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Cottonwood Island Restoration Feasibility Study – Hydrodynamic and Sediment Transport Analysis

Cheegwan Lee
Tarang Khangaonkar

October 2007

Prepared for
Skagit Watershed Council
Mount Vernon, WA

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October 2007

Prepared for
Skagit Watershed Council

Battelle—Pacific Northwest Division
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Executive Summary

The Skagit Watershed Council (SWC) has proposed the restoration of Cottonwood Island, located near the bifurcation of the Skagit River into the North and the South Forks, approximately 10 river miles upstream from the mouth of the River. This area is a riverine tidal and floodplain forest zone that is influenced by tide and is periodically inundated by flooding events. Historically, the Skagit River meandered around the west side of Cottonwood Island. However, in 1889, the existing levee was relocated to the present alignment. This constrained flow and developed a complex cut-off channel to form the present river. Consequently, the old west channel was blocked because of sedimentation at the head of the channel, and in its current state, it does not allow flow to pass when the river is low. SWC and its project partners, including Seattle City Light and the Washington State Department of Natural Resources, are evaluating the feasibility of restoring the historic connection around Cottonwood Island such that the fish have access to refuge in the west channel habitat.

Proposed restoration actions include dike setback and channel dredging to maintain the functioning of fish habitat in the west channel around Cottonwood Island. Battelle Marine Science Laboratory (Battelle) was contracted by SWC to conduct a hydrodynamic and sediment transport modeling analysis as part of the restoration feasibility study. The overall objective of this study is to evaluate whether the proposed restoration of Cottonwood Island is feasible with respect to hydrodynamic and sediment-transport impacts at the restoration site.

For this study, a 3-D hydrodynamic model was developed for the Cottonwood Island restoration site using the existing Skagit Bay model. The Skagit Bay model was developed independently through a previous study by Battelle and SWC using the finite-volume unstructured hydrodynamic model. The model, which includes the Cottonwood Island domain, uses a combination of tides, freshwater discharges, and surface-wind stresses as input. First, the model was validated comparing predicted results with field-observed tide, current, and salinity data collected by SWC for the period of 6/7/2005 to 6/22/2005. The wetting and drying process in the Cottonwood Island and the overbank region was successfully simulated in the model. The validated model was then used to simulate flood inundation, velocity distribution, and sedimentation in the study area for the existing conditions as well as for the restoration alternatives. Changes in hydrodynamics at the site were examined. The potential impact on sedimentation in Cottonwood Island under the restoration scenario was also evaluated based on predicted erosion and sedimentation patterns near the Cottonwood Island restoration area. Specifically, the following restoration alternatives were evaluated.

- Alternative 1 – Dike setback and reconnection
- Alternative 2 – Dike setback with dredging of west channel
- Alternative 3 – Dredging of west channel only (no dike setback)

Based on the model results from the three restoration alternatives listed above, the dike setback without any dredging did not significantly affect hydrodynamics and sedimentation compared to the existing conditions. Alternative 3 appeared to provide the most benefit relative to the costs. However, the model results also indicated that there is a potential for re-sedimentation and re-blocking of the west channel in the future. Accurate quantitative estimates of quantities such as the re-sedimentation rate and the required frequency of maintenance dredging were not calculated during this study.

The specific conclusions of the study are as follows:

- Cottonwood Island is partially or completely inundated by the 10-yr and 25-yr flood flow. Under average- and low-flow conditions, the west channel remained dry. The 1-yr, 2-yr, and 5-yr flood flows were shown to inundate the west channel.

- The model simulation for the existing conditions indicated highest sedimentation near the upstream entrance of the west channel.

- Alternative 1 does not significantly alter the hydrodynamics and sedimentation in the Cottonwood Island study area.

- Alternative 3 provides the most benefits in terms of restoration cost. It is especially attractive because it does not require a dike setback. It also reduces the sedimentation at the entrance of west channel relative to other alternatives.

- The results indicate that the west channel may be successfully restored in habitat functionality with respect to flow connectivity at low-flow conditions by dredging the channel up to an optimal elevation for juvenile fish habitat, just below the low-water level. However, potential re-deposition may eventually block the opening at the head of the west channel. Based on the simulation results, sediment re-deposition may occur near the west-channel entrance as long as sediments are supplied from upstream. Optimal flow velocity (< 0.3 m/s) for juvenile salmon can be achieved in the restored west channel for most flow conditions. After restoration, additional dredging may be required in case of re-deposition of sediment to maintain off-channel functionality and sustainability. Estimates of the channel sedimentation rates and information regarding the frequency of maintenance dredging after restoration may be obtained through additional modeling and data collection that were beyond the scope of this study.

Acronyms

3-D	three dimensional (2-D = two dimensional)
DEM	Digital Elevation Model
FVCOM	Finite-Volume Coastal Ocean Model
GLO	Government Land Office
HSSC	Highest Suspended Sediment Concentration
LIDAR	Light Detection And Ranging
MLLW	Mean Lower Low Water
MSL	Mean Sea Level
MWL	Mean Water Level
NAVD 88	North American Vertical Datum of 1988
NGVD 29	National Geodetic Vertical Datum of 1929
NOAA	National Oceanic and Atmospheric Administration
PSLC	Puget Sound LIDAR Consortium
RM	River Mile
SRSC	Skagit River System Cooperative
SWC	Skagit Watershed Council
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
UW	University of Washington
WDFW	Washington Department of Fish and Wild Life

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1.0 Introduction

1.1 Background

The Cottonwood Island restoration site is located where the North and the South Forks of the Skagit River bifurcate approximately 10 river miles (RM) upstream from the mouth of the River (see Figure 1-1). The site is a riverine tidal and floodplain forest zone that is freshwater influenced by tide and is occasionally inundated by flooding events (Miller Consulting et al. 2004). The project site occupies approximately 165 acres, and its edge habitat is mostly classified as natural bank with approximately 1,275 ft of interspersed bar habitat. The light detection and ranging (LIDAR) survey shows that the elevation of this island varies in the range of 10 to 20 ft relative to mean water level (MWL), and several off-channel distributaries exist. Historically, the Skagit River meandered around the west side of Cottonwood Island. However, following dike construction activities in 1889, which also moved the levee to the current alignment, the flow upstream of Cottonwood Island was constrained. A complex cut-off channel then developed to form the present river. Consequently, the old west channel became blocked and filled in because of sedimentation at the head of the channel and presently does not allow flow to pass through during low-river-flow conditions.

Restoration concepts proposed for the Cottonwood Island site are based on the results of the *Big Bend Feasibility Study* (Miller Consulting et al. 2004). The study recommended several potential restoration actions, such as setback of the dike at certain locations and/or other physical modifications in this reach of the Skagit River adjacent to Cottonwood Island. The study classified the restoration potential at Cottonwood Island as "high" in terms of providing habitat and fish benefit as well as ease of implementation with respect to ownership. Restoration actions at this site would provide benefits such as fish access to off-channel habitat used for migration as well as juvenile refuge and rearing that has been lost or degraded. The accumulation of sandy over-bank deposits at the mouth of the west channel around Cottonwood Island has blocked the flow of water. This has also limited the access for fish migration from the main stem and eliminated rearing opportunities. Reconnecting the off-channel slough to the main stem of the river and maintaining the functioning fish habitat after restoration would be critical to the success of the Cottonwood Restoration Project.

This study is a feasibility assessment to understand the hydrodynamic and sedimentation response to the proposed restoration actions such as channel dredging and dike modifications. The approach is to refine the previous hydrodynamic model of the Skagit River developed for the Rawlins Road Restoration Project (Yang et al. 2006) and conduct a focused application for the Cottonwood Island site to examine the hydrodynamic and sediment transport features in detail.

1.2 Study Objectives

The overall objective of this study is to evaluate whether restoring the Cottonwood Island area by reconnecting the historic west channel is feasible. Several restoration alternatives are under consideration, and it was the objective of this study to estimate the potential for success associated with the proposed habitat-restoration alternatives with respect to hydrodynamic and sediment-transport impacts. To accomplish this objective, the approach adopted was to develop a hydrodynamic model for this tidally influenced and hydrologically complex area to better understand the system. The model results are then

expected to provide information about hydrologic/hydraulic and potential morphological impacts of the proposed restoration actions. Specific objectives of this study are as follows.

- Analyzing the tidal and riverine hydrology, sediment transport, artificial structures influencing the study area, and further development of the hydrodynamic model around the Cottonwood Island region so that key physical processes are captured
- Examining the hydrodynamic and sediment transport processes of the study area for the existing conditions during various flow conditions
- Developing restoration alternatives and applications of the model to assess the hydrodynamic and morphological response of the study area for the proposed restoration alternatives
- Conducting a preliminary analysis of sediment deposition, erosion, and morphological changes that could occur and assess the sustainability of the proposed restoration actions.

The Skagit Bay model was previously calibrated using data collected by the Skagit Watershed Council (SWC) in 2005 (Yang and Khangaonkar 2006) and later validated as part of the McGlinn Causeway Feasibility Study (Yang and Khangaonkar 2007) using data collected by the U.S. Geological Survey (USGS).

The model domain will be modified around the Cottonwood Island area, and more grid points will be added to include the region of interest. The validation exercise as part of this study will simply be a check to verify that model calibration is still valid at the same level of accuracy as before.

1.3 Report Organization

Section 1 provides project background and objectives.

Section 2 summarizes data acquisition and model grid development: Battelle developed the geometry of the study area and set up conveyance properties for the channels using available information. This included existing structures (bridges, levees) provided by SWC, survey transects of river channels from the U.S. Army Corps of Engineers (USACE) and Snohomish County, and bathymetry LIDAR data from the Skagit River System Cooperative (SRSC) and the Puget Sound LIDAR Consortium. This also included the development of the new model grid for the Cottonwood Island area, including the compound channel inside the levee system.

Section 3 describes model setup and validation: The model was set up with the same boundary conditions and forcing used for the SWC Rawlins Road Restoration Project, which corresponds to June 2005, to validate the model. The updated model simulations were compared with velocity, salinity, and tide data collected as part of the SWC Rawlins Road Restoration Project.

Section 4 includes simulation of the existing conditions in Cottonwood Island: Following model validation, the model was applied to simulate the hydraulic and sediment transport responses of the existing conditions for six representative hydrographs (average, 1 yr, 2 yr, 5 yr, 10 yr, 25 yr). The model results, including surface-elevation distribution, velocity distribution, bed-stress distribution, and sedimentation patterns, are presented.

Section 5 provides the results of simulating the restoration scenario in Cottonwood Island: The model was applied to simulate the Cottonwood Island restoration scenarios to assess their feasibility. This

included dike setback and/or channel modifications to the existing bathymetry and geometry of the model grid in the Cottonwood Island area. The model results, such as surface-elevation distributions, velocity distributions, bed-stress distribution, and sedimentation patterns, were analyzed and compared with the existing (baseline) conditions.

Section 6 presents conclusion of this study.

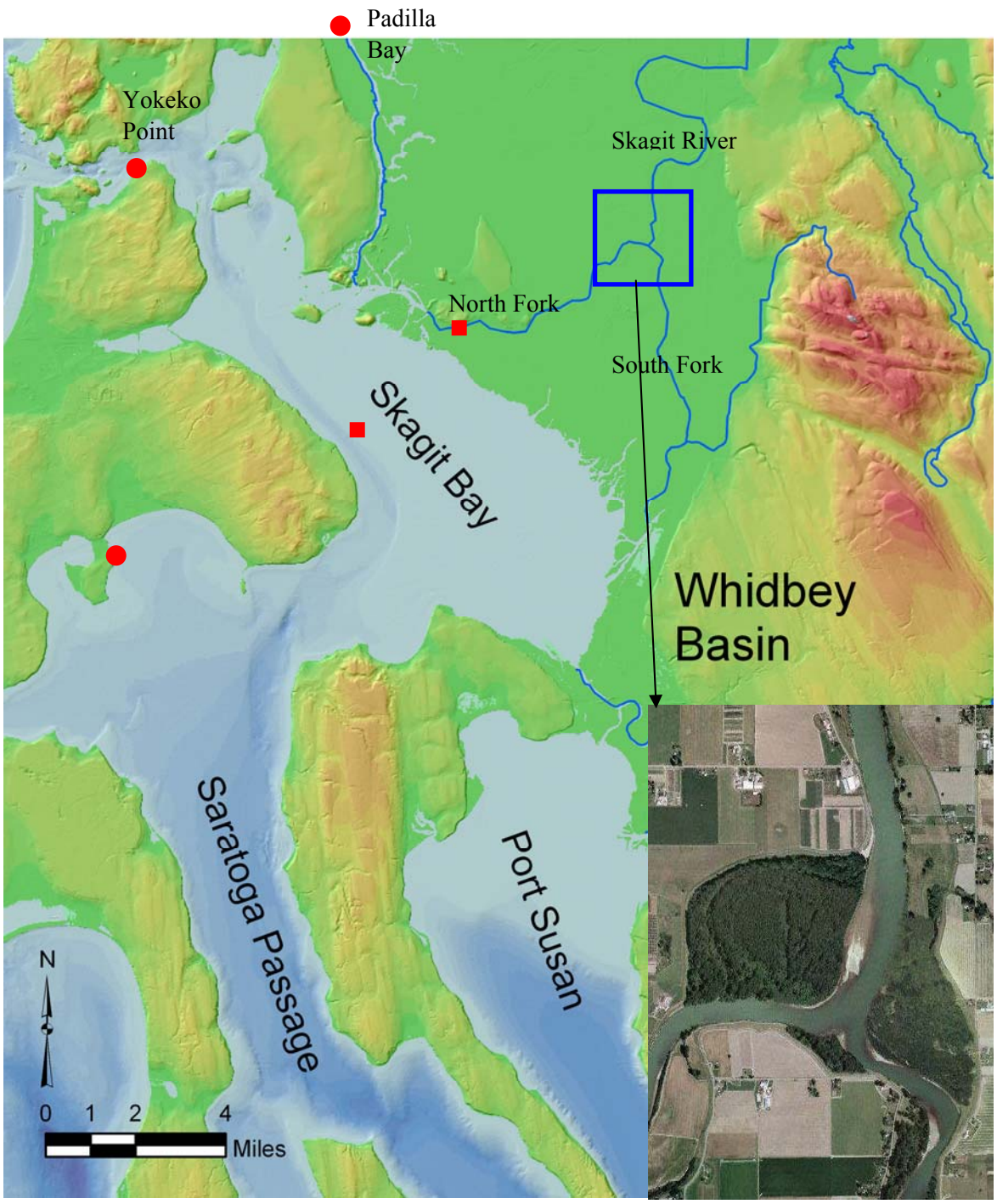

FIGURE 1-1

Location of Cottonwood Island in Whidbey Basin

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2.0 Review of Existing Data and the Skagit Bay Model

In this section, the available existing information and the field-survey data collected previously for SWC as part of the Rawlins Road Restoration study (Yang and Khangaonkar 2006) are reviewed. Also reviewed is the hydrodynamic model developed for Skagit Bay as part of the previous study. The typical data required for hydrodynamic model setup and validation include tides, currents, historical river flow, salinity, temperature, bathymetry, and meteorological information. For the sediment-transport model, the bed sediment depth, the sediment properties, and the sediment loading data are required.

River flow, bathymetry, wind, and tide data were obtained from different agencies. The river flow for the Skagit River was obtained from the USGS gauge at Mount Vernon (12200500). Tidal elevations along the open boundaries, i.e., entrance of Swinomish Channel at Padilla bay, Deception Pass, and the Skagit Bay, were obtained using the tide predications based on National Oceanic Service algorithms (XTIDE). Wind data were obtained from the National Oceanic and Atmospheric Administration (NOAA) National Weather Service site at Paine Field Airport near the city of Everett, WA. Bathymetry data for the Skagit Bay model domain were obtained from the University of Washington's (UW's) Puget Sound Digital Elevation Model (DEM). River cross section data for the Skagit River were obtained from USACE, Seattle District, and Skagit County. LIDAR data for the intertidal zones at the mouth of the Skagit River were obtained from SRSC and the Puget Sound LIDAR Consortium (PSLC). LIDAR data for the Cottonwood Island area were obtained from the SRSC.

Oceanographic data, such as time series of tidal elevation, velocity, and salinity near the study area, are typically of interest in terms of estuarine circulation and transport processes. These data were collected by SWC specifically for model calibration as part of the Rawlins Road Restoration Feasibility Study, which was also used for model validation in this study. Tidal elevation, currents, and salinity time histories were collected at two mooring stations: one on the North Fork of the Skagit River and one near the deep channel of Skagit Bay. These data covered a 2-week summer period from June 7, 2005, to June 22, 2005. No field data were collected at Cottonwood Island for this study, but it is assumed that the existing data are sufficient to validate the model for the purpose of this study.

Sediment data are required to assess sediment transport, erosion, and deposition characteristics as well as a potential for morphological change in the Cottonwood Island area. Sediment transport analysis relies on sediment data, including sediment depth, bottom sediment type and size distribution, bed erodibility, and sediment supply from upstream. The sediment data used in this project were obtained from the previous study reports (Pentec Environmental 2002; Collins 1998) on data collected by the USACE and USGS.

2.1 Study Area

Figure 2-1 shows the Cottonwood Island restoration site owned by the Washington Department of Fish and Wild Life (WDFW) at the bifurcation of the North and South Forks of the Skagit River. The site is a riverine tidal and floodplain forest zone that is influenced by tide, but primarily freshwater, and is periodically inundated by flooding events (SRSC and WDFW 2005). The project site occupies approximately 165 acres, and its edge habitat is mostly classified as a natural bank with approximately 1,275 ft of interspersed bar habitat. The LIDAR survey shows that the elevation of this island is variable

in the range of 10 to 20 ft relative to MWL, and several off-channel distributaries exist. Historically, the Skagit River meandered around the north and west side of Cottonwood Island. This channel is now blocked because of sedimentation at the upstream entrance of the channel and does not allow flow to pass through during low-river-flow conditions. The dimensions of the channel are 4,820 ft in length by 47.5 ft average width. The downstream end of the channels holds standing water near the confluence with the North Fork. Large wood debris (>12 inches) is found throughout the channel at a frequency of 22.8 pieces per mile (Miller Consulting et al. 2004).

Historically, the Cottonwood Island area was an active portion of the Skagit river delta system and has been subject to deposition. Sampled bed sediment indicates that the river channel is mostly composed of sand having a median diameter of 0.6 mm (Pentec Environmental 2002). However, after the construction of a new levee system along the upstream bank in 1889, the flow has been constrained, and the tendency for sediment to deposit has increased. According to a series of Government Land Office (GLO) maps (1894 and 1897) and Corps record, the complex cut-off channel had developed to form the present day river channel after the levee was moved closer to the river by at least 500 feet at the northern most edge of the island. Furthermore, the removing of log jams near the forks may be partly responsible for the channel readjustment (Miller Consulting et al. 2004).

The project site is connected to the Skagit Bay through 10 miles of the Skagit River downstream of the project site. The Skagit Bay is located in the Whidbey Basin of the Puget Sound estuarine system. Skagit Bay connects to the Saratoga Passage west of Camano Island, which then leads to the Puget Sound Main Basin through Possession Sound at the southern end of Whidbey Basin. At the north end of Whidbey Basin, Skagit Bay connects to the Strait of Juan de Fuca through Deception Pass and to the Padilla Bay through Swinomish Channel. The Skagit River is the largest river in the Puget Sound estuarine system. It discharges nearly 39% of the total sediment and more than 20% of the freshwater into Puget Sound (Downing 1983). Fir Island, which is the Skagit Estuary delta region enclosed by dikes, divides the Skagit River into the North Fork and South Fork branches. The North Fork and South Fork carry about two-thirds and one-third of the river flow, respectively (Pickett 1997). A large tidal mudflat area exists at the mouth of the Skagit River estuary, and most of the northeastern region of the bay is above the mean lower low water (MLLW) line. The deepest region in the bay is about 30 m deep near the southern entrance of the bay. A deep channel exists along the Whidbey Island shoreline of Skagit Bay, which extends north towards Deception Pass.

The flow field near the Cottonwood Island area is dominated by river flow but influenced by tide. The episodic flood events are typically most important in terms of transporting, eroding, and depositing sediments. The salinity stratification is likely not as important at this project site. Wind is also not likely to be important, relative to the dominant effects of river flow constrained by channel morphology and levee along the river.

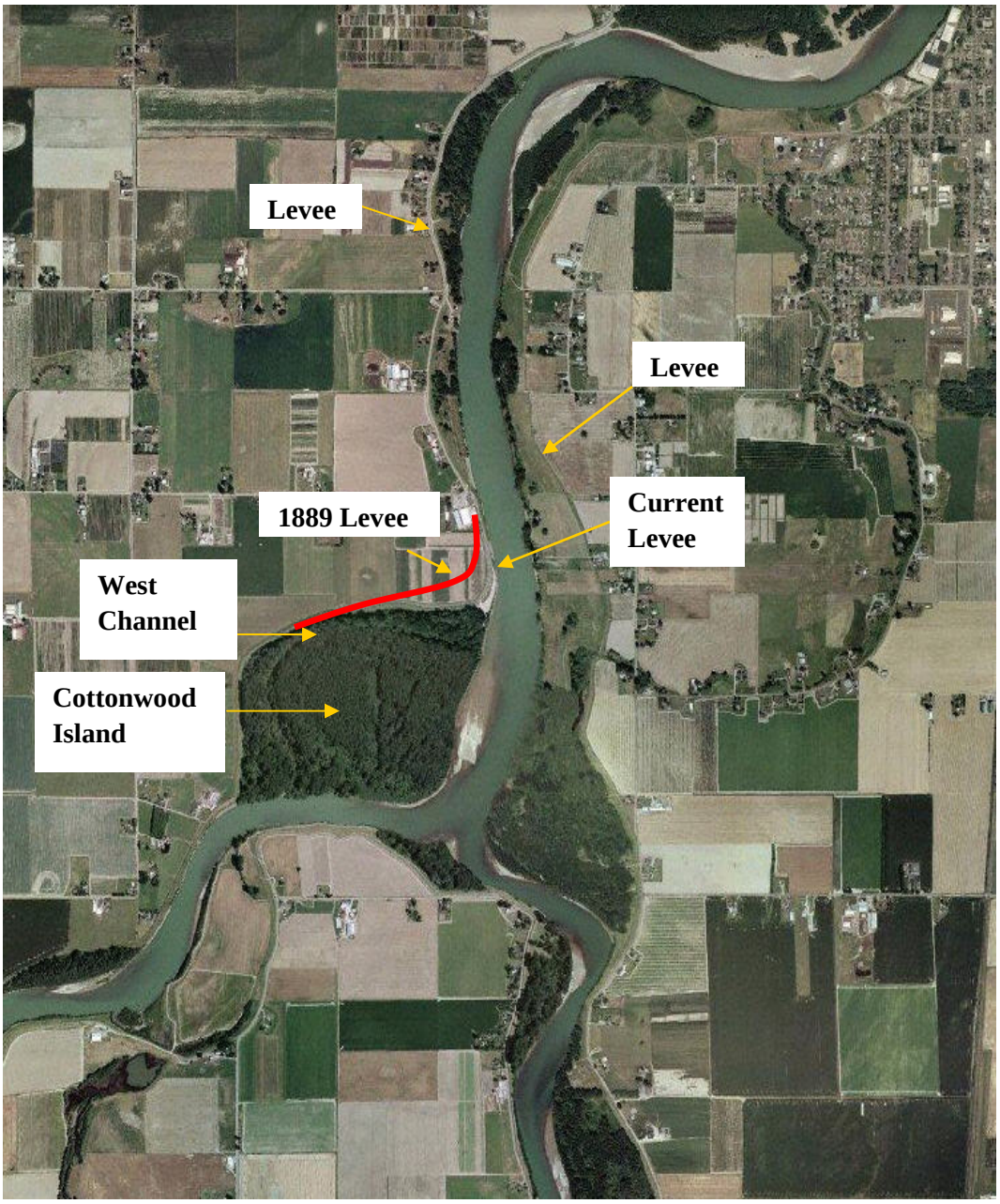

FIGURE 2-1

Study Area of Cottonwood Island

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2.2 Geometric and Hydrodynamic Data

2.2.1 Bathymetry Data

Bathymetry data in the Cottonwood Island and main water body of the Skagit Bay were obtained from the several agencies. The cross-section data in the Skagit River from USACE and Skagit County were used to define the bathymetry in the Skagit River sections of the model (USACE 2004). Cross-section data were National Geodetic Vertical Datum (NGVD) 29 and were converted to Mean Sea Level (MSL) by subtracting 0.21 m (NGVD29=MSL-0.68 ft). Channel cross-section data were linearly interpolated to construct the bathymetry of the refined grid of the model at the project site. The LIDAR data in the Cottonwood Island area and in mudflat regions near the mouth of the Skagit River were obtained from SRSC, PSLC, and USGS. UW Puget Sound DEM data were used to define the main water body of Skagit Bay. The data have 30-ft by 30-ft spatial resolution. The UW DEM data were referenced to National American Vertical Datum (NAVD) 88. In the study area, the MSL is about 1.33 m above the NAVD 88 datum, and the corresponding MLLW level is about 0.50 m below the NAVD 88 datum. All bathymetry data used in the model were converted to MSL datum before being used in the model development. Detailed descriptions of bathymetry data for Skagit Bay can be found in previous Battelle study reports (Yang et al. 2006; Yang and Khangaonkar 2006).

