides the percentage of the time that bed shear stresses exceed 0.11 Pa (i.e. sand erosion) at the 11 time series stations at the High-Flow (Bank-Full) Condition. Examination of time series of bed shear stress at stations in the Old Stillaguamish River (P1, P2, P4, P5, and P6) shows that bed shear stresses are not significantly different in the Preferred Restoration Alternative Scenario relative to those in the Baseline Scenario. Bed shear at these locations will be greater than 0.11 Pa (sand erosion) for 100% of the time. Station P10 and P11 (South Pass) experience ≈ 80 - 90% in the percentage of time when the bed shear stress exceeds 0.11 Pa, which is lower compared to the Lower Old Stillaguamish River. The percentage of time the bed shear stress exceeds 0.11 Pa are ≈ 60 - 80 % at Stations P7 and P8 located in West Pass. Overall, the results indicate that the Preferred Restoration Alternative Scenario would increase the percentage of time for bed shear stress to exceeds 0.11 Pa at West Pass and South Pass, while the Lower Old Stillaguamish River would experience the same condition in the percentage of time bed shear stress that exceed 0.11 Pa. In summary, the increases in bed shear will ensure that sediment deposition is not predicted to be a problem, yet the increases are small enough such that increased scour is also not likely other than that predicted at the mouths of the tidal drainage channels at restoration sites.

Table 4.1. Bed Shear Stress Response for All Scenarios

Location	Percentage of Time of Bottom Shear Stress* [%]	
	Alternative	Baseline
	>0.11 Pa (Sand)	>0.11 Pa (Sand)
P1	100	100
P2	100	100
P3	100	100
P4	100	100
P5	100	100
P6	100	100
P7	66.91	63.91
P8	75.27	75.25
P9	4.89	1.95
P10	90.77	89.48
P11	85.68	79.15

5.0   Wave and Storm Climate Assessment

5.1   Introduction

During stakeholder meetings conducted by DU, concern was expressed that proposed restoration alternatives included dike removal along the West Pass of Old Stillaguamish River along the north border of Leque Island. If implemented, during extreme high-water and storm conditions, there would be potential for increased exposure to wave overtopping onto City of Stanwood properties north of West Pass on the Old Stillaguamish River. The task discussed in this section was initiated to address this concern with the objective of assessing wave and storm induced exposure to extreme high-water surface elevations from Port Susan Bay and Leque Island. This involves estimating wave climate in the study area. Exposure to wave impacts during extreme environmental conditions consisting of a combination of high tides, high river flows, and peak storm conditions in Port Susan Bay were evaluated.

We selected a design condition of a 100-year event for storm and wind and applied coastal engineering principles to estimate the following quantities.

1. Extreme tidal elevation typically corresponding to extreme tidal elevation and storm surge ($\eta_{tide+surge}$)
2. Half of significant wave height (η_{wave})
3. Wind setup for 100-year storm/wind (η_{wds})
4. Wave setup for 100-year storm/wind (η_{wvs})
5. Wave runup (η_{R2})
6. Sea level rise (η_{slr}).

Exposure to wave impacts will be in the form of maximum wave surface level (η_{max}) that includes wave effects super imposed on other components that affect water surface elevations.

5.2   Extreme Water Surface Elevation

The 100-year maximum water elevation in Port Susan Bay near the project site was estimated to evaluate the risk of flooding or overtopping on the restored dike around the restored project site under extreme tidal elevation, storm surge, and future sea level rise. The 100-year maximum water surface level (η_{max}) is computed as the sum of the following components:

$$\eta_{max} = \eta_{tide+surge} + \eta_{slr} + \eta_{wave} + \eta_{wds} + \eta_{wvs} + \eta_{R2} \qquad \text{(Eq. 1)}$$

$\eta_{tide+surge}$	Extreme tidal elevation from long-term (>100 years) records
η_{slr}	Sea level rise – year 2100
η_{wave}	Half of significant wave height – 100-year storm/wind
η_{wds}	Wind setup – 100-year storm/wind
η_{wvs}	Wave setup – 100-year storm/wind
η_{R2}	Wave runup with 2% exceedance – 100-year storm/wind.

5.2.1 Extreme Tidal & Storm Elevation ($\eta_{tide+surge}$)

The maximum tidal elevation ($\eta_{tide+surge}$) was estimated by evaluating the data taken from the NOAA tidal elevation database, which contains 113 years of records. The Seattle Station (9447130; Seattle, Washington) was selected as representative of the MSL in Puget Sound and the project site that included the effects of region-wide storm surge propagating into Puget Sound from the Pacific continental shelf. Because extreme tidal and storm elevation affect local tides, the frequency and intensity of storm events must be considered in the calculation of extreme water surface elevation. Generally, intense storm events occur less frequently than smaller storms. According to the NOAA database, tidal heights above Mean Higher High Water in Puget Sound range from 0.45 m to 0.97 m for a storm with a return frequency varying from once in one year to once in 100 years (Figure 5.1). Additionally, tidal heights below Mean Lower Low Water in Puget Sound range from −0.9 m to −1.5 m for a storm with a return frequency of once in 100 years. The 100-yr extreme tidal elevation change was therefore set at +0.97 m.
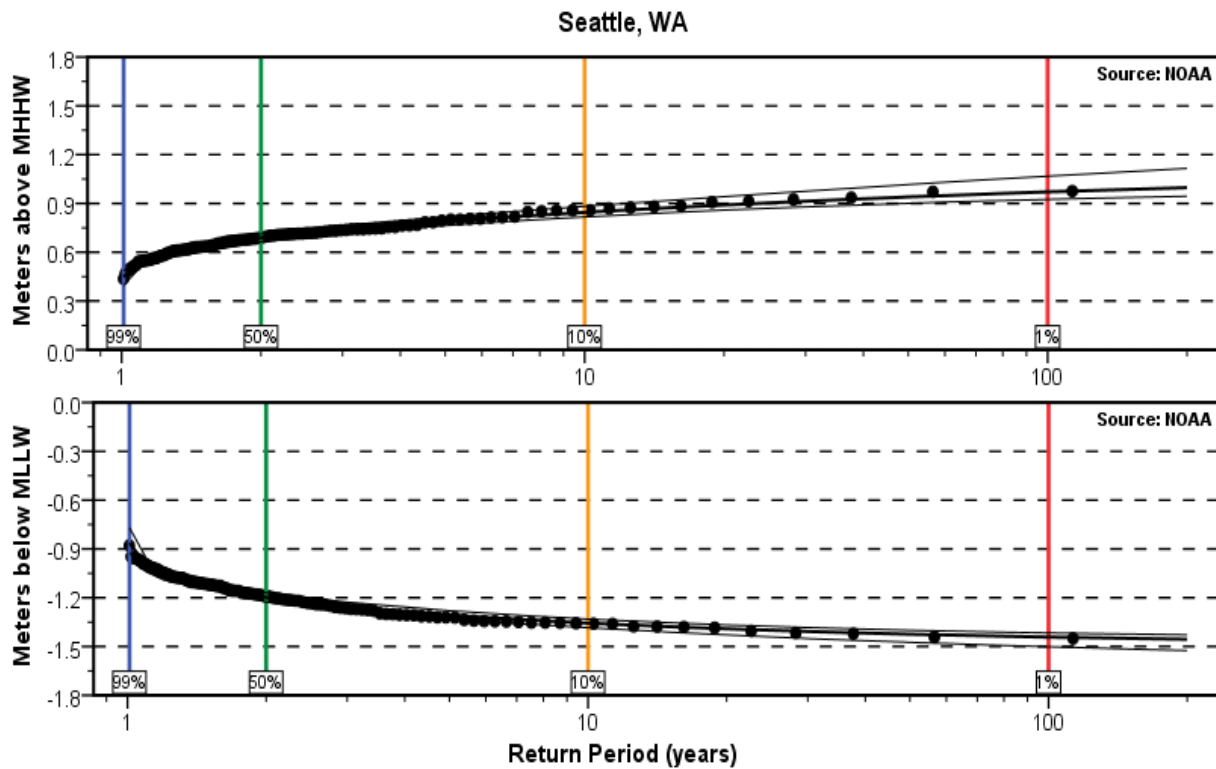
Figure 5.1. Return Period of Tidal Elevation for 100-Year Event (Source: NOAA)

5.2.2 100-year Storm - Significant Wave Height (η_{wave})

To compute significant wave height, two sets of information are needed: 1) design wind magnitude and duration and 2) fetch length, which is the horizontal distance over which wave-generating winds blow. In deeper waters wave height is controlled by either fetch length or duration depending on which becomes limiting. The 100-year wind speed information was obtained from Yang et al. (2014), who estimated the 100-year wind speed based on 66 years of long-term wind record (1948 to 2013) at NOAA's National Climate Data Center station (72797524255) on Whidbey Island. Wind data were recorded at a station height of 14.3 m above MSL.

To simulate the wind-driven storm surge, wind forcing at a 10-m height should be used in the model. Therefore, wind speed data were adjusted from 14.3 m to the standard 10-m height based on the wind profile power law. The relation between peak wind speed and the probability of exceedance can be obtained by a regression-fit to the data:

$$V_{wind} = 29.58 \exp(-0.003P) \tag{Eq. 2}$$

where V_{wind} is the peak wind speed corresponding to the percentage of storm occurrence P over a 100-year period. Based on Equation (2), the peak wind speed for a 100-year storm event (P = 1) was 29.49 m/s (Figure 5.2, left). Analysis of wind speed and direction distributions for the entire record period showed that wind directions were primarily from south southwest from April to September and from northwest from October to March.
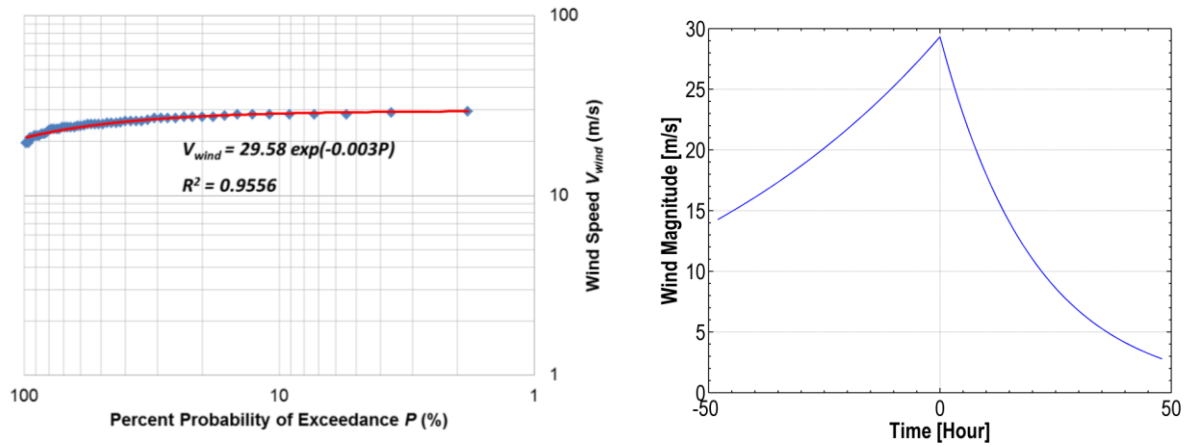
Figure 5.2. Wind Cumulative Frequency Curve at National Climatic Data Center Station on Whidbey Island (left). A modified wind duration model adapted for this study (right)

Wind duration is required to compute the maximum significant wave height limited by duration. A wind duration model estimated by Emmanuel (2000) from an empirical study on Pacific hurricanes from 1970 to 1999 was used to derive a wind duration model with the maximum speed at 29.49 m/s (Figure 5.2, right). The modeled wind magnitude was then classified into 1-hour wind data bins, which were then used to construct a histogram of wind frequency at hourly intervals for different wind magnitudes. A 4-hour wind duration, which is associated with the maximum of 100-year storm event at 28 m/s, was obtained (Figure 5.3).

Two fetch lengths were considered as a conservative approach. In Port Susan fetch settings, the fetch extends along the Port Susan from Possession Sound to Livingston Bay, which has length of ≈ 17 km. This provides the longest feasible fetch that can generate waves towards Port Susan Bay tide flats. The second fetch settings, titled Leque Island fetch provides normal incident approach across Port Susan Bay to Leque Island. Figure 5.4 presents the fetch profiles for each wind direction along and across the Port Susan Bay.
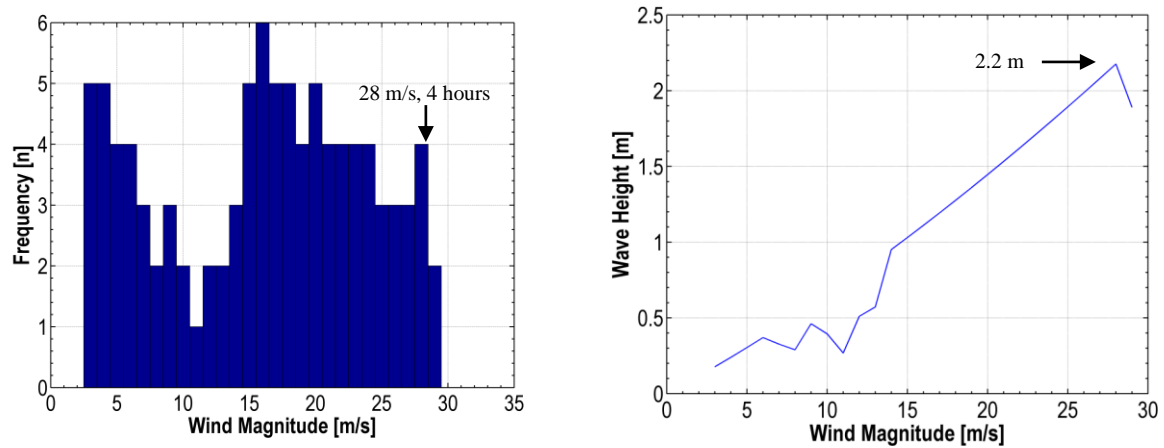
Figure 5.3. Histogram of Wind Frequency at Hourly Interval for Different Wind Magnitude (left) and Significant Wave Height (H_{sig}) Estimation Based on Wind Duration and Speed (right)
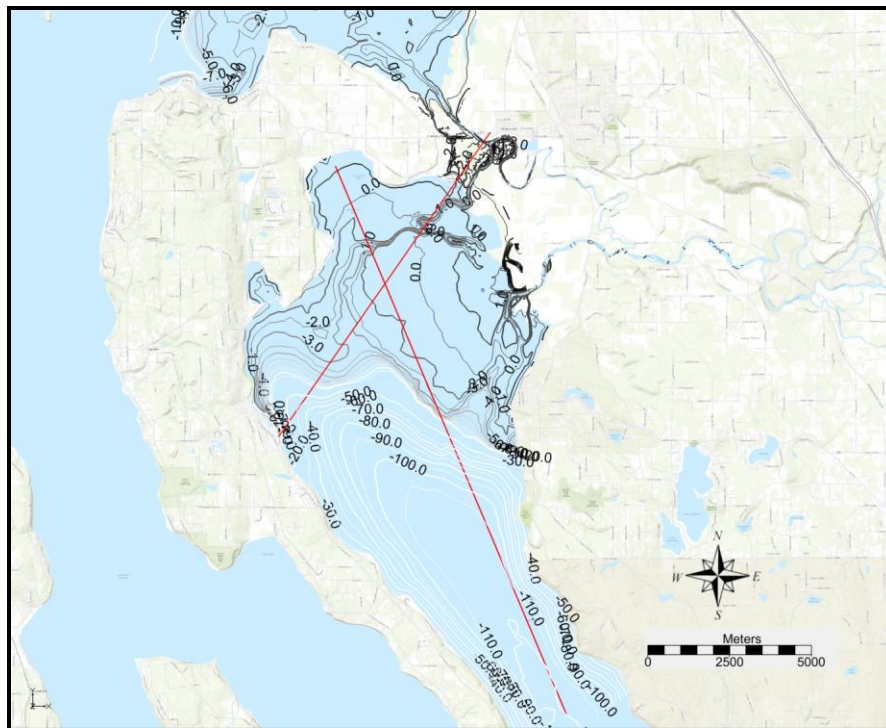
Figure 5.4. Selected Fetch Alignments Needed to Calculate 100-Year Significant Wave Heights

Table 5.1 summaries the significant wave height calculations for Port Susan and Leque Island fetches. In calculating the significant wave height, Port Susan has average water depth of 83.3 m above MSL, which was used for the deep-water linear wave analysis (*Shore Protection Manual* [SPM] Volume I, 1984). Port Susan has longer fetch length of 16.7 km that resulted in higher significant wave height of 2.2 m and higher wave period of 3.9 seconds compared with Leque Island.

Table 5.1. Summary of Wave Analysis for Calculating Significant Wave Height

Parameter	Port Susan	Leque Island (South Pass)
Fetch length	16.7 km	6.5 km
Average water depth	82.0 m (NAVD88) + 1.3 (MSL) = 83.3 m (MSL)	1.2 m (NAVD88) + 1.31 (MSL) = 2.51 m (MSL)
Wind speed[1]	28 m/s	28 m/s
Wind duration[1]	4 hours	4 hours
Wave analysis method	Linear wave analysis for deep water (SPM Volume I, 1984)	Linear wave analysis for shallow water (SPM Volume I, 1984)
Drag coefficient, CD	0.0021	
Significant wave height, Hsig	2.2 m, η_wave = 1.1 m	0.8 m, η_wave = 0.4 m
Significant wave period, T	3.9 s	3.1 s
Breaking depth	2.79 m (MSL)	1.0 m (MSL)

[1]Based on empirical wind duration during Pacific hurricanes from 1970-1999 (Emmanuel, 2000) and 100-year wind storm (Yang et al., 2014)

5.2.3   Wave Setup (η_{wvs}) and Runup (η_{R2})

Wave setup is the increase in mean water level above MSL due to momentum transfer to the water column by waves that are breaking or otherwise dissipating their energy. In other words, wave setup is the increase in water level with waves of periods ranging from several to tens of periods of the dominant incident wind wave period. A typical wind wave period is in the range of 8 to 15 seconds. Wave runup is the uprush of water from wave action on a shore barrier intercepting the still water level. The extent of runup can vary greatly from wave to wave in storm conditions, so a wide distribution of wave runup elevations provides the precise description for a specific situation. Wave runup was calculated based on laboratory experiments of runup on smooth impermeable slopes. The wave runup calculations are made given the deep-water significant wave height, peak wave period, and foreshore slope. Wave runup depends primarily on the levee bank slope, the water depth at the levee toe, fetch length, wind speed, and wave approach angle.

In the calculation of wave setup and wave runup, a longer fetch is one of the key factors that results in a greater wave height values. To evaluate wave setup and wave runup values, significant wave height (H_{sig}) and period (T) were used and applied to the wave setup and wave runup equations stated in SPM. The 2% wave runup elevation, which represents the elevation above the still water level that is exceeded by only 2% of the waves, was calculated. Table 5.2 presents a summary of the parameters and estimated wave setup and wave runup at the Port Susan and Leque Island fetches. Illustrations of wave setup and wave runup are presented in Figure 5.5.

Table 5.2. Summary of Calculated Wave Setup and Wave Runup, Including Input Wave Parameters

Location	Port Susan	Leque Island
Significant wave height, H_{sig} (m)	2.2	0.8
Significant wave period, T (s)	3.9	3.1
Wave setup ($\boldsymbol{\eta_{wvs}}$) at breaking depth (m)	0.1	0.002
Wave setup ($\boldsymbol{\eta_{wvs}}$) at 0 depth (m)	0.4	0.2
beach slope	1:200	1:200
Wave runup ($\boldsymbol{\eta_{R2}}$ / 2% exceedance) (m)	0.2	0.1
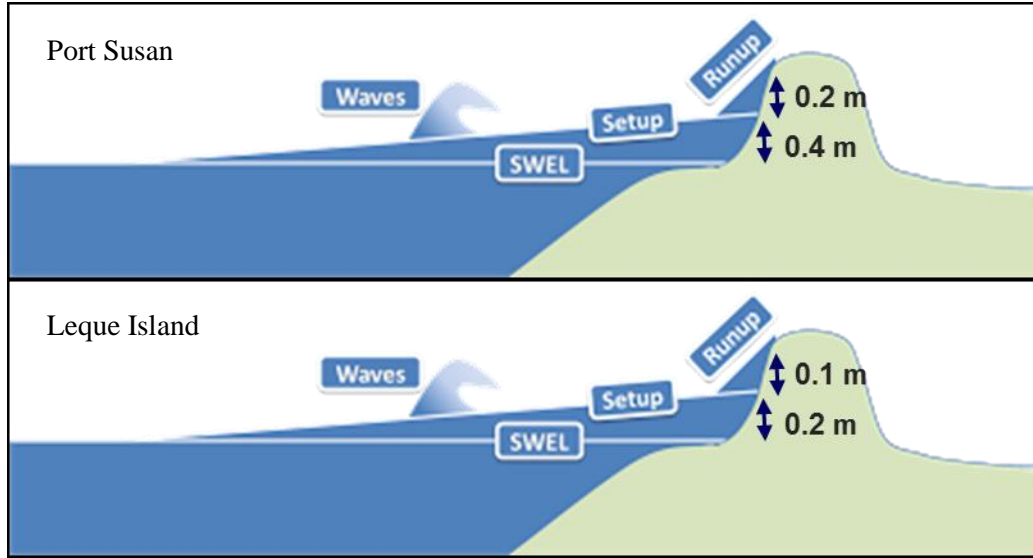
Figure 5.5. Illustration of Wind Setup and Wind Runup for Port Susan Fetch and Leque Island Fetch

5.2.4   100 Year Local Wind Setup (η_{wds})

To consider both the local setup by the wind stress acting on the model domain free surface and the effects of the wind stress acting over the larger scale coastal ocean outside the model domain, the FVCOM model was used to estimate local wind setup (local surge rise) using the 100-year wind forcing that was already explained in Section 5.2.2. The wind forcing was set at high tide, and the model was forced by a 2-week tide that is used for hydrographic assessment. It should be noted that the wind-induced surge was simulated under 2-week normal tide conditions. The results show a local surge elevation of about 0.6 m (Figure 5.6). The maximum sea elevation at normal condition is 2.9 m and at surge is 3.5 m (NAVD 88).
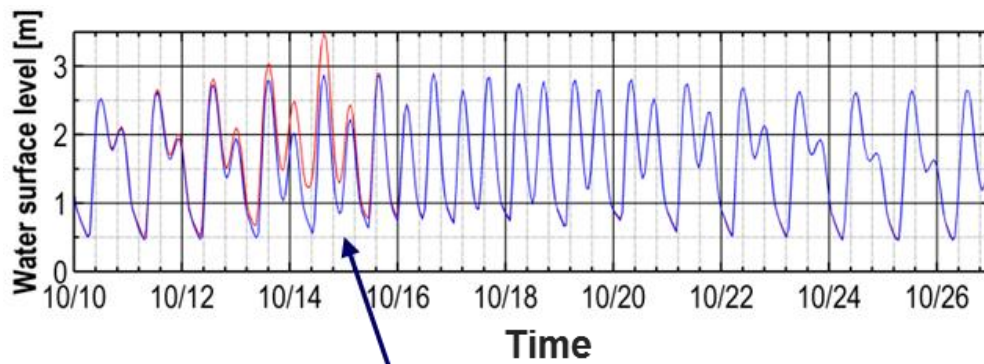
Figure 5.6. Time Series of Water Surface Elevation Generated from Model Simulation using Normal Wind (blue) and 100 Year Local Wind Setup

5.2.5 Long-Term Sea Level Rise (η_{slr})

Information on projected long-term sea level rise was obtained from several sources, including the National Research Council (NRC), NOAA, and the USACE Climate Adaptation Project. By year 2100, NRC predicts sea level could rise to 0.618 m at Seattle NOAA Gauge (9447130). USACE and NOAA predict sea level rise under different emission rates. Under the lowest emission rate, sea levels are expected to rise around 0.2 m (above MSL) at Seattle. Sea levels could rise by 0.5 m under an intermediate emission rate. Under the highest emission rate, sea levels are expected to be three times higher than that in intermediate emission rate (≈ 1.5 m above MSL). This extreme sea level rise could increase the potential for flooding and damage from storm surges. Figure 5.7 shows the long-term projected seal level rise reported by NRC as well as the projected sea level rise by USACE and NOAA for different emission rate scenarios.
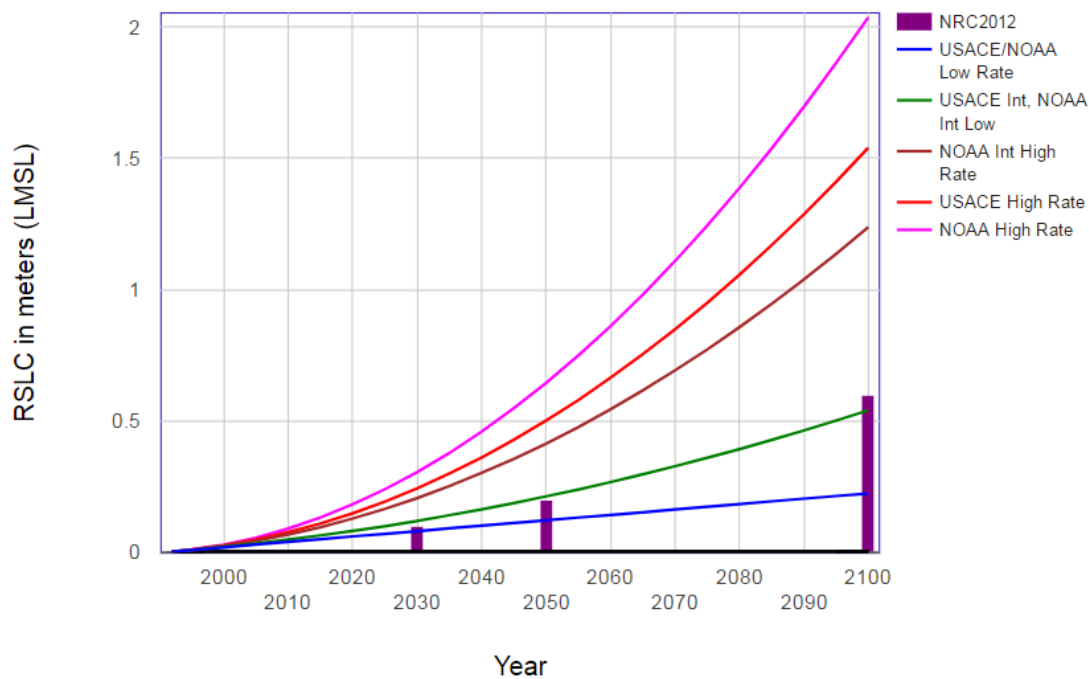
Figure 5.7. Relative Sea Level Change Projection for Seattle Gauge (9447130)

For this extreme wave analysis, a predicted sea level rise under an intermediate emission rate by NOAA or USACE was selected. The predicted value of 0.5 m is comparable with the NRC prediction of 0.618 m.

5.2.6 Extreme Water Elevation

After all components contributing to water surface elevation were estimated, the extreme water elevation is calculated using Equation (1) by summing all the wave components. The empirical method in Equation (1) assumed there is no interaction among wave, relative sea level rise, windstorm surge, and extreme high tide. The final values of the extreme water elevation at Port Susan and Leque Island are presented in Table 5.3.