Due to the lack of cross-section data in the main channel around Cottonwood Island, the bathymetry information combined with LIDAR data were linearly interpolated and locally adjusted by professional judgment based on the available information, such as aerial photos and cross-section profiles. Figure 2-2 shows the UW DEM, SRSC LIDAR topography, and cross-section data in the Skagit Bay and Cottonwood Island area. The SRSC LIDAR data have a resolution of 6 ft by 6 ft, providing detailed topography of the project site, including the over-bank elevation inside the levee system.

2.2.2 River-Inflow Data

The Skagit River delivers freshwater to Skagit Bay through the North Fork and South Fork branches. The major contributions of the river flow are rain storms and snow-melt runoff during the spring. Major flood flows in the Skagit River occur during winter storms moving eastward across the basin with heavy precipitation and also during periods with warm snow-melting temperatures. Historical flow data indicate that the peak flow has been significantly reduced after dams were constructed (1920~late 1950). The record of historic peak flood flow was about 500,000 cfs in 1815 (estimate in USGS peak flood flow data file). However, the highest flood flow after the construction of dams was 166,000 cfs, which occurred in October 2003 (USACE 2004).

Two different sets of river inflow data were used for upstream river-boundary conditions. One flow data set corresponds to flow during the field-data-collection period of 2005. This was used to validate the hydrodynamic model. Higher flood flows were used to evaluate sediment transport processes at the project site. The Skagit River flows were obtained from the USGS gauge 12200500 at Mount Vernon, Washington, at RM 15.7. Figure 2-3 shows the hydrograph of the Skagit River for the period from June 6 to 24, 2005 that was used for model validation. The previous Skagit Bay model (Yang and Khangaonkar 2006) also used these flow data, corresponding to field-data collection efforts. No high-flow event was observed, and the average river flow during this period was about 11,000 cfs. Daily variations in the river flow are evident during normal flow conditions because of the daily peaking-mode operation of the Skagit Hydropower Project owned and operated by Seattle City Light.

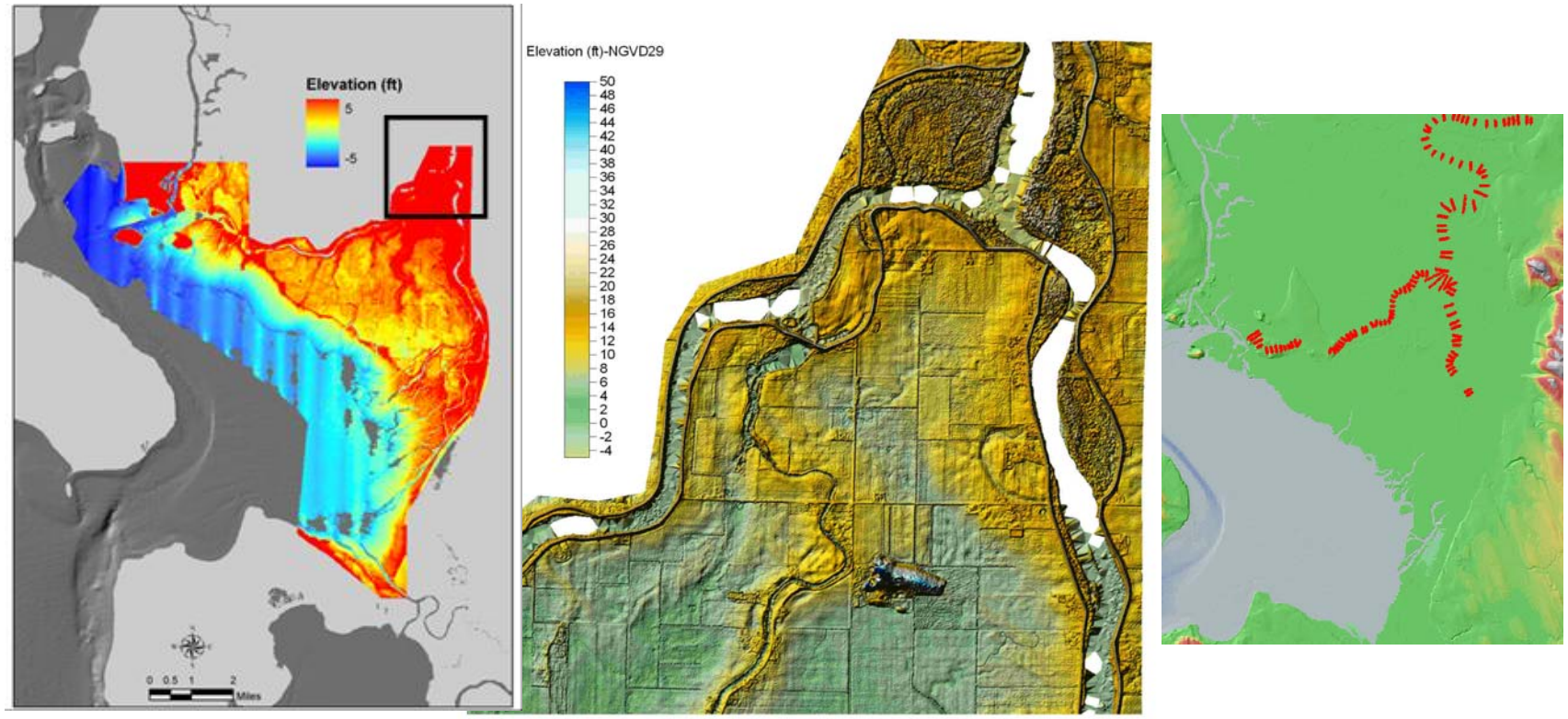
Figure 2-4 shows the six historical hydrographs representing the average, 1-yr, 2-yr, 5-yr, 10-yr, and 25-yr episodic flow events used for the model application to sediment transport analysis. In evaluating sediment transport in the river, it is generally understood that flood events carry most of the sediments and affect channel morphology. The historical daily river flow data during the period of 1900~2003 were analyzed to select the actual hydrograph corresponding to selected design peak flows. Peak flows were estimated using information in the USACE Skagit River Flood Damage Reduction Feasibility Study (USACE 2004). The base flow of each hydrograph was set to average flow conditions to remove the effects of different base flow conditions. Flood events greater than 25-yr recurrence are not considered because the flows greater than 25-yr flows overtop the levee constructed downstream of Mount Vernon. It is beyond the scope of this study to analyze extreme flows and the full Skagit River flood plain.

2.2.3 Wind Data

Wind data are required to correctly simulate the motion induced by wind stress at the water surface. Wind data were obtained from the NOAA's National Weather Service site at the Everett/Paine Field Station about 30 miles south of the study area. Figure 2-5 shows a windstick plot for Paine Field wind data for June 2005. The average wind speed during the period of interest was about 4.5 m/s. The dominant wind direction is towards the southwest.

2.2.4 Tide Data

Skagit Bay is influenced by tides, predominantly propagating from Possession Sound south of the study area to the open boundaries at Skagit Bay. The northern open boundaries include the Swinomish Channel, which connects to Padilla Bay and Deception Pass, which connect to the Strait of Juan de Fuca. Tidal elevations along these open boundaries are needed such that the open boundary conditions for simulating tidal elevations and currents may be specified. Directly measured tide data near the study area do not exist for the study period. However, predicted tidal elevations were available through the NOAA tide-prediction network for Crescent Harbor, located near the mouth of Skagit Bay, Yokeko Point, near Deception Pass, and Padilla Bay, near the entrance of Swinomish Channel. The predicted tidal elevations were calculated using the XTIDE program based on NOAA's National Oceanic Service tidal prediction algorithms. Figure 2-6 shows predicted tidal elevations at Crescent Harbor, Yokeko Point, and Swinomish Channel for the period of June 6 to 24, 2005. Tidal elevations at the Crescent Harbor and Yokeko Point stations are very similar, except that the tidal range in Yokeko Point is slightly reduced. The tidal range in the Swinomish Channel is further reduced compared to Yokeko Point. Figure 2-6 shows clear spring-neap tidal signatures and large diurnal inequalities in all the four stations.



Note:

- Source: UW DEM, SRSC, ACE, and Skagit County

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FIGURE 2-2
LIDAR Bathymetry and River Cross-Section Data in Cottonwood Island Area

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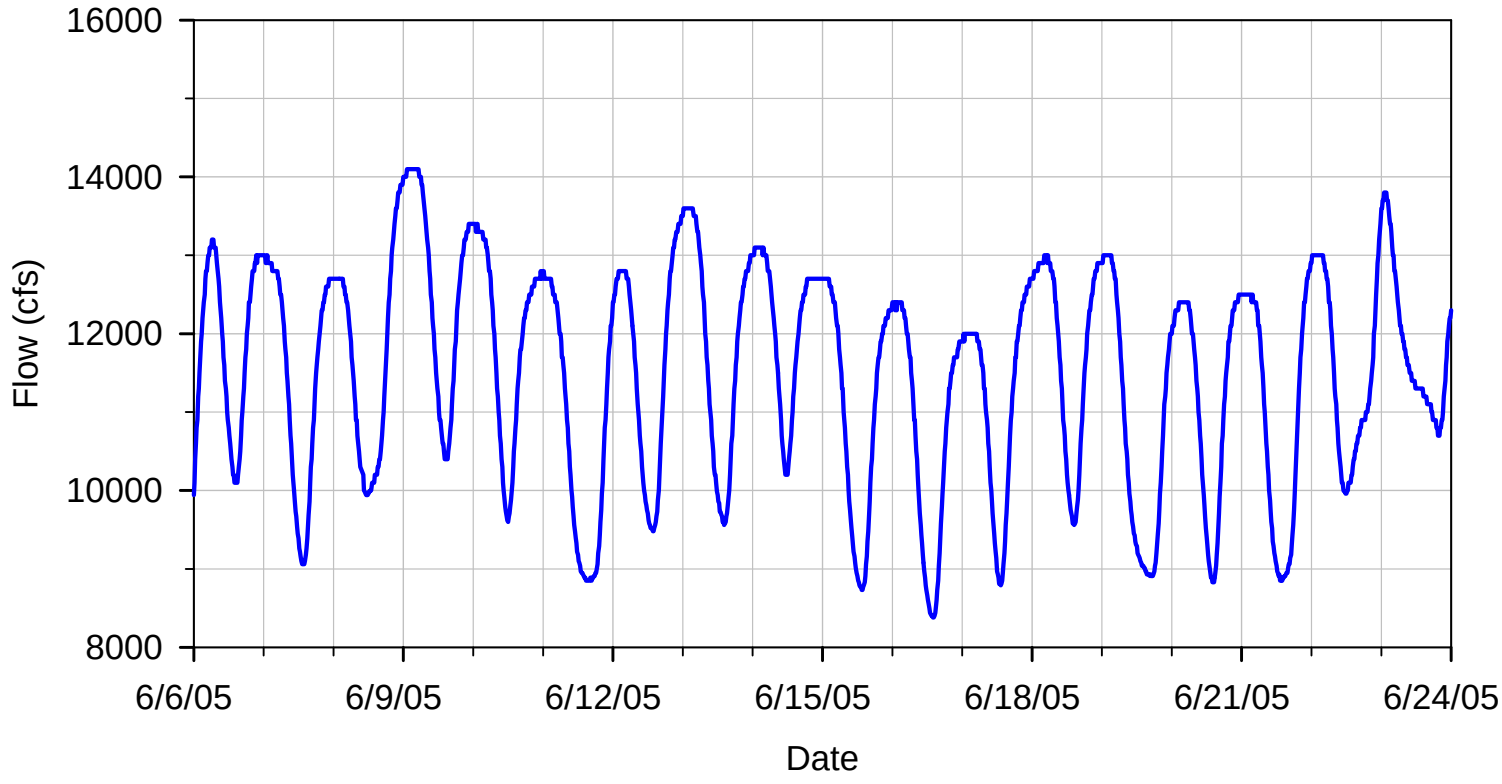

Note:

- USGS Gauge 12200500
- Time is in Pacific time zone
- 1 cfs=0.02832 m^3/s

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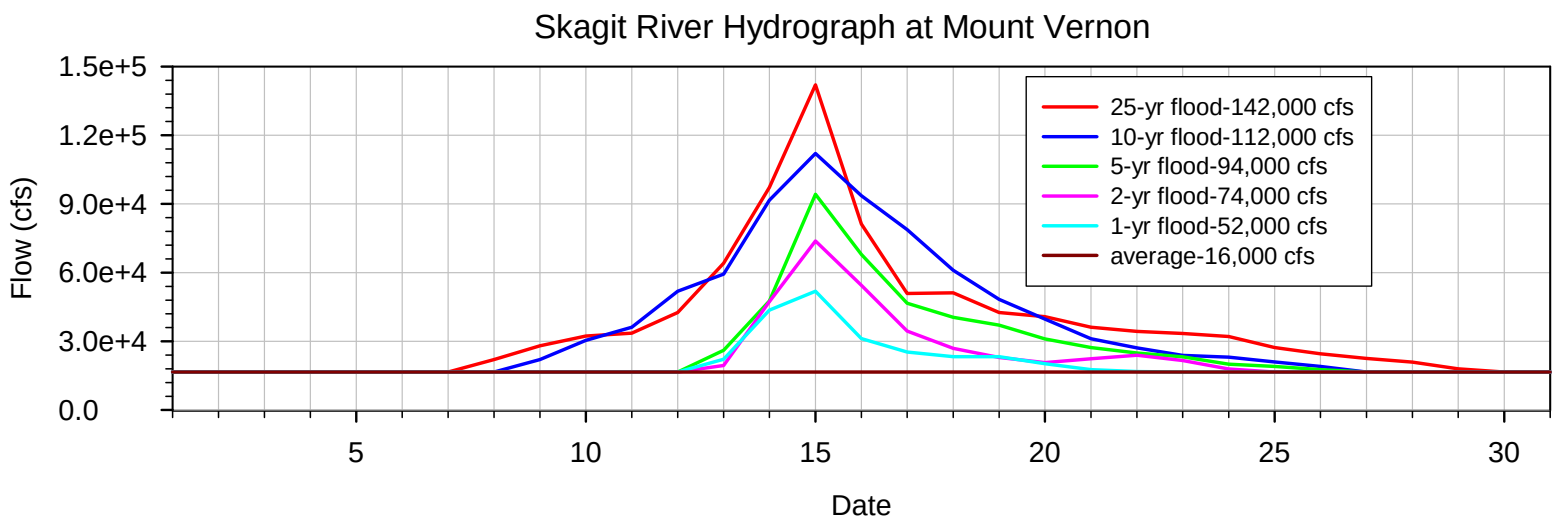
FIGURE 2-3

Skagit River Flow at Mount Vernon

Skagit Watershed Council
Mount Vernon, WA



Note:

- USGS gauge station 12200500
- 1 cfs=0.02832 m^3/s

FIGURE 2-4

Hydrographs of Six Flood Events at Mount Vernon

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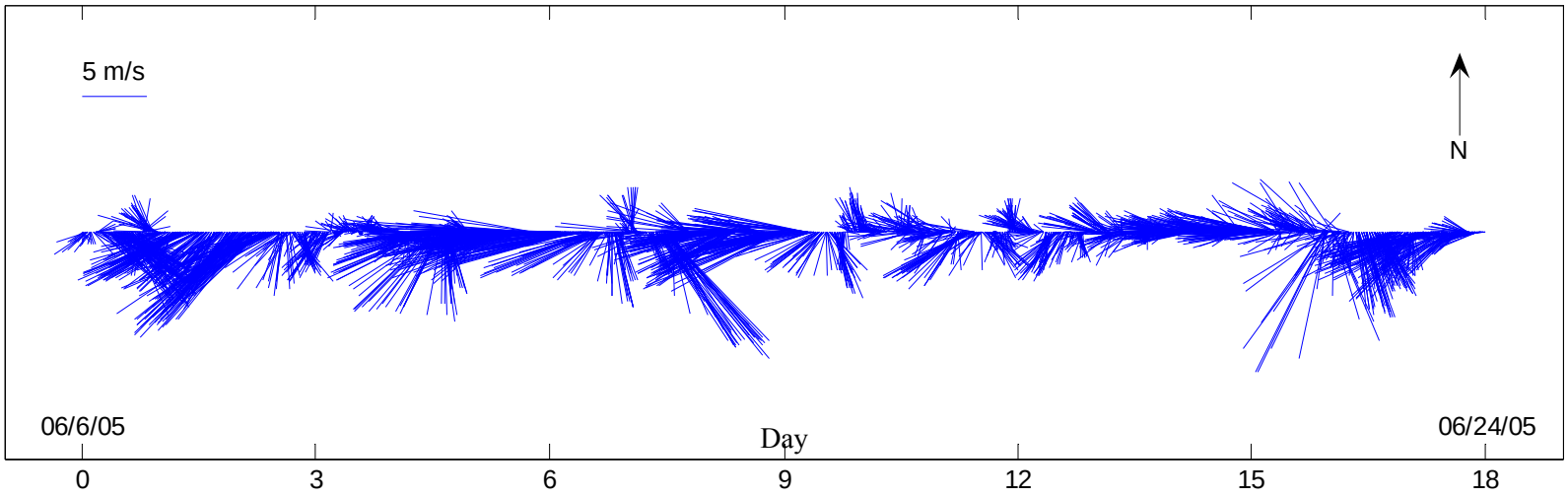

Note:

- Wind-Direction Convention: Measured from North in Clockwise. 0 is South to North, 90 is West to East.
- Source: National Weather Service
- 1 m/s =2.2 mph

FIGURE 2-5

Wind Stick Distribution at Paine Field

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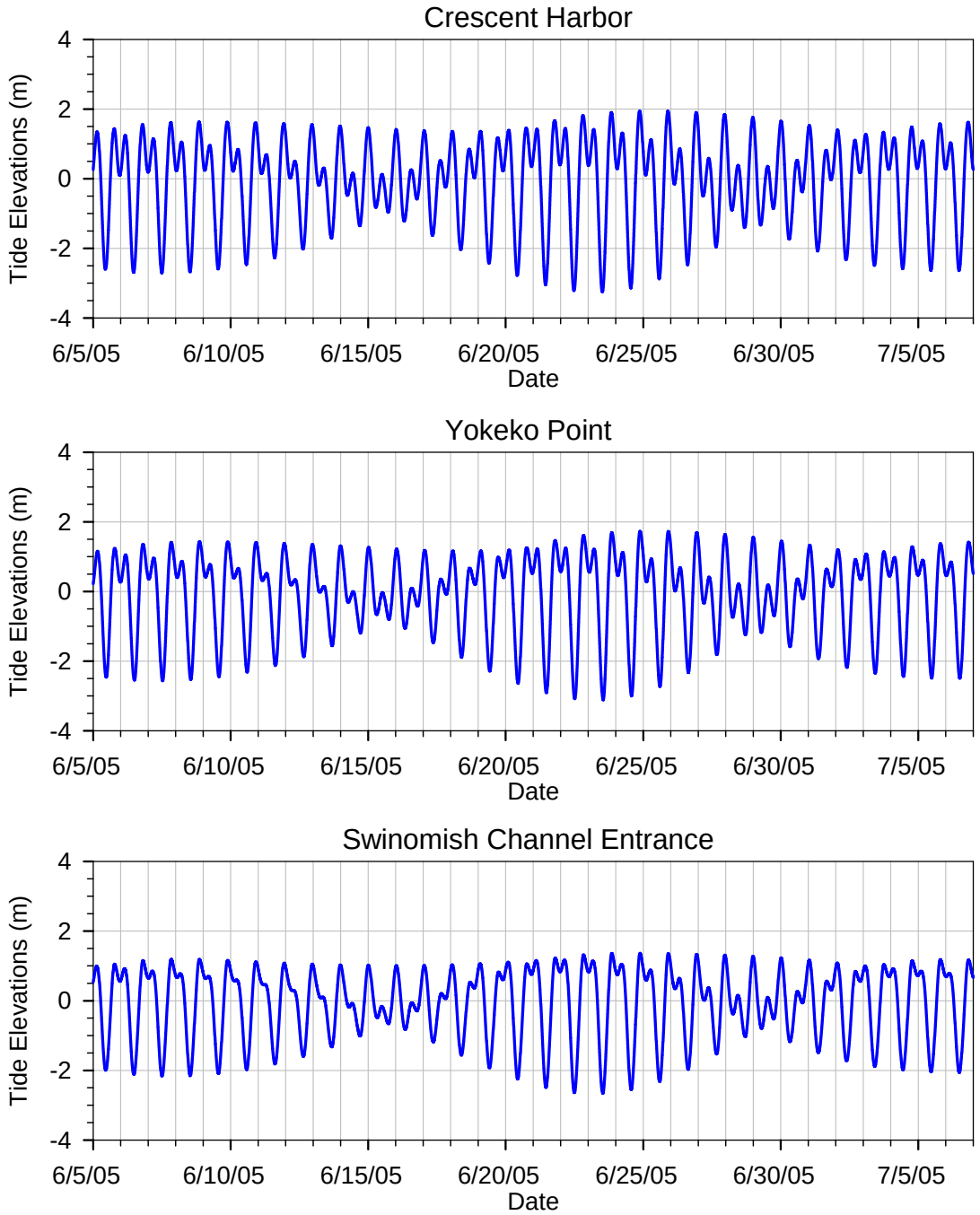

Note:

- Times are in Pacific time zone
- 1 m =3.281 ft

FIGURE 2-6
Predicted Tide at Open Boundaries

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2.3 Historical Map and Aerial Photos

Historical maps and Aerial photos of the project site were reviewed. This information is very useful for understanding the morphological evolution of the project site after the current alignment of the levee system constructed between 1894 and 1897. The 1894 GLO map indicates that the west channel at the Cottonwood Island had been a main stem river channel with a sharply meandering bend. A subsequent 1897 map (Secretary of War 1911) in Figure 2-7 shows the development of the complex cut-off channel. The 1889 levee footprint implied that the levee had been moved closer to the bank by at least 500 ft. This levee movement is believed to have caused the river to abandon the west channel as shown in the subsequent aerial photos. The 1937 aerial photo shows that the abandoned West Channel was filled with deposited sediments, but it had not been blocked by sand deposits at the upstream entrance. Also, the 1937 aerial photo shows that the west channel was wider than the current state without vegetation. The subsequent aerial photos imply that the off-channel entrance was blocked by sedimentation after 1937. The comparison of 1998 and 2006 aerial photos shows no significant change in terms of channel morphology. This may be attributed to the stabilization of the river bank by vegetation and the establishment of a dynamic equilibrium in sediment transport. The blockage of the off-channel entrance is a major concern in assessing restoration feasibility because it could occur again after the restoration actions, which include channel dredging and modification.