Table 5.3. Summary of Calculated Extreme Water Elevation and all Wave Components (above MSL)

Location	Port Susan	Leque
Extreme tide, $\eta_{tide+surge}$ (m)	2.4	2.4
Wind setup, η_{wds} (m)	0.6	0.6
Sea level rise, η_{slr} (m)	0.5	0.5
Significant wave height, H_{sig} (m)	2.2; η_{wave} = 1.1m	0.8 m, η_wave = 0.4 m
Extreme water elevation, η_{max} (m)	4.6	3.9
Total	or 5.9 m above NAVD88	or 5.2 m above NAVD88

The main difference in extreme water elevation calculations for the two sites is in the calculation of significant wave height, which varies depending on location. Longer wave fetch gives higher significant wave heights. The estimated significant wave height at Port Susan is 1.1 m, which is higher than that at Leque Island (i.e., 0.4 m). The total estimated extreme water elevation at Port Susan and Leque Island are 4.6 m and 3.9 m (above MSL, or 5.9 m and 5.2 m above NAVD88), respectively, which are most likely will inundate the restoration area.

Figure 5.8 and Figure 5.9 present profiles of the extreme water elevation along the Post Susan and Leque Island fetches. The Leque Island profile also extends over the land at the northern part of West Pass. The profiles include 100-year sea level rise that contributes a 0.5 m increase of sea surface elevation. Those extreme values were estimated under assumptions that the 100-year maximum wind was blowing following typical Pacific storms with the peak speed of 29.49 m/s in the same direction and the storm event would occur at the same time as the extreme high tide. It should be noted that the wind-induced surge was simulated under normal spring tide condition.
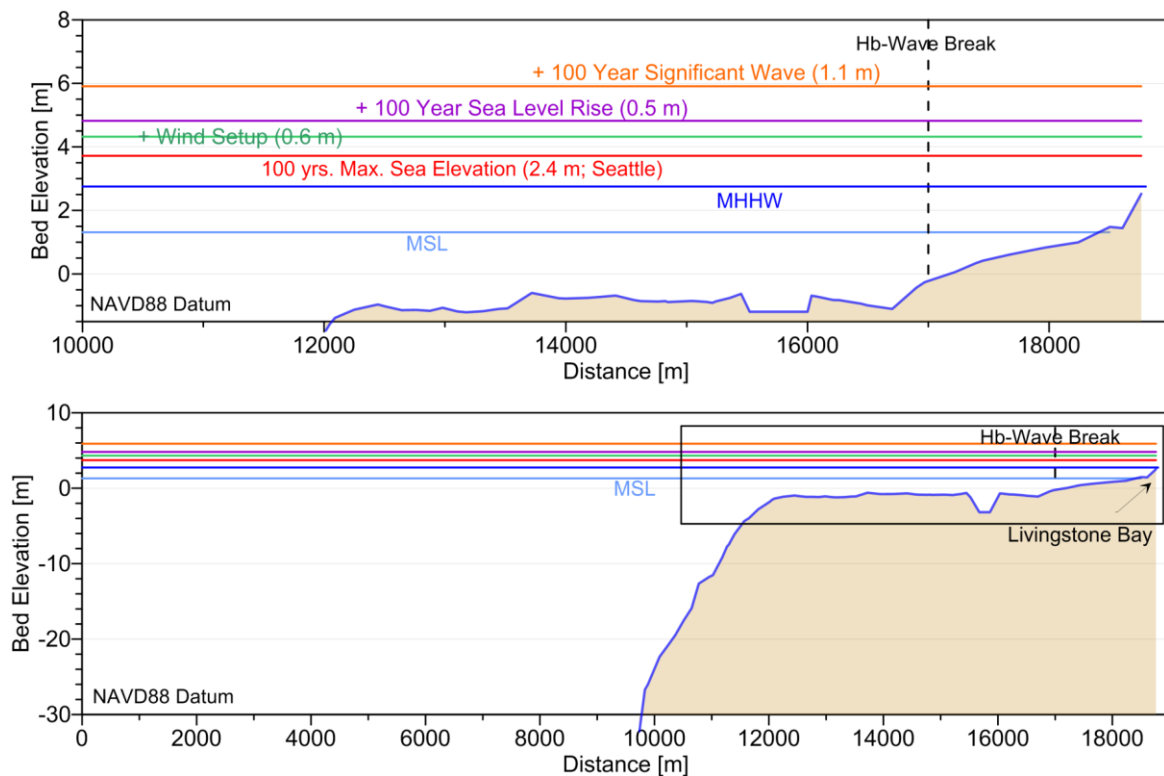
Figure 5.8. Summation of Components Contributing to High Water Surface Elevation for Port Susan
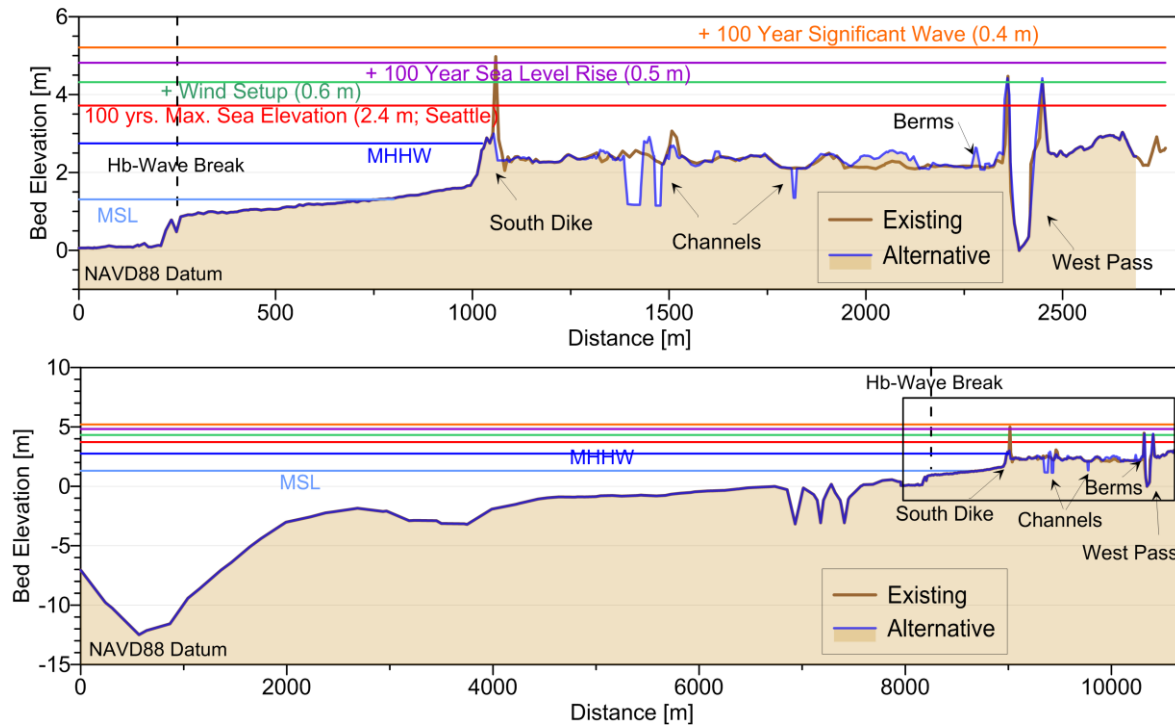
Figure 5.9. Summation of Components Contributing to High Water Surface Elevation for Leque Island

6.0   Conclusions

DU in collaboration with the WDFW and the Stillaguamish Tribe have evaluated dike removal and dike breaching actions as part of near-shore restoration efforts at Leque Island and zis a ba sites near the mouth of the OSRC. A three-dimensional hydrodynamic model of Port Susan Bay, Skagit Bay, and the interconnecting region including the restoration sites at Leque Island and zis a ba region was developed. The model was applied to generate detailed quantitative oceanographic information for the Preferred Restoration Alternative Scenario as part of the restoration feasibility assessment. The effects of restoration involving combinations of creating tidal channels and removal of sections of dikes from the Leque Island and zis a ba sites were evaluated and compared with baseline (i.e., existing) conditions. A series of hydrodynamic modeling simulations including a typical condition of October 2005 and a high-flow condition representing bank-full conditions were performed for both scenarios, and a set of parameters (i.e., water elevation, salinity, and bed shear stress) was evaluated to quantify the hydrodynamic response of the near-shore restoration project.

The refined and updated model was first applied to existing conditions prior to restoration representing the Baseline Scenario. The predicted results were compared with observed data collected in Port Susan Bay near the mouth of the Stillaguamish River estuary in October 2005. The baseline simulation successfully reproduced coastal hydrodynamics in the intertidal region of interest in Port Susan Bay near the mouth of the Stillaguamish River, which is tidally dominated with large variations in water-surface levels (≈3 m range) and salinity (0 to 25 ppt). The baseline simulation also showed that the model results, especially water levels in the Stillaguamish River distributaries entering Port Susan Bay (Hatt Slough and OSRC), are sensitive to the respective distributary channel characteristics over the tidal flats in Port Susan Bay. Initial calibration and setup of the intertidal channels is therefore of much importance. The salinity levels and intrusion upriver near the project sites at Leque Island and zis a ba on the OSRC were also sensitive to the fraction of the fresh water split between Old Stillaguamish River and Hatt Slough. Following validation, the model was applied to test the response of the Preferred Restoration Alternative Scenarios at Leque Island and zis a ba for typical estuarine flow conditions and high-flow (bank-full) conditions.

Examination of the simulation results for the typical estuarine flow conditions of October 2005 shows that that Preferred Restoration Alternative Scenarios at Leque Island and zis a ba results in immediate desired tidal response and restoration of estuarine functions over the Leque Island and zis a ba project sites that were previously diked off and shielded from tidal exposure. In addition, the results show clearly that proposed actions will likely not cause a significant change in the hydrodynamic behavior of the estuary.

Simulations with the Preferred Restoration Alternative also showed a small lowering in water-surface levels in West Pass, South Pass, and OSRC stations. The mean water surface elevation for the Preferred Restoration Alternative Scenario is ≈ 0.01 m lower relative to the Baseline Scenario. Although small, this result indicates that there is a small decrease in pressure gradient relative to baseline conditions as the tidal prism is now distributed over the restored area. During incoming tide, instead of being forced up to the West Pass and Old Stillaguamish River, the flow is partly distributed over the large area of Leque Island resulting in the small reduction in water surface elevations.

During high tide, Leque Island is nearly fully inundated with saline water from Port Susan (0 to 20 psu). The tidal channels connecting Leque Island with South Pass and Port Susan bring seawater into the Leque Island site. The tidal channel at the northwest side connecting Davis Slough and Leque Island also contributes to the inundation. Similarly, zis a ba is inundated through the tidal channels; however, the zis a ba restoration also includes construction of a berm that separates zis a ba into east and west basins and results in different salinity condition across the berm. Saline water (≈ 14 ppt) inundation occurs

through the west side of the site due to the presence of the berm. The western side of the berm is inundated with tidal flood water mostly from South Pass but also influenced by mixed water from West Pass. On the eastern side of the berm, less saline water (≈ 4 ppt) floods into the marshes from the Old Stillaguamish River.

The results show that under the Preferred Restoration Alternative Scenario, there are notable changes to salinity relative to the Baseline Scenario. The results indicate that proposed restoration will likely decrease the amount of seawater intrusion into the OSRC, West Pass and South Pass channels. As a result, predicted salinities in the Preferred Alternative Scenario are ≈ 0.5 ppt lower than the Baseline Scenario in West Pass, South Pass, and the lower OSRC stations.

Examination of tidally averaged velocities and flows shows that outflow of freshwater from OSRC primarily occurs through the South Pass during ebb which also carries the majority of net outflow to Port Susan Bay and remains relatively unchanged in the Preferred Restoration Alternative Scenario. Results indicate that proposed restoration action will not result in significant changes in velocities at most locations. At the Leque Island and zis a ba restoration sites, bed shear stress is predicted to be highest near the entrances of the tidal channel that drain the sites. It is expected that the mouths of these tidal channels entrances will likely evolve until an equilibrium cross section is reached.

The potential for erosion and flooding related damage was examined using the bank-full river flow condition for the Baseline and Preferred Alternative Scenarios. The results reflect the fact that the locations of the Leque Island and zis a ba restoration sites are near the river mouth. These sites are primarily dominated by the influence of tidal exchange flow and not significantly affected by changes in river flow. During high-flow (bank-full) conditions, besides experiencing lower salinities, the Leque Island and zis a ba sites also experienced increases in velocity magnitudes and bed shear stresses relative to typical flow conditions, especially in the main river channels. However, results for the Preferred Restoration Alternative Scenario show that the velocity magnitudes under high flows are relative unchanged compared to the Baseline Scenario. In South Pass, velocity magnitudes were predicted to be higher relative to the Baseline Scenario during peak flood period by ≈ 0.12 m/s and relatively no change is seen during ebb when peak velocities are nearly twice as high as those during the flood. During the high-flow condition, under Preferred Restoration Alternative Scenario, bed shear stresses in West Pass and South Pass are slightly higher. In Old Stillaguamish River bend around zis a ba, decrease in bed shear is noticeable associated with reduced flow due to the fraction that is diverted through the tidal channels over east zis a ba site. These changes are small relative to typical magnitude of bed shear stress which is significantly higher than that needed for movement of silt and sand and will not result in significant increase in scour or channel widening.

Results do not show a further increase or reduction in water-surface levels or inundation as a result of restoration related change relative to the baseline for high-flow conditions.

Restoration projects such as these involve removal of dikes that allow tidal waters to move up the previously diked-off regions. During periods when high flows, high tides, and stormy conditions occur, upland properties previously protected by the dikes may be directly exposed. To assess the potential for flooding of properties adjacent to project sites, an estimate of the extreme high-water level was made. The estimate of maximum potential water level near the project site considered the extreme high tide, wind-induced storm surge, significant wave height, and future sea level rise based on numerical model results and coastal engineering calculations. The maximum water level projections for a 100-year return period were 4.6 m and 3.9 m (above MSL, or 5.9 m and 5.2 m above NAVD88) for Port Susan Bay and Leque Island, respectively. The differences are primarily from the different fetch lengths and associated differences in significant wave heights. Those extreme values were estimated under assumptions that the 100-year maximum wind was blowing following typical Pacific storms with the peak speed of 29.49 m/s

in the same direction, and the storm event would occur at the same time as the extreme high tide. It should be noted that the wind-induced surge was simulated under the normal spring tide condition. These results were factored into the decision by the project team to retain the dike section along the southern back of West Pass of the OSRC to serve as wave overtopping inundation barrier for the City of Stanwood properties north of the project site.

Overall, simulation results indicate that the Preferred Restoration Alternative Scenario provides an estuarine response consistent with the planned design. The preferred restoration actions would result in relatively minor changes in water surface elevations and salinity in the OSRC surrounding the restoration sites. Because of changes in the tidal prism from increased storage and drainage from the restoration sites, minor changes in velocity magnitude and associated bed shear stresses are predicted. At most locations in the surrounding river channels, under typical flow conditions, there is a small reduction in bed shear stress and a small increase in bed shear stress near the mouths of tidal drainage channels from the restoration sites. These changes in bed shear are negligible relative to the typical magnitude of bed shear stress under Baseline conditions which is significantly higher than that needed for movement of silt and sand. The overall conclusion based on the result is that tidal estuarine functions will be successfully restored at the Leque Island and zis a ba sites through the proposed actions and should lead to an increase in available tidal marsh area in the system. Also, impacts to existing circulation and estuarine characteristics would be relatively small.

7.0   References

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Appendix A

**Time Series and Cumulative Frequency Plots –
October 2005 Conditions:
Water Surface Elevation, Salinity, Velocity, and Bed Shear**

Appendix A

Time Series & Cumulative Frequency Plots –
October 2005 Conditions:
Water Surface Elevation, Salinity, Velocity, and Bed Shear

October 2005 water surface elevations, salinities, velocities, and bed sheers for the Leque Island and zis a ba sites are provided in this appendix.
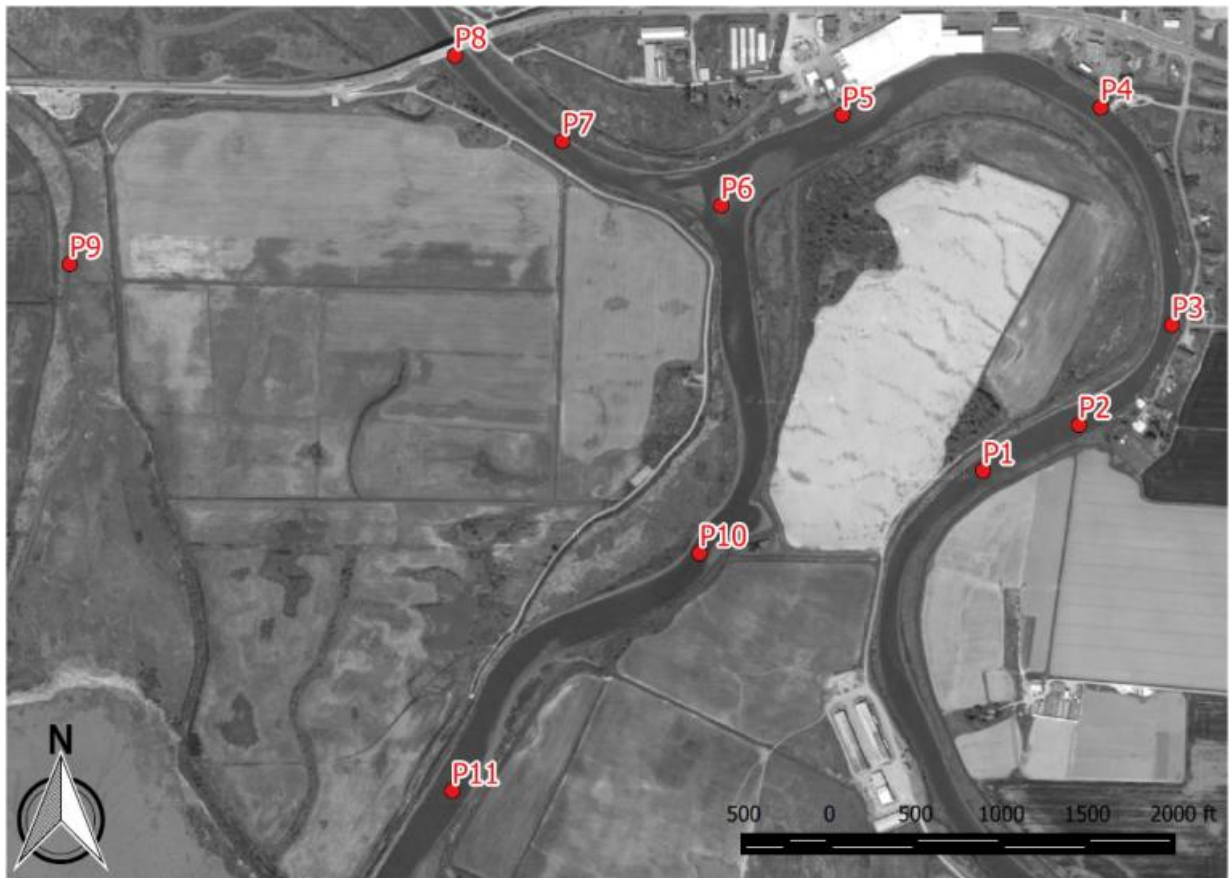

Figure A.1. Leque and zis a ba Restoration Site Plan View and Time Series Station Locations
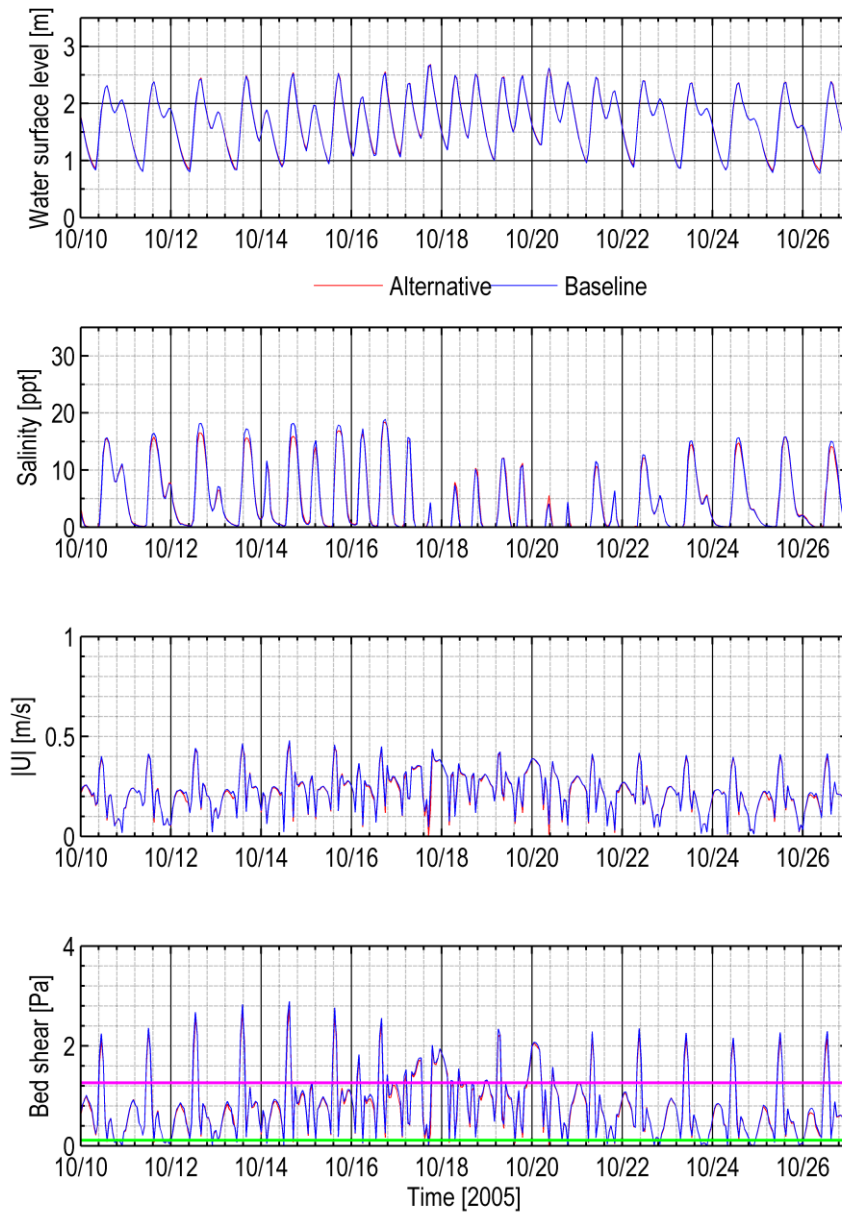
Figure A.2.   Preferred vs. Baseline Scenarios – Time Series of Water Surface Elevation, Salinity, Velocity Magnitude, and Bed Shear Stress at Station P1, October 2005 Period

A.2
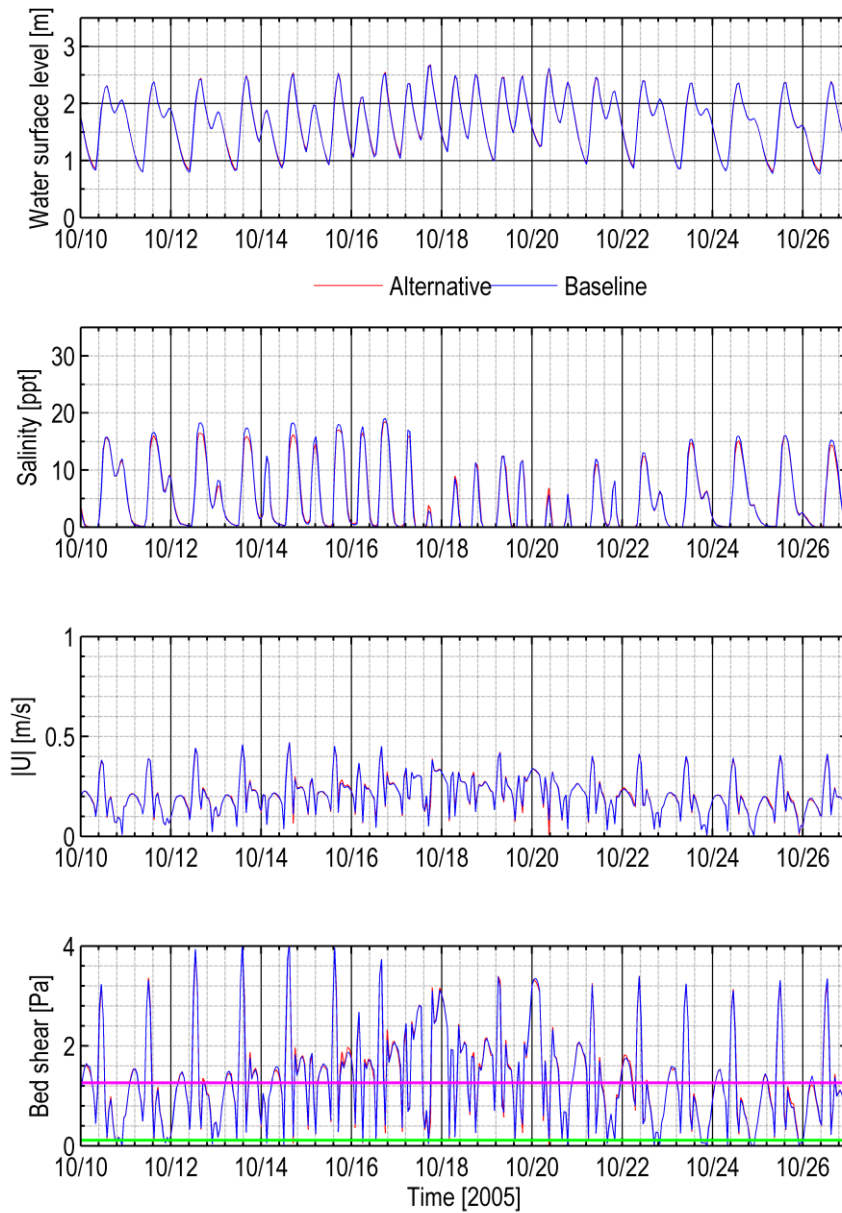
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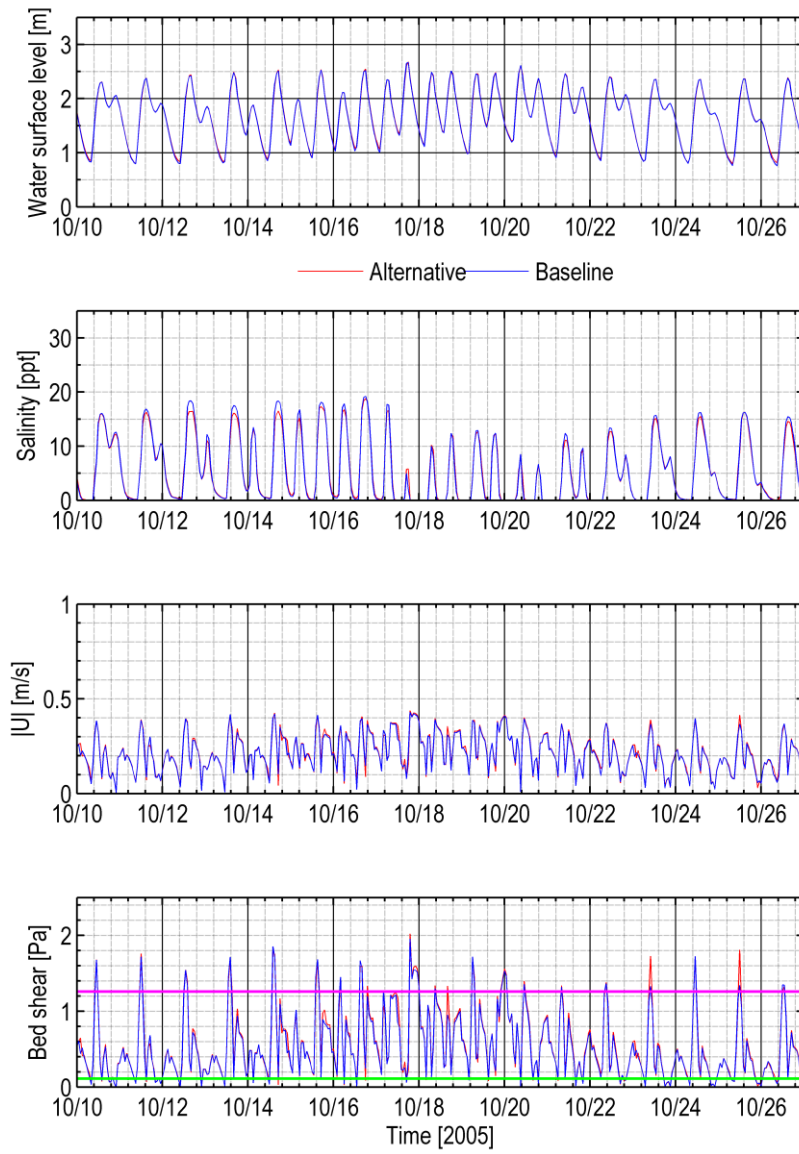
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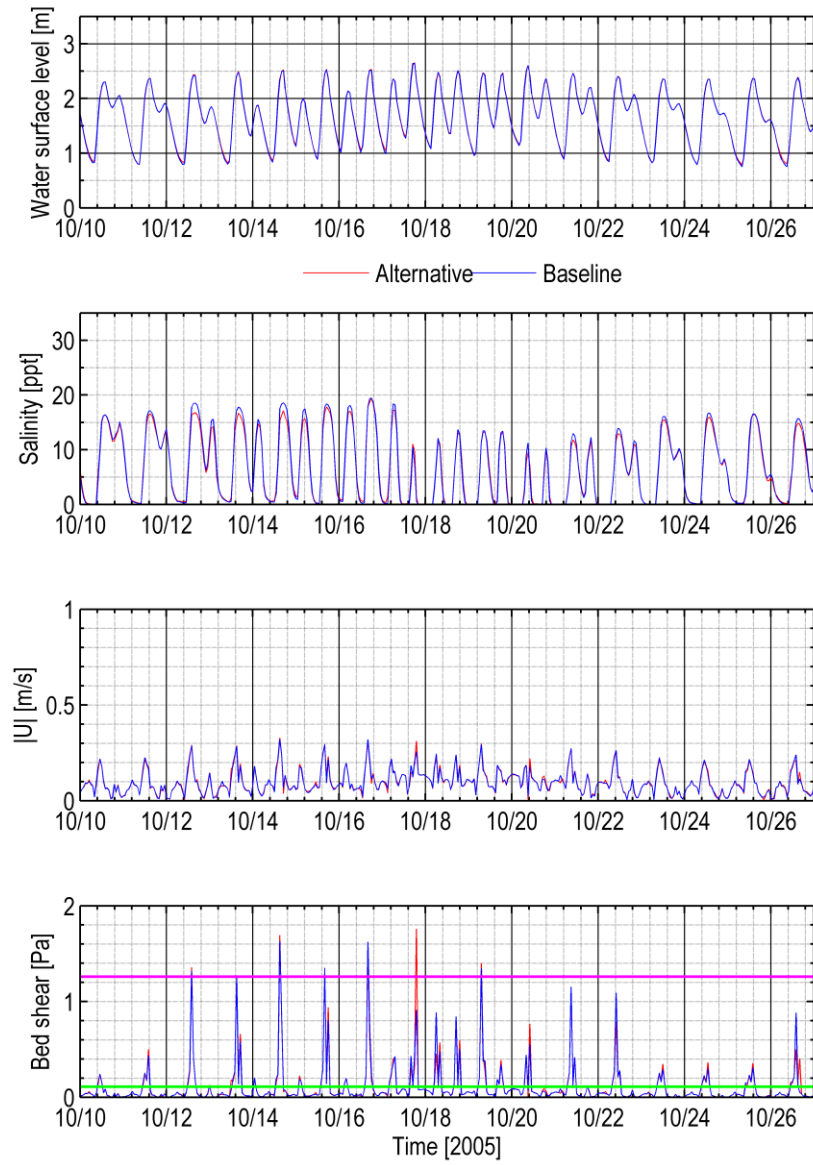
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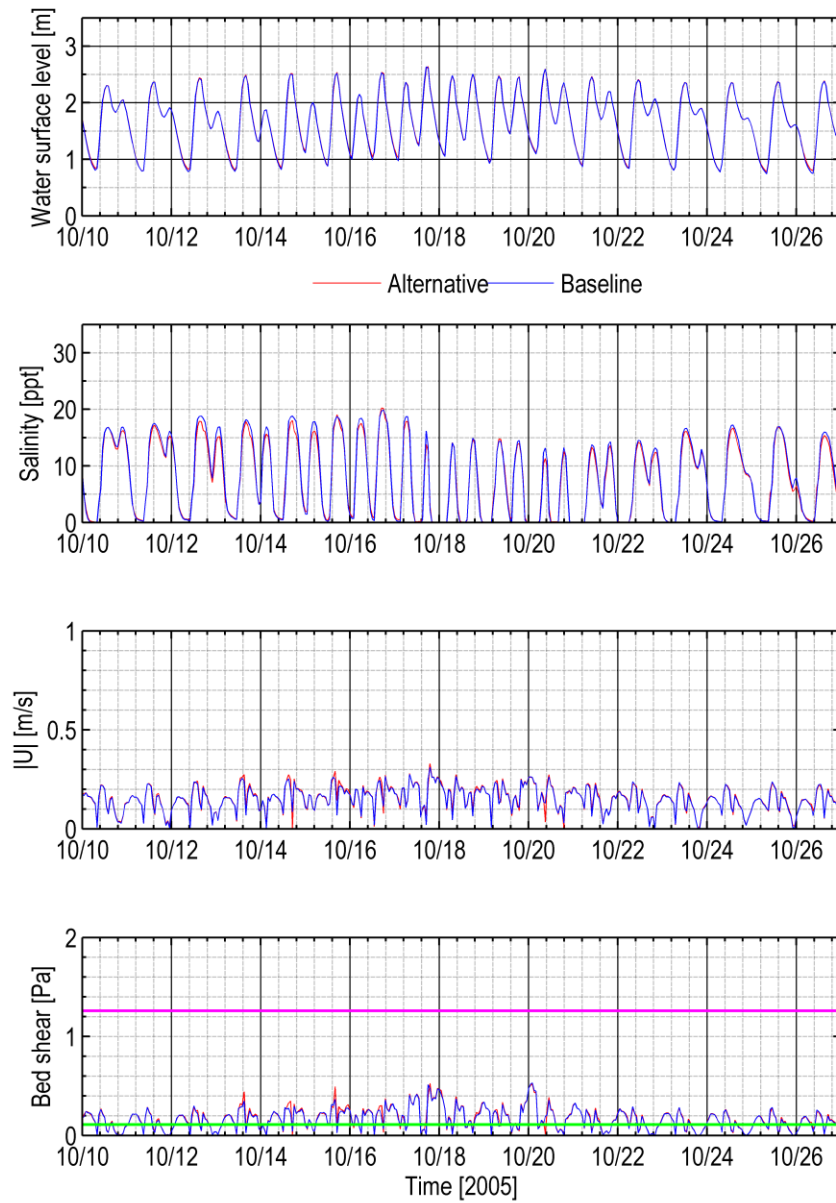
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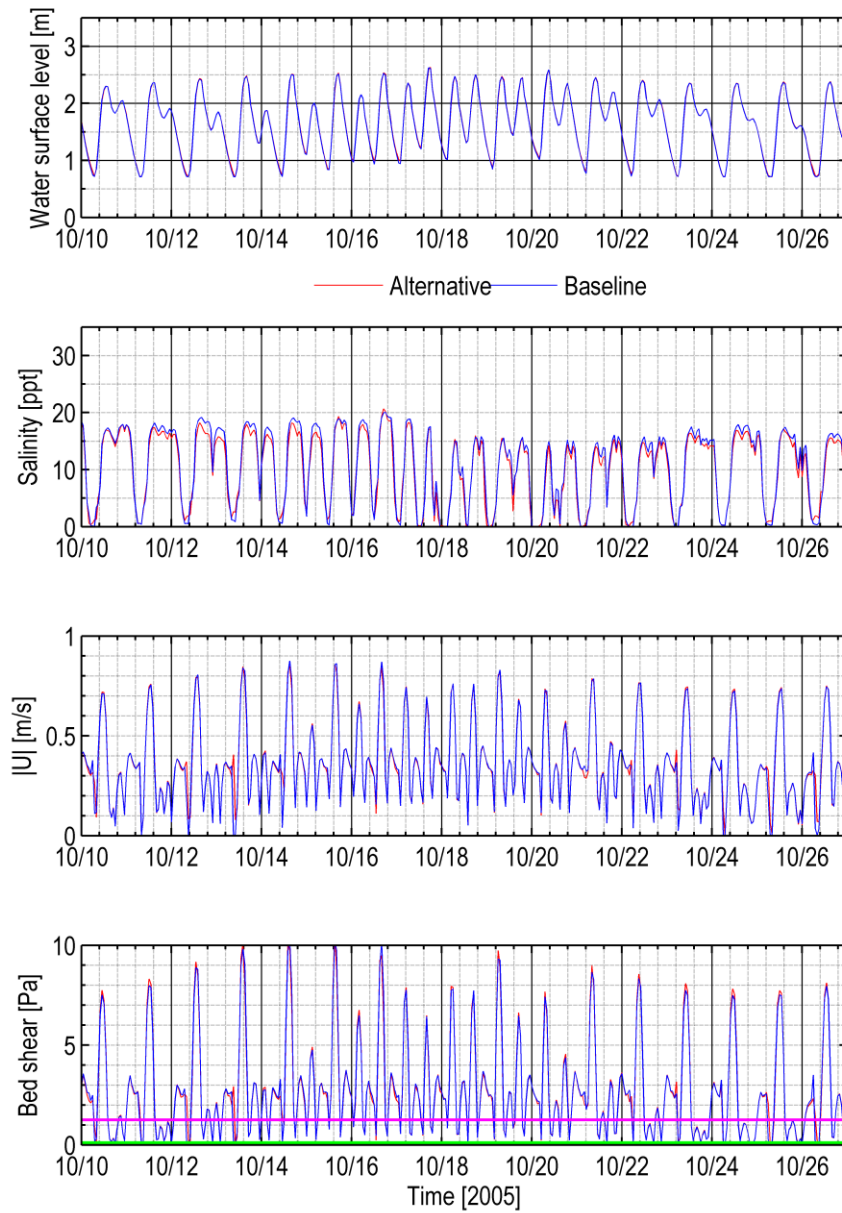
Figure A.7. Preferred vs. Baseline Scenarios – Time Series of Water Surface Elevation, Salinity, Velocity Magnitude, and Bed Shear Stress at Station P6, October 2005 Period
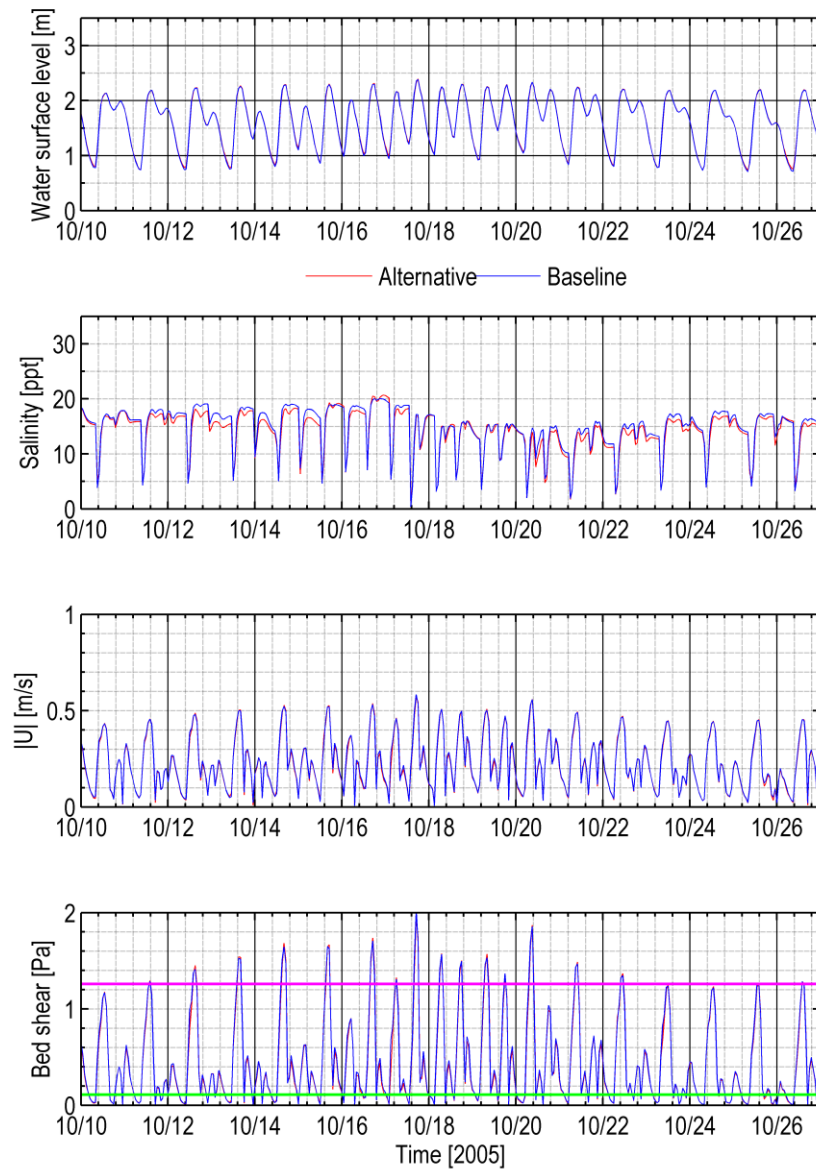
Figure A.8. Preferred vs. Baseline Scenarios – Time Series of Water Surface Elevation, Salinity, Velocity Magnitude, and Bed Shear Stress at Station P7, October 2005 Period
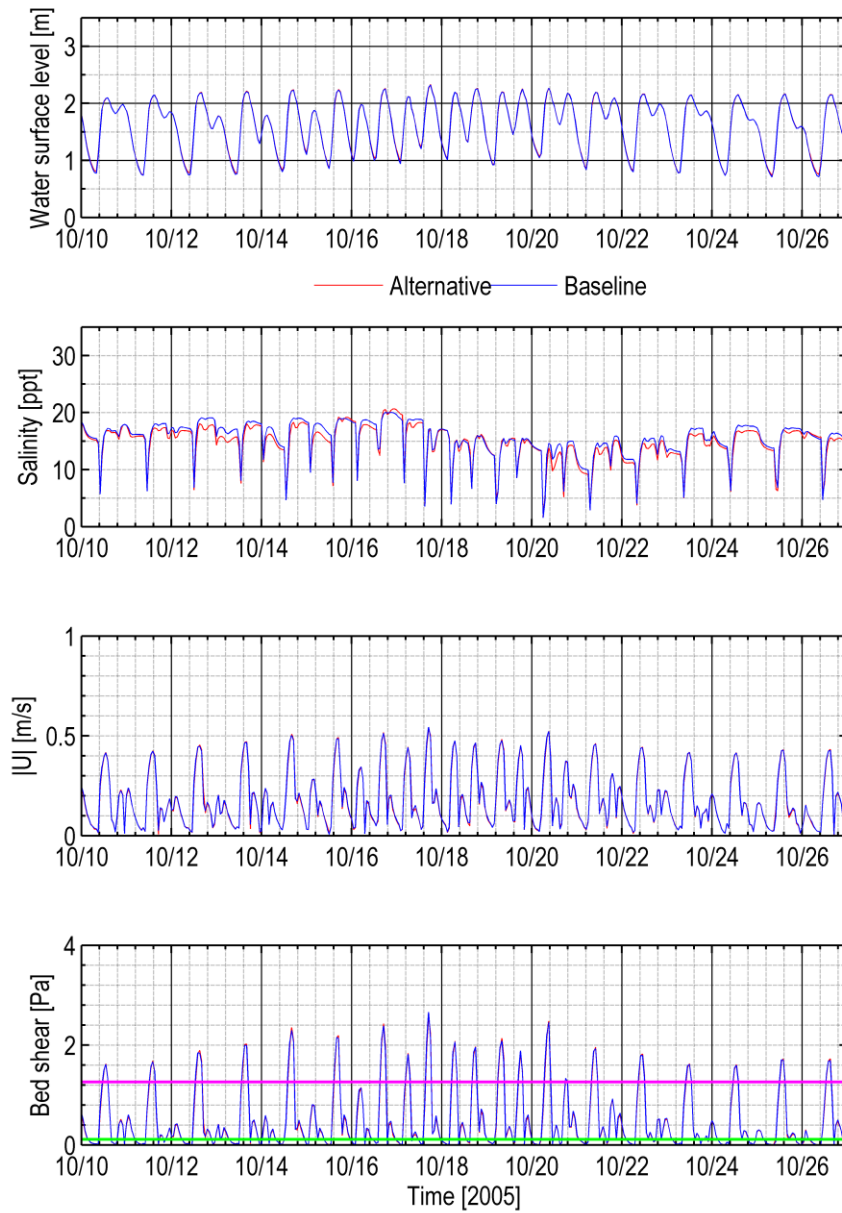
Figure A.9. Preferred vs. Baseline Scenarios – Time Series of Water Surface Elevation, Salinity, Velocity Magnitude, and Bed Shear Stress at Station P8, October 2005 Period
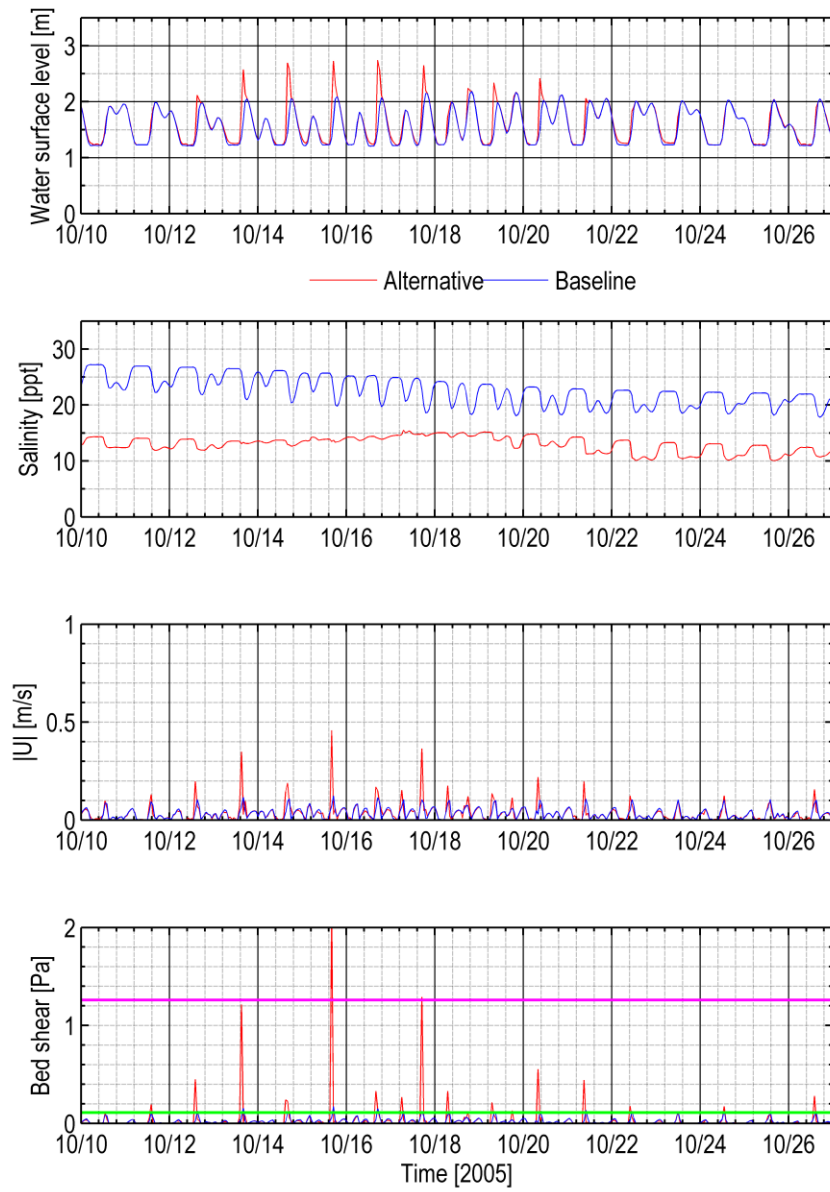
Figure A.10. Preferred vs. Baseline Scenarios – Time Series of Water Surface Elevation, Salinity, Velocity Magnitude, and Bed Shear Stress at Station P9, October 2005 Period
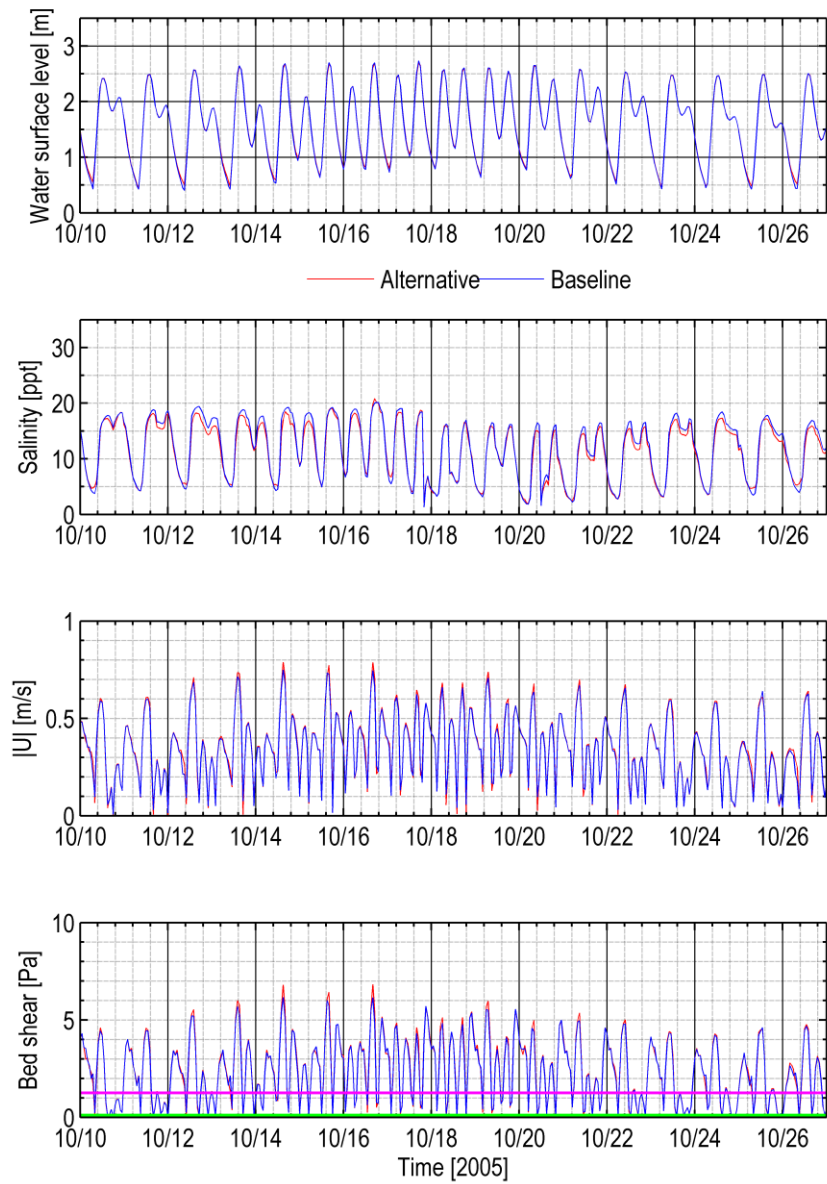
Figure A.11.   Preferred vs. Baseline Scenarios – Time Series of Water Surface Elevation, Salinity, Velocity Magnitude, and Bed Shear Stress at Station P10, October 2005 Period
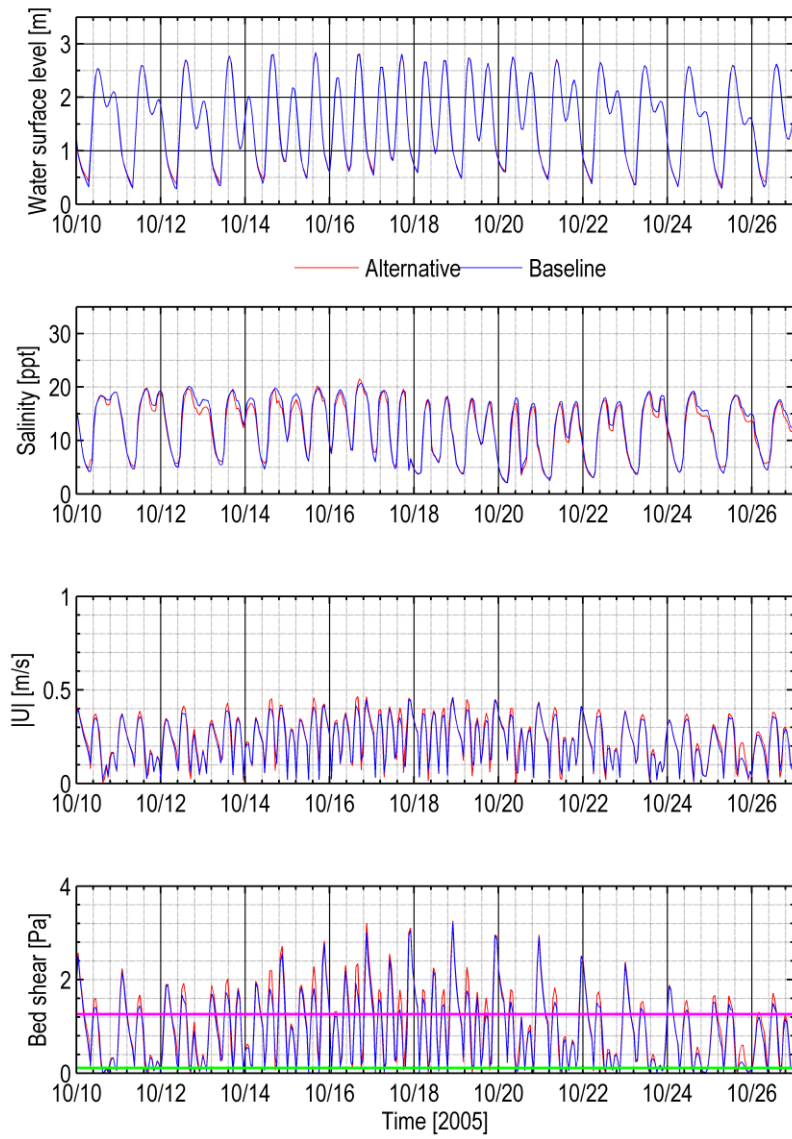
Figure A.12. Preferred vs. Baseline Scenarios – Time Series of Water Surface Elevation, Salinity, Velocity Magnitude, and Bed Shear Stress at Station P11, October 2005 Period
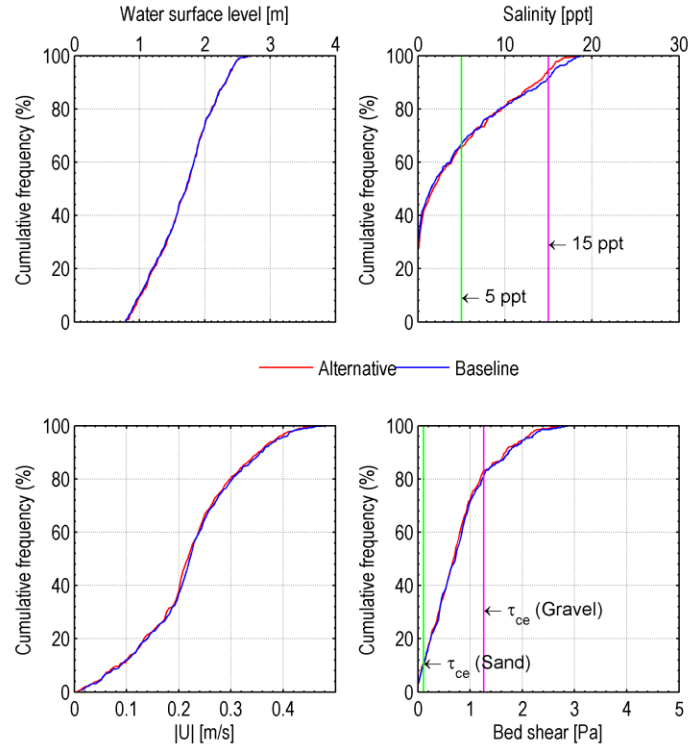
Figure A.13. Preferred vs. Baseline Scenarios– Cumulative Frequency of Water Surface Elevation, Salinity, Velocity Magnitude, and Bed Shear Stress at Station P1, October 2005 Period
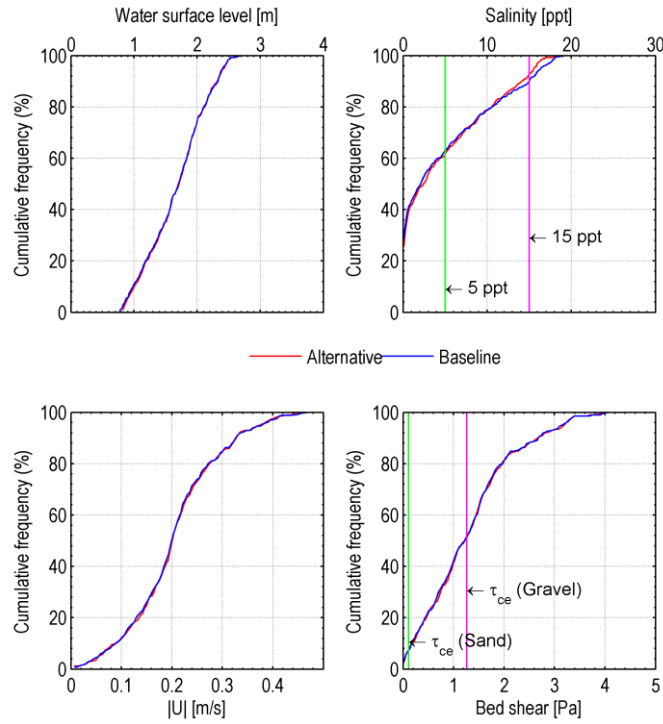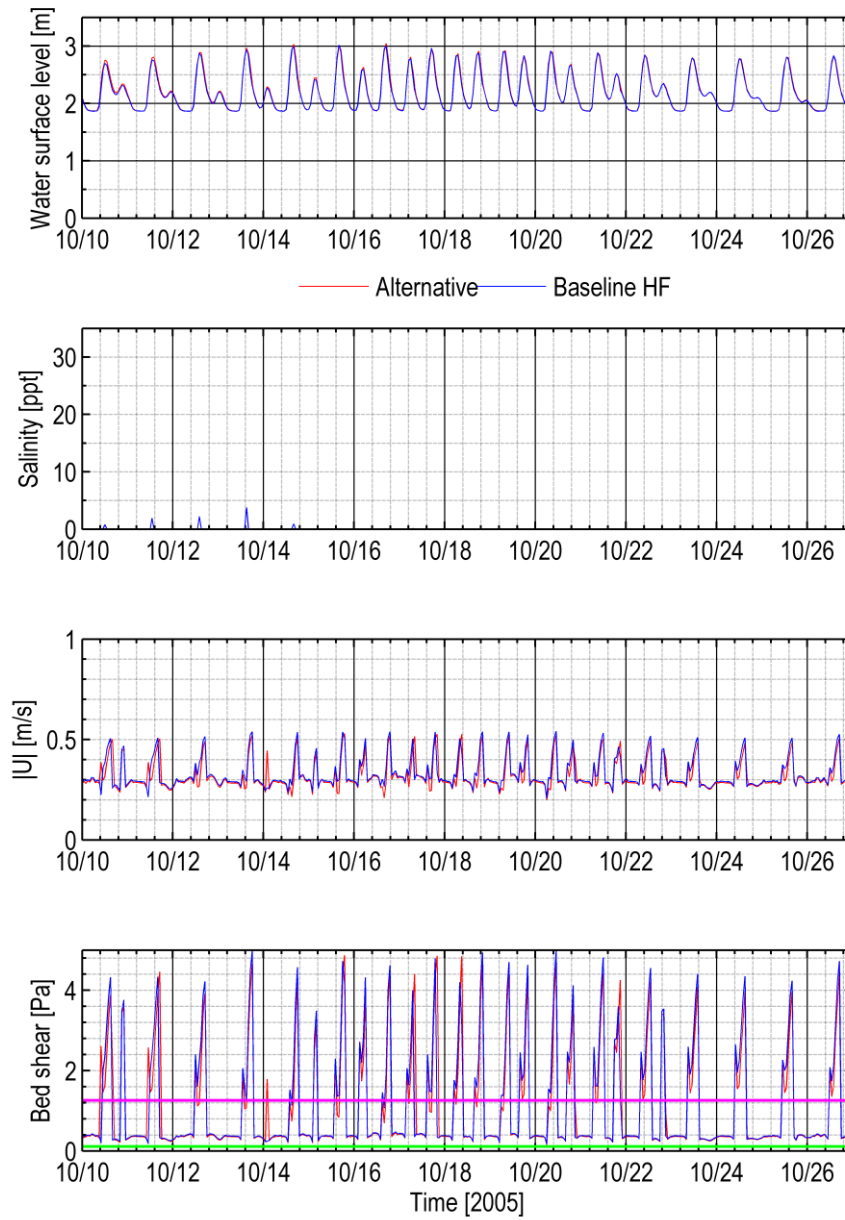