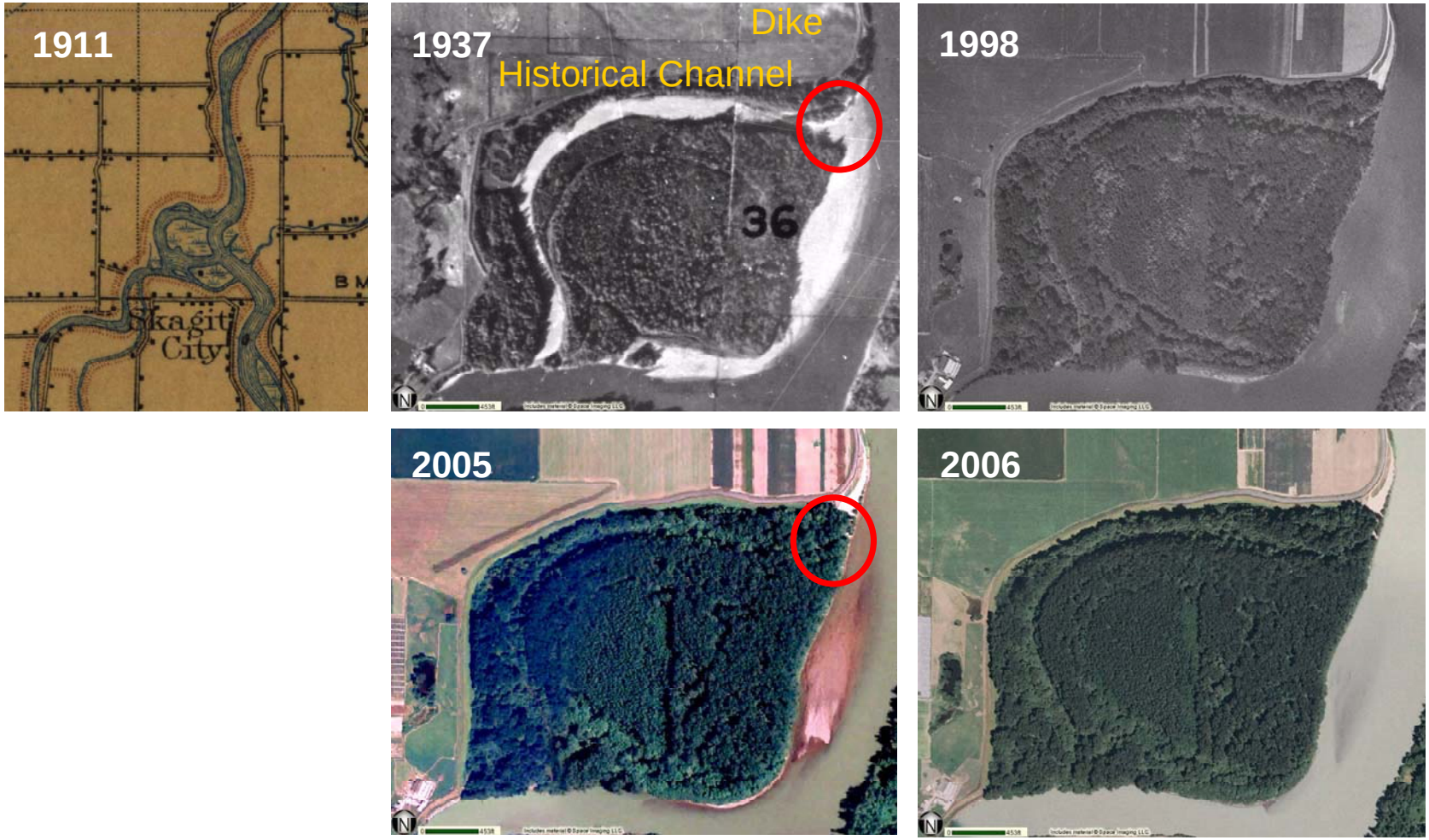

FIGURE 2-7
Historical Map and Aerial Photos of Cottonwood Island

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2.4 Sediment Data

2.4.1 Initial Bed Condition

The characterization of bed and suspended sediment in the study area is important to accurately simulate sediment transport, which is used to determine erosion and the deposition rate between the bed and the water column. The initial bed conditions include sediment depth, sediment type, particle-size distribution, and sediment erodibility. Those data were obtained from a USACE Flood Hazard Mitigation Study (Pentec Environmental 2002). The study report contains the extensive sediment data collected in the Skagit River. The bed sample materials were collected at the locations shown in Figure 2-8. Recent surveys of river profiles were also available as shown in Figure 2-9. The 1999 and 1975 surveys performed by West Consultants (2001) indicate that a significant aggradation has occurred throughout the North Fork reach (Reach 1). The river bottom elevation at thalweg rose over 3 m (10 ft) around RM 6.2 as a result of sedimentation. The average sedimentation was about 1.06 m (3.5 ft) in the North Fork. In the South Fork (Reach 2), they found that the river bed profile remained mostly unchanged during the period except for some aggradation around RM 7. The averaged aggradation over the reach was 0.076 m (0.25 ft). In the upstream reach (Reach 3) of Cottonwood Island, the river-bed profile shows the aggradation between RM 10 and RM 12, but no significant change was observed between RM12 and RM15. The average aggradation was about 0.61 m (2 ft). The sediment type in the forks and the upstream reach was primarily medium to coarse sand (see Figure 2-10). The mean sediment diameters in the North and South Forks were 0.46 and 0.6 mm, respectively. The mean diameter in the Cottonwood Island region and the upstream reach was 0.6 mm.

The initial bed condition for the sediment transport model was set up using these data, assuming that the baseline sediment depth is the 1999 deposition depth relative to 1975 river profile. Based on the data set, the initial sediment depth was set to the averaged aggradation value in each reach, which were 1.06 m (3.5 ft), 0.076 m (0.25 ft), and 0.61 m (2 ft). For the purpose of this study, focusing on the initial response of the sediment bed in the Cottonwood Island area after restoration, the use of averaged sediment depth in each reach was considered reasonable. A single sediment class size of 0.6 mm was set in the model as the size corresponding to the dominant sediment class in the Skagit River in the study area and upstream reach.

2.4.2 Upstream Sediment Loading Condition

The suspended sediment rating curve was estimated from the USGS data measured during 1980~1991 at Mount Vernon (see Figure 2-11). Bed-load data were not included in the measurement. USGS data was scattered particularly in high discharge regimes greater than 20,000 cfs. The following polynomial fit was developed.

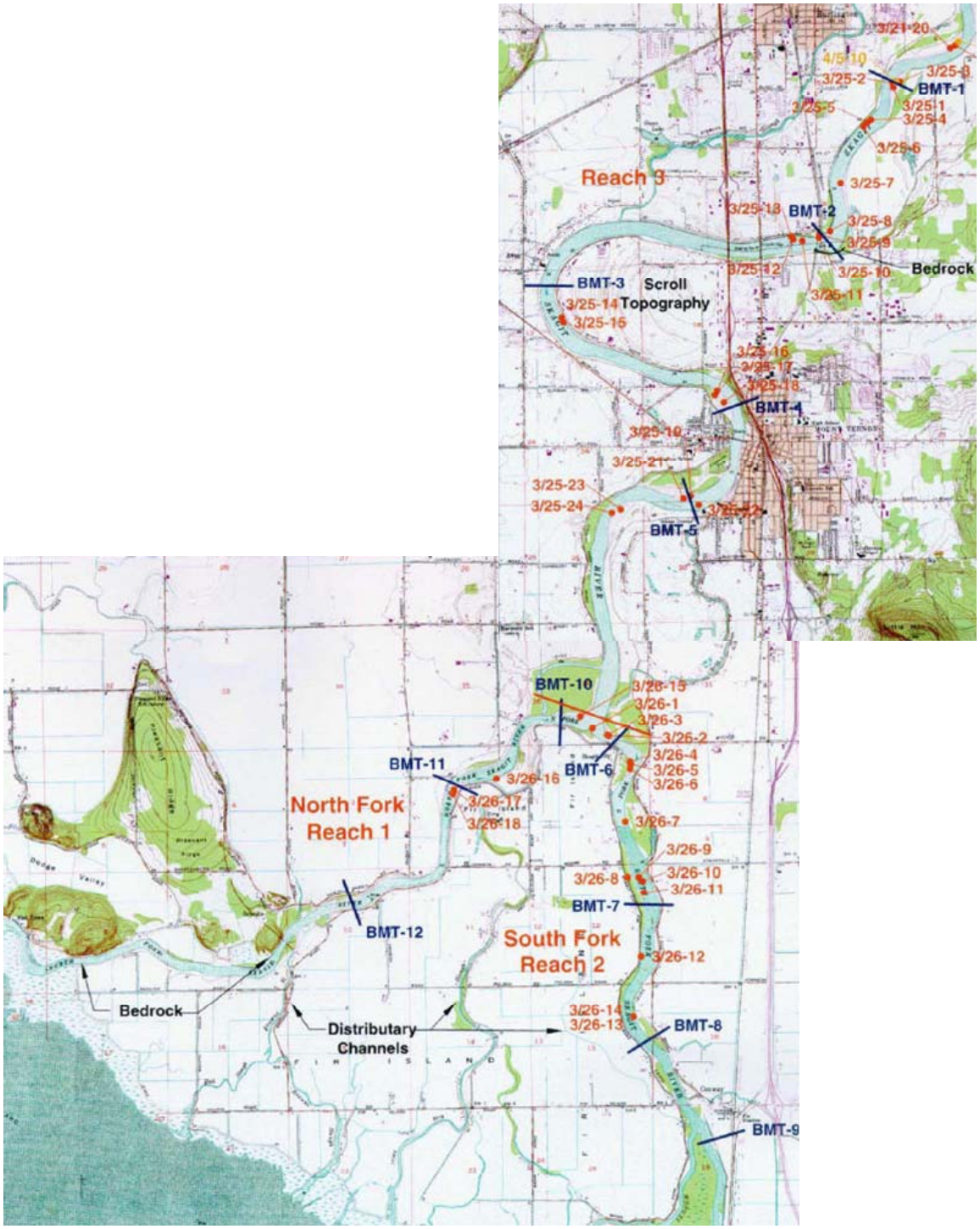
$$Q_s = 3\times10^{-6}Q_w^{2.1332} \quad , R^2=0.6343 \tag{2.1}$$

where Q_s is the sediment discharge in tons/day, and Q_w is the river flow in cfs (Miller et al. 2004). The boundary conditions for upstream sediment loading for six hydrographs (average, 1-yr, 2-yr, 5-yr, 10-yr, 25-yr recurrence) were estimated using the above relationship as shown in Figure 2-11. The sediment discharge rate for average flow is 3×10^3 tons/day, and the peak discharge rate for 25-yr flood flow is close to 3×10^5 tons/day

The seasonal variation in river flow will significantly impact the sediment delivery. A large portion of the annual sediment load is carried by episodic flood events during a small percentage of the year. For medium sand typical in the study area, a higher flow carries more sediment in suspended mode rather than bed-load. Therefore, the bed-load mode was not considered in this modeling study, which focuses more on evaluating the initial response of the sediment bed and suspended sediment transport, deposition, and erosion.

2.4.3 Critical Shear Stress and Settling Velocity

The critical shear stress (τ_c) for the erosion of mean sand particles (0.6 mm) was calculated from the *Shields* diagram (Shields 1936). The critical shear stress is a threshold-bed shear stress for the incipient motion of sediment particles. For turbulent flow over a rough bed, the critical shear stress becomes linearly proportional to the sediment size. The calculated value for a mean sand particle is 0.3 Pa. The amount of eroded sediment is proportional to the bed shear stress when the bed shear stress exceeds the threshold value. The settling velocity data are required in the model setup to calculate the settling flux in the water column and at the boundary between the water column and the bed. The settling velocity of a mean sand particle is 5 cm/s in quiescent water, calculated by Stoke's law (Julien 1998).



Note: The figure was obtained from the study report by Pentec Environmental (2002).

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FIGURE 2-8

Sediment Sampling Locations

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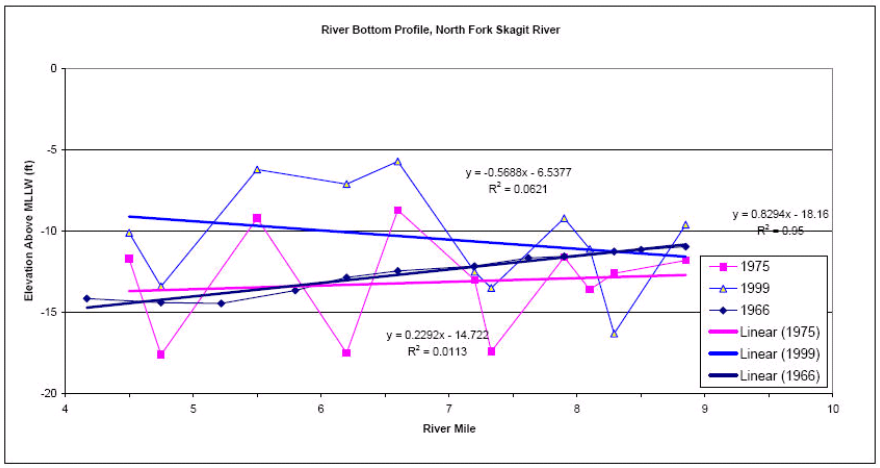
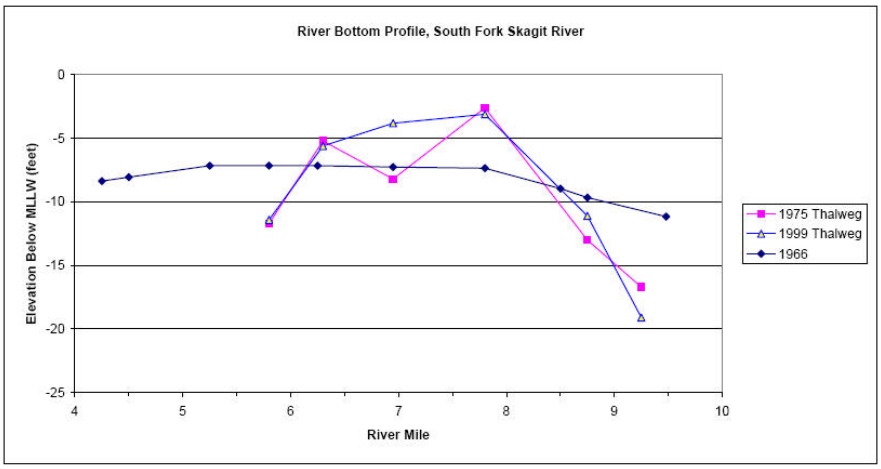
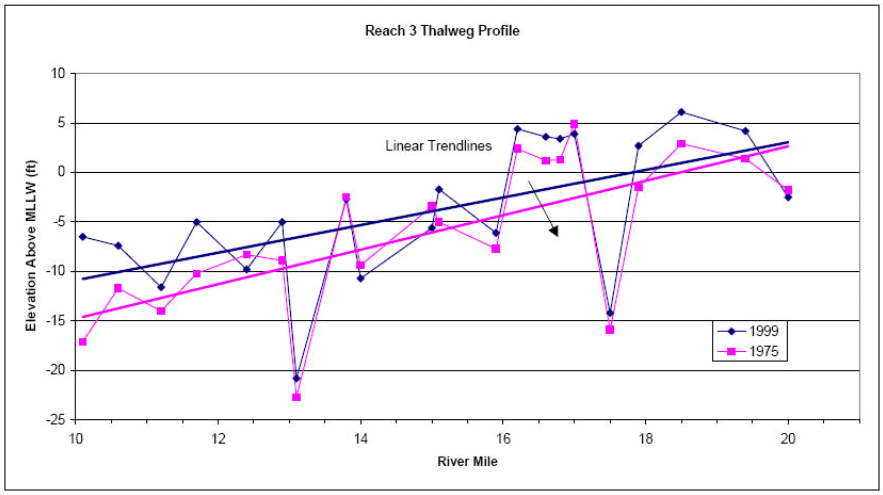
Mount Vernon, WA







Note: The plots were obtained from the study report by Pentec Environmental (2002).

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FIGURE 2-9
River Bottom Profiles at North Fork, South Fork, and Upstream Reach of Cottonwood Island.

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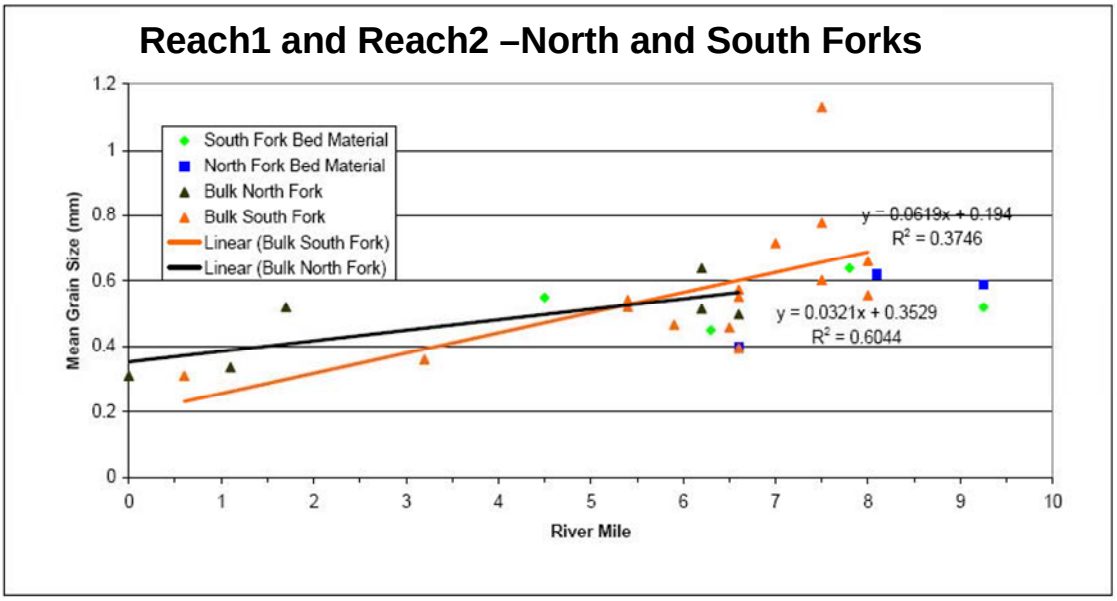
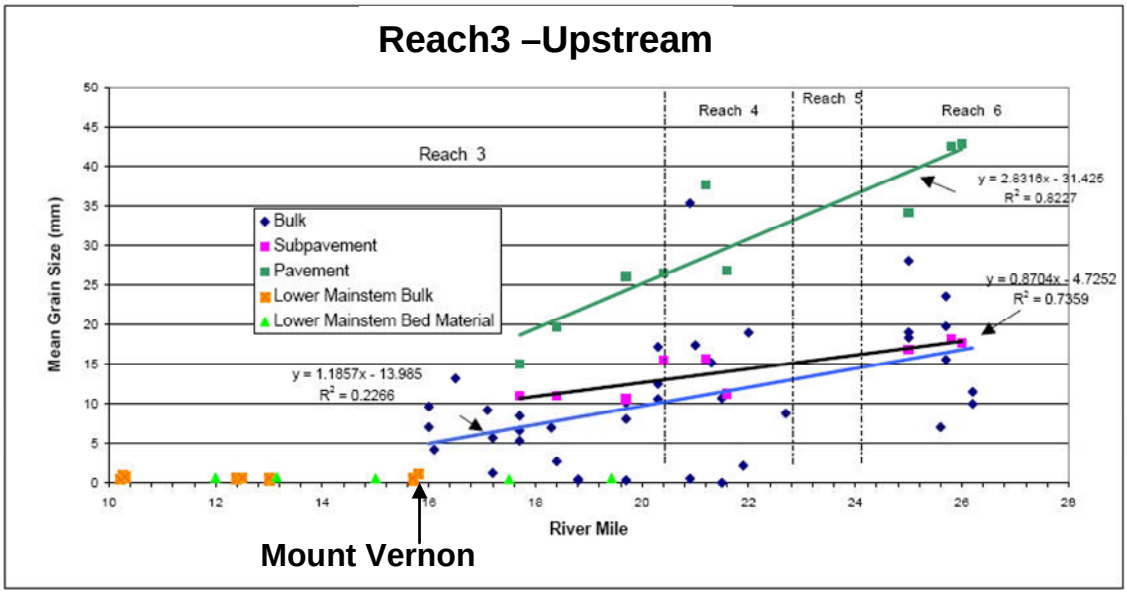
Mount Vernon, WA





Note: The plots were obtained from the study report by Pentec Environmental (2002).