Figure A.14. Preferred vs. Baseline Scenarios– Cumulative Frequency of Water Surface Elevation, Salinity, Velocity Magnitude, and Bed Shear Stress at Station P2, October 2005 Period

A.13
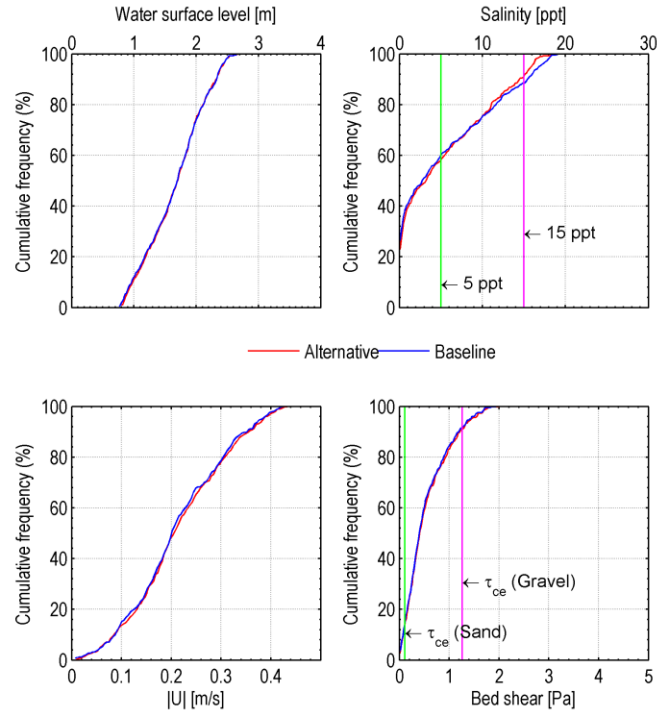
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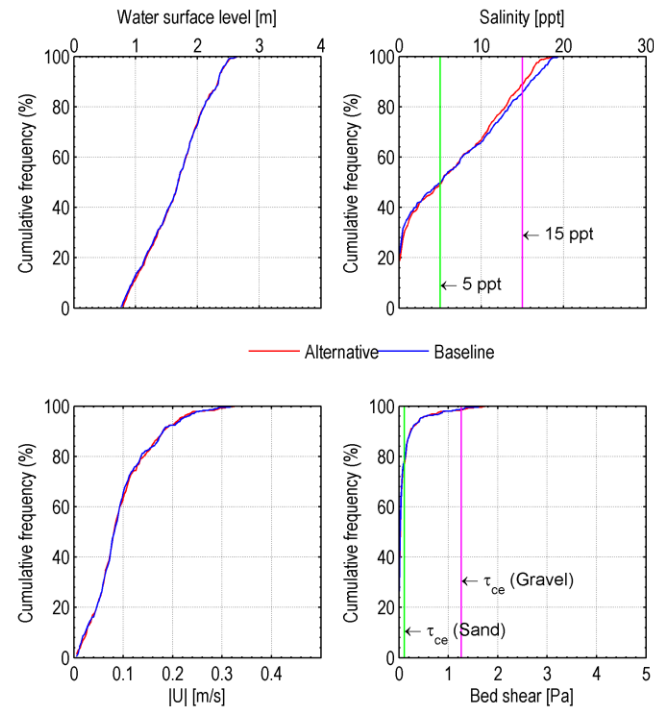
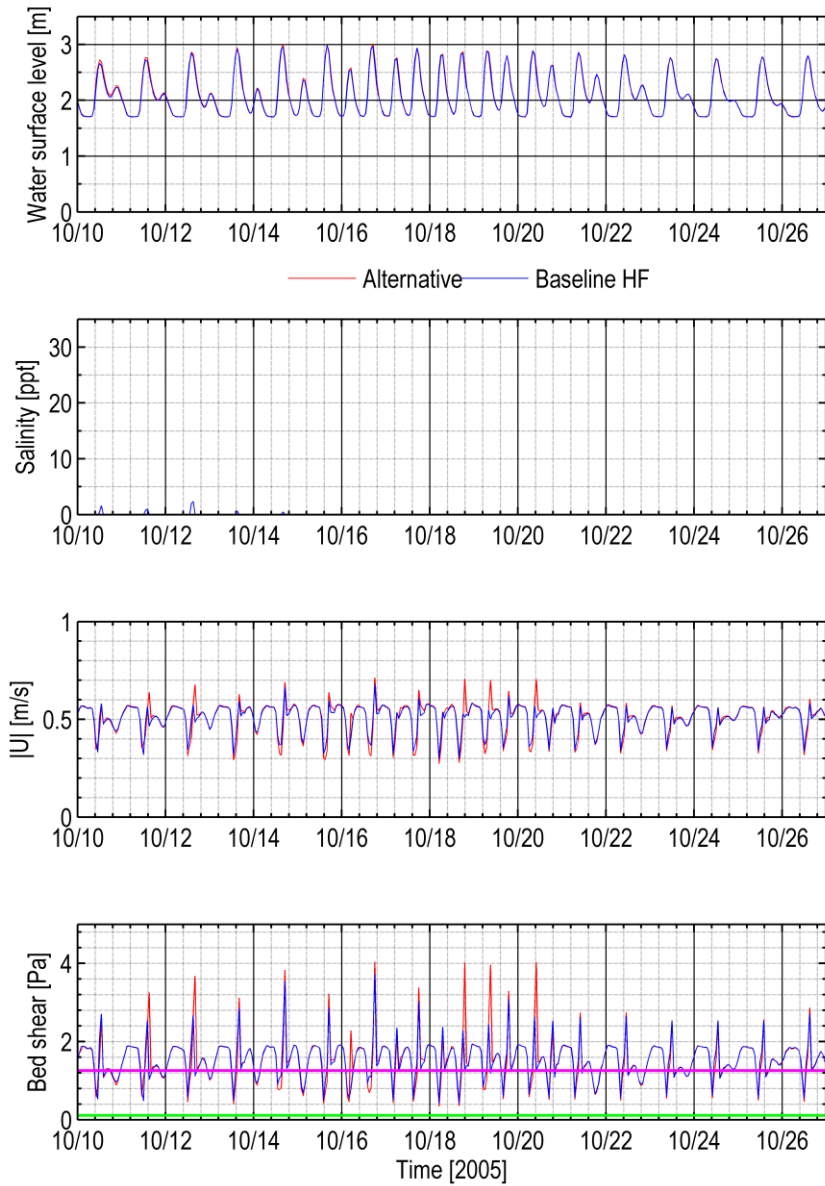**Figure A.16**. Preferred vs. Baseline Scenarios– Cumulative Frequency of Water Surface Elevation, Salinity, Velocity Magnitude, and Bed Shear Stress at Station P4, October 2005 Period
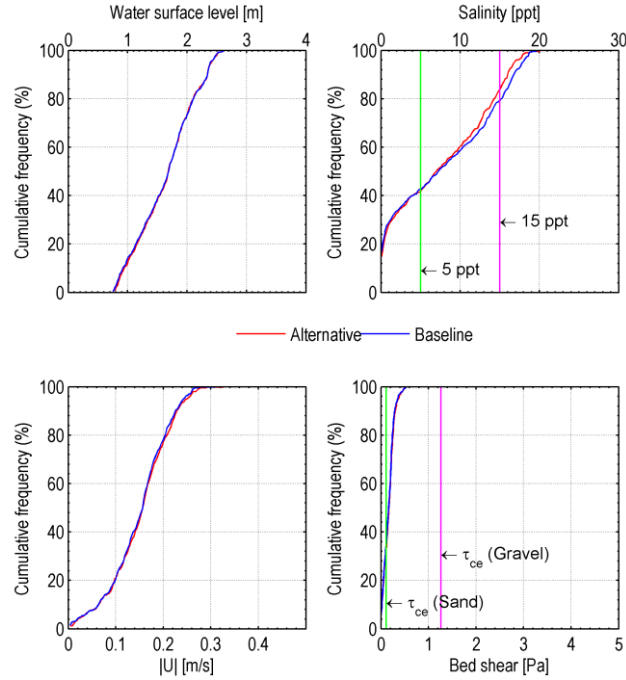
Figure A.17.   Preferred vs. Baseline Scenarios– Cumulative Frequency of Water Surface Elevation, Salinity, Velocity Magnitude, and Bed Shear Stress at Station P5, October 2005 Period
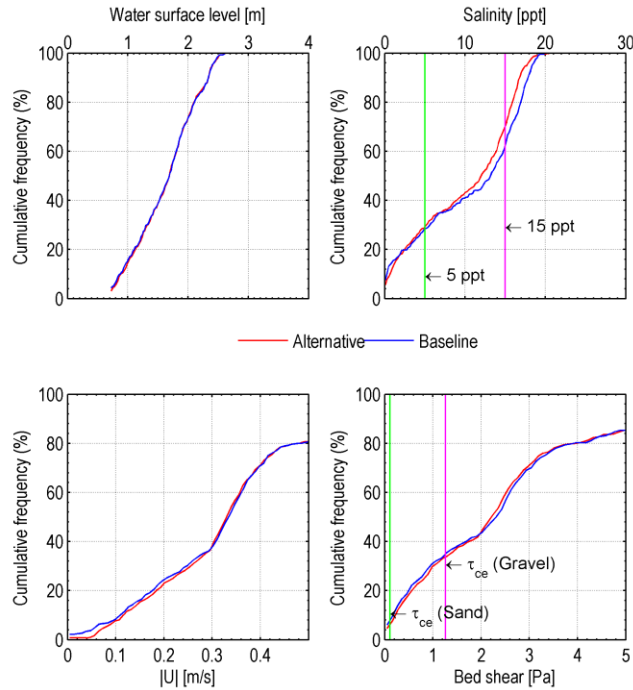
Figure A.18.   Preferred vs. Baseline Scenarios– Cumulative Frequency of Water Surface Elevation, Salinity, Velocity Magnitude, and Bed Shear Stress at Station P6, October 2005 Period
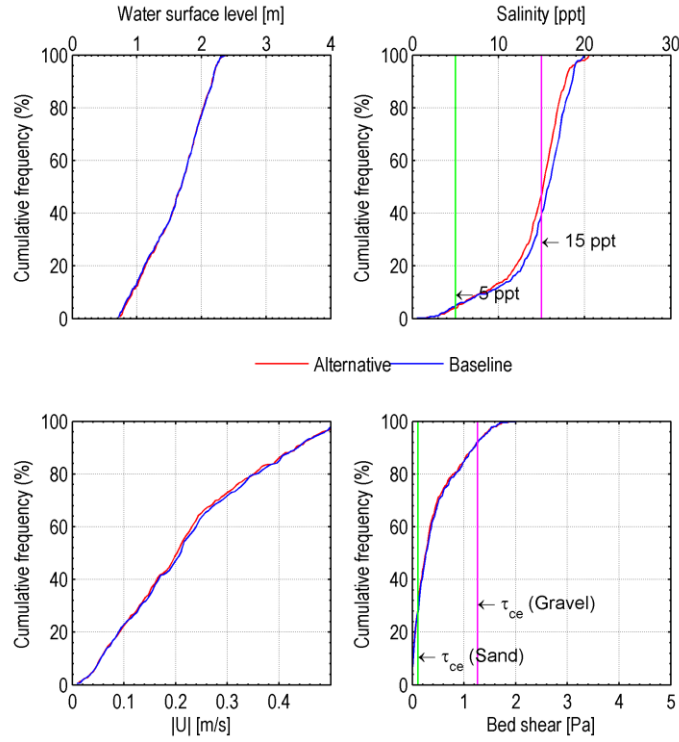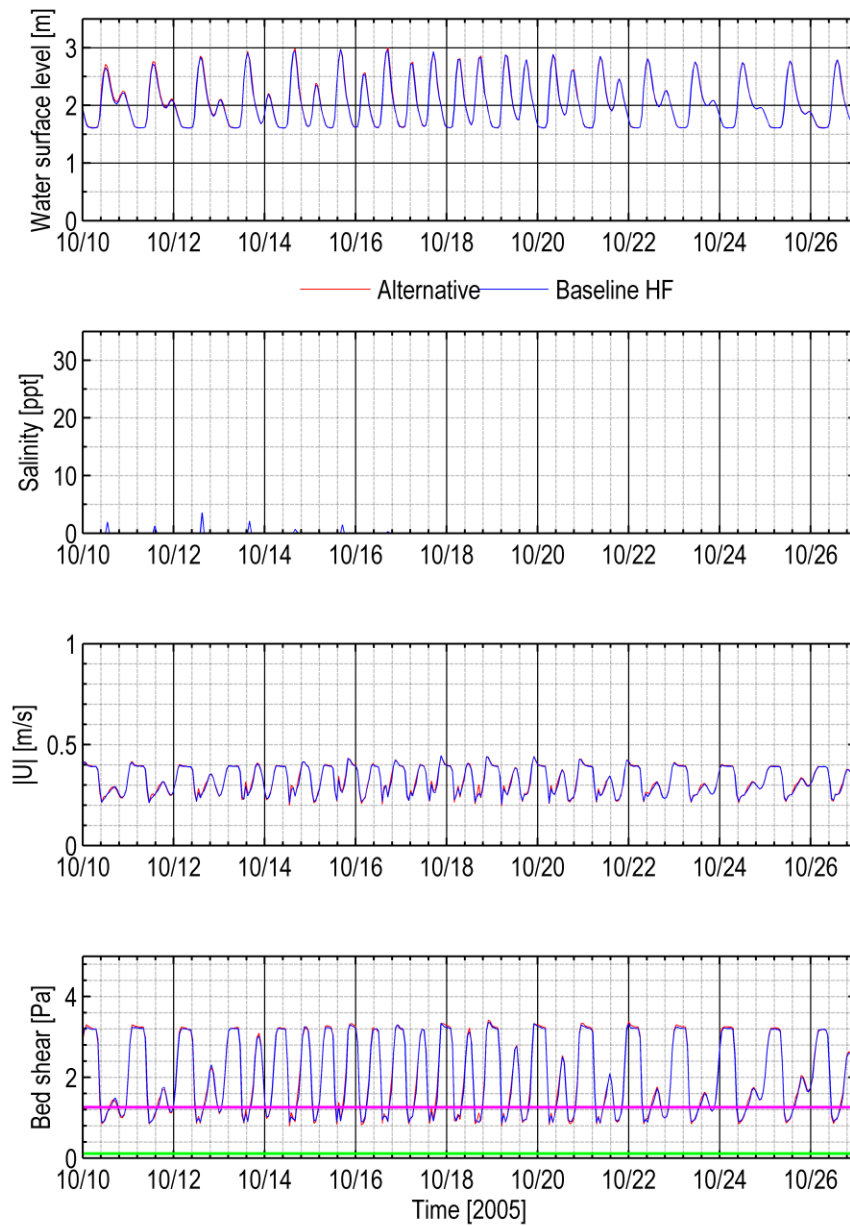
Figure A.19.   Preferred vs. Baseline Scenarios– Cumulative Frequency of Water Surface Elevation, Salinity, Velocity Magnitude, and Bed Shear Stress at Station P7, October 2005 Period
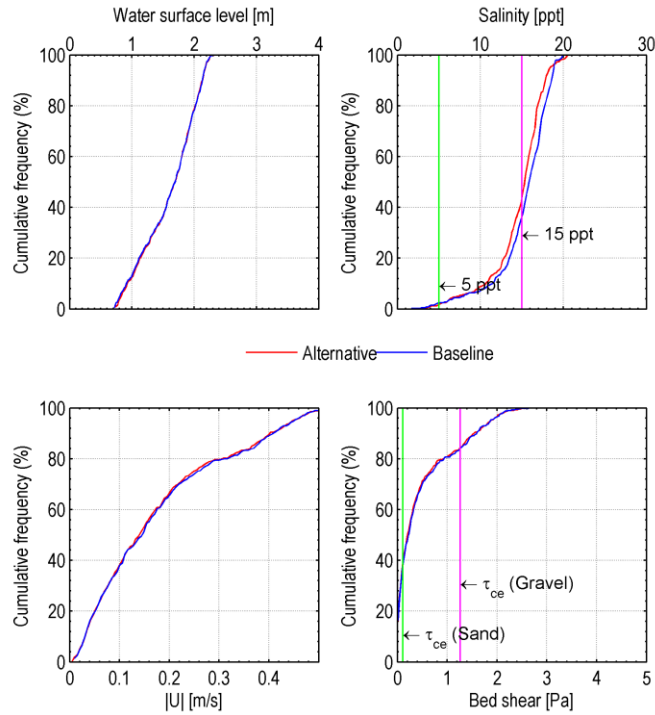
Figure A.20.   Preferred vs. Baseline Scenarios– Cumulative Frequency of Water Surface Elevation, Salinity, Velocity Magnitude, and Bed Shear Stress at Station P8, October 2005 Period
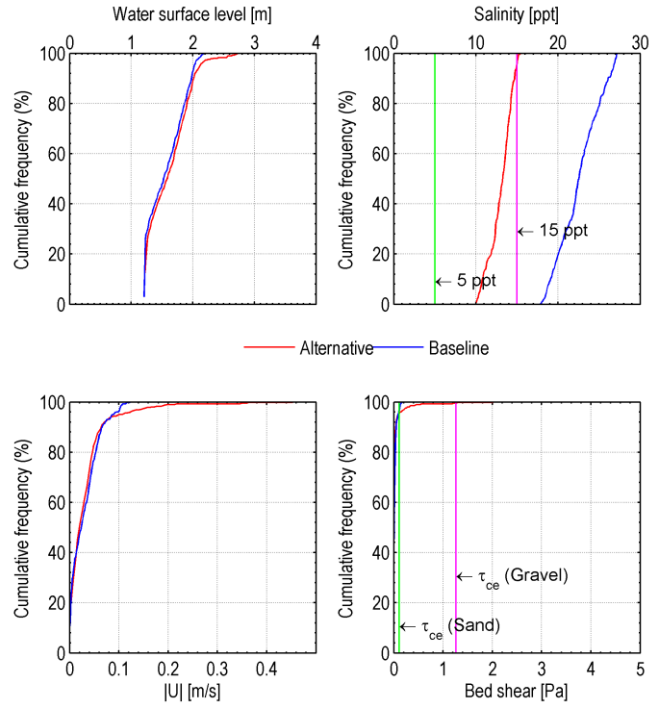
Figure A.21. Preferred vs. Baseline Scenarios– Cumulative Frequency of Water Surface Elevation, Salinity, Velocity Magnitude, and Bed Shear Stress at Station P9, October 2005 Period
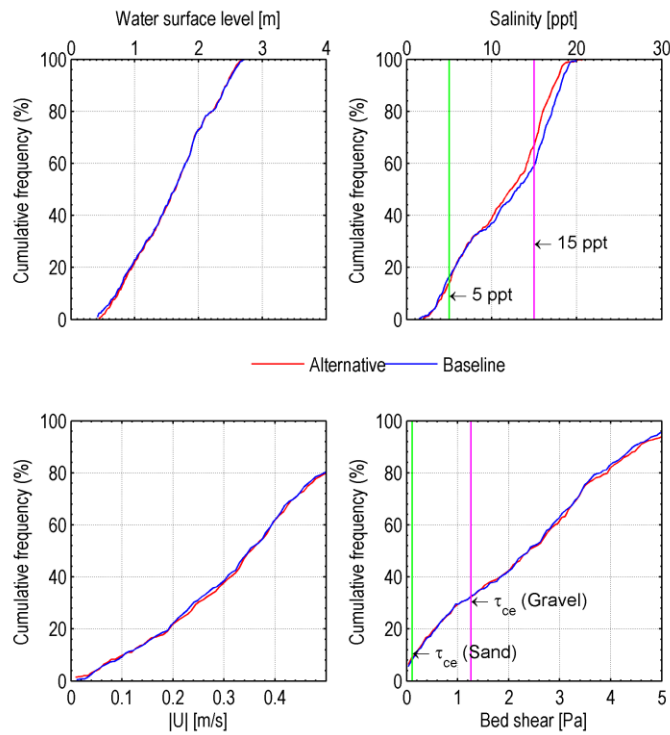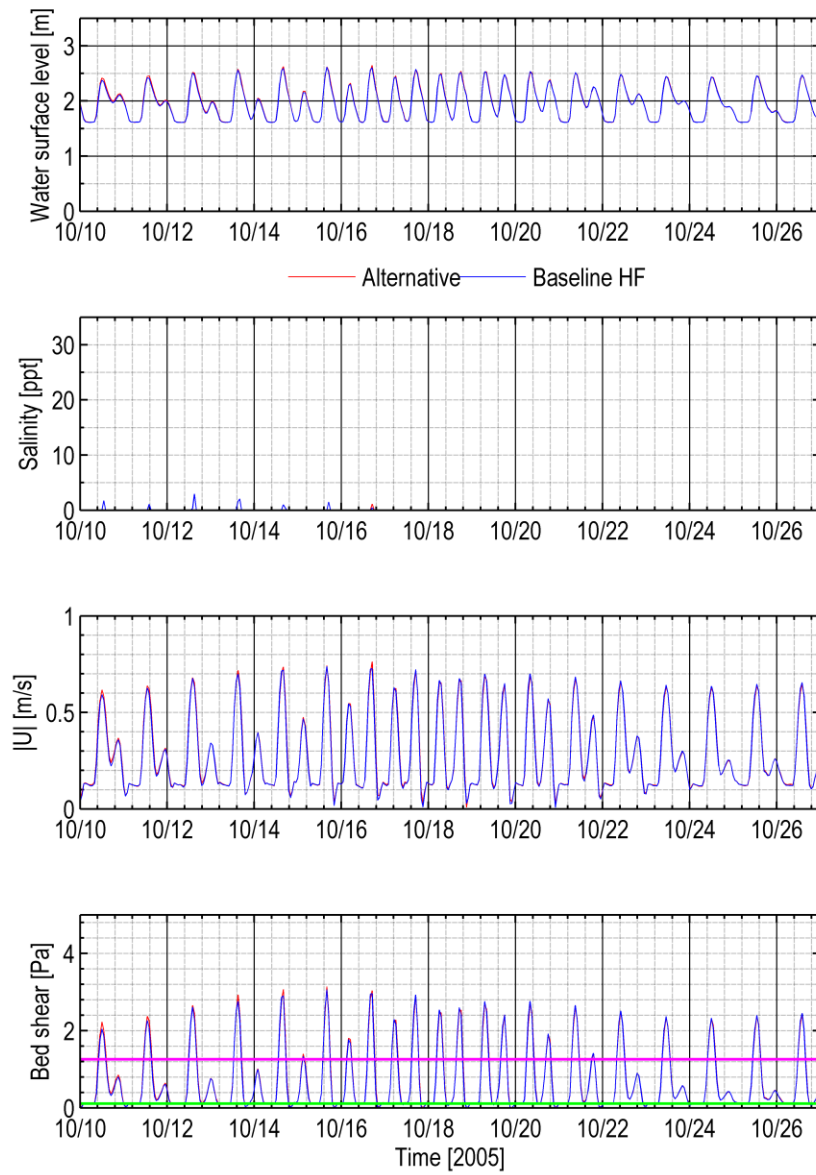

Figure A.22. Preferred vs. Baseline Scenarios– Cumulative Frequency of Water Surface Elevation, Salinity, Velocity Magnitude, and Bed Shear Stress at Station P10, October 2005 Period
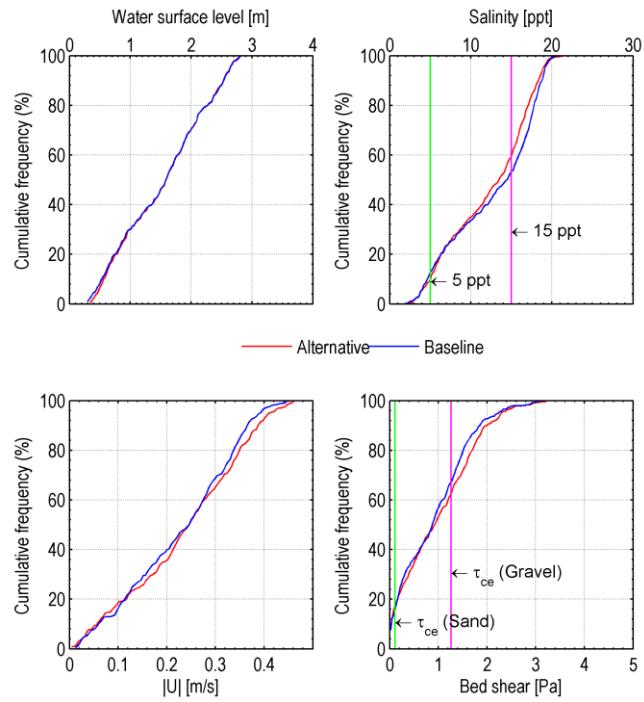
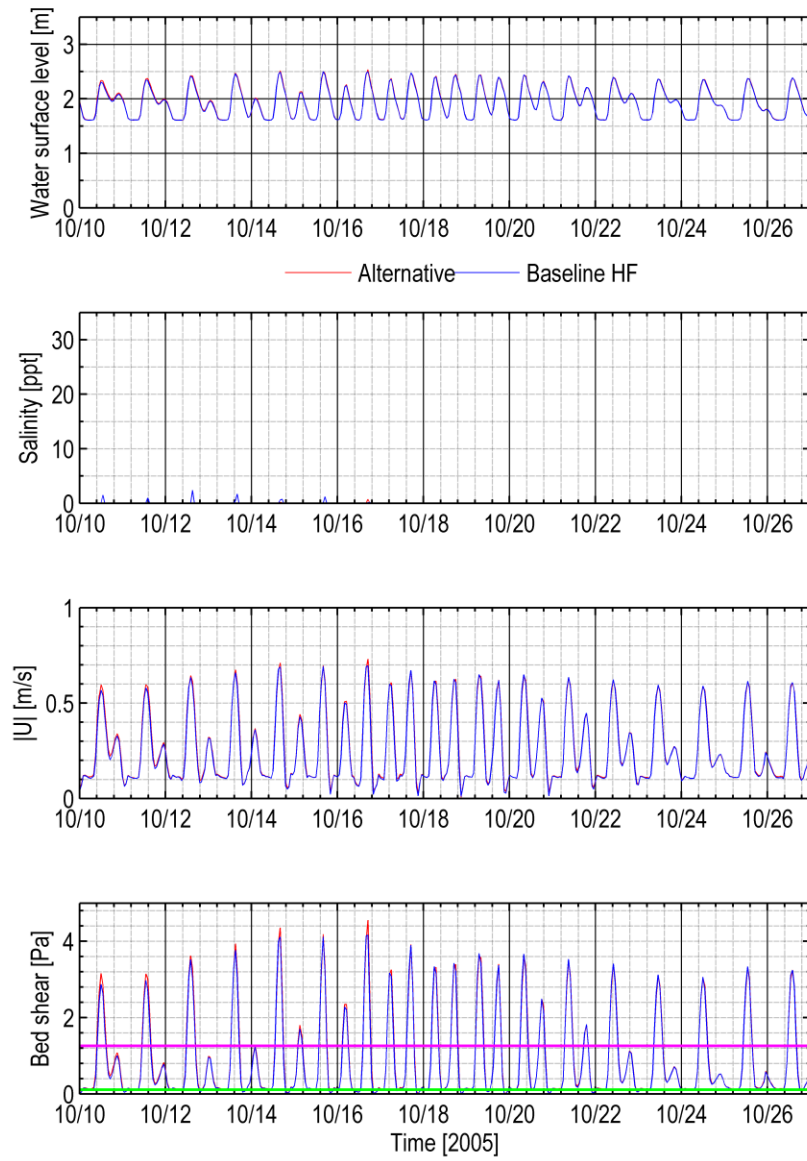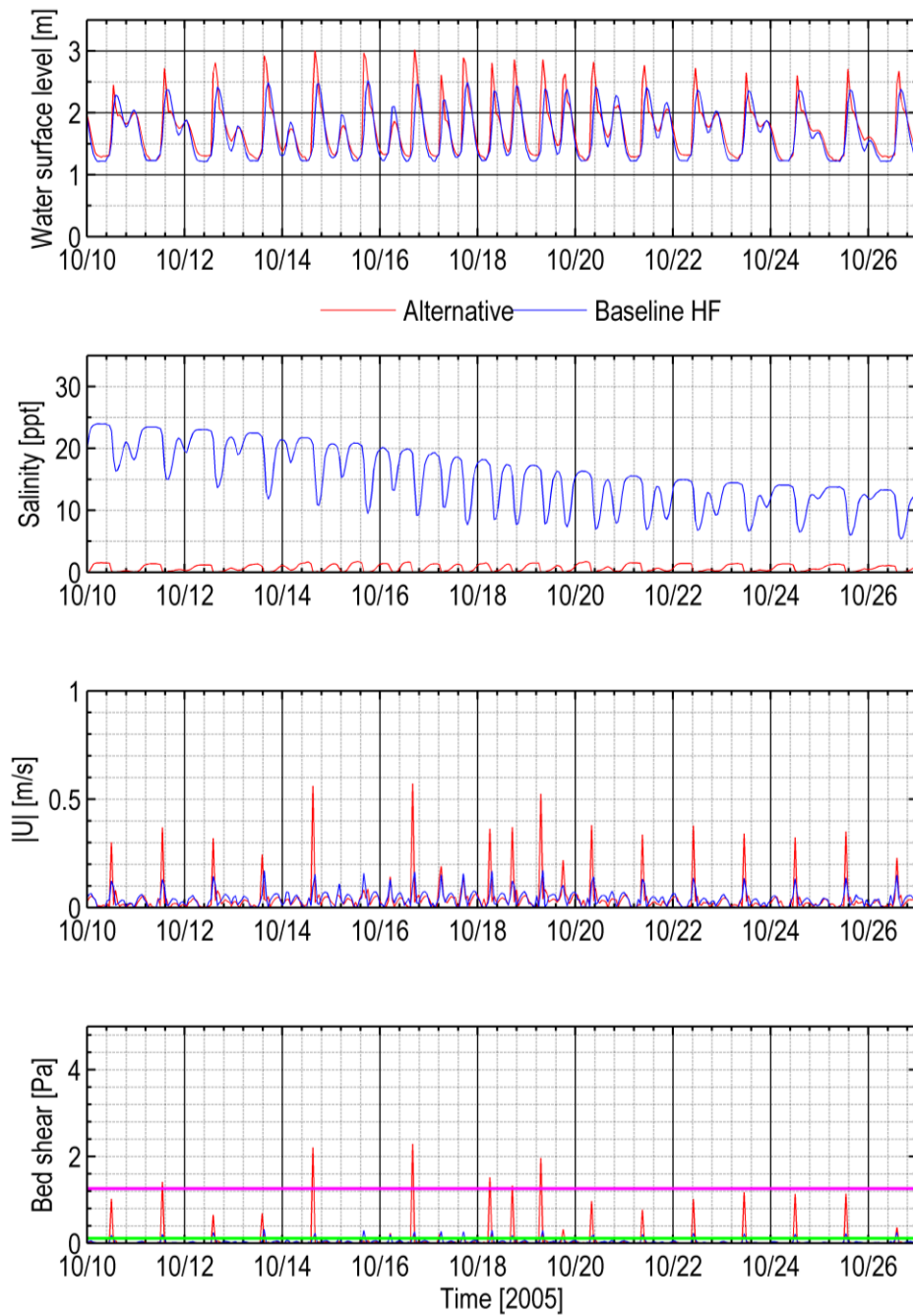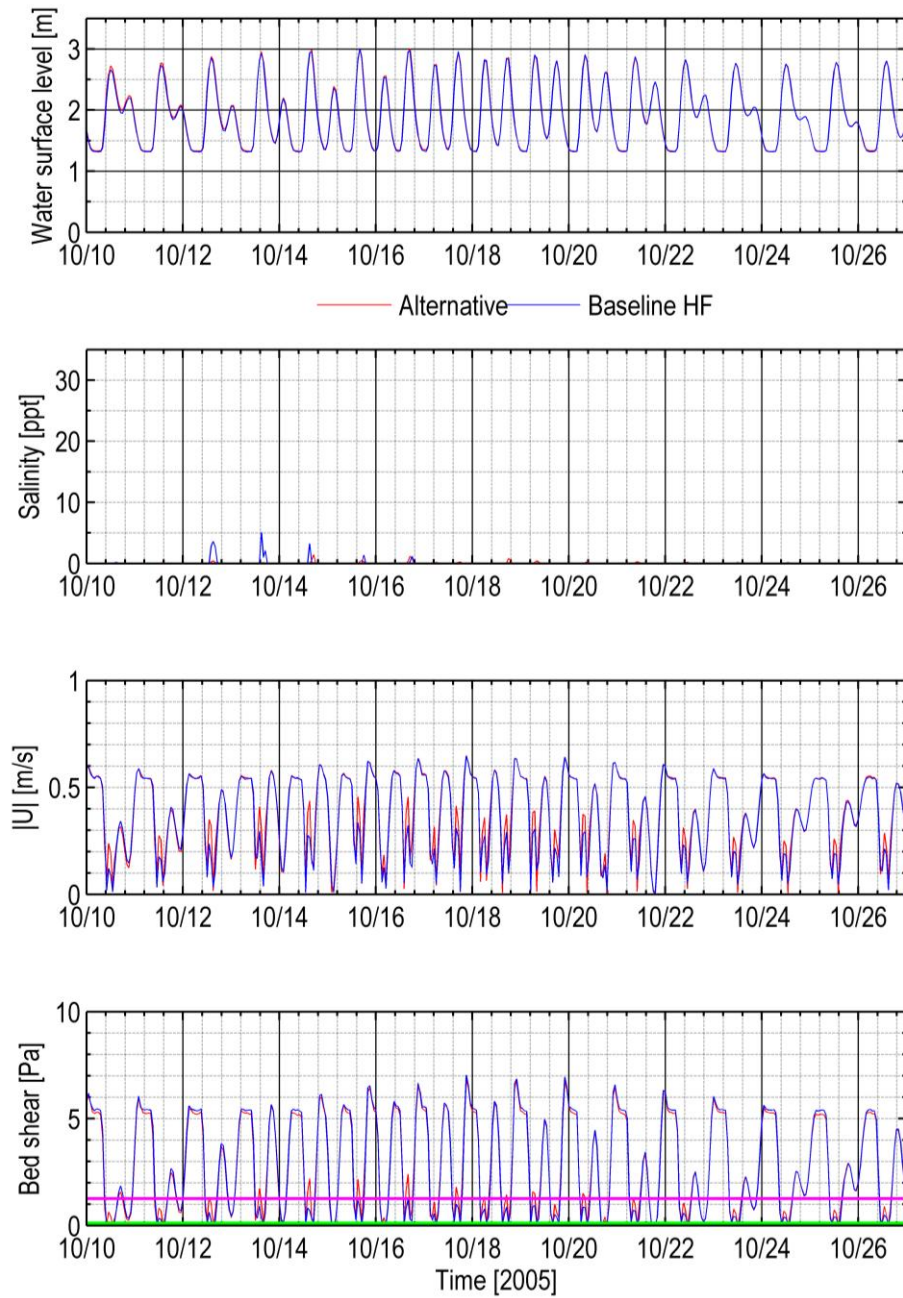**Figure A.23**.   Preferred vs. Baseline Scenarios– Cumulative Frequency of Water Surface Elevation, Salinity, Velocity Magnitude, and Bed Shear Stress at Station P11, October 2005 Period

A.18

Appendix B

Plan View Contour Plots – October 2005 Conditions:

Salinity and Velocity

Appendix B

Plan View Contour Plots – October 2005 Conditions: Salinity and Velocity

Plan view contour plots of the October 2005 water surface elevations, salinities, velocities, and bed sheers for the Leque Island and zis a ba restoration sites are provided in this appendix.
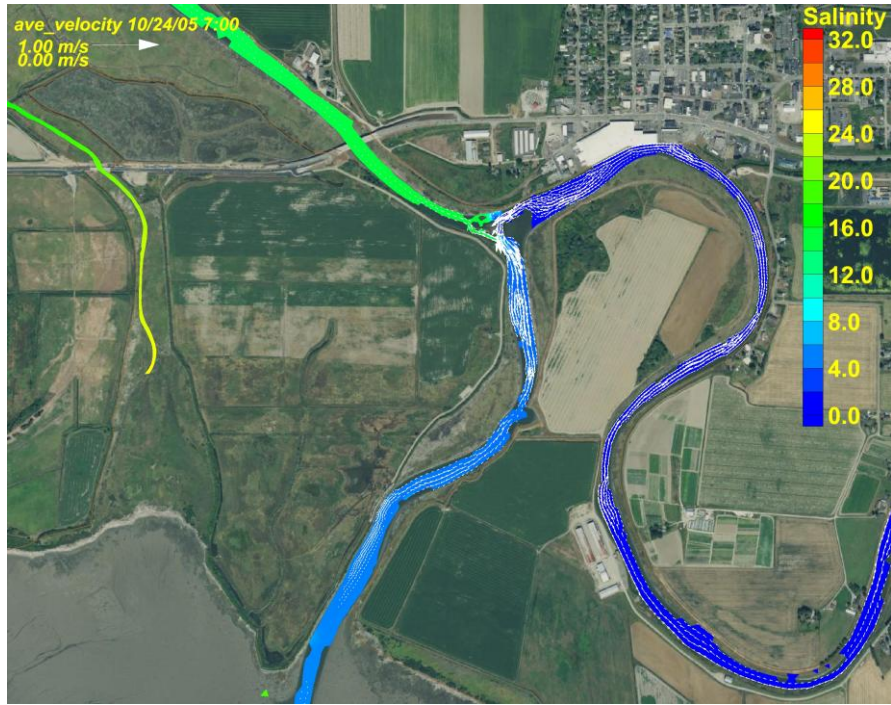
Figure B.1.   Baseline Condition – Salinity Contours and Velocity Vectors, October 24, 2005, at Low Tide (07:00)
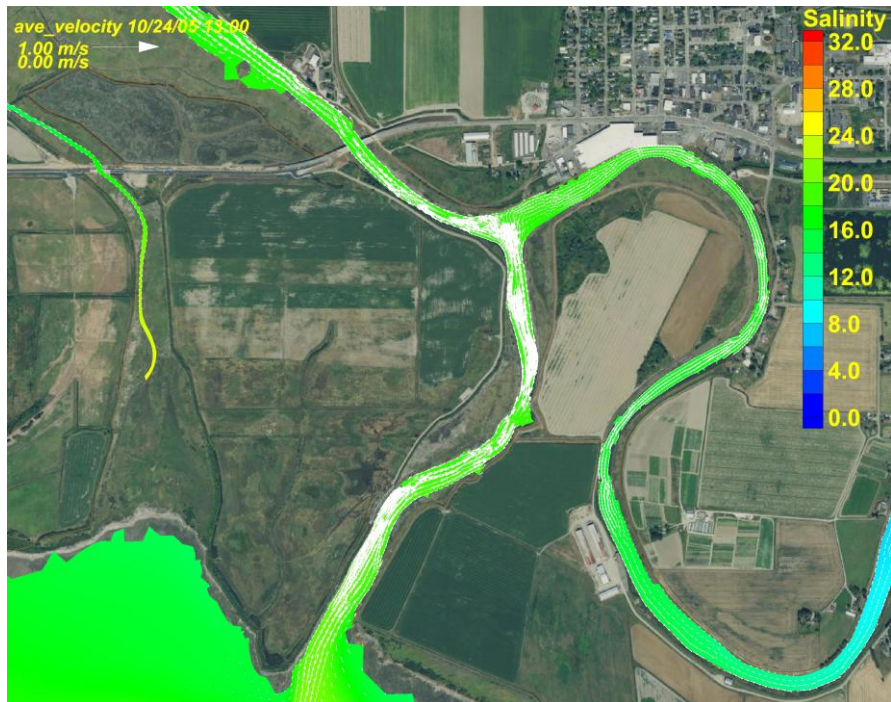
Figure B.2.   Baseline Condition – Salinity Contours and Velocity Vectors, October 24, 2005, at High Tide (13:00)
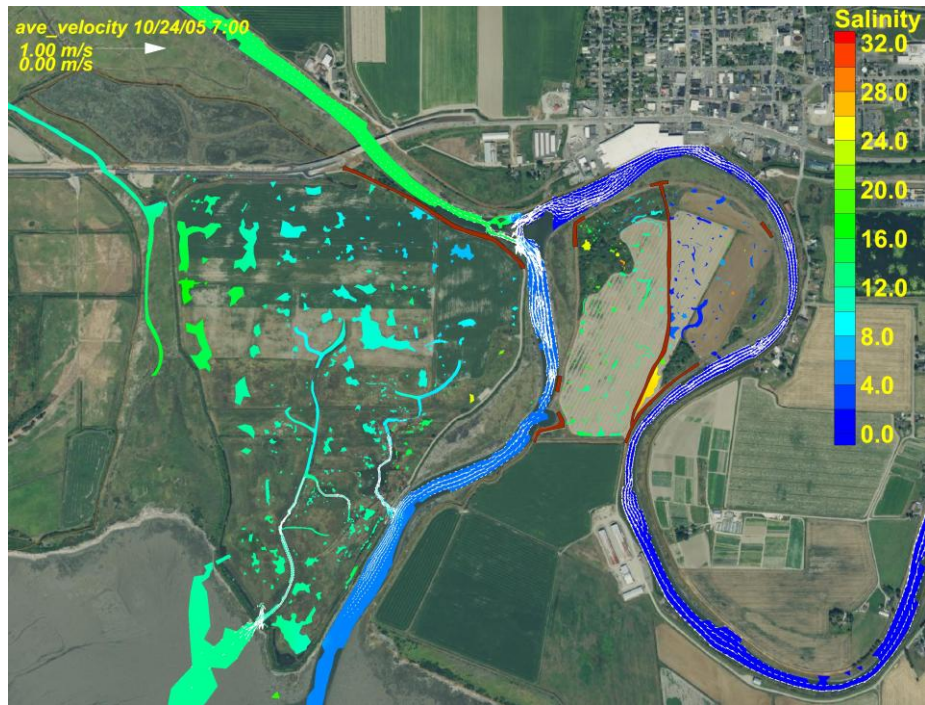
Figure B.3.   Preferred Restoration Alternative Scenario – Salinity Contours and Velocity Vectors, October 24, 2005, at Low Tide (07:00).
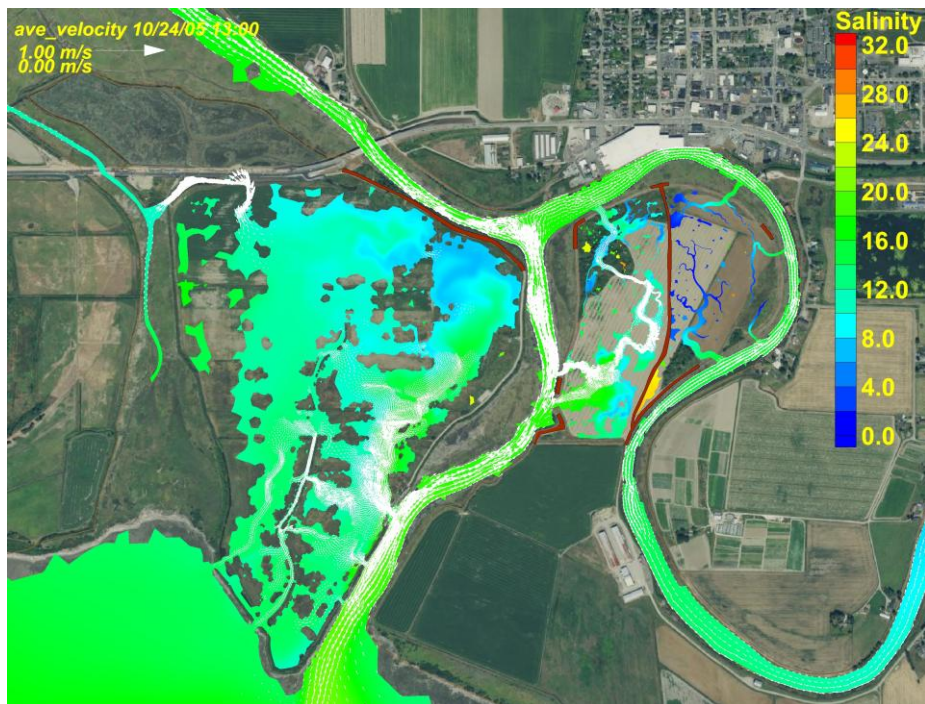
Figure B.3.   Preferred Restoration Alternative Scenario – Salinity Contours and Velocity Vectors, October 24, 2005, at High Tide (13:00)
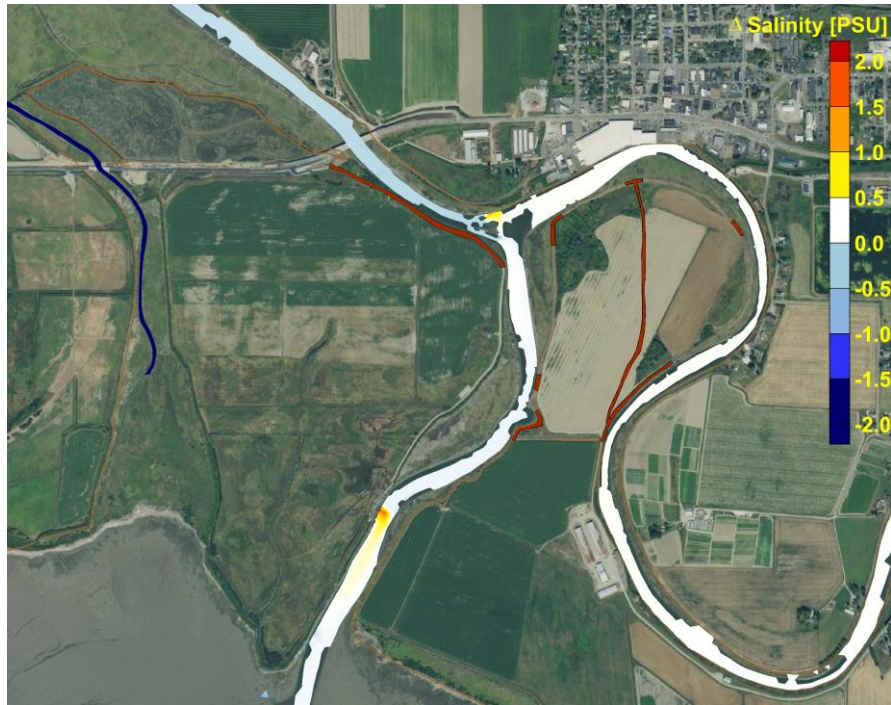
Figure B.5.   Salinity Difference Contours of Preferred Restoration Alternative Scenario Relative to Baseline at Peak Ebb Tide (07:00) on October 24, 2005
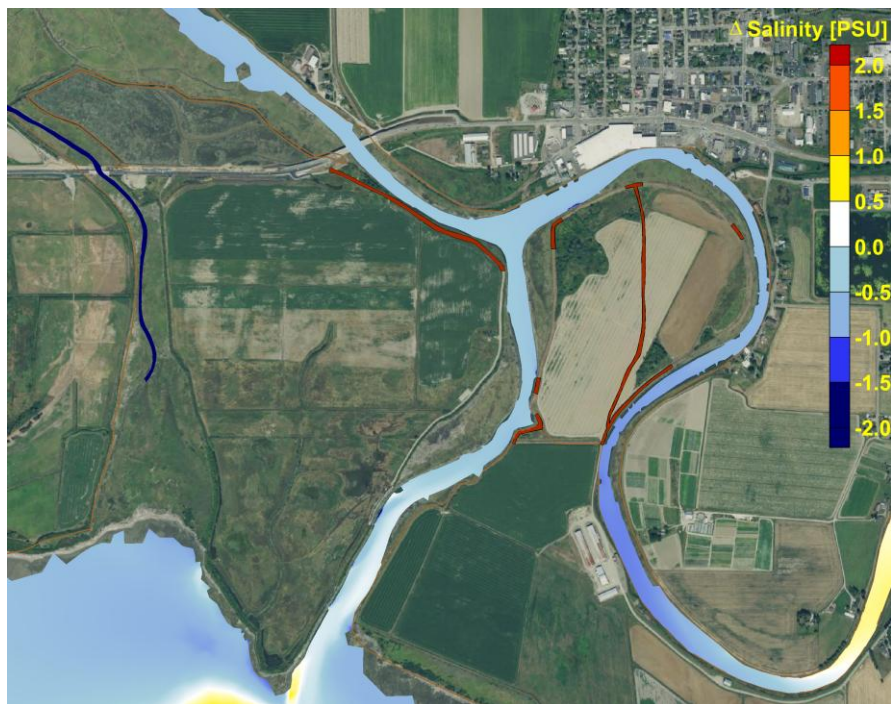
Figure B.6.   Salinity Difference Contours of Preferred Restoration Alternative Scenario Relative to Baseline at Peak Flood Tide (13:00) on October 24, 2005