FIGURE 2-10
Mean Sediment Diameter at North Fork, South Fork, and Upstream of Cottonwood Island

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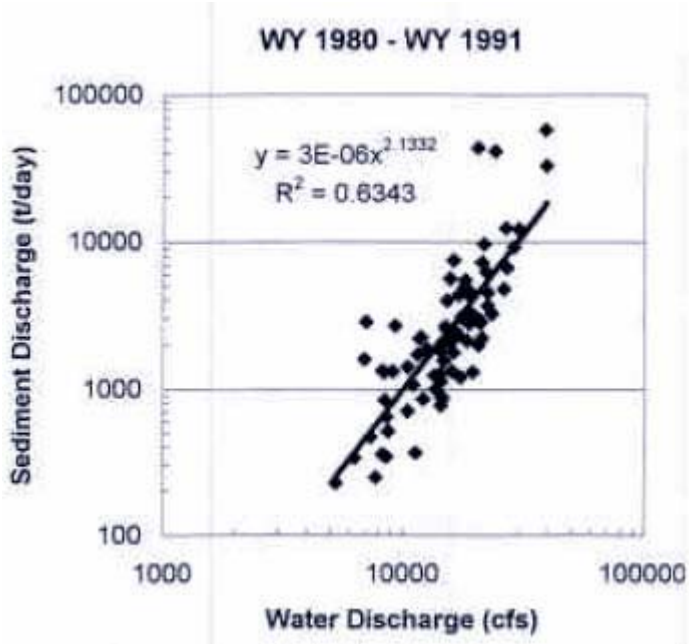

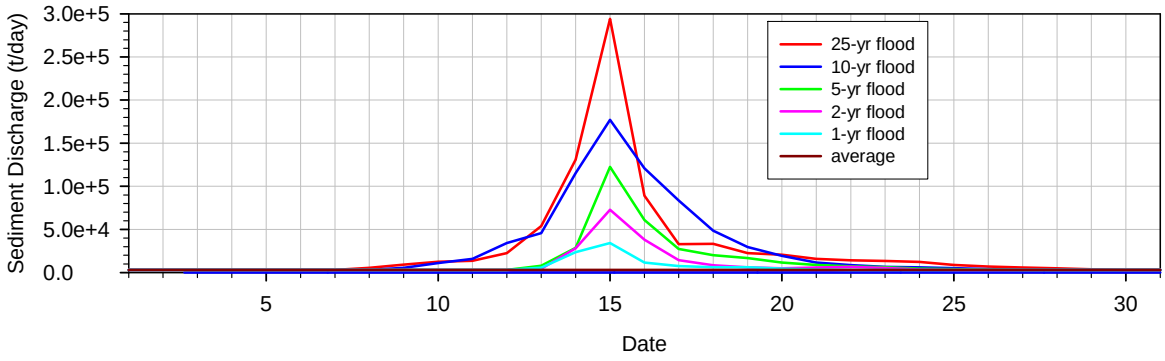

Note: USGS measurement was made during 1980~1991 (Miller et al. 2004).

FIGURE 2-11
USGS Suspended Sediment Rating Curve and calculated sediment loading at Mount Vernon

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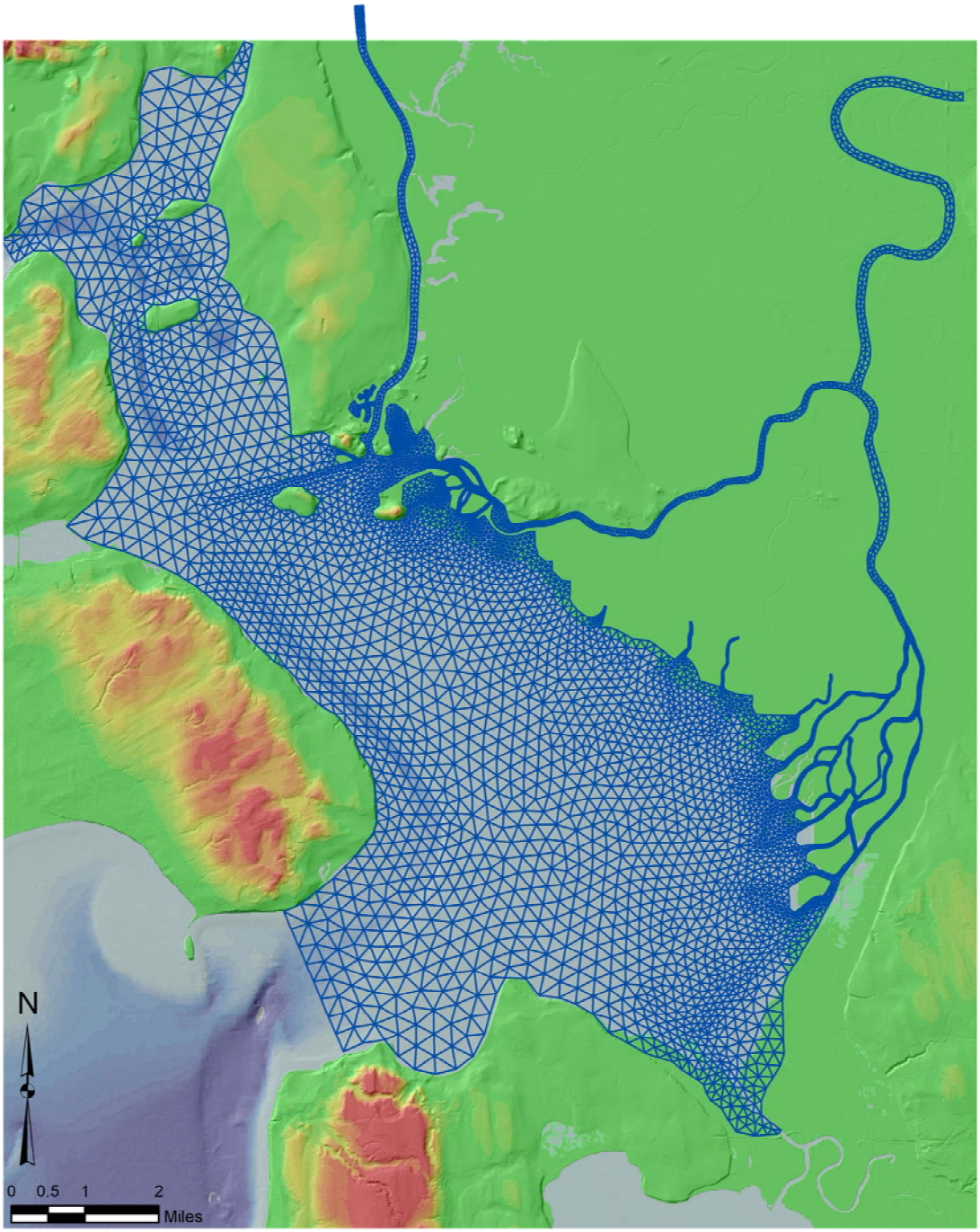
2.5 Review of Existing Skagit Bay Hydrodynamic Model

The Skagit Bay 3-D hydrodynamic model was initially developed for SWC as part of the Rawlins Road Restoration Feasibility Study (Yang and Khangaonkar 2006). The model used the Finite-Volume Coastal Ocean Model (FVCOM) code developed by Chen et al. (2003). FVCOM solves the 3-D momentum, continuity, temperature, salinity, and density equations in an integral form by computing fluxes between non-overlapping, horizontal, and triangular control volumes. This finite-volume approach combines the advantages of finite-element methods for flexibility in handling complex shorelines and the superior ability of finite difference methods for simple discrete structures and computation efficiency. A sigma-stretched coordinate system was used in the vertical plane to better represent the irregular bathymetry. Unstructured triangular cells were used in the lateral plane. The model employs the Mellor Yamada level 2.5 turbulent closure scheme for vertical mixing and the Smagorinsky scheme for horizontal mixing. The model has been successfully applied to simulate hydrodynamics and transport processes in lakes and estuaries (Zheng et al. 2003; Chen et al. 2004).

The Skagit Bay model domain covers the entire Skagit Bay as shown in Figure 2-12. Model open boundaries consist of the southern open boundary at the mouth of Skagit Bay, the northwestern open boundary at Deception Pass, and the northeastern open boundary at the entrance of Swinomish Channel at Padilla Bay. Because the study area (Rawlins Road) is located in the north corner of Fir Island, and the flow in West Pass of the Stillaguamish River is relatively small, it was approximated as a closed boundary. Tidal elevations predicted using the XTIDE program based on National Oceanic Service algorithms were specified at the open boundary. Salinity profiles along the open boundaries were initially estimated based on historical data in Puget Sound and were further adjusted during model calibration. The upstream end of the model domain extends considerably upstream of the estuary past Cottonwood Island up to RM 15.7. The flow and stage data from the USGS stream gage at the Mt. Vernon Station at RM 15.7 was used to specify the conditions at the upstream model flow boundary. The model consists of 9,122 elements and 5,496 nodes in the horizontal plane. To simulate the tidal-wave propagation and salinity intrusion properly in the multi-channel and tidal mud-flat area, finer grid cells were specified in the North Fork and the South Fork river delta region. At least four node points were specified across the width to represent the river cross-section profiles in the model. The model element size varied from 16 m near the mouth of the estuary to 400 m at the entrance of Skagit Bay. The model grid resolution was gradually reduced away from the estuarine delta to the open boundaries to maintain the computational efficiency of the model.

The Skagit Bay model was calibrated to field data for the period of June 6 to June 23, 2005. These oceanographic data were collected specifically for the hydrodynamic model development of Skagit Bay. Because of the existence of a large tidal mudflat region in the study domain, wetting and drying processes of the inter-tidal zone were simulated in the model. A water depth of 20 cm was used as the dry cell criteria in the model (i.e., when the depth fell below 20 cm, the model assumed that element was dry). The model was calibrated by matching model results to field data by adjusting salinity open-boundary conditions, refining the bathymetry, and adjusting bottom roughness. The model was successfully calibrated to the field data, including time series of water-surface elevation, velocity, and salinity as well as salinity profiles. Details of model calibration can be found in Yang and Khangaonkar (2006).



Note:

- Number of elements = 9,122
- Number of nodes = 5,496
- Number of layers = 10

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FIGURE 2-12

Existing Skagit Bay Model Grid

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Mount Vernon, WA

3.0 Cottonwood Island Hydrodynamic Model Setup and Validation

In this section, the development and validation of the 3-D hydrodynamic model for Cottonwood Island are described in detail. Because the hydrodynamic model for the Skagit Bay domain, including the upstream Skagit River, was available from a previous study, the existing model grid was modified by simply redefining the model domain boundary containing Cottonwood Island, following the levee along the Skagit River, and refining the model grid in the project site. The refined model was validated with salinity and velocity observed during a period of June 7-23 in 2005, using the same boundary conditions and forcing used in the Rawlins Road Restoration Study.

3.1 Model Setup

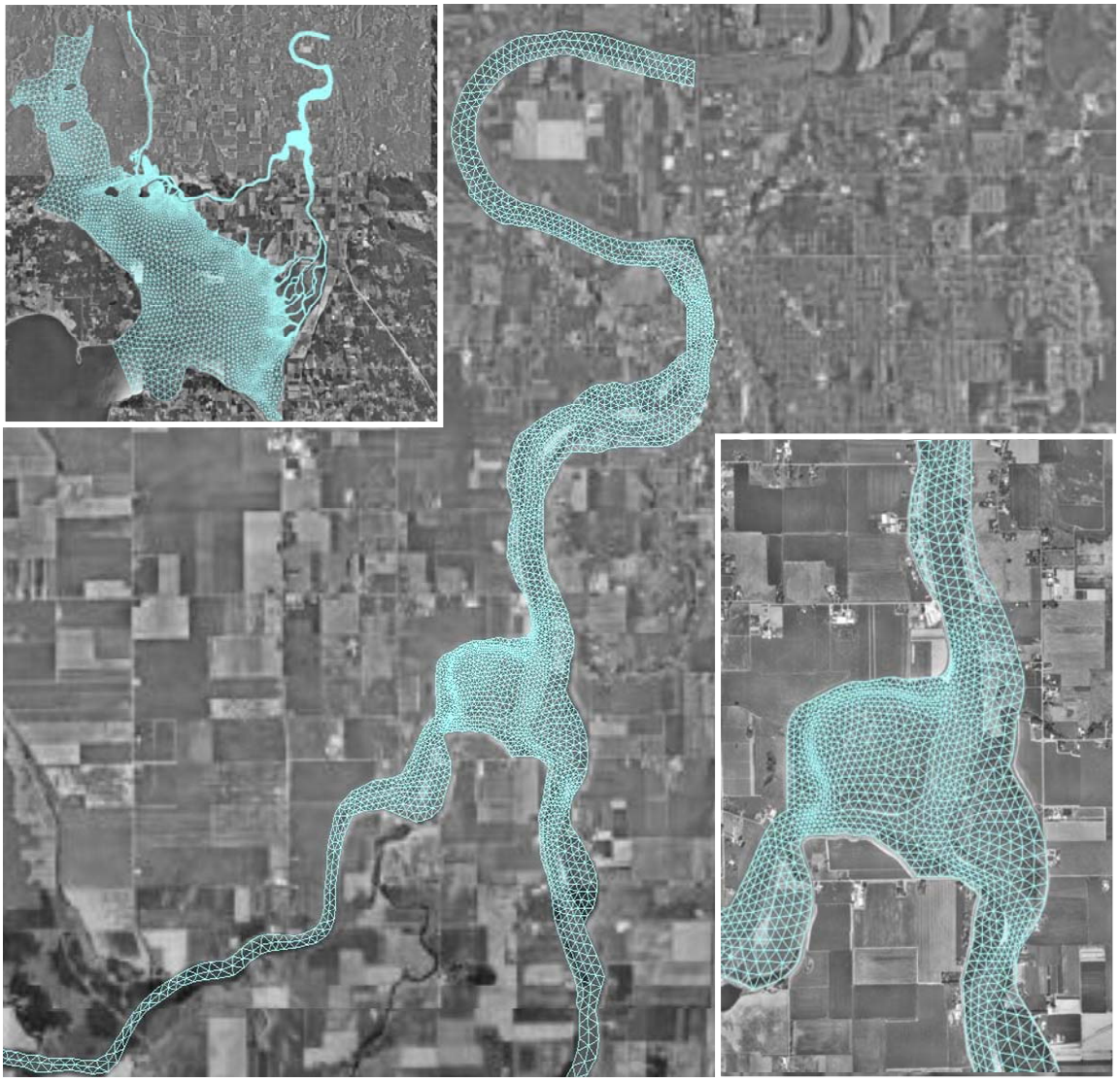
Data required for the hydrodynamic model setup and validation were described in Section 2. The hydrodynamic model setup procedure for Cottonwood Island consists of two steps: 1) construction of model domain along the levee and refinement of the existing unstructured model grid in the study area, and 2) specification of the model boundary conditions and forcing mechanisms. These two procedures are described in detail below.

3.1.1 Model Grid

A large portion of the grid including the Skagit Bay and downstream reaches of the North and South Forks remained unchanged from the existing grid. New land boundary was constructed along the levee in the Skagit River reach near Cottonwood Island. It is expected that a 25-yr flood flow would increase the water surface elevation up to the levee height, immersing the Cottonwood Island and over-bank region inside the levee. To accurately simulate the velocity field and flow inundation in various flow conditions, the model grid was developed such that the main channel and over-bank region were resolved effectively by aligning the grid lines with the boundary. A higher resolution grid was generated for the Cottonwood Island such that the geometry of levees, off-channels, and topography was represented accurately. This was particularly important for the west channel where the primary concern is for fish access after restoration. The model consists of 13,250 elements and 7,741 nodes in the horizontal plane. Five uniform vertical layers were specified in the water column in a sigma-stretched coordinate system. The model was set up in the Universal Transverse Mercator North American Datum 83 (Zone 10) coordinates in the horizontal plane with reference to MSL at Skagit Bay in the elevation. Figure 3-1 shows the final model grid. The minimum grid size is 10 m in the West Channel. The model bathymetry in the Cottonwood Island area was interpolated using both LIDAR data from SRSC and cross-section data from USACE and Skagit County as described in Section 2.3. Figure 3-2 shows the topographic elevation represented in the model.

3.1.2 Model Boundary Conditions

Boundary conditions used in this validation exercise were identical to those used in the calibration corresponding to the June 2005 period, as described in Section 2.6.



Note:

- Number of elements = 13,250
- Number of nodes = 7,741
- Number of layers = 5

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FIGURE 3-1

Model Grid for Cottonwood Island for Existing Conditions, Including Skagit Bay

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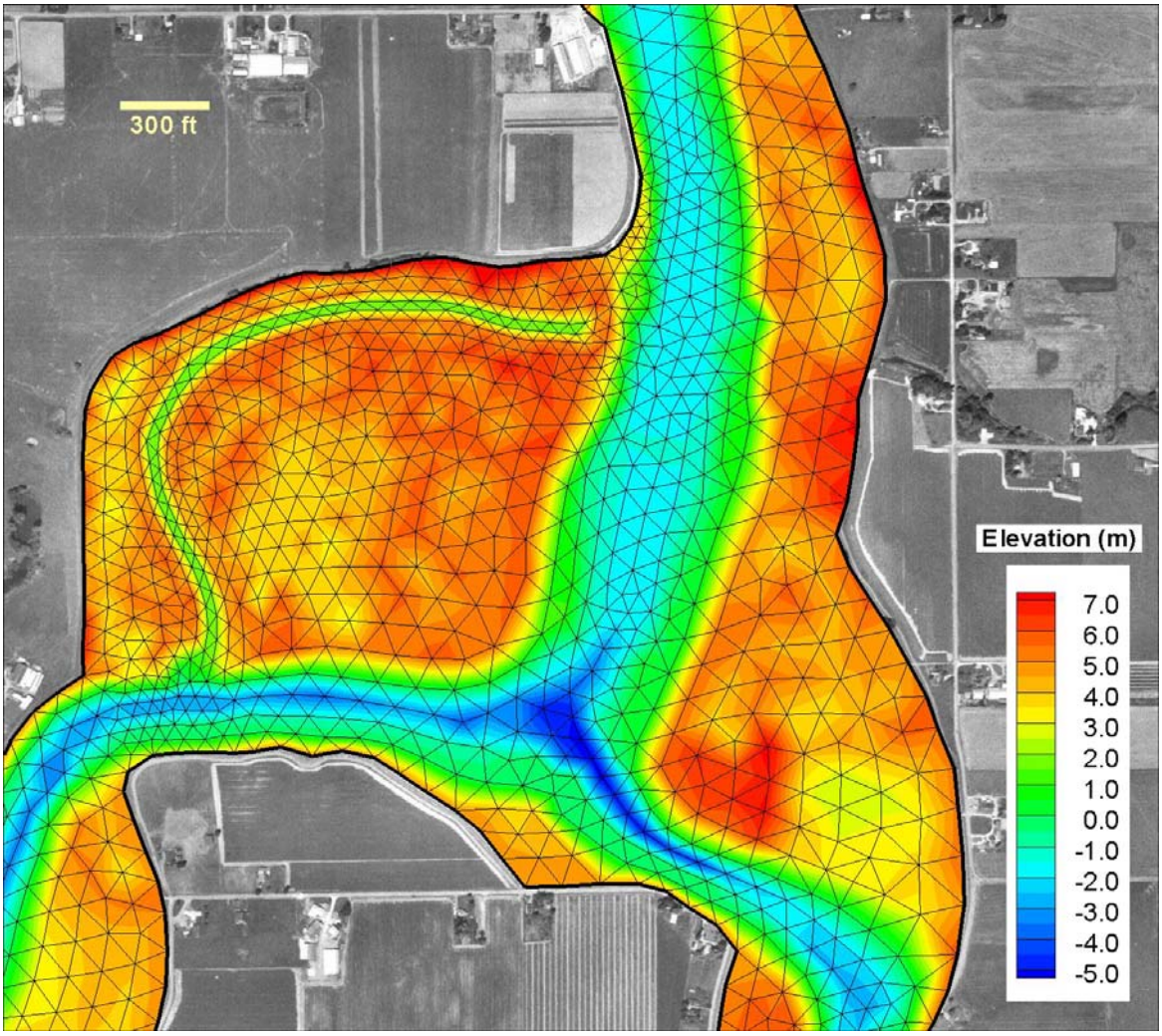
Mount Vernon, WA



Note:

- Elevation datum is MSL.

FIGURE 3-2
Topographic Elevation of Study Area Represented in the Model

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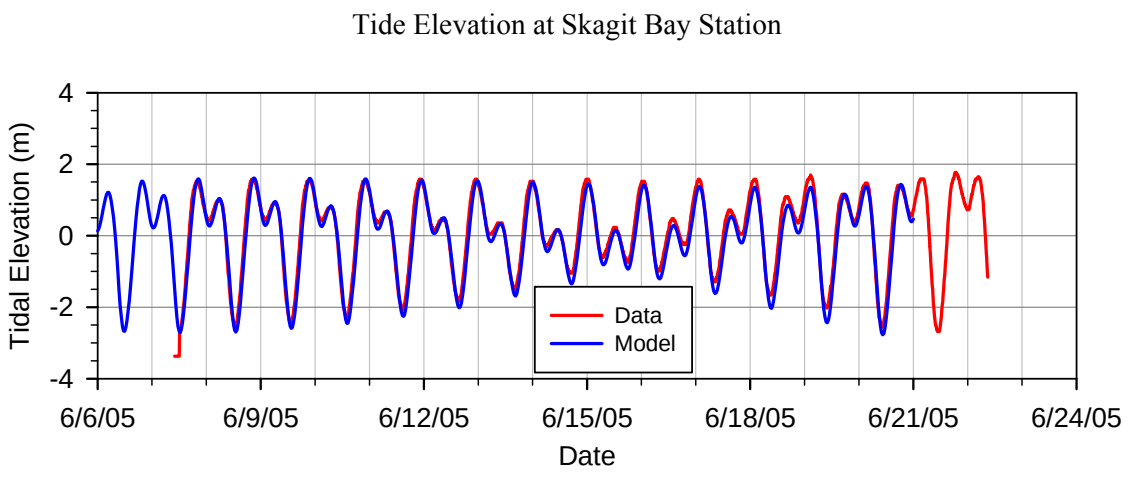
3.2 Model Validation Results

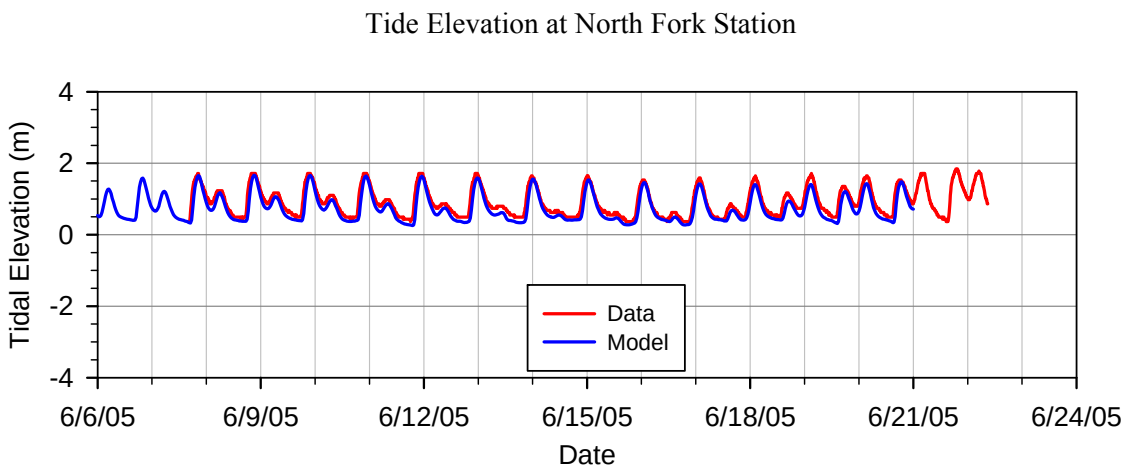
The model was validated with field data collected during the period of 6/21/2005 to 6/6/2006 for the Rawlins Road Restoration Project. Simulating the wetting and drying processes is important in terms of evaluating the restoration scenarios because Cottonwood Island is a floodplain forest subject to flood inundation. A minimum water depth of 10 cm was set as the dry-cell criteria (i.e., when the depth fell below 10 cm, the model assumed that the element was dry) to simulate the wetting and drying processes. Model parameters for the Cottonwood Island model were kept the same as the existing Skagit Bay model.