Appendix C

Time Series Plots – High-Flow (bank-full) Conditions:
Water Surface Elevation, Salinity, Velocity, and Bed Shear

Appendix C

Time Series Plots – High-Flow (bank-full) Conditions: Water Surface Elevation, Salinity, Velocity, and Bed Shear

Time series plots at high-flow (bank-full) condition water surface elevations, salinities, velocities, and bed sheers for Leque Island and zis a ba restoration site stations are provided in this appendix.
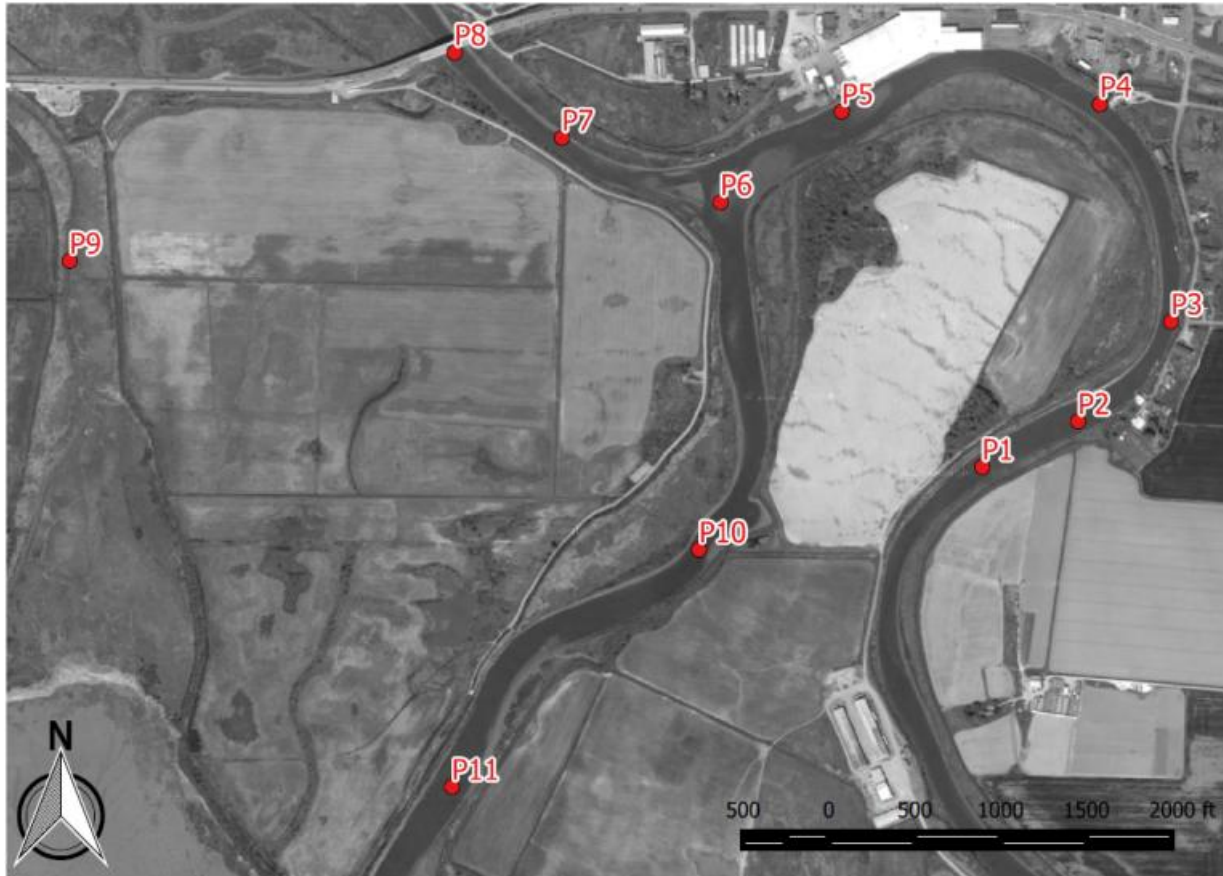
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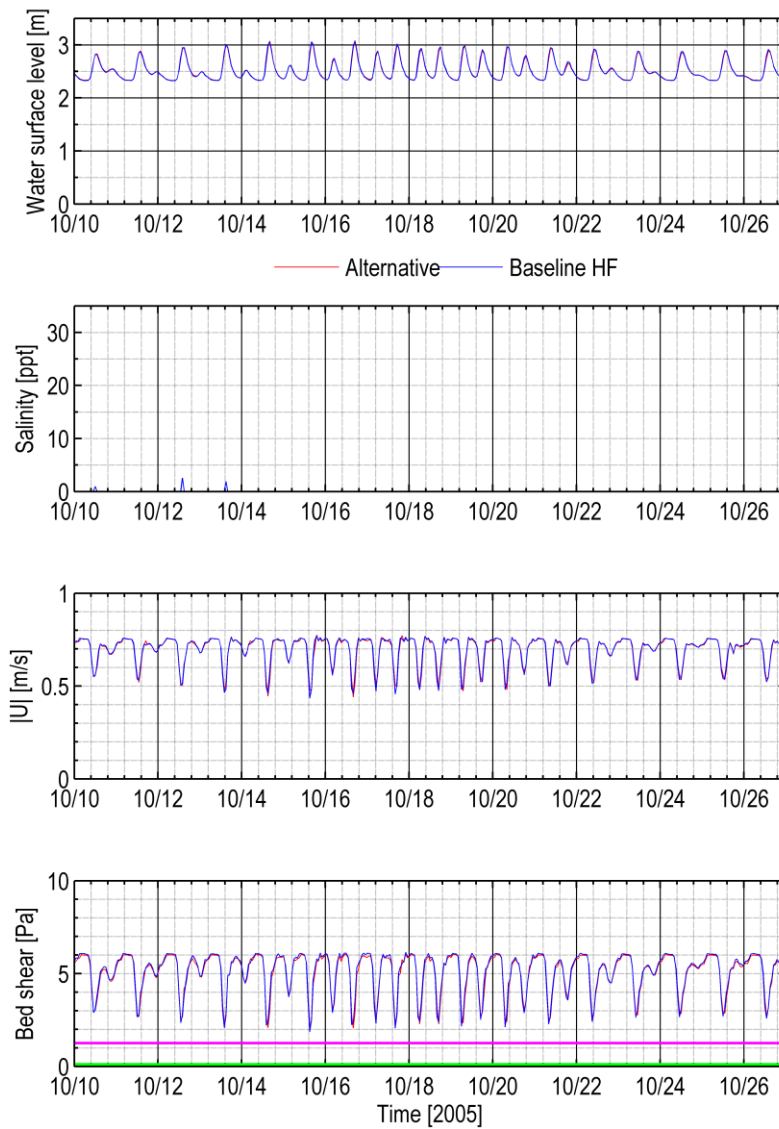
Figure C.2.   Preferred vs. Baseline Scenarios – Time Series of Water Surface Elevation, Salinity, Velocity Magnitude, and Bed Shear Stress at Station P1, Bank-Full Conditions at 26,508 cfs River Flow (tides and wind corresponding to October 2005)
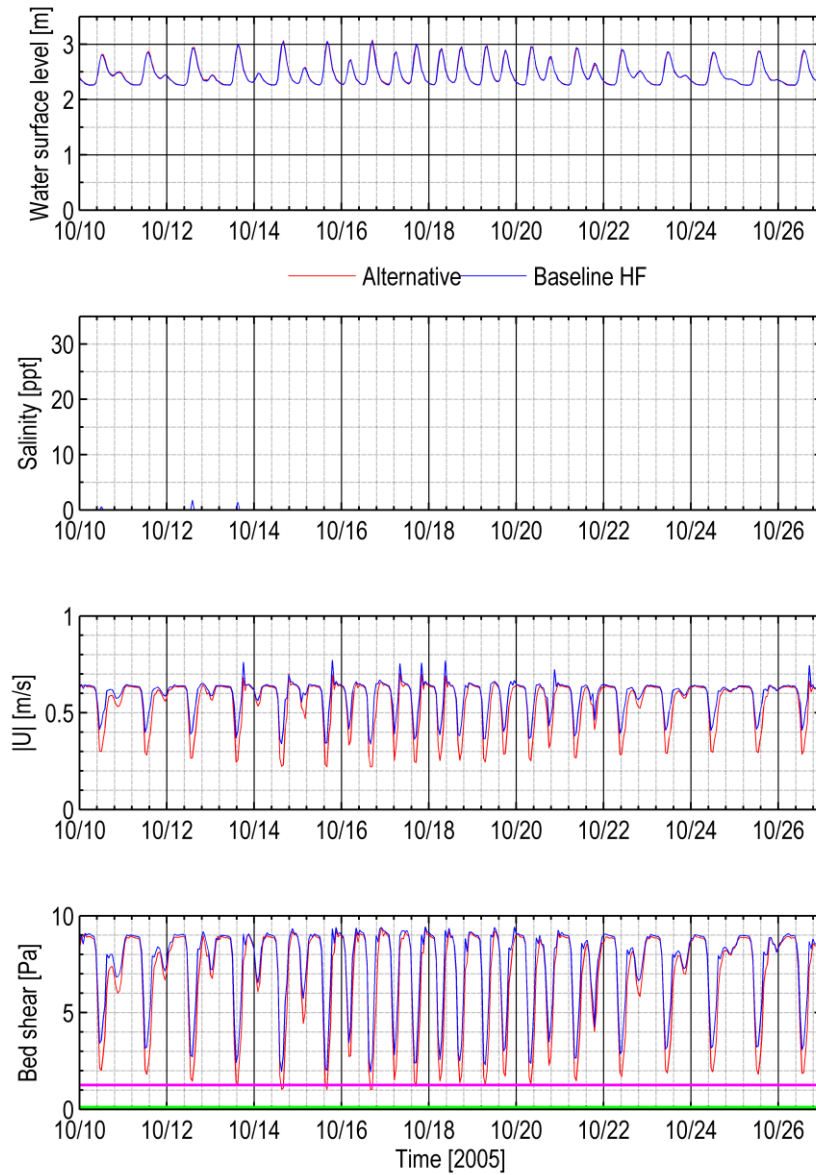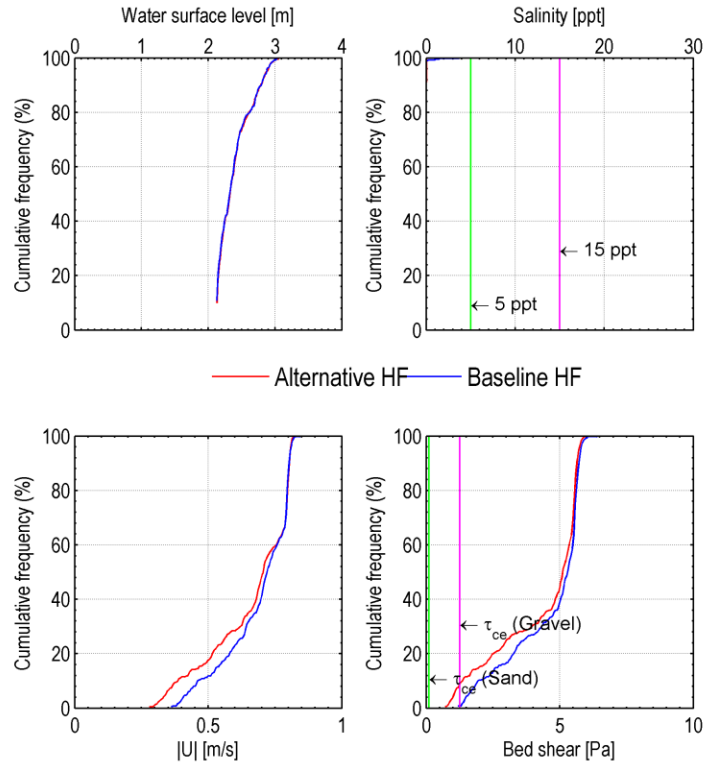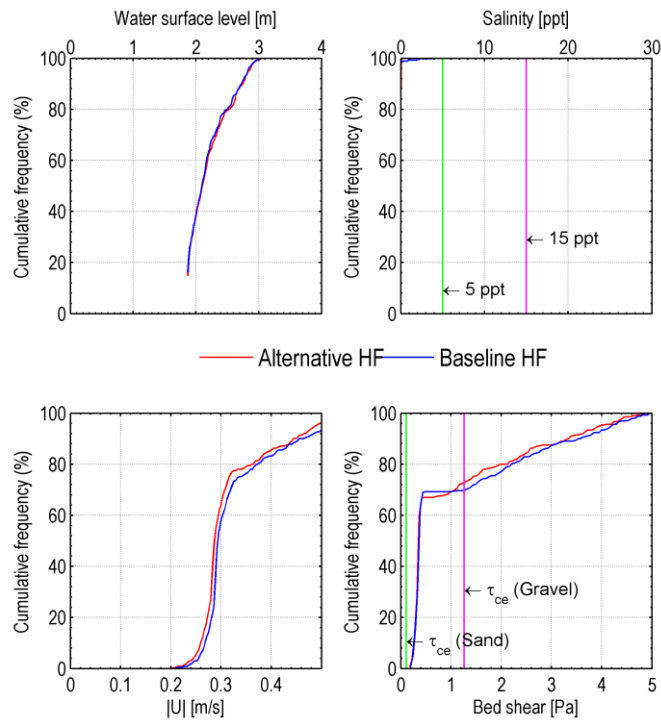
Figure C.3. Preferred vs. Baseline Scenarios – Time Series of Water Surface Elevation, Salinity, Velocity Magnitude, and Bed Shear Stress at Station P2, Bank-Full Conditions at 26,508 cfs River Flow (tides and wind corresponding to October 2005)
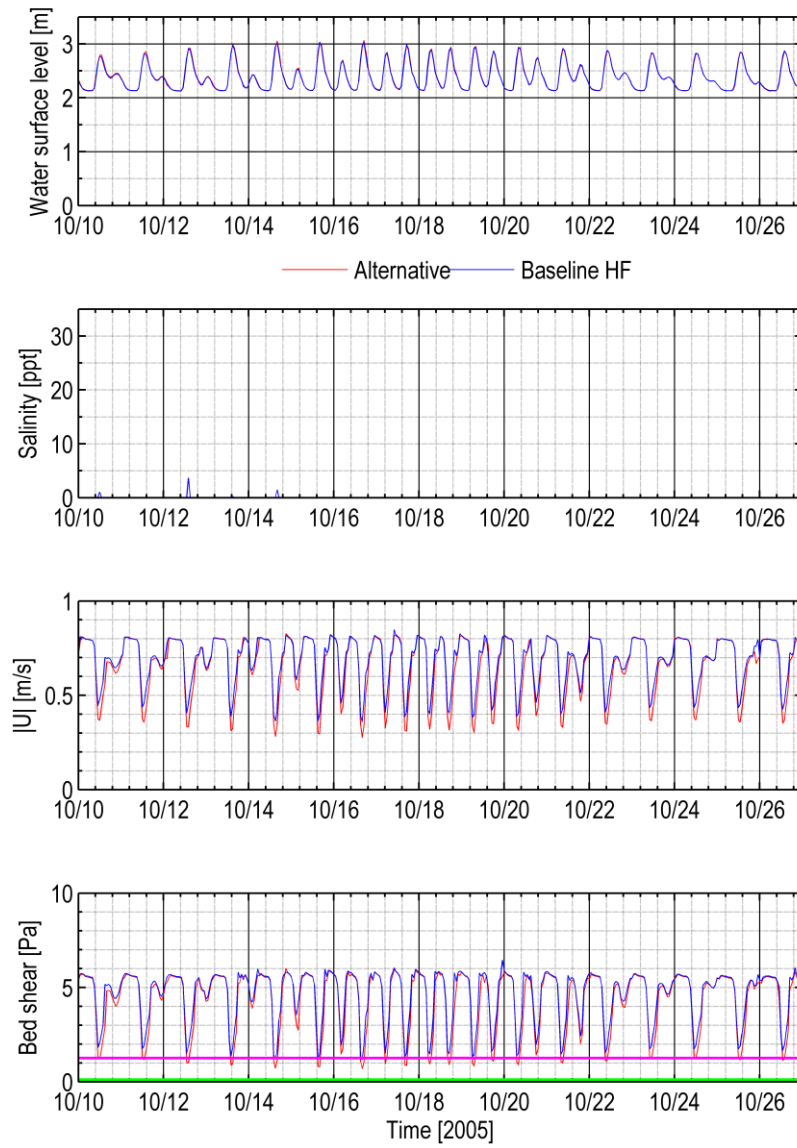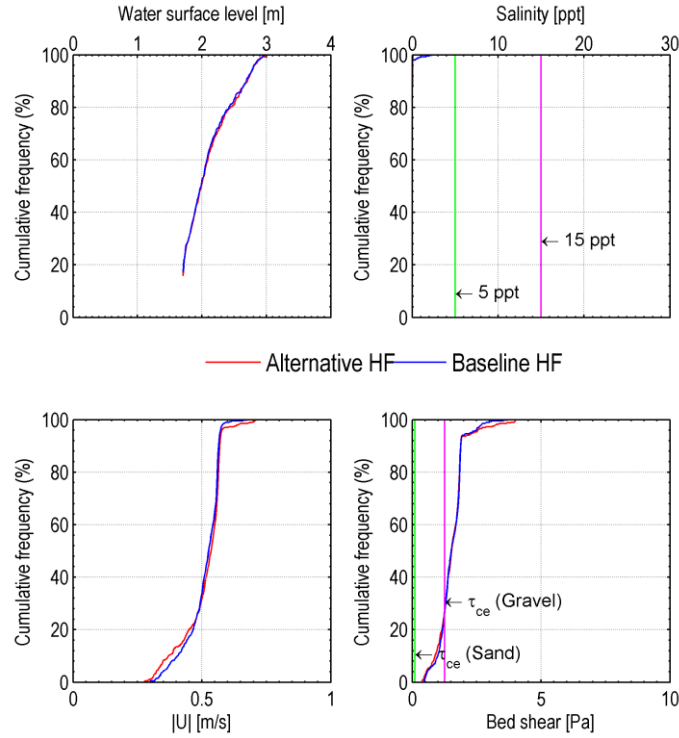
Figure C.4.   Preferred vs. Baseline Scenarios – Time Series of Water Surface Elevation, Salinity, Velocity Magnitude, and Bed Shear Stress at Station P3, Bank-Full Conditions at 26,508 cfs River Flow (tides and wind corresponding to October 2005)

Figure C.5. Preferred vs. Baseline Scenarios – Time Series of Water Surface Elevation, Salinity, Velocity Magnitude, and Bed Shear Stress at Station P4, Bank-Full Conditions at 26,508 cfs River Flow (tides and wind corresponding to October 2005)
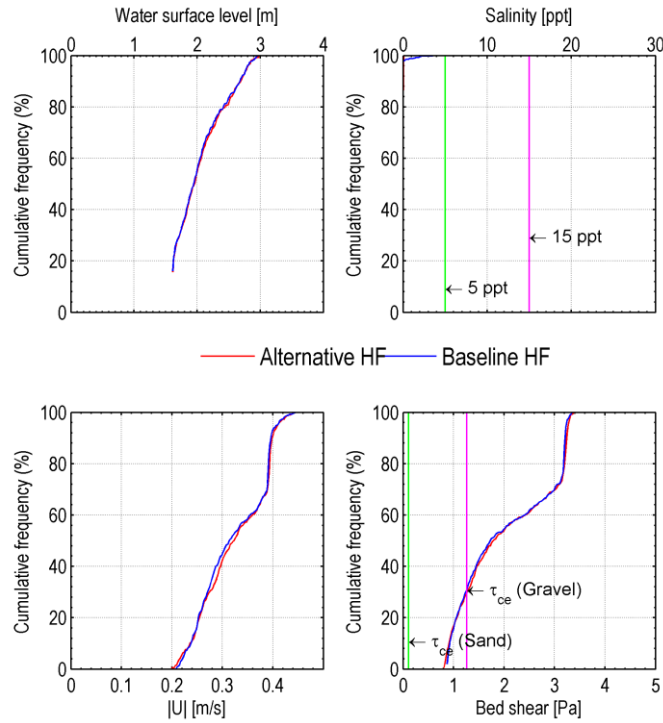
Figure C.6. Preferred vs. Baseline Scenarios – Time Series of Water Surface Elevation, Salinity, Velocity Magnitude, and Bed Shear Stress at Station P5, Bank-Full Conditions at 26,508 cfs River Flow (tides and wind corresponding to October 2005)
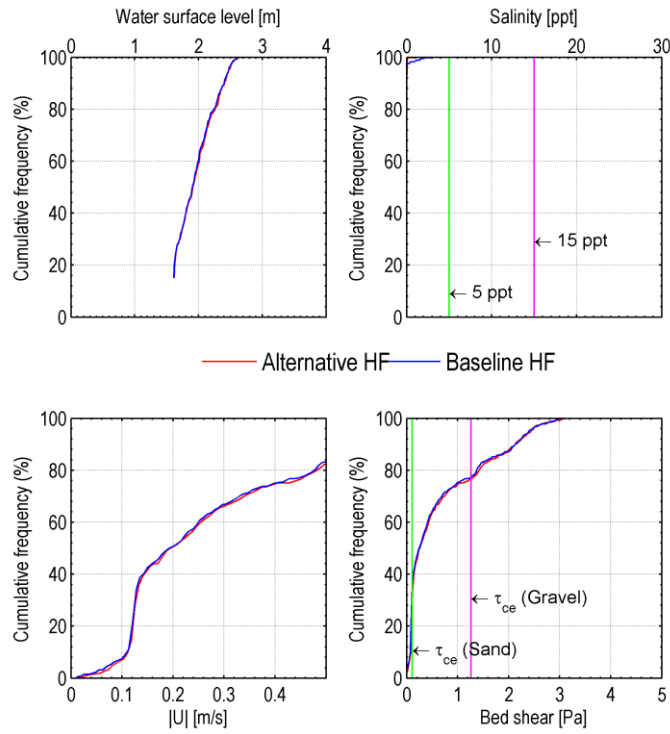
Figure C.7. Preferred vs. Baseline Scenarios – Time Series Of Water Surface Elevation, Salinity, Velocity Magnitude, and Bed Shear Stress at Station P6, Bank-Full Conditions at 26,508 cfs River Flow (tides and wind corresponding to October 2005)
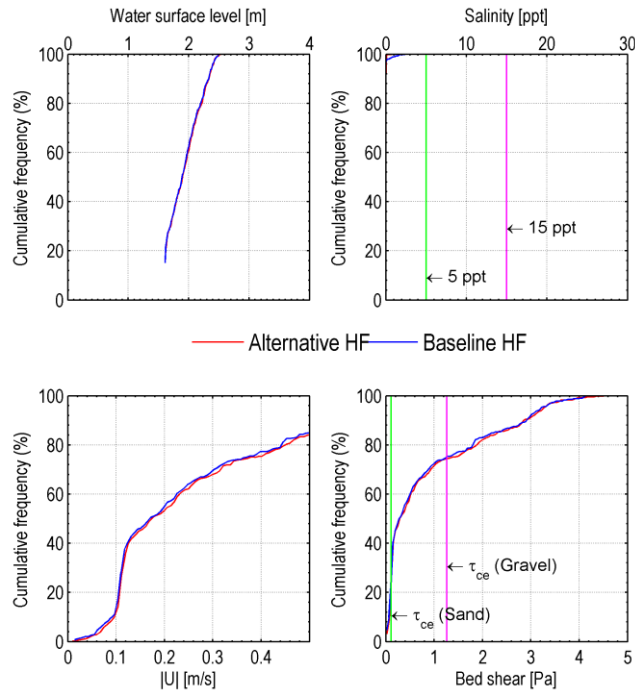
Figure C.8. Preferred vs. Baseline Scenarios – Time Series of Water Surface Elevation, Salinity, Velocity Magnitude, and Bed Shear Stress at Station P7, Bank-Full Conditions at 26,508 cfs River Flow (tides and wind corresponding to October 2005)
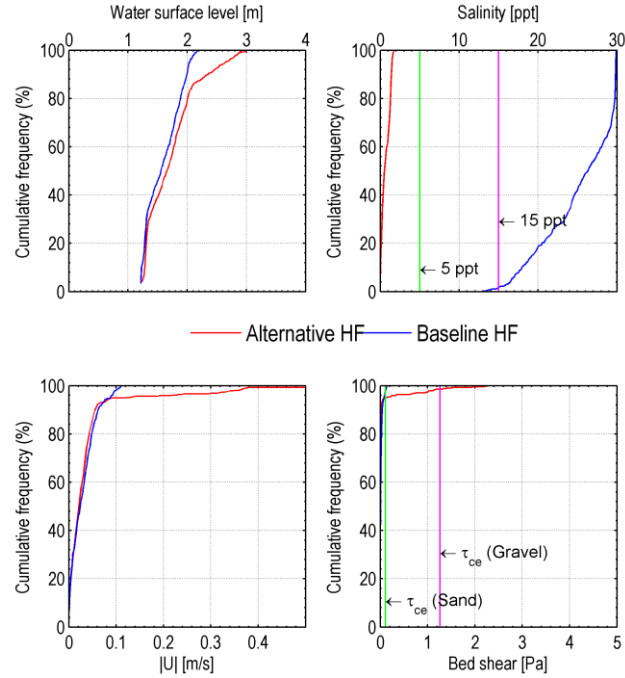
Figure C.9. Preferred vs. Baseline Scenarios – Time Series of Water Surface Elevation, Salinity, Velocity Magnitude, and Bed Shear Stress at Station P8, Bank-Full Conditions at 26,508 cfs River Flow (tides and wind corresponding to October 2005)
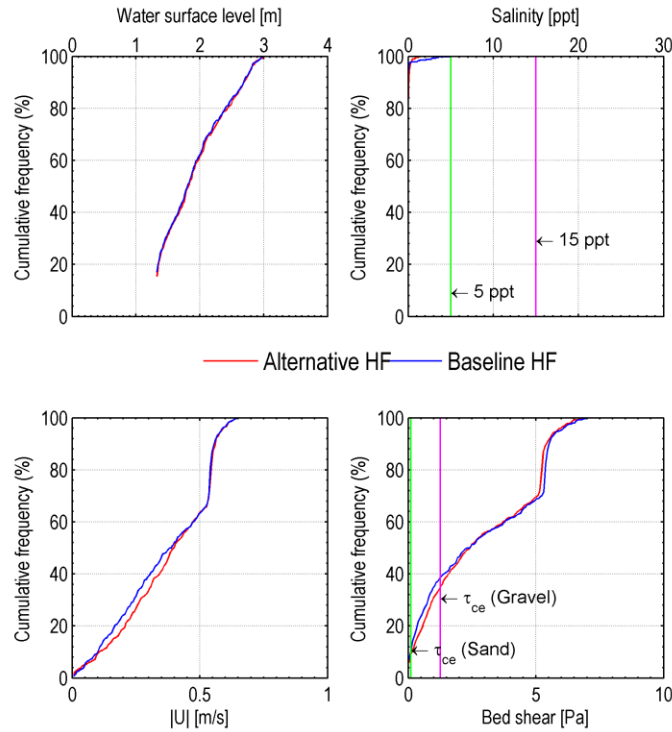
Figure C.10. Preferred vs. Baseline Scenarios – Time Series of Water Surface Elevation, Salinity, Velocity Magnitude, and Bed Shear Stress at Station P9, Bank-Full Conditions at 26,508 cfs River Flow (tides and wind corresponding to October 2005)
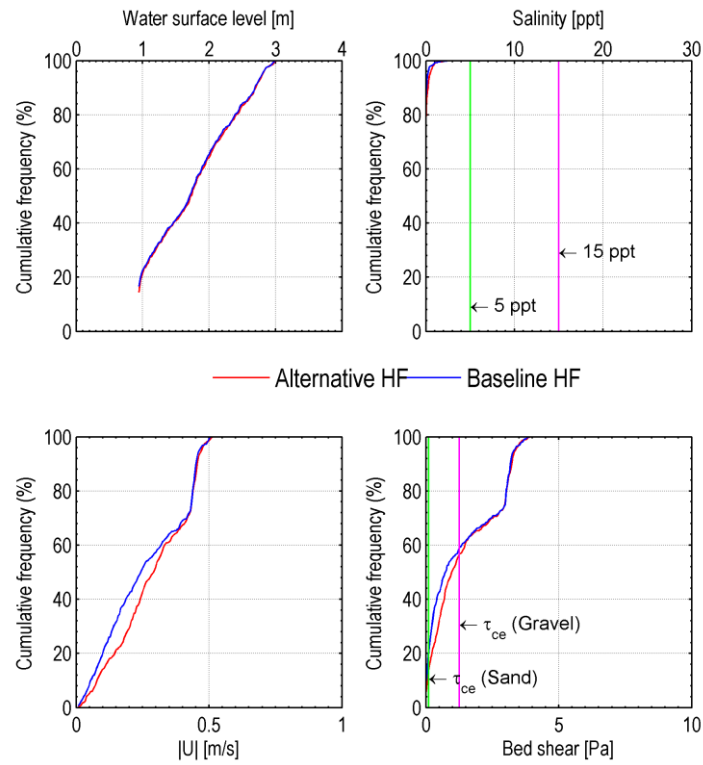
Figure C.11. Preferred vs. Baseline Scenarios – Time Series of Water Surface Elevation, Salinity, Velocity Magnitude, and Bed Shear Stress at Station P10, Bank-Full Conditions at 26,508 cfs River flow (tides and wind corresponding to October 2005)
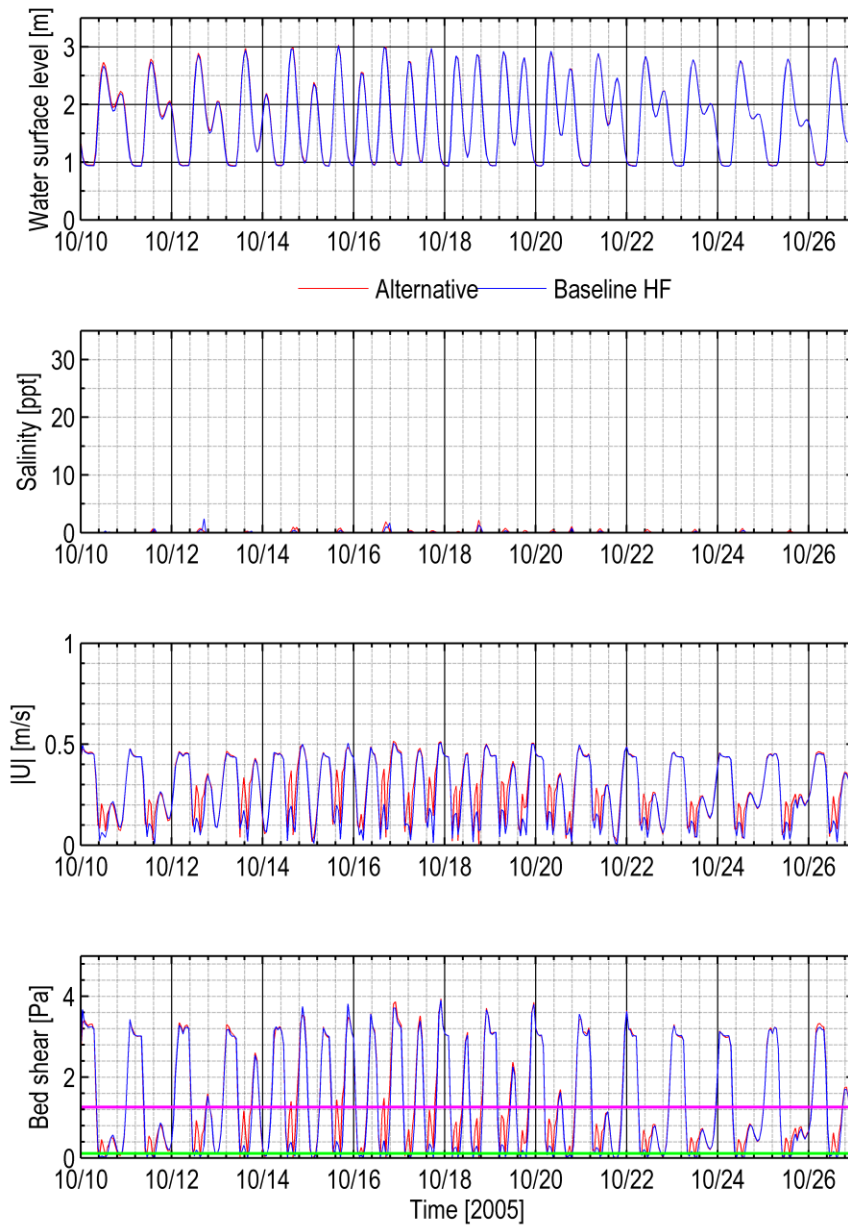
Figure C.12. Preferred vs. Baseline Scenarios – Time Series of Water Surface Elevation, Salinity, Velocity Magnitude, and Bed Shear Stress at Station P11, Bank-Full Conditions at 26,508 cfs River flow (tides and wind corresponding to October 2005)
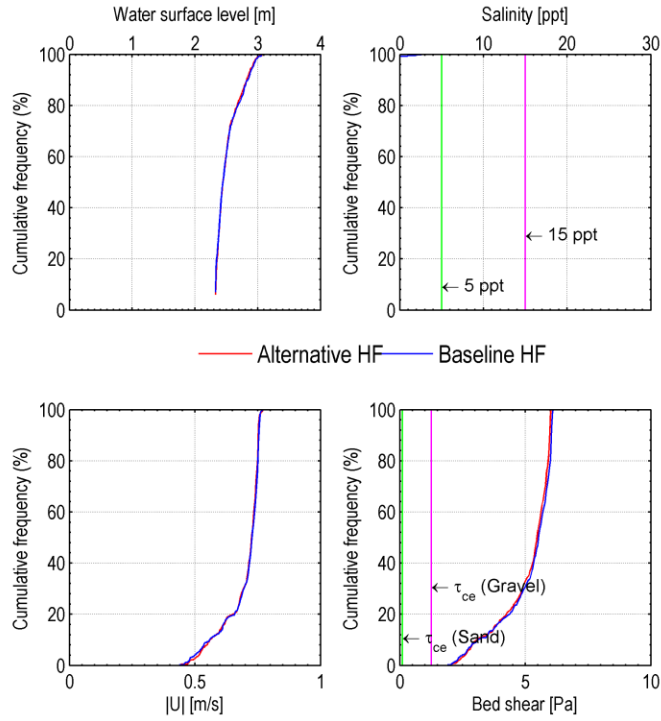
Figure C.13.   Preferred vs. Baseline Scenarios– Cumulative Frequency of Water Surface Elevation, Salinity, Velocity Magnitude, and Bed Shear Stress at Station P1, October 2005 Period
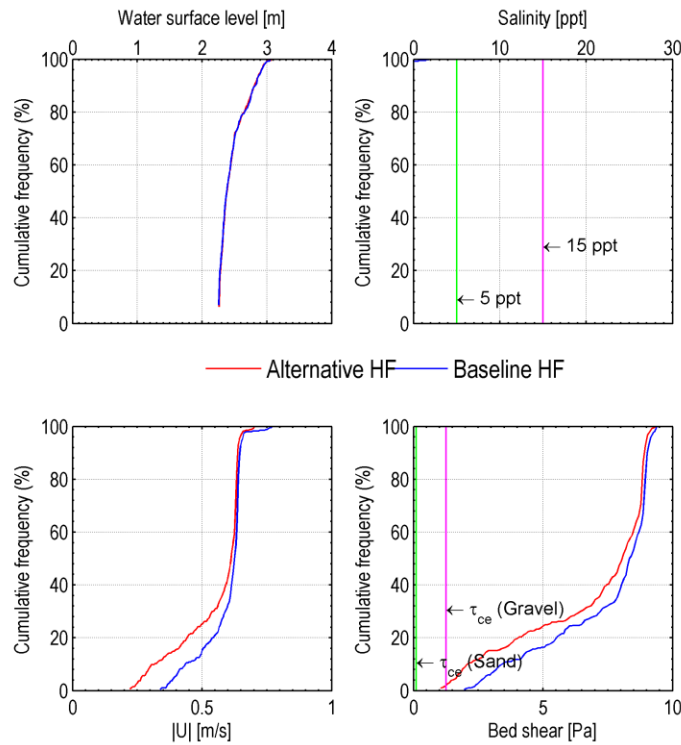
Figure C.14.   Preferred vs. Baseline Scenarios– Cumulative Frequency of Water Surface Elevation, Salinity, Velocity Magnitude, and Bed Shear Stress at Station P2, October 2005 Period

Figure C.15.   Preferred vs. Baseline Scenarios– Cumulative Frequency of Water Surface Elevation, Salinity, Velocity Magnitude, and Bed Shear Stress at Station P3, October 2005 Period

Figure C.16.   Preferred vs. Baseline Scenarios– Cumulative Frequency of Water Surface Elevation, Salinity, Velocity Magnitude, and Bed Shear Stress at Station P4, October 2005 Period

Figure C.17. Preferred vs. Baseline Scenarios– Cumulative Frequency of Water Surface Elevation, Salinity, Velocity Magnitude, and Bed Shear Stress at Station P5, October 2005 Period

Figure C.18. Preferred vs. Baseline Scenarios– Cumulative Frequency of Water Surface Elevation, Salinity, Velocity Magnitude, and Bed Shear Stress at Station P6, October 2005 Period

Figure C.19. Preferred vs. Baseline Scenarios– Cumulative Frequency of Water Surface Elevation, Salinity, Velocity Magnitude, and Bed Shear Stress at Station P7, October 2005 Period

Figure C.20. Preferred vs. Baseline Scenarios– Cumulative Frequency of Water Surface Elevation, Salinity, Velocity Magnitude, and Bed Shear Stress at Station P8, October 2005 Period

C.16

Figure C.21. Preferred vs. Baseline Scenarios – Cumulative Frequency of Water Surface Elevation, Salinity, Velocity Magnitude, and Bed Shear Stress at Station P9, October 2005 Period

Figure C.22. Preferred vs. Baseline Scenarios – Cumulative Frequency of Water Surface Elevation, Salinity, Velocity Magnitude, and Bed Shear Stress at Station P10, October 2005 Period

C.17

Figure C.23. Preferred vs. Baseline Scenarios– Cumulative Frequency of Water Surface Elevation, Salinity, Velocity Magnitude, and Bed Shear Stress at Station P11, October 2005 Period

Appendix D

Plan View Contour Plots – High-Flow (bank-full) Conditions: Salinity and Velocity

Appendix D

Plan View Contour Plots – High-Flow (bank-full) Conditions: Salinity and Velocity

Plan view contour plots at high-flow (bank-full) condition for water surface elevation, salinity, velocity, and bed sheer for the Leque Island and zis a ba restoration site stations are provided in this appendix.
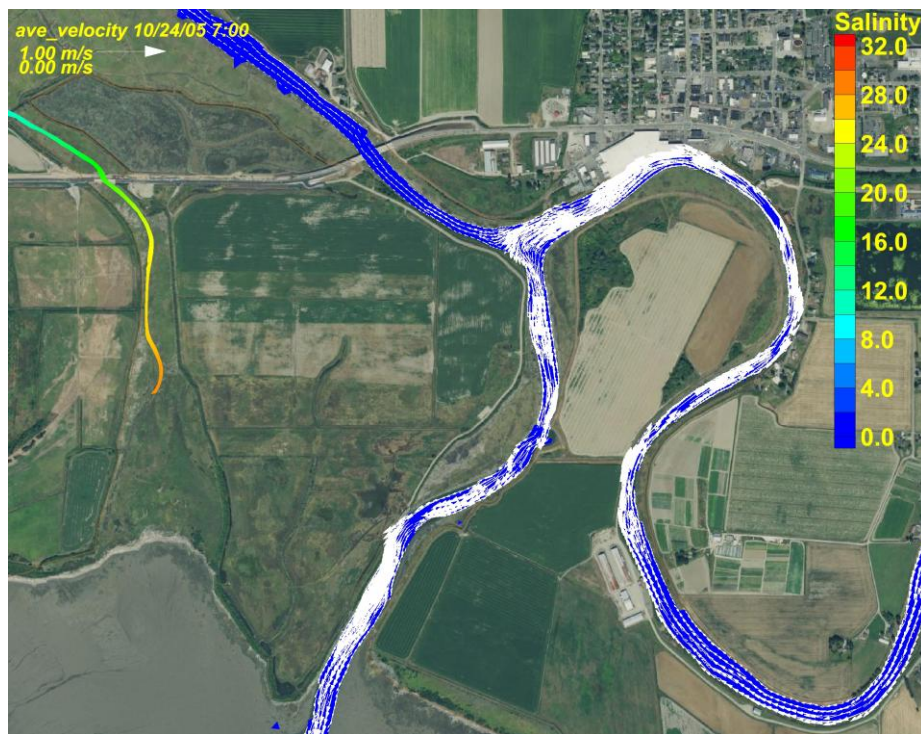
Figure D.1. Baseline Condition – Salinity Contours and Velocity Vectors, High-Flow (Bank-Full) Condition at 26,508 cfs and Low Tide based on October 24, 2005 (13:00)
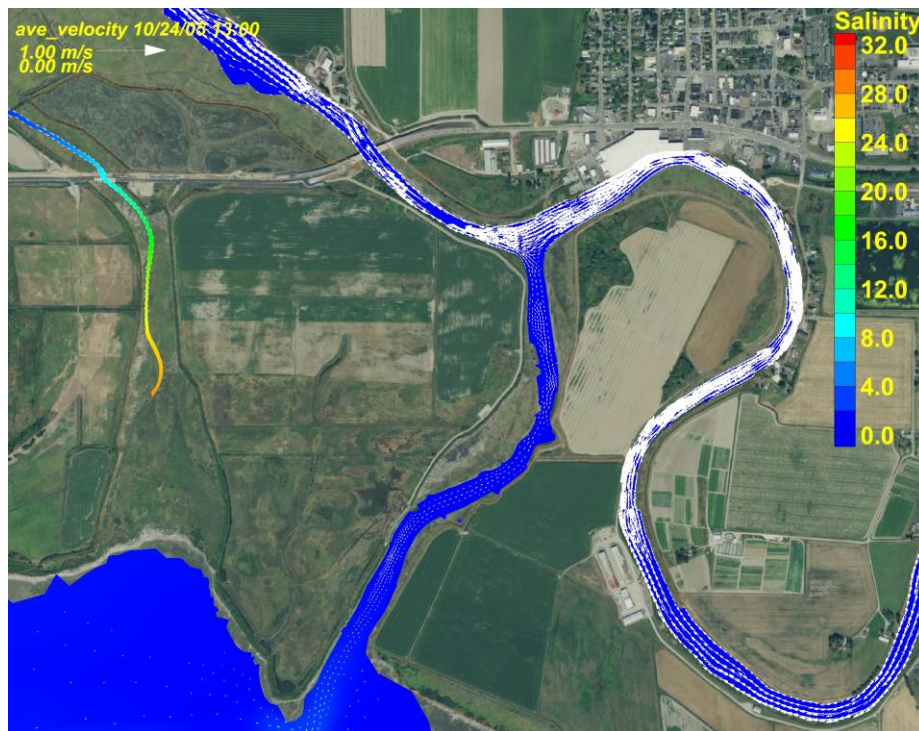
Figure D.2. Baseline Condition – Salinity Contours and Velocity Vectors, High-Flow (Bank-Full) Condition at 26,508 cfs and High Tide based on October 24, 2005 (07:00)
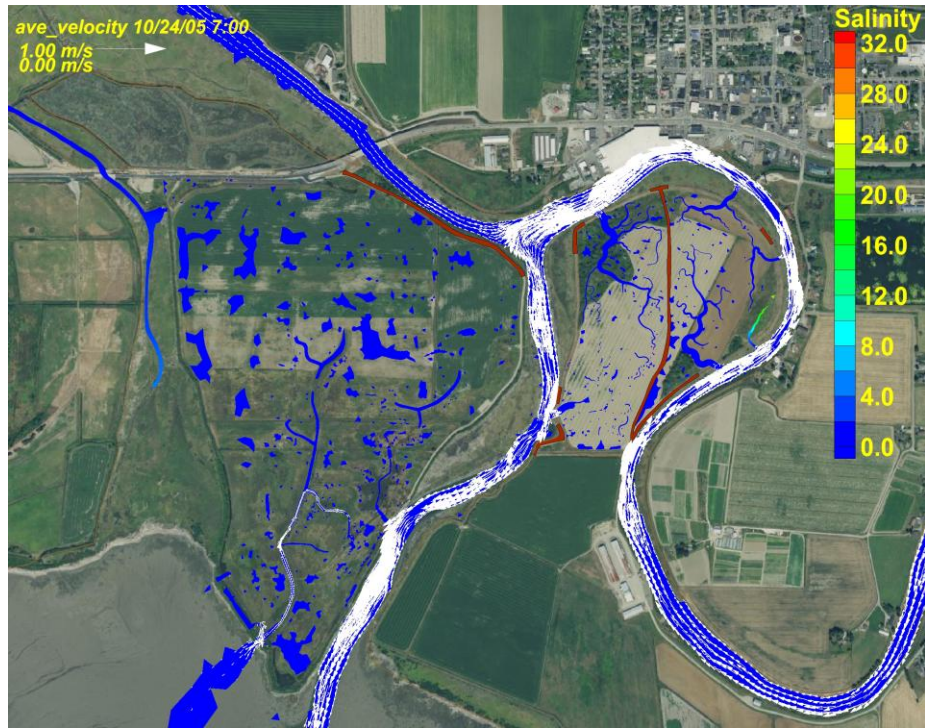
Figure D.3. Preferred Restoration Alternative Scenario – Salinity Contours and Velocity Vectors, High-Flow (Bank-Full) Condition at 26,508 cfs And Low Tide Based on October 24, 2005 (07:00)
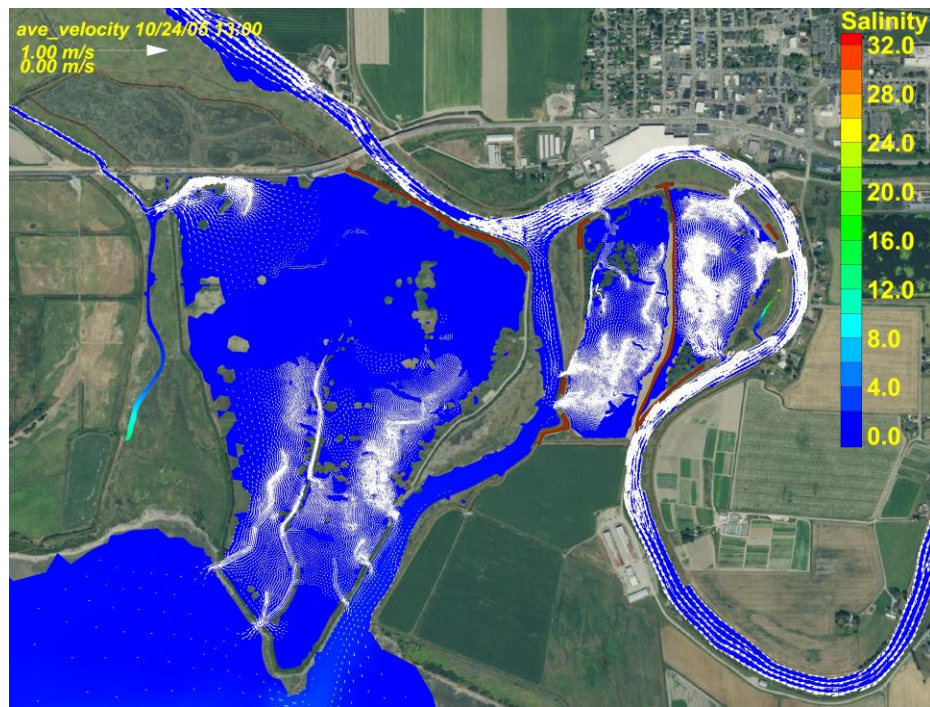
Figure D.4. Preferred Restoration Alternative Scenario – Salinity Contours and Velocity Vectors, High-Flow (Bank-Full) Condition at 26,508 Cfs and High Tide based on October 24, 2005 (13:00)

D.3
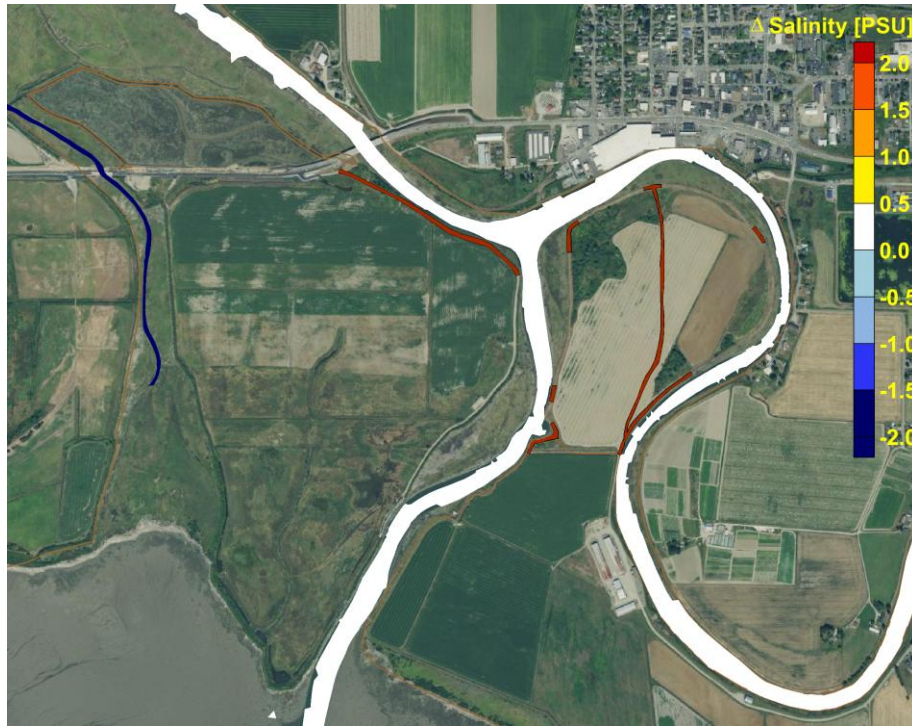
Figure D.5. Salinity Difference Contours of Preferred Restoration Alternative Scenario Relative to Baseline at Low Flow (Bank-Full) Condition at 26,508 Cfs and Low Tide based on October 24, 2005 (07:00)
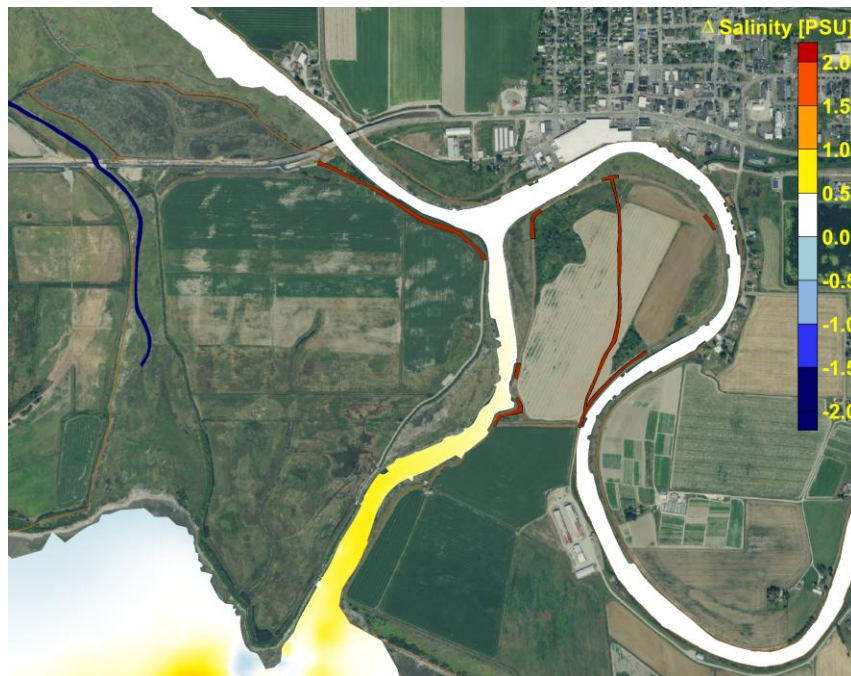
Figure D.6. Salinity Difference Contours of Preferred Restoration Alternative Scenario Relative to Baseline at High-Flow (Bank-Full) condition at 26,508 cfs and High Tide based on October 24, 2005 (13:00)