The purpose of the model validation is to confirm that the new model developed for the Cottonwood Island restoration study still performs at the same level of accuracy as it was in the previous Skagit Bay model calibration. Extensive model tuning to improve the agreement between model prediction and observed data was not required. Predicted water-surface elevation, velocity, and salinity time series were compared to the field data. Figure 3-3 compares the predicted tidal elevations at the Skagit Bay and North Fork stations. Predicted water-surface elevations matched the observed data well. The spring-neap tidal cycle and the diurnal inequality were reproduced well in the model. Predicted high and low tidal phases were also in good agreement with observed data. The tidal elevation at the Skagit Bay station shows a full tidal range of 4 m as observed in the Puget Sound coastal region. As the tide propagates further upstream towards the mudflat area of Skagit Bay, tidal elevations are affected by shallow-water depths and river backwater as observed at the North Fork station. Tidal elevations during low tides at North Fork were elevated because of the shallow mudflat area near the river mouth. Tidal elevations would be further elevated during the high-flow event because of the river backwater effect.

Predicted velocities in general matched the observed data at both the North Fork and Skagit Bay stations (Figure 3-4 and 3-5). Unlike water-surface elevations, the signature of the neap-spring tidal cycle and diurnal inequality was not strong in velocity distributions because of the damping effects of river inflow and the presence of a shallow marsh area. Velocities are dominant in the east component of the North Fork station because of the orientations of the river channels. The dominant velocity along the deep Skagit Bay Channel (45° from North) was observed at the Skagit Bay station.

Figure 3-6 compares the salinity time series at the North Fork and Skagit Bay stations with the observed data. Overall, predicted salinities matched the observed data reasonably well, similar to those in the previous Skagit Bay model calibration. The predicted and observed salinity at North Fork were close to zero for the entire simulation period, indicating that salinity intrusion did not reach upstream to the North Fork Station. Salinities at the Skagit Bay station showed strong variations as a result of tidal fluctuations and the spring-neap tidal cycle. Salinities in the bay increased up to 30 ppt during flood tides because of the intrusion of Puget Sound water and dropped below 10 ppt during ebb tides because of the dispersion and spreading of the Skagit River freshwater plume. Predicted salinities matched this pattern of observed data.





Note:

- Tidal elevation is with reference to Mean Sea Level (MSL).
- 1 m = 3.281 ft

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FIGURE 3-3

Comparisons of Predicted and Measured Tidal Elevations—Skagit Bay and North Fork Stations

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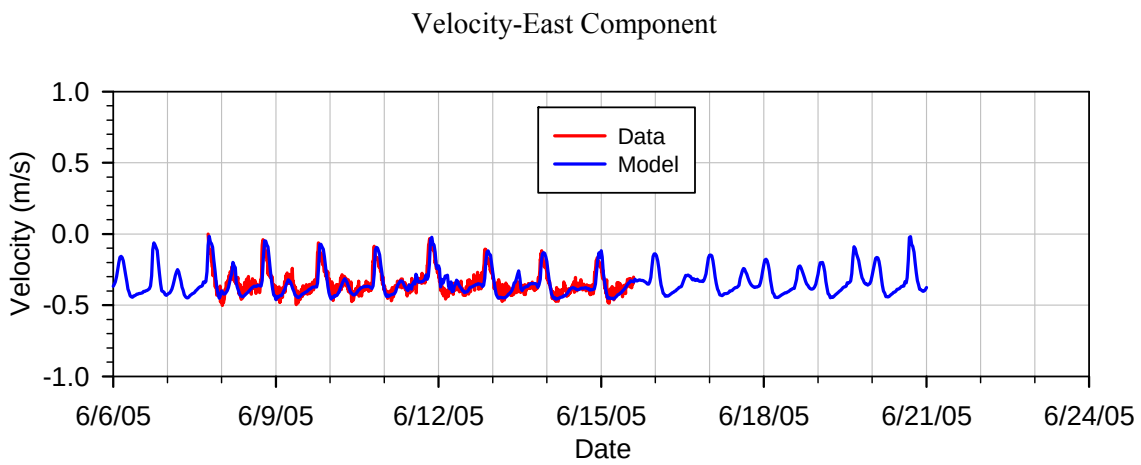
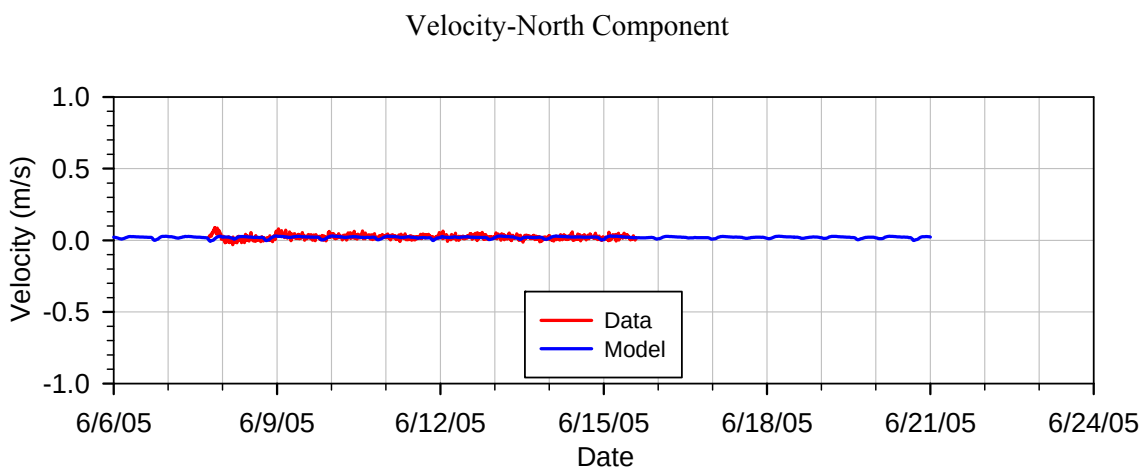
Mount Vernon, WA





Note:

- Times are in Pacific Time Zone.
- Comparisons correspond to mid-layer depth.
- 1 m = 3.281 ft

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FIGURE 3-4

Comparisons of Predicted and Measured Velocities at North Fork Station

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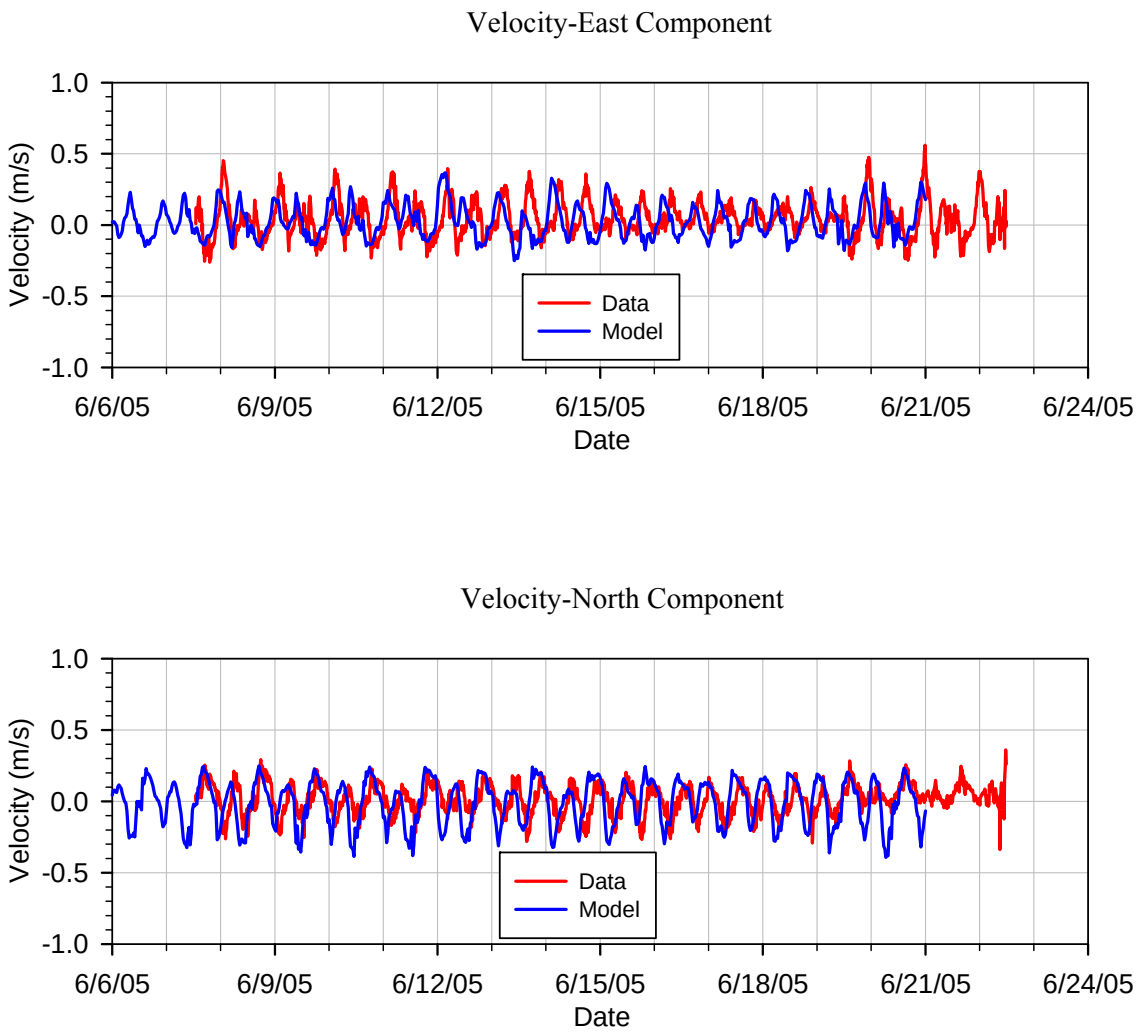

Note:

- Times are in Pacific Time Zone.
- Comparisons correspond to mid-layer depth.
- 1 m /s = 3.281 ft/s

FIGURE 3-5

Comparisons of Predicted and Measured Velocities at Skagit Bay Station

Skagit Watershed Council
Mount Vernon, WA

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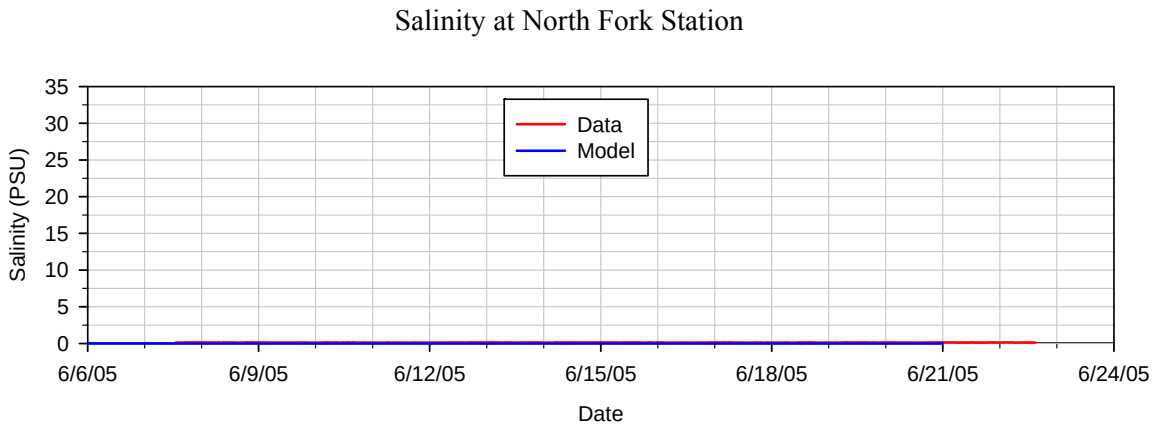

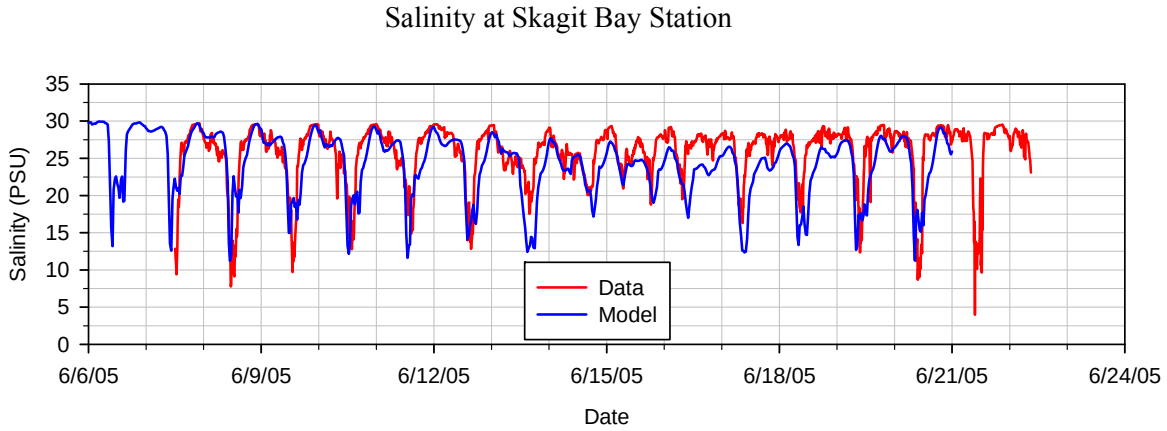

FIGURE 3-6
Comparisons of Predicted and Measured Salinity at North Fork and Skagit Bay Stations

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4.0 Hydrodynamic and Sediment-Transport Model Application for Existing Conditions

After the hydrodynamic model for Cottonwood Island was validated, a sediment transport model was developed to evaluate the response of the system when subjected to six representative hydrologic events in the Cottonwood Island restoration area. Model parameters and forcing functions in the hydrodynamic model were retained at the same values as those set up for the model validation. A sediment transport model was set up using existing sediment data. The model was used to simulate flow inundation, velocity distribution, bed shear-stress distribution, and sedimentation patterns in the study area. Sediment transport simulations for the existing conditions were conducted for an extended period (32 days) from June 6 to July 7, 2005.

4.1 Hydrodynamic and Sediment Transport Model Setup for Flood Hydrographs

To simulate hydrodynamics for the existing conditions in Cottonwood Island, the model parameters, geometry, and bathymetry in the hydrodynamic model were kept the same as the model validation. The tidal open boundary and wind forcing data were extended from the 14-day model validation period to 32 days (i.e., 6/6/2005-7/6/2005) to match with the entire duration of the 25-yr flood hydrograph. Six flood hydrographs (average, 1 yr, 2 yr, 5 yr, 10 yr, 25 yr) shown in Figure 2-4 were independently applied to the upstream river boundary to assess the effects of individual hydrographs on hydraulics and sedimentation at the project site. As described in Section 2.3, the hydrographs were selected from the 60-yr historical daily flow data after dam construction (1940-2000) as measured by USGS at Mount Vernon. The time history of each hydrograph was adjusted such that the peak flow occurred on day 15. This would allow consistent comparison of simulation results at the peak flow time with the same model run period.

The following three data sets were required to set up the sediment-transport model: 1) initial concentration of suspended sediment, 2) initial bed conditions (sediment depth, particle-size distribution), and 3) sediment loading at upstream river boundary. The setup of the initial conditions and the sediment loading condition was based on the data set collected by USACE and USGS as described in Section 2.5. It was assumed that the initial suspended sediment in the water column was zero. The initial sediment depth was set to the average values of bed-elevation change measured in 1999 relative to 1975, corresponding to 3.5 ft in the North Fork, 0.25 ft in the South Fork, and 2 ft from the fork to the upstream reach, including the west channel. A single sediment class size (0.6 mm) corresponding to medium sand was used, which is the dominant class at the project site based on the USACE field data (Pentec Environmental 2002). The settling velocity of this sediment is 50 mm/s. The upstream boundary condition for the sediment load was specified corresponding to each hydrograph, based on the USGS rating curve shown in Figure 2-10.

The bed-sediment dynamics model consisted of two parts: sediment dynamics in the water column and the bed layer model. The sediment-dynamics model includes entrainment and deposition. The bed model calculates the modification of sediment texture in the specified bed layers. The two models were coupled to interact through entrainment and deposition processes such that the sediment mass is conserved. To calculate sediment entrainment, the popular entrainment formula developed by van Rijn (1984) was used. The settling flux ($w \cdot C$) of the sediment was simply calculated by multiplying the

settling velocity (w) with concentration (C) in the normal range of concentration. For a simplified analysis, a single layer of bed corresponding to the initial bed thickness was set in the current model, which is composed of 0.6 mm sand.

4.2 Model Simulation Results

Figure 4-1- 4-3 present the time-series plots of water-surface elevation and bed shear stress at stations S1, S2, and S3, representing the simulation results using six hydrographs as the upstream conditions for the river-flow boundary. The station S1 was located near the west bank of the main channel near the sand deposits blocking the upstream entrance of the west channel. Station S2 was located on the sand deposits and station S3 inside the west channel. The bed elevations at the stations were 0.42 m, 4.7 m, and 2.1 m above MSL, respectively. The water-surface elevations at all stations responded directly to the hydrographs. For the 25-yr flood flow conditions, the water surface elevation reached close to the levee height (~7 m relative to MSL). The peak water surface elevation for a 25-yr flood flow was a little lower than the result of the USACE HEC-RAS simulation for the project "Skagit River Flood Damage Reduction Feasibility Study" (USACE 2004). The difference in predicting the water-surface elevation may be attributed to the difference in the hydrograph used for each simulation. The daily peaking of water-surface elevation indicates the influence of flood and ebb tide. However, this tidal peaking disappears as the water surface elevation exceeds a certain height at larger river flows. Station S1 was always wet, while S2 was dried because of a high elevation of sand deposits until the 5-yr or larger flow overtops it. The west channel always remained dry during the average flow conditions but started to fill with water when the water-surface elevation exceeded the channel-bed elevation (2.1 m). A high bed shear stress at station S1 indicates that sediment particles in the main channel are subject to significant erosion during all f1ood flows exceeding the average flow. The average flow appears to be the critical or just above the critical condition (τ_c=0.3 Pa) for this class of sediment (0.6 mm). However, the bed shear stress at station S2 exceeded the critical condition during only a short period when the water-surface elevation overtopped the sand deposits. The largest bed shear stress at S2 is only about 1 Pa, which indicates that the sand deposits may not be easily scoured away. The bed shear stress at station S3 in the west channel is well below the critical condition in most flow conditions. It only exceeds the critical condition during the peak of the 25-yr flood flow, which implies the depositional environment. Interestingly, a sudden drop and increase in the bed stress for 10-yr and 25-yr flows is predicted at a day before and after the peak water-surface elevation at stations S1 and S2 (see Figure 4-1). The same phenomenon also occurred at S2 (Figure 4-2). This phenomenon was caused by abrupt (~several hours) velocity change by a large pressure gradient variation due to 1) flow diversion and disconnection from the main river channel to the west channel and 2) the wetting and drying of the Cottonwood Islands. As Cottonwood Island begins to submerge when the water-surface elevation exceeds the land elevation, the release of a constrained flood-pressure wave begins. Consequently, the velocity at the channel decreases. As the water-surface elevation decreases from the peak and Cottonwood Island starts to dry, the reverse phenomenon, which increases the velocity, occurs.

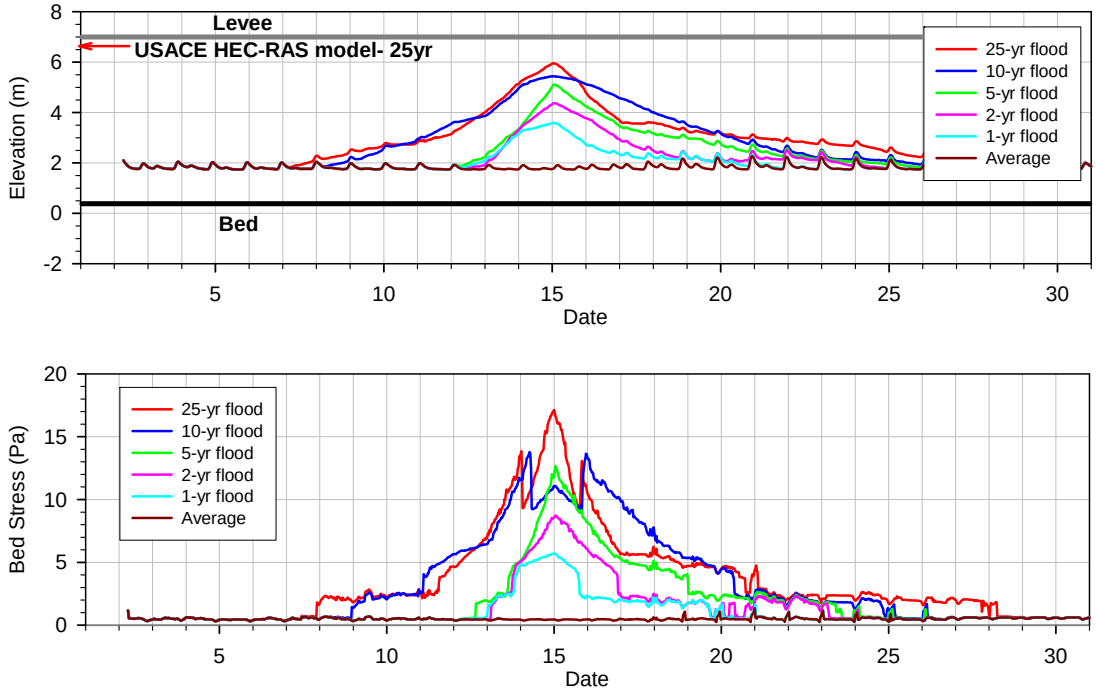
Figure 4-4 shows the predicted inundation, surface velocity, and bed shear-stress distributions at the peak flow (i.e., day 15) for the six hydrographs. As indicated in the time-series plot of water-surface elevation, Cottonwood Island was completely dry under average flow conditions. The west channel was filled with water coming through the south entrance connected to the North Fork under higher flows. Flows higher than the 5-yr return interval connected the upstream west channel entrance to the main river stem, allowing direct diverted inflows to the channel. Under 10-yr flood-flow conditions, the lower elevation area of Cottonwood Island was immersed. Most of the area of Cottonwood Island was

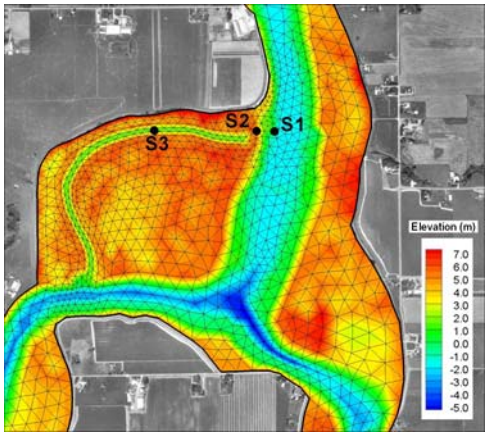
completely inundated by a 25-yr flood flow. The surface-velocity distribution shows that the velocity significantly increases with increasing flow rate, exceeding 3 m/s at the upstream end of the main channel of Cottonwood Island for 25-yr flood flow. For average flow conditions, the upstream velocity was in the range of 1~1.5 m/s. However, the velocities in the west channel were very small (< 10 cm/s) during most of the time for all flow conditions due to its orientation to the main flow direction and high bed elevation. The highest velocity magnitude was 0.35 m/s, corresponding to the peak bed shear-stress value in the 25-yr flood flow. The upstream velocity was significantly reduced from the west channel entrance to the split due to flow divergence caused by the wider and deeper channel. At the split where the river divides into the North and South Forks, the flow becomes stagnant at the tip of the fork. The bed shear-stress distribution also shows very similar patterns and variation in the velocity as it is proportional to the square of the velocity. The peak bed shear stress exceeded the critical shear stress for initiation of sediment movement (white line) in most areas of the main river channel, showing the highest value at the upstream end of Cottonwood Island in the range of 7~25 Pa over the six flow conditions. Similar to the velocity distribution, the bed shear stress was significantly reduced near the West Channel entrance because of flow divergence due to the variation in channel geometry. However, the bed shear stress was below the critical value in most area of Cottonwood Island, including the West Channel, even for high flows. For the 25-yr flood flow conditions, only the southern part of Cottonwood Island was above the critical conditions, and the values were in the range of 0.3~5.0 Pa. In the sand deposit region near the upstream entrance of the West Channel, the bed shear stresses were relatively low to moderate (< 1~2 Pa), but a high gradient of bed shear stress was predicted because of reduced velocity in the over-bank region.