Appendix E

Plan View Contour Plots – October 2005 Conditions: Bed Shear

Appendix E

Plan View Contour Plots – October 2005 Conditions: Bed Shear

October 2005 plan view contour plots at high-flow (bank-full) condition for bed sheers for the Leque Island and zis a ba restoration site stations are provided in this appendix.
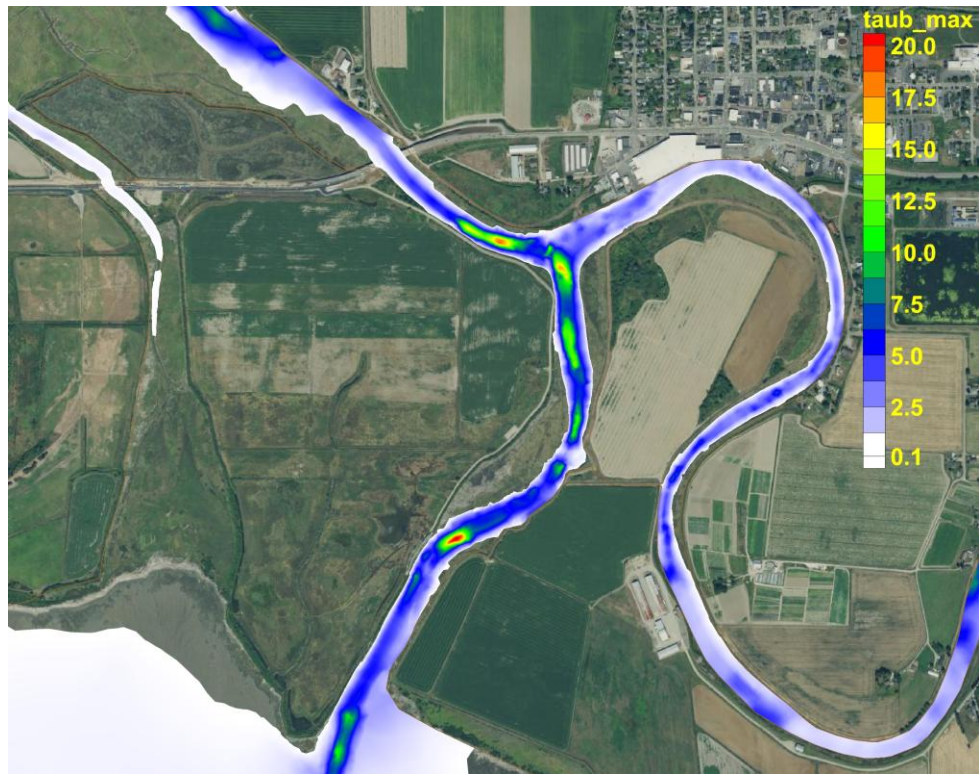
Figure E.1. Baseline Condition – Maximum Bed Shear Stress
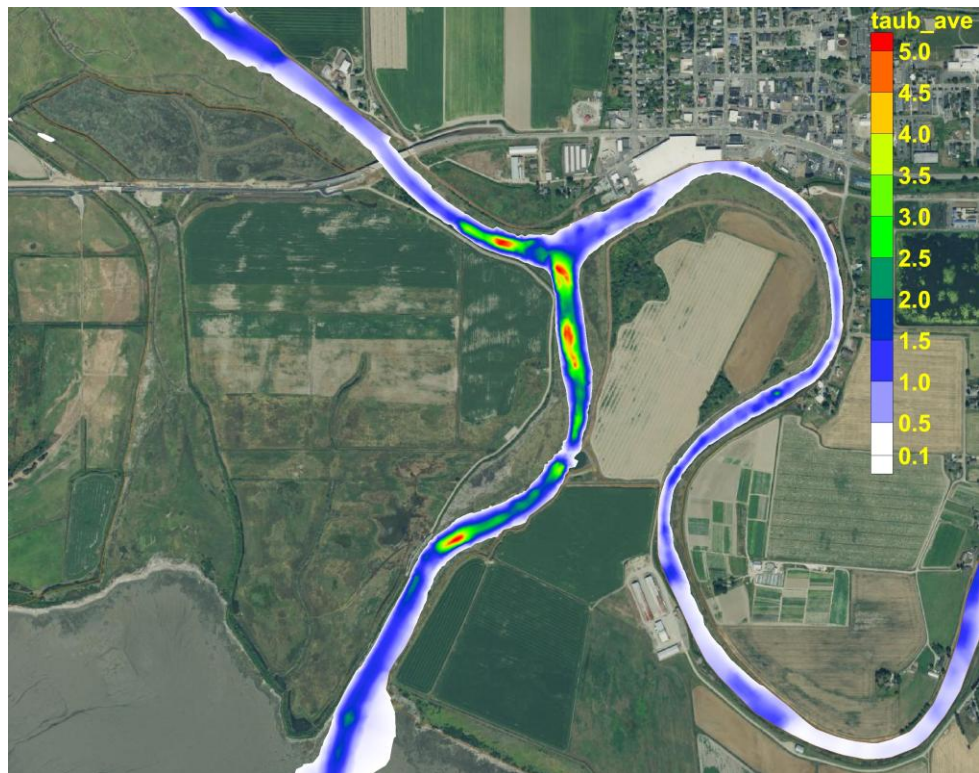
Figure E.2. Baseline Condition – Mean bed Shear Stress
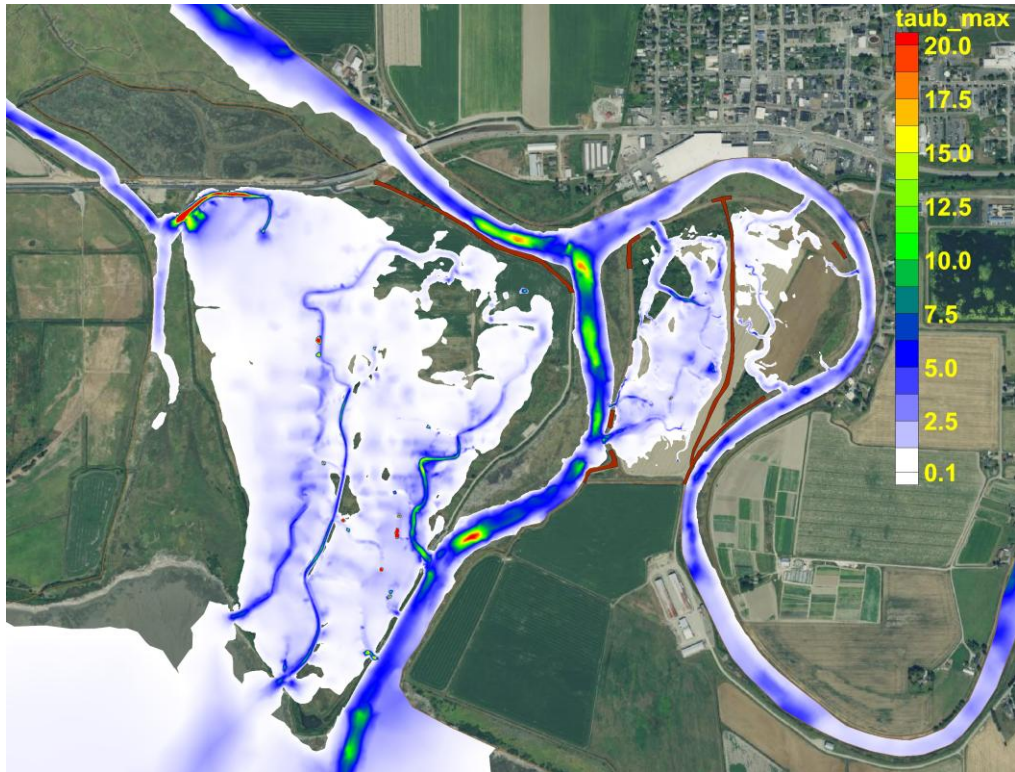
Figure E.3. Preferred Alternative Condition – Maximum Bed Shear Stress
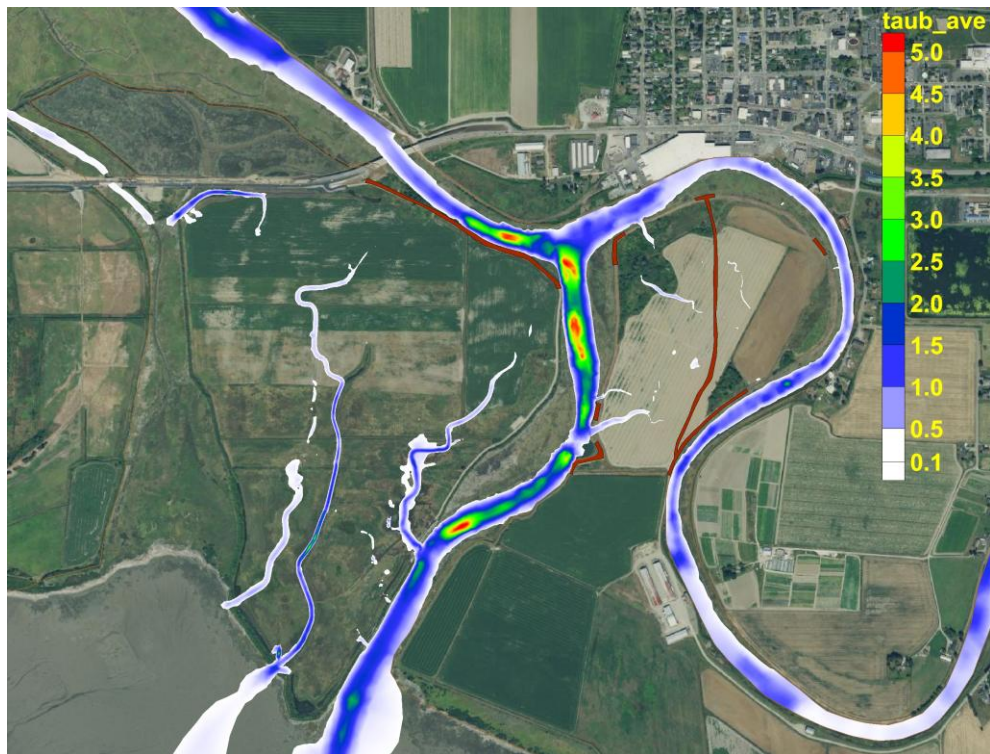
Figure E.4. Preferred Alternative Condition – Mean Bed Shear Stress
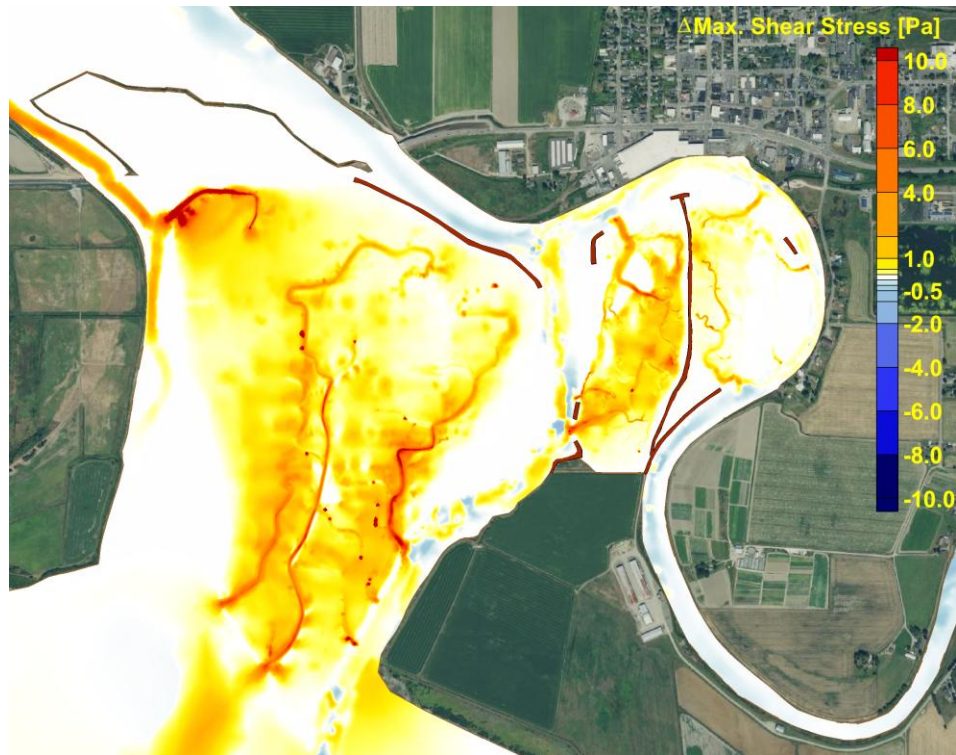
Figure E.5.   Maximum Difference Bed Shear Stress Contours of the Preferred Restoration Alternative Scenario Relative to the Baseline
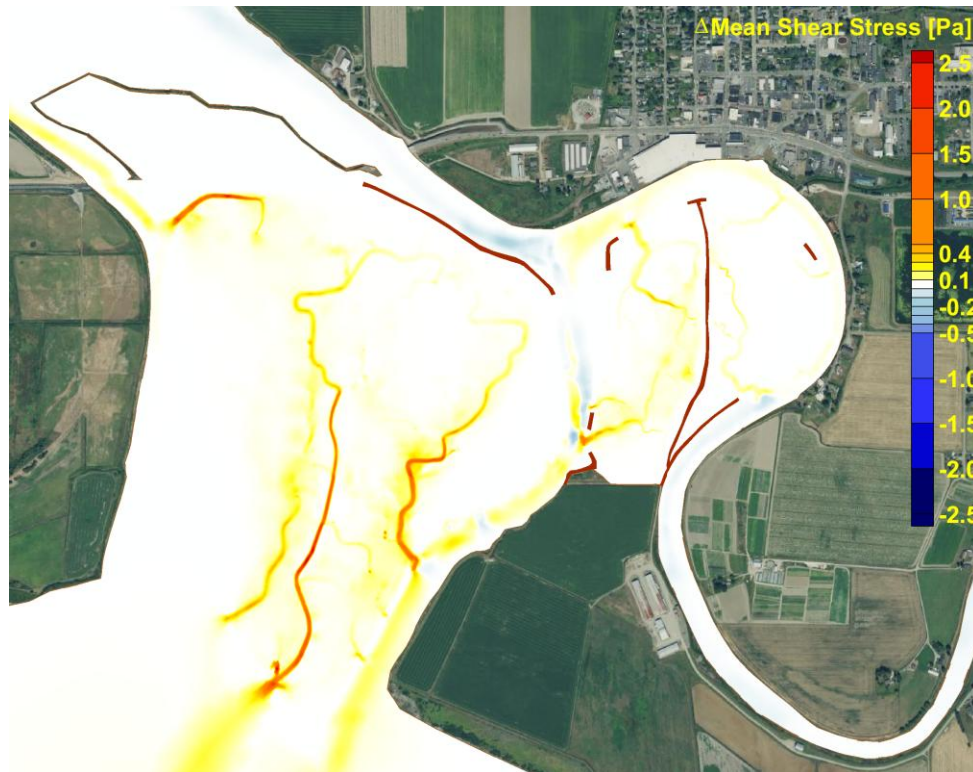
Figure E.6.   Mean difference Bed Shear Stress Contours of the referred Restoration Alternative Scenario Relative to the Baseline

Appendix F

Plan View Contour Plots – High-Flow (bank-full) Conditions: Bed Shear

Appendix F

Plan View Contour Plots – High-Flow (bank-full) Conditions: Bed Shear

Plan view contour plots at high-flow (bank-full) conditions for bed sheer for the Leque Island and zis a ba restoration site stations are provided in this appendix.
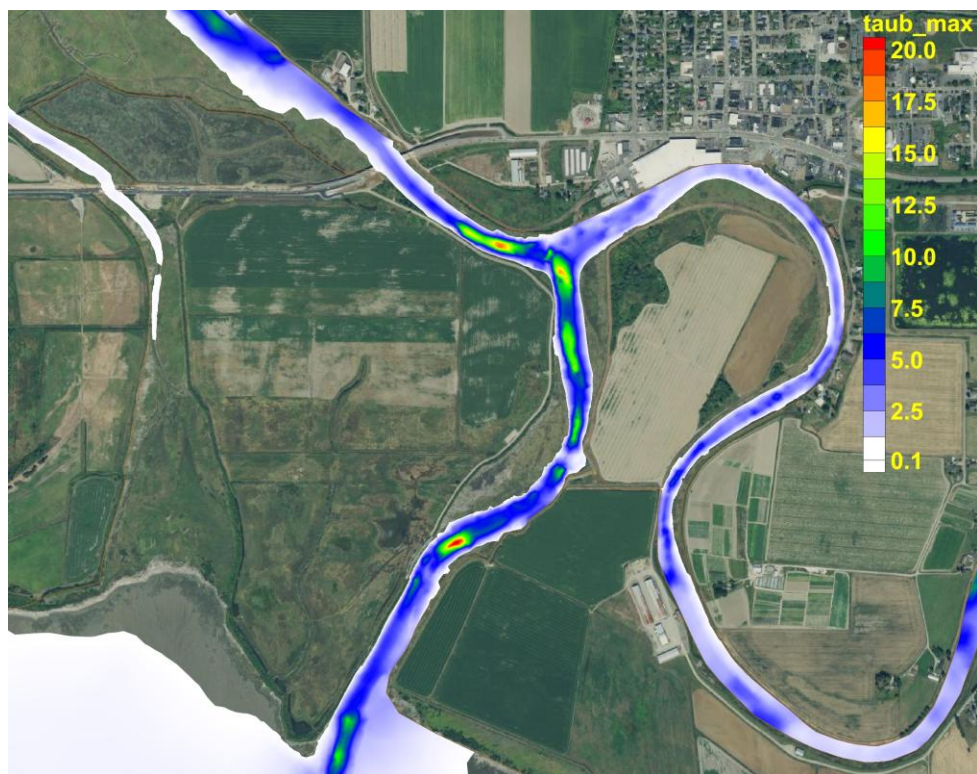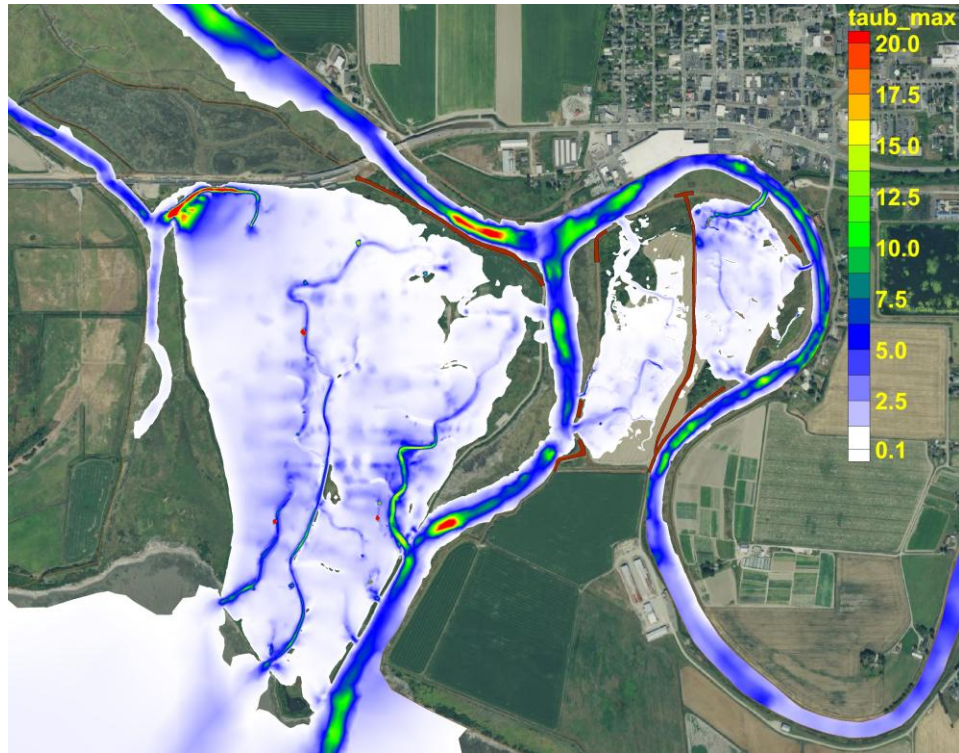
Figure F.1.   Baseline Condition – Maximum Bed Shear Stress, High-Flow (bank-full) Condition at 26,508 cfs
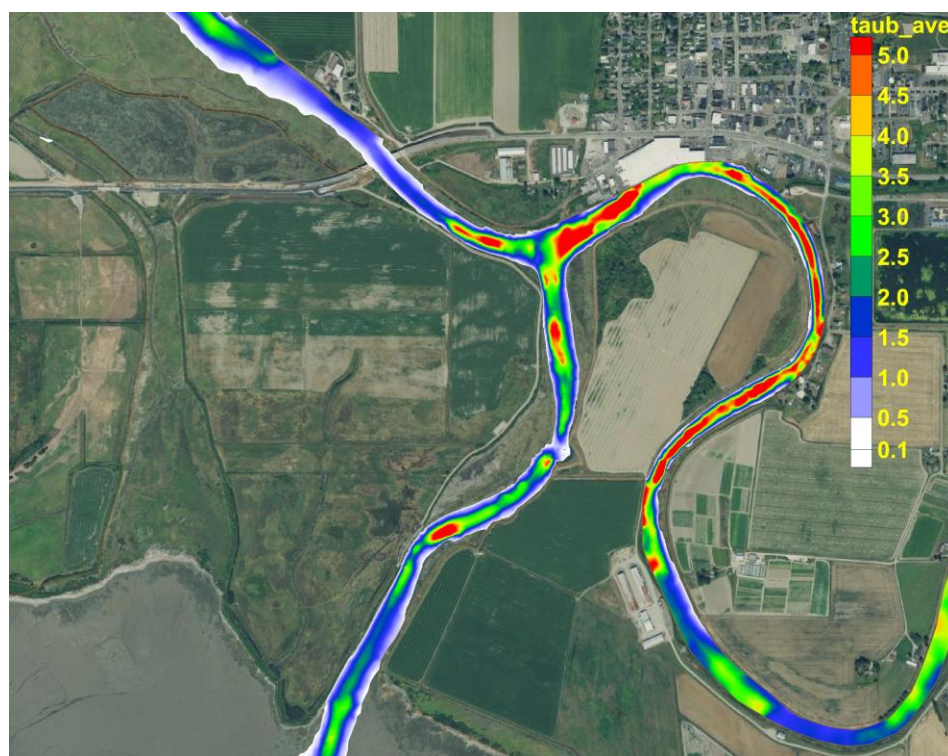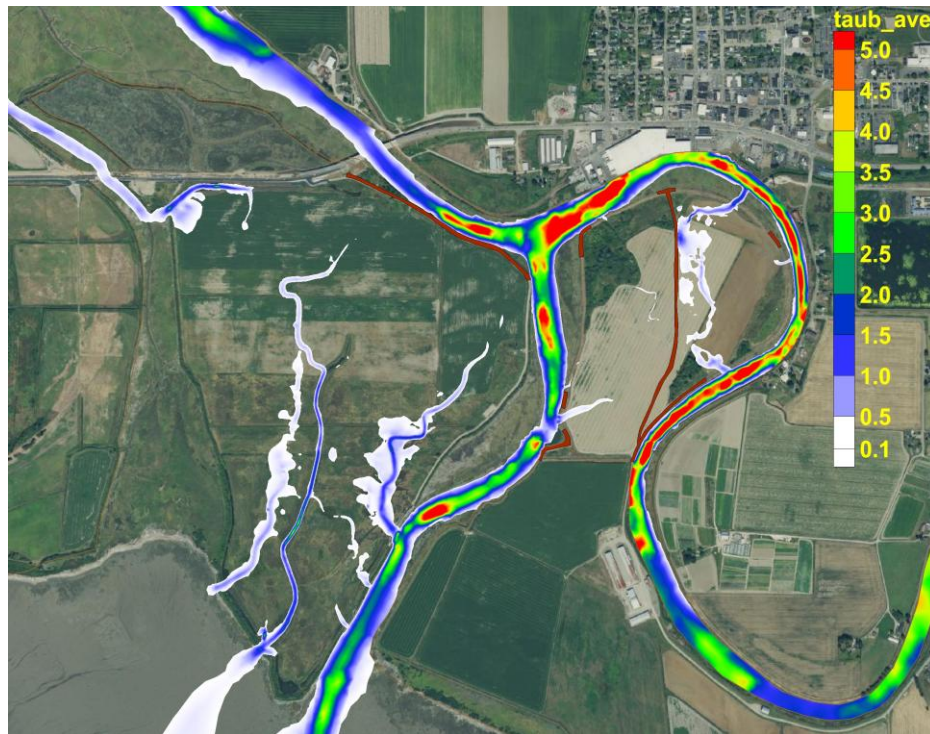

Figure F.2. Baseline Condition – Mean Bed Shear Stress, High-Flow (bank-full) Conditionc at 26,508 cfs
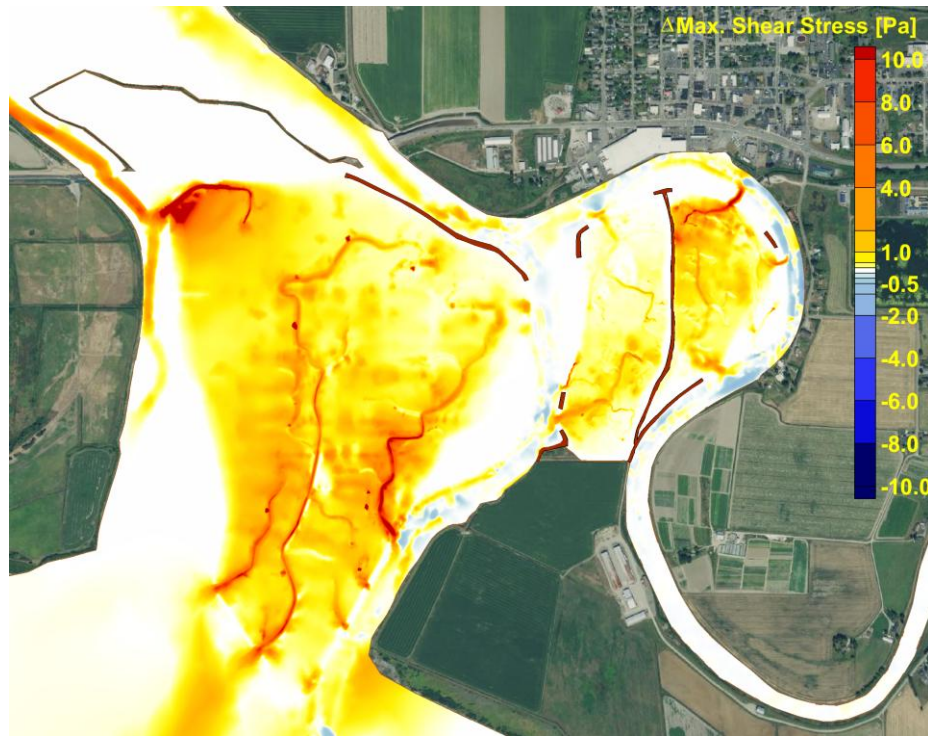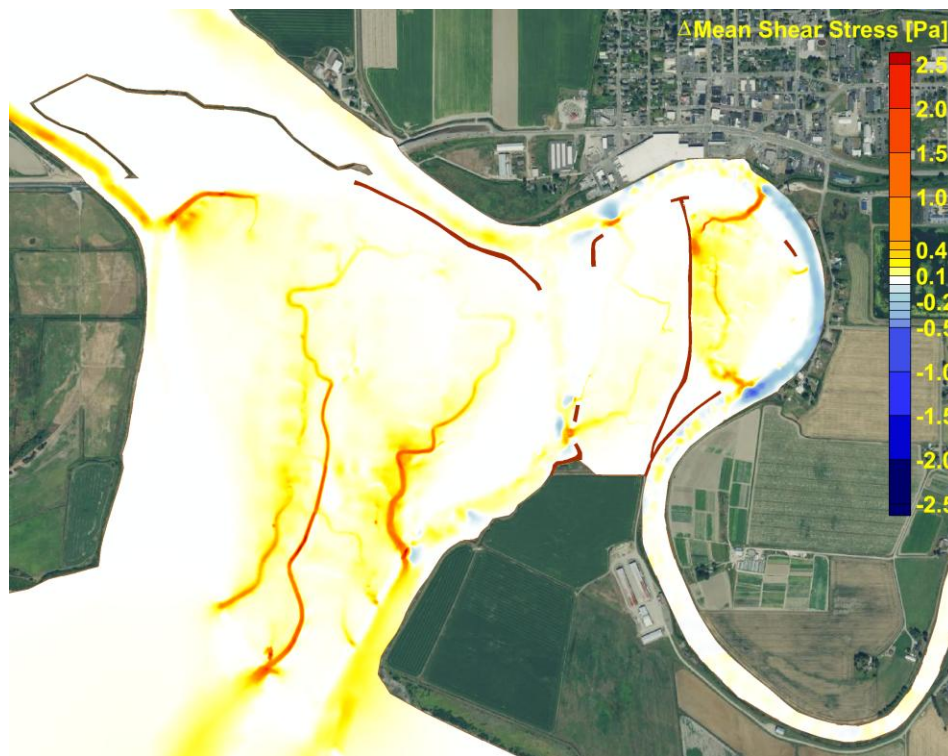
Figure F.3.   Preferred Alternative Condition – Maximum Bed Shear Stress, High-Flow (bank-full) Condition at 26,508 cfs

Figure F.4.   Preferred Alternative Condition – Mean bed Shear Stress, High-Flow (bank-full) Condition at 26,508 cfs

Figure F.5. Maximum Difference Bed Shear Stress Contours of the Preferred Restoration Alternative Scenario Relative to the baseline at High-Flow (bank-full) Condition at 26,508 cfs

Figure F.6.   Mean Difference Bed Shear Stress Contours of the Preferred Restoration Alternative Scenario Relative to the Baseline at High-Flow (Bank-Full) Conditions at 26,508 cfs