Figure 4-5 shows the distribution of depth-averaged suspended sediment concentration corresponding to the peak velocity distribution. The majority portion of the sediments was confined to the bottom layer of the water column due to the high settling velocity (5 cm/s) of a medium sand particle. The suspended-sediment-concentration pattern was directly correlated to the bed shear-stress pattern. The highest suspended sediment concentration (HSSC) was predicted just downstream of the highest bed shear-stress region. The location of HSSC tended to move further downstream in higher flow conditions because the higher velocity carried the sediment plume faster before deposition. Other reasons can also be attributed to sediment availability for resuspension. In high-flow conditions, the amount of sediments available to resuspension in the highest bed stress zone will be eventually limited because of continuous erosion unless the sediments are supplied infinitely from the bed. Consequently, the suspended sediment concentration in this region would be spatially phased out of the bed shear-stress distribution. The peak concentration in the sediment plume was about 30 mg/L for average flow conditions and reached about 300 mg/L for 25-yr flood flow conditions. The suspended sediment concentration in the inundated Cottonwood Island, including the west channel, remained a very low value—less than 10 mg/L. This implies that a high settling velocity of medium sand prevented transport and deposition of sediment particles from the bottom layer of the lower main channel to the higher Cottonwood Island and west channel.

Figure 4-6 shows the end-point sedimentation patterns resulting from simulating six flow conditions at the end of model simulation (day 32). The net sedimentation distribution was computed by subtracting the initial sediment depth from the final sediment depth at every grid point, showing net erosion and deposition during the simulation period. In this study, the effect of morphological change on the hydrodynamics was not considered. Similarly, the bed-load transport phenomena were also not considered. Therefore, the predicted sedimentation pattern is more likely the initial response of the sediment bed to a flow condition and needs to be carefully interpreted in the quantitative sediment budget analysis. Regardless of flow conditions, the highest sedimentation zone (hot spot) was predicted along

the west bank of the main channel and at the historic downstream mouth of the west channel, indicating that the model results confirm the historic blockage and sedimentation in the west channel under the present configuration. For the 10-yr and 25-yr flood flow conditions, nearly 1.5 m of deposition was predicted at the channel entrance. This value might be over-predicted because the morphological effect on hydrodynamics was not considered. The highest erosion occurred at the upstream of Cottonwood Island at the highest bed shear-stress zone. The high deposition location along the west bank matched well with sand deposits blocking the west channel entrance observed in the aerial photos. The deposition and erosion pattern indicates that the dike movement at the upstream corner of Cottonwood Island constrained the flow, increasing the velocity and eroding more sediment in this upstream channel. This resulted in sediment being deposited near the entrance of the west channel. Here the flow decreased because of wider and deeper channel geometry. In Cottonwood Island, including the west channel, the predicted sedimentation was low during the simulation period. However, the low sedimentation rate may be significant in terms of long-term maintenance of off-channel flow connected to main-river stem. The quantitative estimation of long-term sedimentation in the off-channels was not included in this phase of the study.





Note:

- Water-surface elevation is relative to MSL.
- S1-0.41 m (1. 35 ft) above MSL
- S2-4.70 m (15.4 ft) above MSL
- S3-2.10 m (6.89 ft) above MSL

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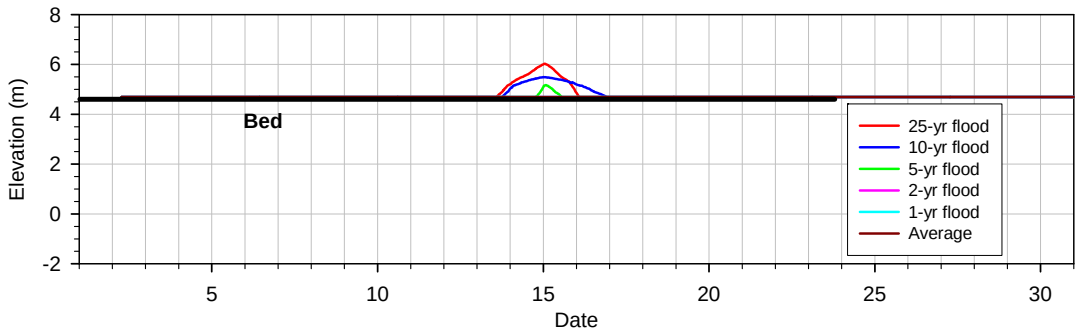
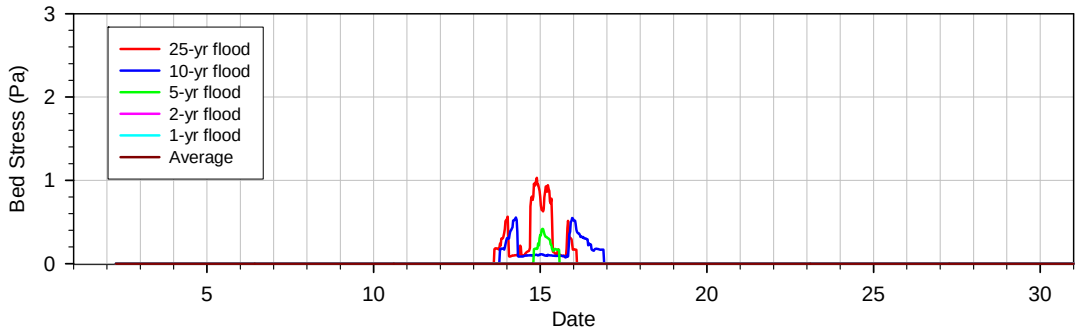
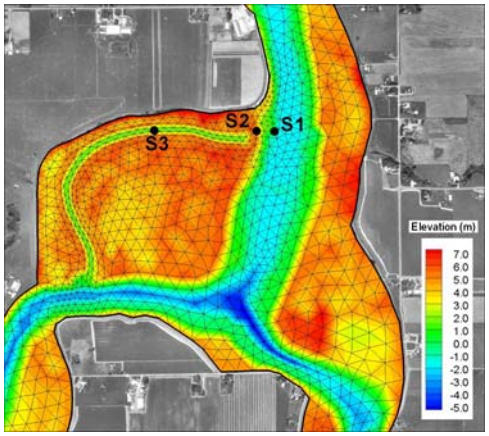
FIGURE 4-1

Predicted Water-Surface Elevation and Bed Shear Stress at Station S1

Skagit Watershed Council
Mount Vernon, WA







Note:

- Water-surface elevation is relative to MSL.
- S1-0.41 m (1. 35 ft) above MSL
- S2-4.70 m (15.4 ft) above MSL
- S3-2.10 m (6.89 ft) above MSL

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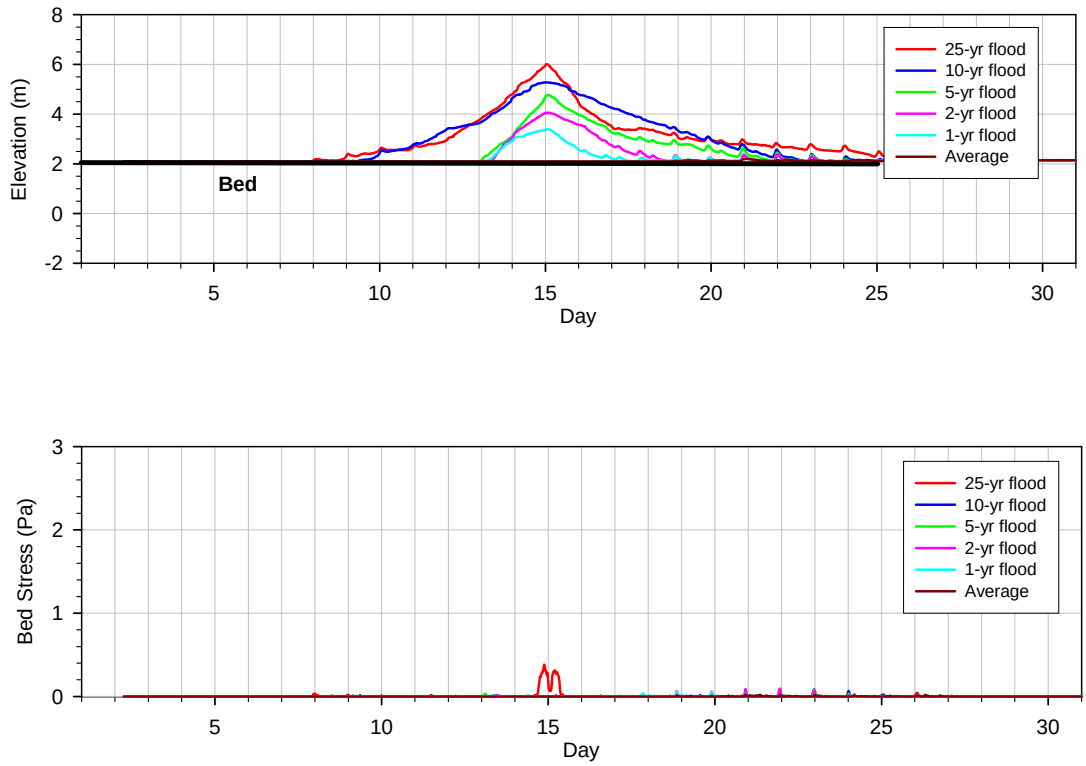
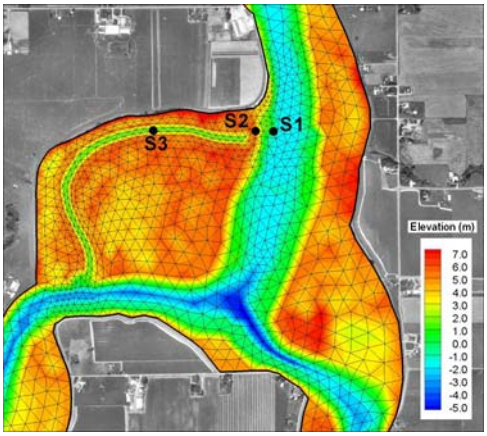
FIGURE 4-2

Predicted Water-Surface Elevation and Bed Shear Stress at Station S2

Skagit Watershed Council
Mount Vernon, WA





Note:

- Water-surface elevation is relative to MSL.
- S1-0.41 m (1. 35 ft) above MSL
- S2-4.70 m (15.4 ft) above MSL
- S3-2.10 m (6.89 ft) above MSL

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FIGURE 4-3

Predicted Water-Surface Elevation and Bed Shear Stress at Station S3

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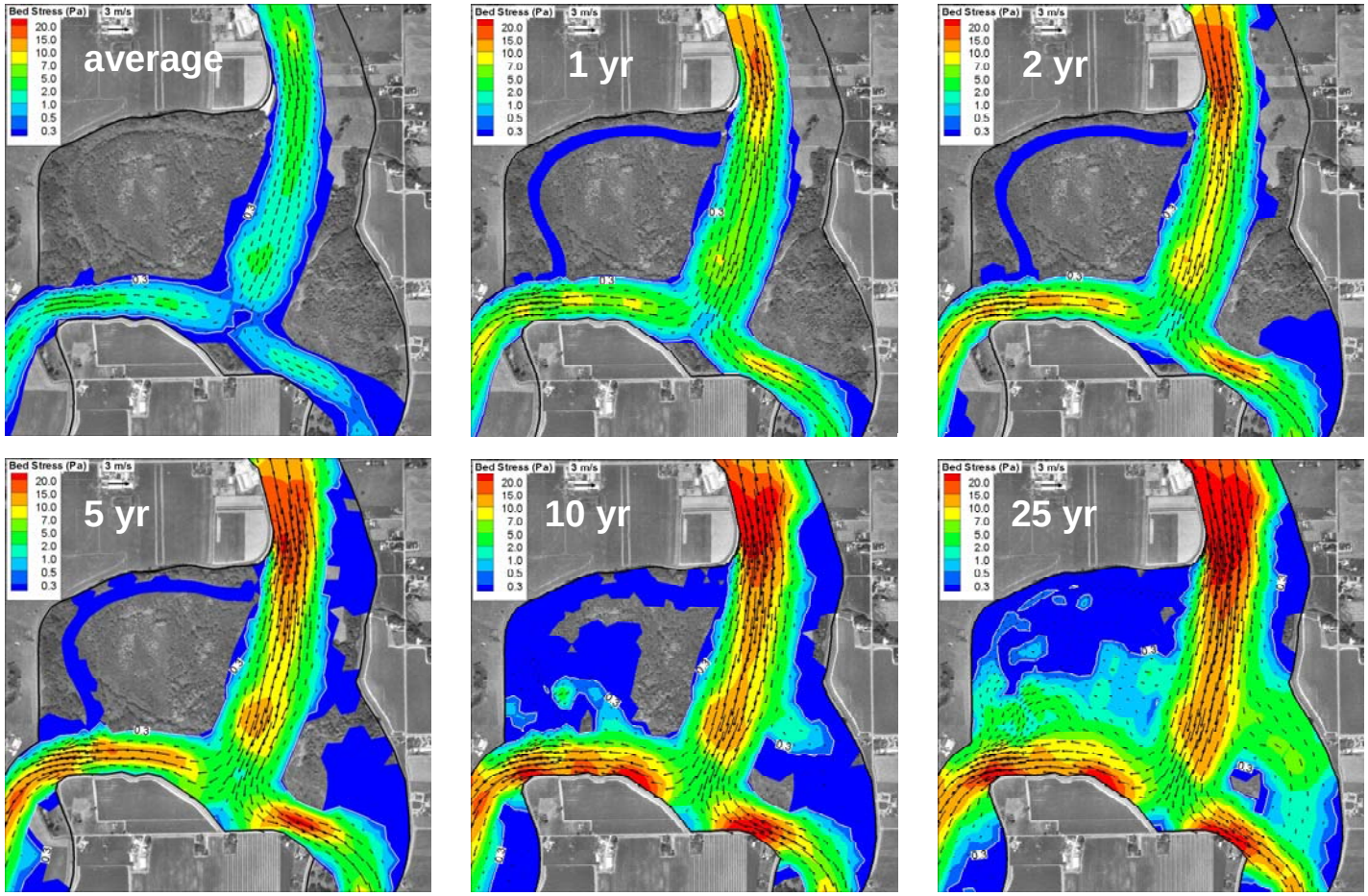
Mount Vernon, WA



Note:

- No color indicates dried area.

FIGURE 4-4

Peak Surface Velocity and Bed Shear-Stress Distribution for Existing Conditions

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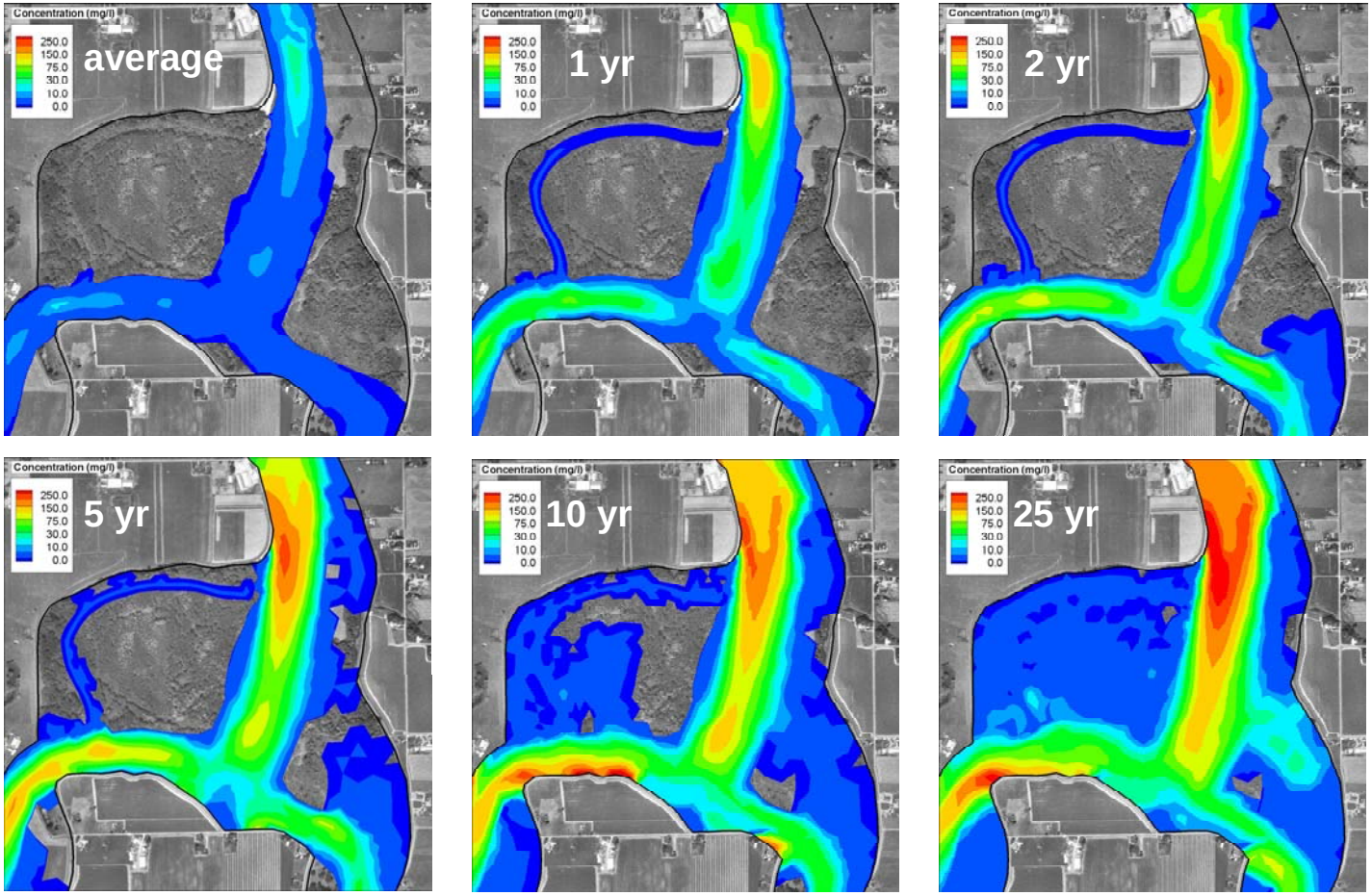

Note:

- Suspended sediment concentration was depth-averaged.

FIGURE 4-5

Peak Suspended Sediment Concentration Distribution for Existing Conditions

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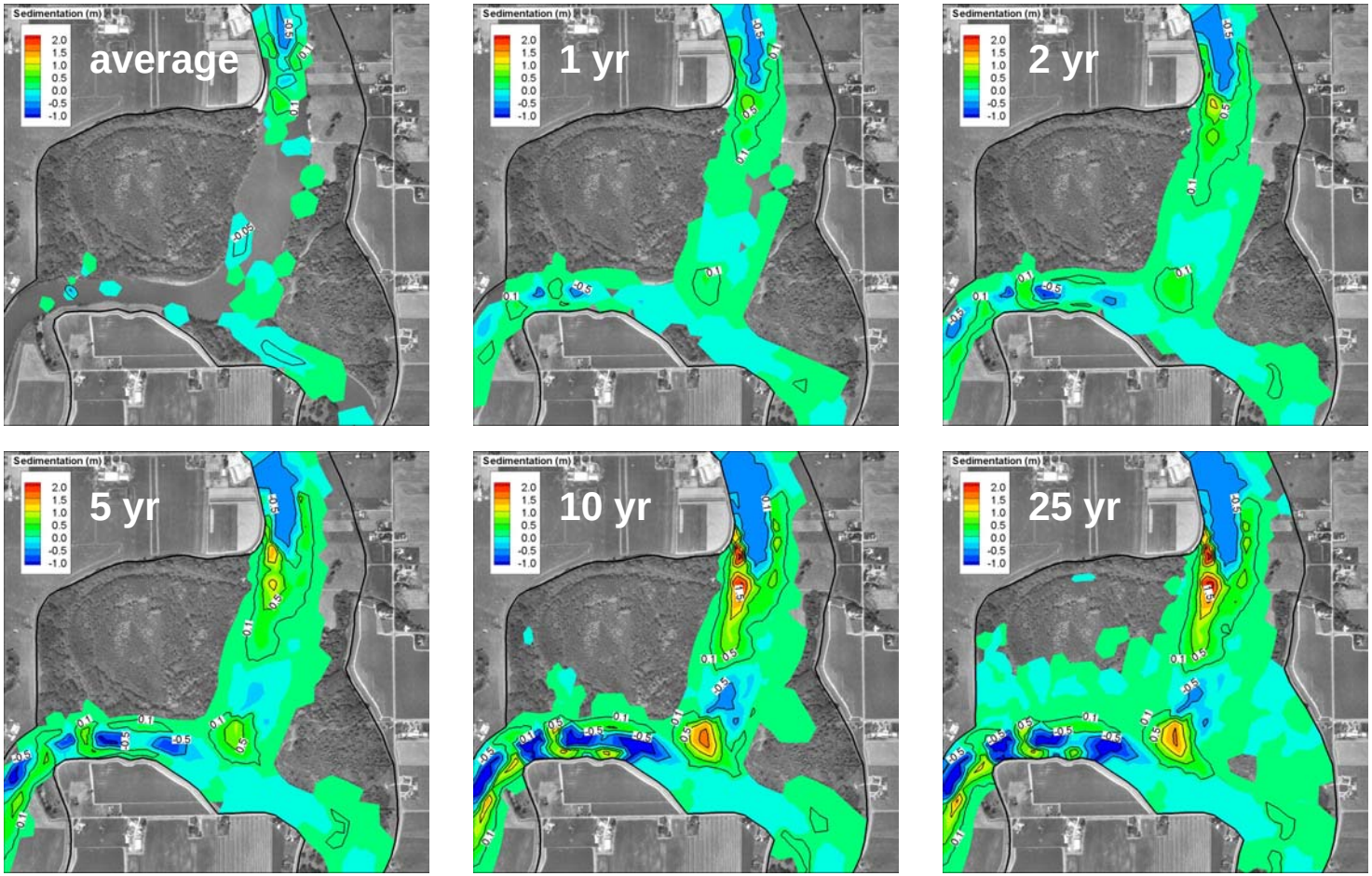

FIGURE 4-6

Endpoint Sedimentation for Existing Conditions

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5.0 Model Application to Assess Hydraulic Feasibility of Proposed Restoration Scenarios

The objective of this study for the Cottonwood restoration project is to assess the feasibility of restoring flow and access to the west channel around Cottonwood Island through proposed restoration actions including dike setback, dredging, and channel modifications. One of the major concerns for the Cottonwood Island site is that the initial benefits obtained through restoration actions may be lost in subsequent years due to potential sedimentation in the west channel and re-blocking of the channel entrance. Project feasibility in terms of sustained benefit of access to fish habitat in the west channel was tested by evaluating the hydrodynamics and sedimentation response of three restoration scenarios for 25-yr flood flow conditions. The response was also evaluated for low flow conditions to verify that selected alternatives would function during a low river stage. Model parameters and forcing functions were retained at the same values as those set up for the model validation and existing conditions. The model results include water-surface inundation, velocity distribution, bed shear-stress distribution, and sedimentation pattern. Simulation results for the restoration scenarios were compared with the existing (baseline) conditions to assess the impact of restoration alternatives relative to the baseline conditions.

5.1 Description of Restoration Alternatives

The restoration alternatives were designed with the intent of modifying the hydraulic behavior of the river near Cottonwood Island such that the west channel around Cottonwood Island would be reconnected, and more water would be diverted from the main river stem. The desired end result would be access to habitat for downstream migrating fish and a channel configuration that is naturally self-sustaining. The configurations of restoration alternatives were determined through discussions with SWC[(a)] (Figure 5-1). The following three restoration alternatives were selected.

- *Alternative 1*—Dike Setback and Reconnection.
  The dike along the west bank was set back to the 1889 alignment position, and the sand deposits blocking the entrance were removed to reconnect the channel to the main stem of the North Fork Skagit River. The model boundary and grids were modified according to the dike setback alignment, and the bathymetry was set at 5 m above MSL based on SRSC LIDAR data. No dredging or other changes were made to the west channel (elevation of 2 m above MSL).

- *Alternative 2*—Dike Setback with Dredging of West Channel.
  Alternative 2 includes dike setback exactly as in Alternative 1. This alternative also includes dredging of the west channel to a width of 30 m and a deepening of the channel by 1 m (elevation of 1 m above MSL).

(a) Project Progress Meeting on July 24, 2007, and E-mail Communications.

- *Alternative 3*—Dredging of West Channel Only (No Dike Setback).
  In this alternative, the dike setback was eliminated and returned to existing conditions. Instead, the west channel was dredged further until it sustained sufficient flow under low flow conditions (i.e., 8,000 cfs). The bathymetry of the channel (1 m below MSL) was adjusted using professional judgment. Alternative 3 was developed based on the results of Alternatives 1 and 2 to allow continuous flow with appropriate velocity through the channel in all flow conditions, thus restoring fish habitat to natural functionality.

Table 5-1 summarizes the information for modifying the channel.

5.2 Hydrodynamic and Sediment Transport Model Application Results

The model was applied to simulate the hydrodynamics and sedimentation for the restoration alternatives. Only the 25-yr flood flow was simulated to focus on the flood-flow event with maximum impact with respect to sediment transport. The model was applied for the same time as in the existing condition simulations presented in Section 4. Based on the results from the 25-yr flood flow, Alternative 3 was also run during the low-flow conditions to verify the functionality of the west channel for the low-flow conditions.

Figure 5-2 shows the comparison of predicted surface velocity and bed shear-stress distributions of 25-yr flood flow conditions at the peak flow rate (140,000 cfs) on day 15 among the existing and alternative conditions. The following Figures 5-3 through 5-4 show the time-series plots of water-surface elevation, velocity, and bed shear stress at stations S1, S2, and S3, representing the flow characteristics of the main river channel, sand-deposit location, and West Channel.

The simulation results shown in Figure 5-2 indicate that Cottonwood Island was completely inundated during the 25-yr flood flow for all alternatives. The land acquired through dike setback was also submerged when the water-surface elevation was greater than the land elevation (5 m). Generally, the amount of direct overland flow to the west channel was small due to high elevations. A part of the upstream water flowed through the west channel, which was connected to the main river stem. The minimum water-surface elevation (or flow rate) to maintain a flow through the channel is determined by the channel elevation. The flow velocity in the channel after restoration was relatively small (< 0.7 m/s) but increased significantly in comparison with the existing conditions (< 0.3 m/s) for the 25-yr flood flow. The bed shear-stress distribution showed the highest bed shear stress in the upstream channel close to 25 Pa, which corresponds to the peak surface velocity exceeding 3 m/s for all the alternative conditions. In general, in the time-series plots, the bed shear stress at the main river channel far exceeded a critical condition for sediment erosion during the entire simulation period. In the west channel, however, it was below the critical condition during most of the time except for a peak flow period (day 14 ~ day 15). A sudden drop and increase of velocity and bed shear stress during the peak period occurred, caused by a large variation of pressure gradient due to the wetting and drying of Cottonwood Island as explained in Section 4.3.

In Alternative 1, the re-connection of the upstream channel entrance allowed water to flow through the west channel only when the river flow rate was greater than 20,000 cfs. The reason for this is attributed to the high bed elevation (2.1 m above MSL)—see Figures 2-4 and 5-5. At station S1, the results of water-surface elevation, velocity, and bed shear-stress time series were very similar to that of the existing conditions during the entire simulation period, indicating a negligible effect of channel re-connection on the main river flow. At station S2, the flow velocity was in the range of 0.02 ~ 0.2 m/s

until the water-surface elevation reached about 4 m (day 13). After day 13, the flow rate continued to increase, and the velocity also increased up to 0.7 m/s. The bed shear stress remained below the critical conditions during most of time except for a peak flow period (day 14 ~ day 15). The peak bed shear stress was about 1 Pa. This implies that this location may be still subject to deposition even after a dredging. In the west channel where station S3 is located, the flow velocity was in the range of 0.0 ~ 0.3 m/s until day 13 and reached the peak velocity of 0.7 m/s. Compared to the existing conditions, the peak velocity nearly doubled. The bed shear stress is generally below critical conditions except for the peak flow period when it increased up to about 1.0 Pa. The horizontal bed shear-stress distribution in Cottonwood Island is very similar to the existing conditions except for a little intrusion by a 0.3-Pa contour line into the upstream entrance because the sand deposits were removed (see Figures 5-3, 5-4, and 5-5).

In Alternative 2, the dike setback and channel modification connected flow through the west channel during the entire simulation period. The water depth was 0.8~1.0 m under average flow (16,500 cfs). Similar to Alternative 1, the dike setback was not much help in diverting the upstream flow to the west channel. However, the channel dredging and widening significantly increased the flow velocity in the west channel compared to the existing conditions. However, a wider channel also kept the velocity and bed shear stress relatively low. At station S1, the resulting time-series plots also showed that the channel modification has no significant impact on the main river flow characteristics. The bed shear stress was a little decreased because of the reduced velocity caused by a diversion of some flows to the west channel. At station S2, the velocity and bed shear stress responded to the hydrograph similar to Alternative 1. In general, the velocity was in the range of 0.01 ~ 0.15 m/s until day 13. A slight decrease in comparison with Alternative 1 may be caused by more flow introduction to the channel. The peak velocity was less than 2 Pa, a little greater than the value in other conditions. At station S3, the channel was filled with water during the whole simulation period. The channel depth was about 1 m under the average flow conditions and increased up to 5 m at the peak. The velocity variation was similar to Alternative 3, showing the range of 0.15 ~ 0.7 m/s. In this Alternative, a minimum velocity of 0.15 m/s was always maintained by the average flow rate. Interestingly, the bed shear stress was 2 ~ 3 times higher than other alternative conditions except during the peak period.

In Alternative 3, the deeper channel dredging maintained the water flow through the west channel even during the low flow condition (8,000 ~ 14,000 cfs) throughout the entire simulation period. The water depth in the channel was in the range of 2.8 m ~ 3.0 m under average flow (16,500 cfs). The dredged channel significantly increased the flow into the west channel compared to the existing conditions. At station S1, there was little noticeable change. The resulting time-series plots showed a similar variation as in Alternatives 1 and 2. Although the bed shear stress was consistently lower than in the other conditions over the simulation period, it did not significantly change the overall flow characteristics in the main channel. The reduction may be attributed to the reduced bottom-layer velocity by a diversion of more flows to the west channel caused by a deeper channel depth than in other alternatives. At station S2, the velocity and bed shear stress responded similarly to Alternative 2. In general, the velocity was in the range of 0.01 ~ 0.10 m/s until day 13. The peak velocity was about 0.7 m/s. During most of the simulation time, the bed shear stress was under critical conditions with the peak bed shear stress around 1 Pa. At station S3, the channel was filled with water during the entire simulation period. The channel depth was 3 m under the average flow conditions and increased up to 7 m at the peak. The velocity variation is similar to Alternative 2, showing a range of 0.15 ~ 0.7 m/s, which maintains a minimum velocity of 0.15 m/s under average flow conditions. The bed shear stress was below the critical conditions except during the peak period.

Figure 5-6 presents the end-point sedimentation patterns for the restoration alternatives at the end of the model simulation (day 32). The net sedimentation distribution was computed by subtracting the initial sediment depth from the final sediment depth at every grid node, showing that net erosion (-) and sedimentation (+) occurred during the simulation period. In this study, the effect of morphological change on the hydrodynamics was not considered. Similarly, bed-load transport was not included. Therefore, the predicted sedimentation pattern is more likely the initial response of the sediment bed to a flow condition and new configuration. The simulation results predicted no dramatic change in sedimentation pattern, especially in the main stem of the North Fork Skagit River for all alternatives in comparison with existing conditions, indicated by similar velocity and shear-stress distributions. However, relative differences in hydrodynamic and sedimentation patterns among the three alternatives, especially in the west channel, are clearly identifiable. For all alternatives, the highest sedimentation zone (hot spot) was always predicted along the west bank of the channel and at the split. The amount of deposition in the hot spot was about 1.5 m. However, the hot-spot center location varied with the alternatives.

Alternative 2 showed little difference from the existing conditions. Dike setback and removal of sand deposits without any dredging in the west channel and acquired land did not significantly affect sediment-transport characteristics. Alternative 2 resulted in more sedimentation of the west channel entrance. The reason is attributed to the formation of an eddy at the entrance caused by widening and deepening of the channel.

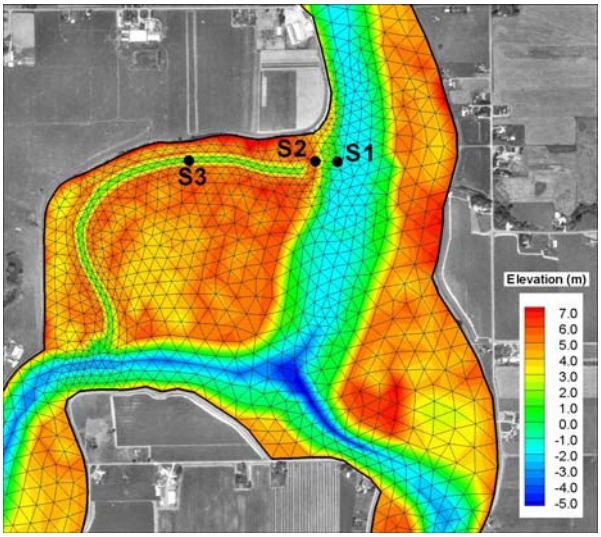
Alternative 3 still shows significant sedimentation at the west channel entrance but provides some benefits from the fact that the hot spot moved about 150 m (500 ft) upstream of the west-channel entrance. Less sedimentation at the west channel would reduce the maintenance cost for dredging after restoration. In the west channel, there was no notable sedimentation predicted. However, similar to the existing conditions demonstrated by historical aerial photos and data, even a low sedimentation rate needs to be considered in terms of long-term maintenance requirements for the restored west channel. The quantitative estimate of long-term sedimentation in the off-channels was not in the scope of this phase of study.

As a result of model simulation for the restoration scenarios, Alternative 3 provides more benefits in terms of restoration cost and reduction of sedimentation at the west channel entrance relative to the others. Therefore, Alternative 3 was tested for a low flow condition (8,000 ~ 14,000 cfs) to evaluate a persistent sustainability and functionality of the west channel. Figure 5-7 presents the surface velocity and bed shear-stress distribution. In the low-flow condition, the west channel was hydraulically connected to the main river. The velocity and bed shear are highest in the upstream of the west-channel entrance, but the magnitudes are small. The contour line of critical bed shear stress (0.3 Pa) retreated to the boundary between the over-bank and the main channel. The highest upstream velocity was about 1.2 m/s. As shown in Figure 5-8, the flow in the west channel is quite influenced by tide. The time-series plots show a strong daily variation phased with tidal elevation changes. The water depth in the west channel varies from 2 m to 3 m. The velocity in the west channel changes from 0 to 0.15 m/s, which is relatively small. The corresponding bed shear stress is negligible (< 0.05 Pa). As for the sedimentation in Figure 5-9, no significant sedimentation and erosion occurred in the low-flow condition.

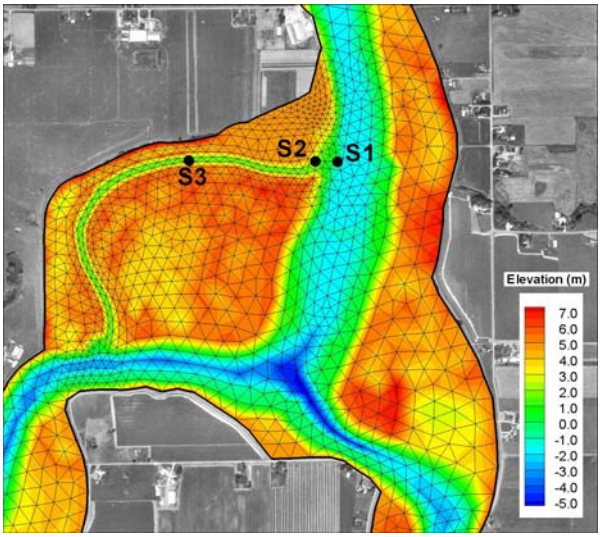
The design and selection of the final restoration configuration may be accomplished by considering 1) the restoration cost, 2) sustainability of flow, and 3) minimization of sedimentation at the channel entrance. The impact of dike setback appears to be insignificant in diverting more flow into the channel or in reducing the sedimentation at the west-channel entrance. The optimum west-channel depth must be

determined by a combination of hydraulic/sediment response and the requirements of an optimal depth for juvenile fish habitat. According to a study for salmon habitat (Bottom et al. 2005), suitable habitats were identified as 1) shallow and slow environments with the water depth between 0.1 m and 2 m, 2) the velocity smaller than 0.3 m/s, 3) environments with salinities in a range between 0 and 5 ppt, and 4) temperatures below 19°C. Cottonwood Island habitat would meet the salinity and temperature conditions. Based on the results for Alternative 3, which appears to be the preferred restoration alternative, the water depth in the West Channel is predicted to range from 2 m to 3 m under the low to average flow conditions. The appropriate dredging depth appears to be 0 ~ 0.5 m above MSL to maintain the appropriate habitat depth during low and average flow conditions.

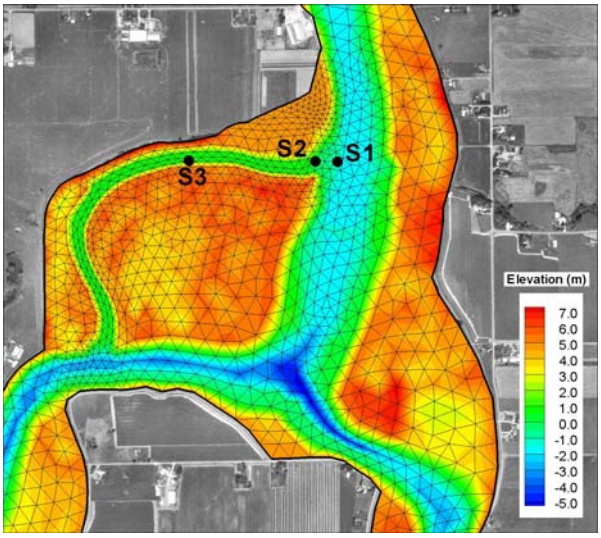
Existing Conditions



Alternative 1



Alternative 2



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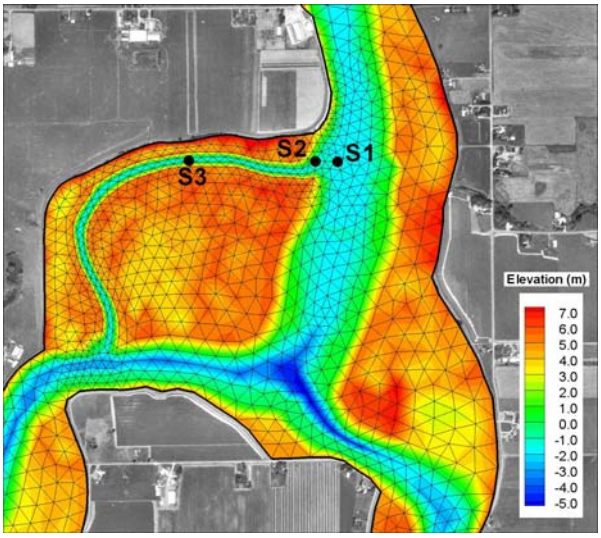

Note:

- Elevation is relative to MSL.

FIGURE 5-1

Comparison of Model Grids between Existing Conditions and Restoration Alternatives

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Table 5-1. Summary of Configurations of Existing Conditions and Restoration Alternatives

	Existing	**Alternative 1**	**Alternative 2**	**Alternative 3**
Channel Elevation (m)	2.1 m	2.1 m	1 m	-1 m
Channel Width (m)	15 m	15 m	30 m	15 m
Dike Setback	-	1889 alignment	1889 alignment	-
Sand Deposits	-	dredged	dredged	dredged

Note: the channel bed elevation is relative to MSL.
+ : above MSL
- : below MSL

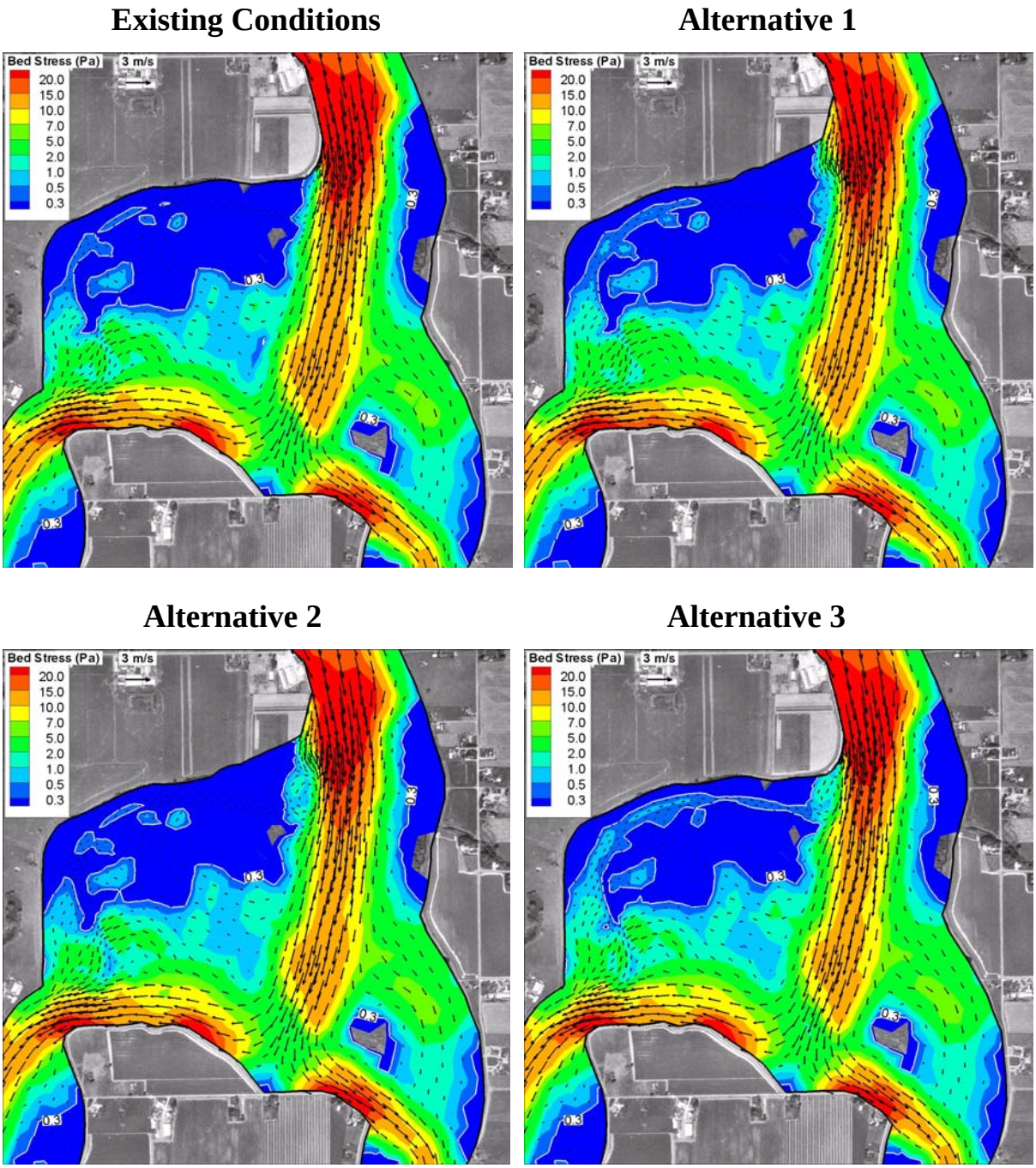

FIGURE 5-2
Peak Surface Velocity and Bed Shear-Stress Distribution of Existing Conditions and Restoration Alternatives—25-yr Flood Flow Conditions
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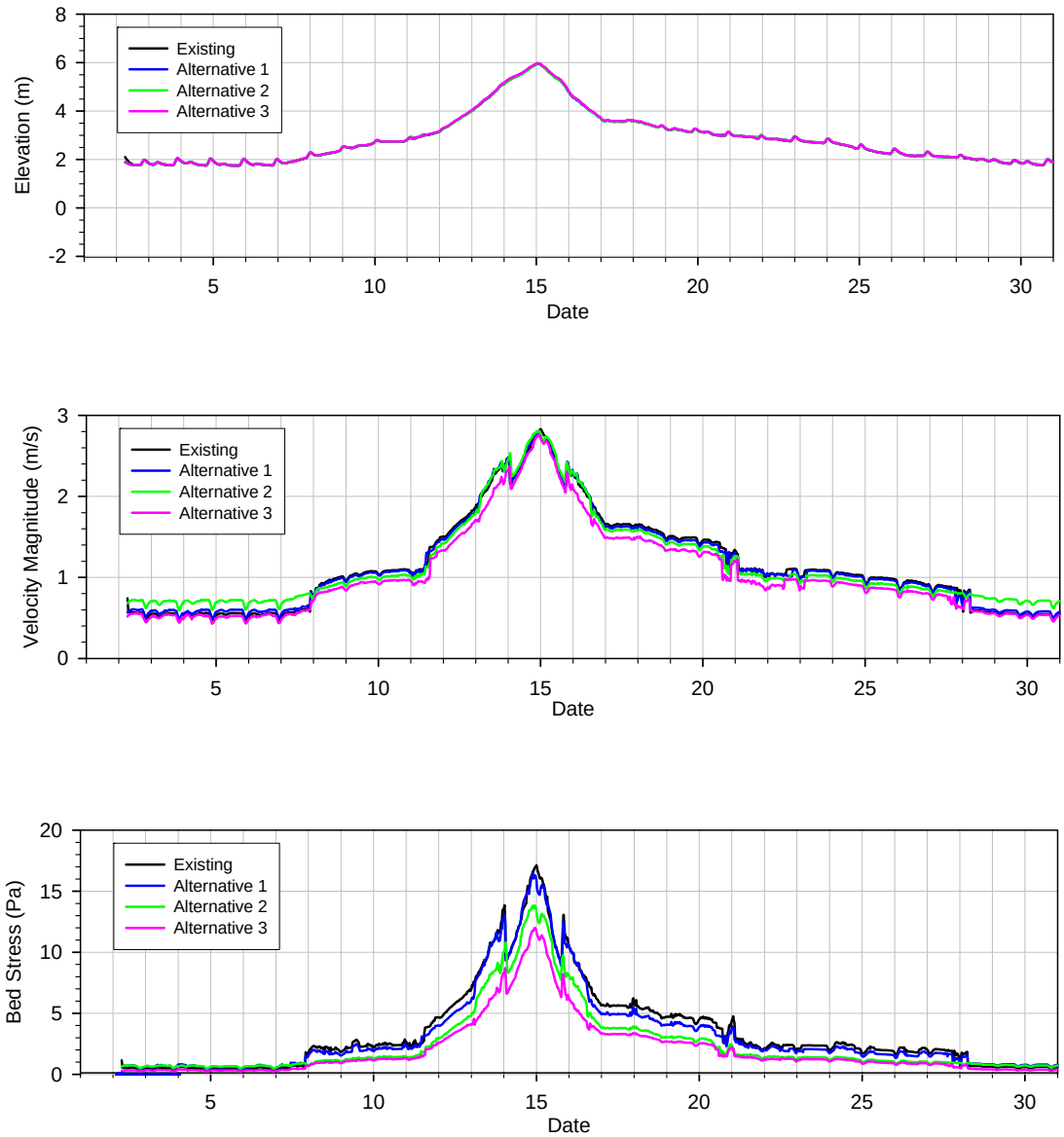

Note: Channel-bed elevation at S1

- Water-surface elevation is relative to MSL.
- Existing: 0.41 m (1. 35 ft) above MSL
- Alternative 1: 0.41 m (1.35 ft) above MSL
- Alternative 2: -0.51 m(1.67 ft) below MSL
- Alternative 3: -1.51 m(4.95 ft) below MSL

FIGURE 5-3

Predicted Water-Surface Elevation and Velocity at Station S1

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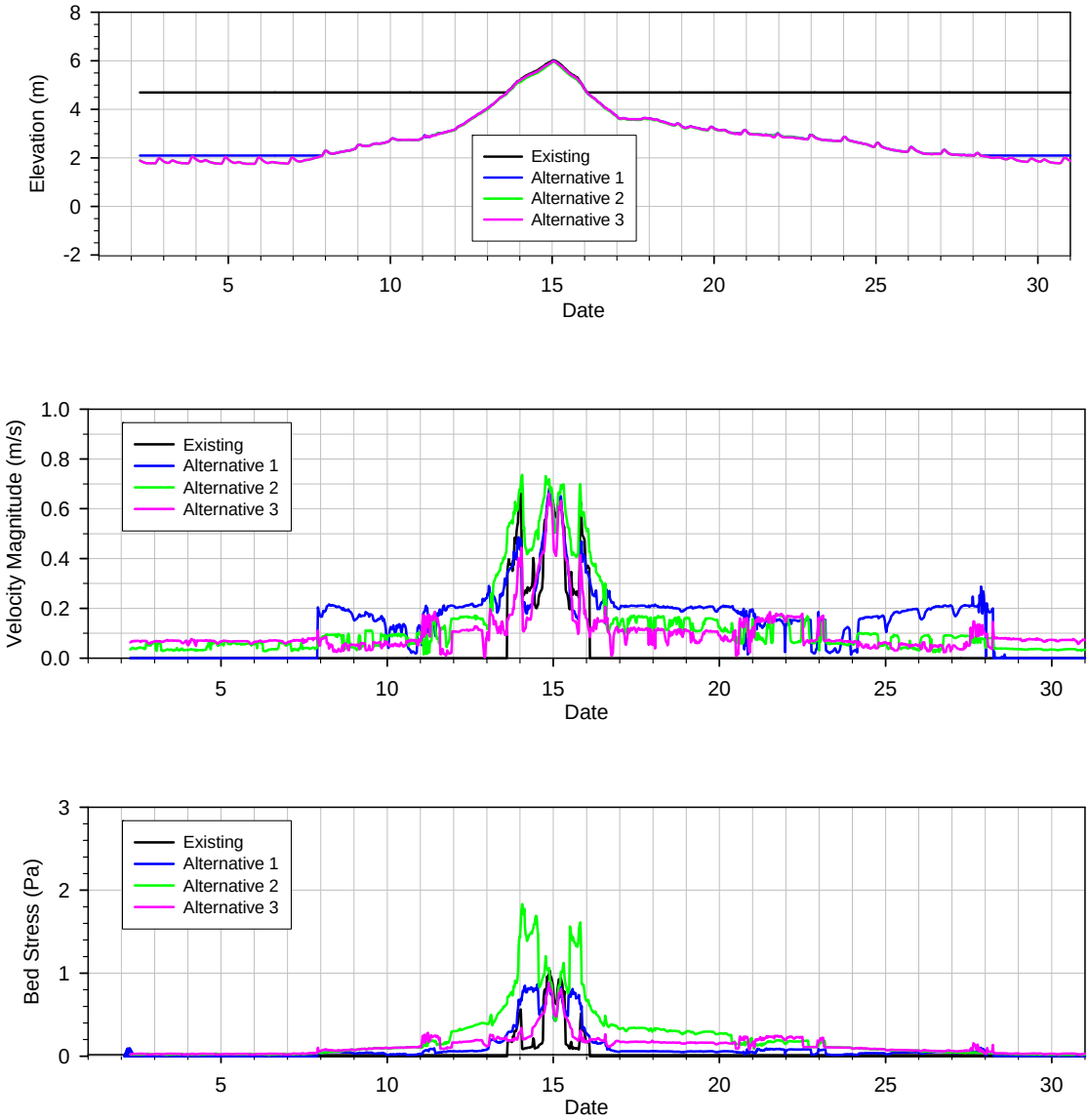

Note: Channel bed elevation at S2

- Water-surface elevation is relative to MSL.
- Existing: 4.59 m (15.1 ft) above MSL
- Alternative 1: 2.1 m (6.89 ft) above MSL
- Alternative 2: 0.0 m (0.00 ft) below MSL
- Alternative 3: -1.1 m (3.61 ft) below MSL

FIGURE 5-4

Predicted Water-Surface Elevation and Velocity at Station S2

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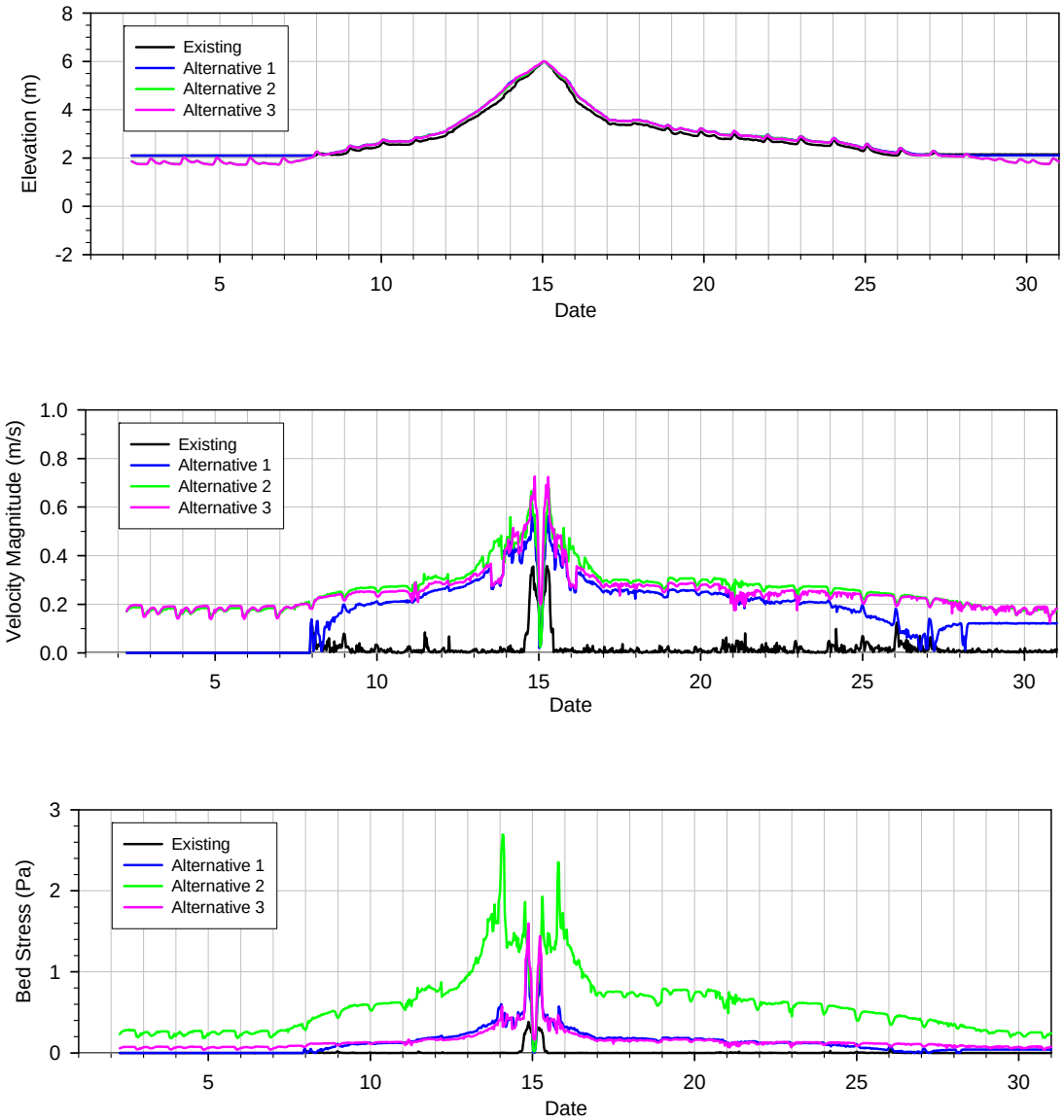

Note: Channel-bed elevation at S3

- Water-surface elevation is relative to MSL.
- Existing: 2.1 m (6. 89 ft) above MSL
- Alternative 1: 2.1 m (6.89 ft) above MSL
- Alternative 2: 1.0 m (3.28 ft) below MSL
- Alternative 3: -1.0 m (3.28 ft) below MSL

FIGURE 5-5

Predicted Water-Surface Elevation and Velocity at Station S3

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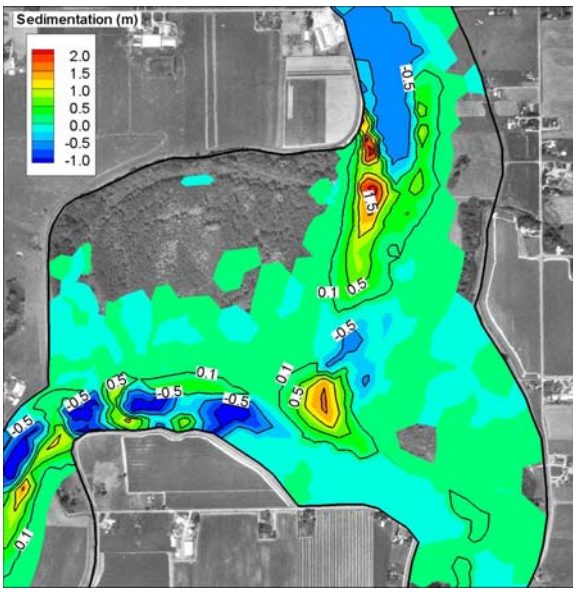
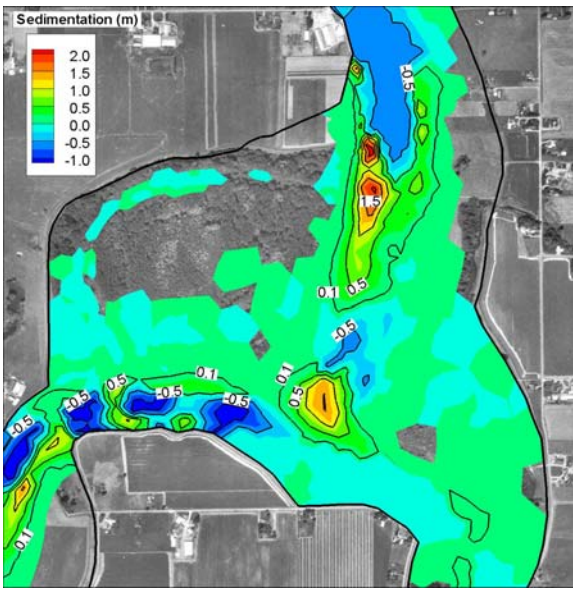
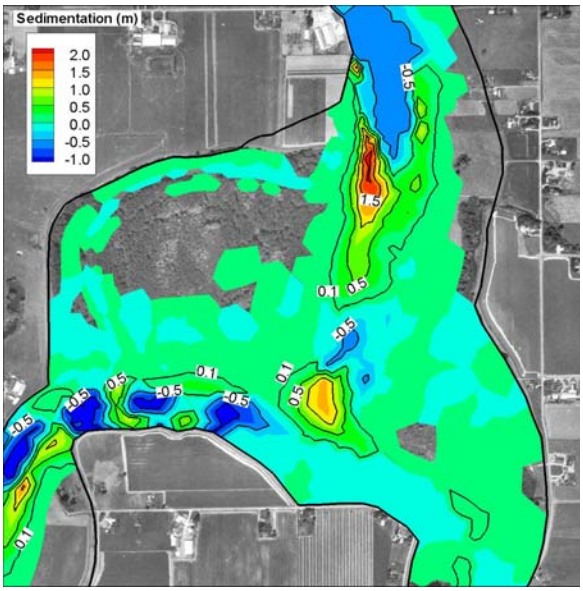
Existing Conditions



Alternative 1



Alternative 2



Alternative 3

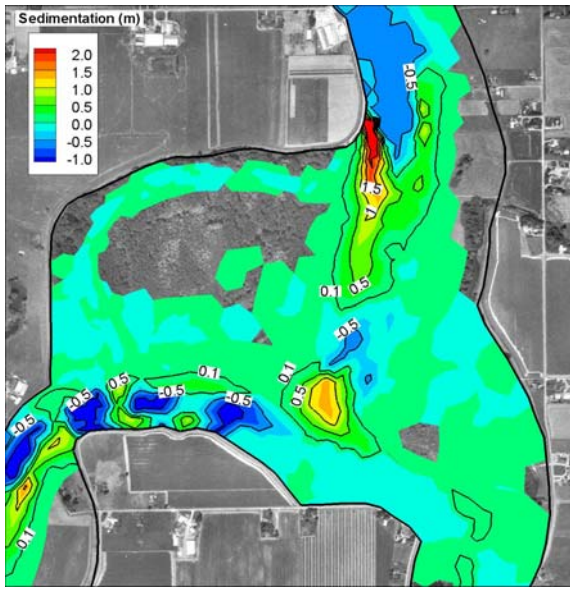


FIGURE 5-6
Sedimentation Distribution of Existing Conditions and Restoration Alternatives—25-yr Flood Flow Conditions
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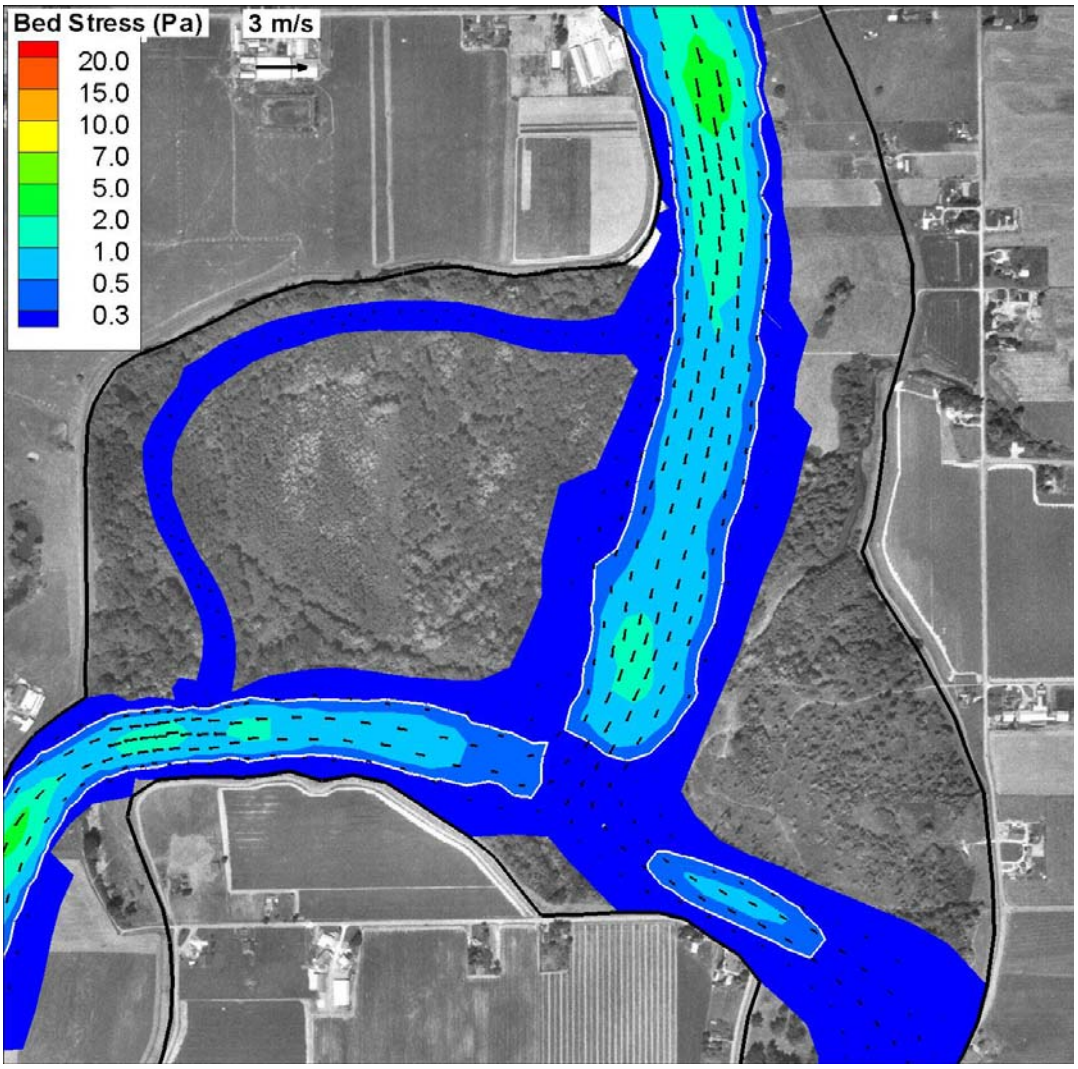

FIGURE 5-7
Surface Velocity and Bed Shear-Stress Distribution of Alternative 3—Low-Flow Conditions

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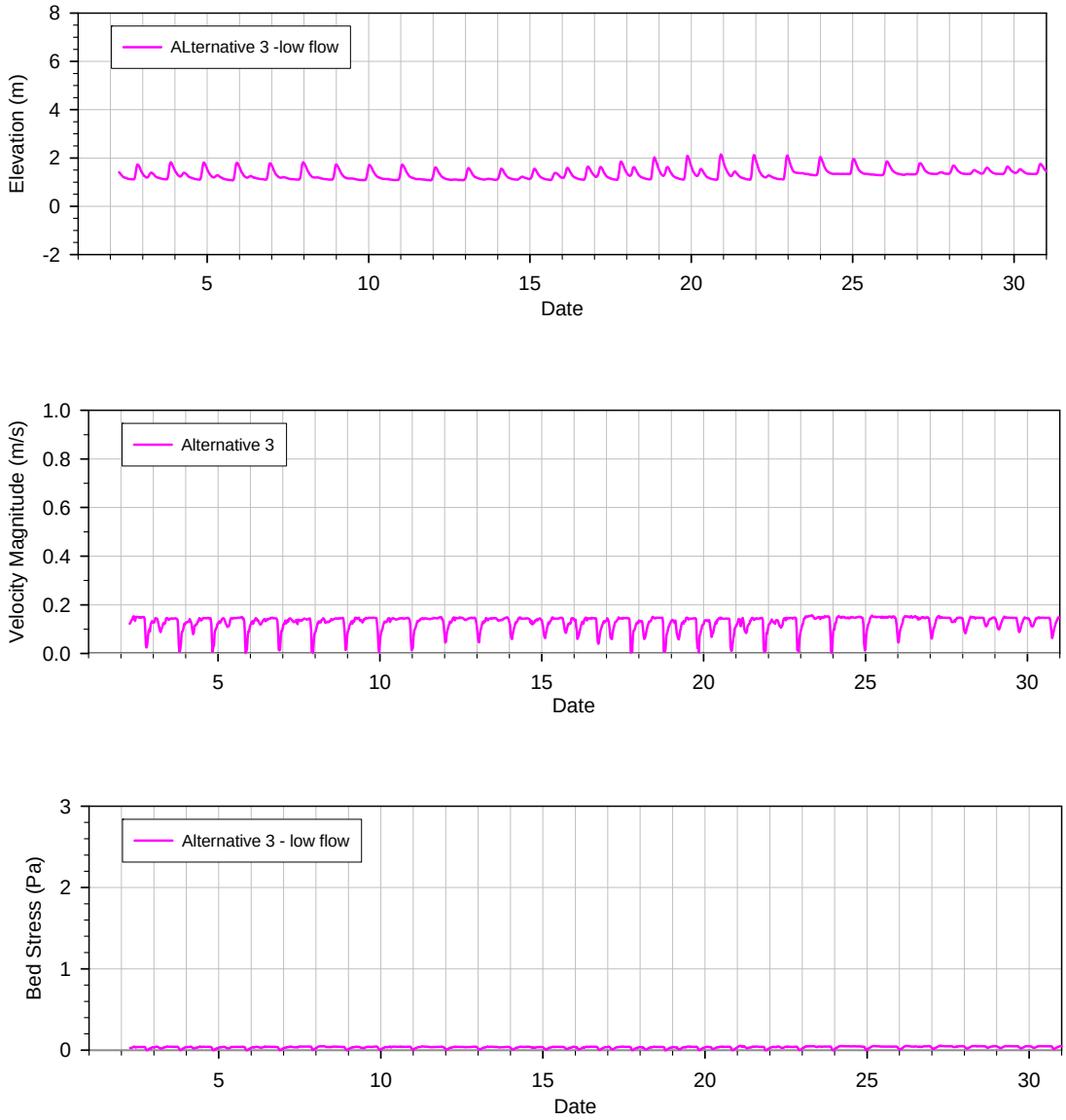

Note: Channel-bed elevation at S3

- Water-surface elevation is relative to MSL.
- Alternative 3: -1.0 m (3.28 ft) below MSL

FIGURE 5-8

Predicted Water-Surface Elevation, Velocity, and Bed Stress at Station S3

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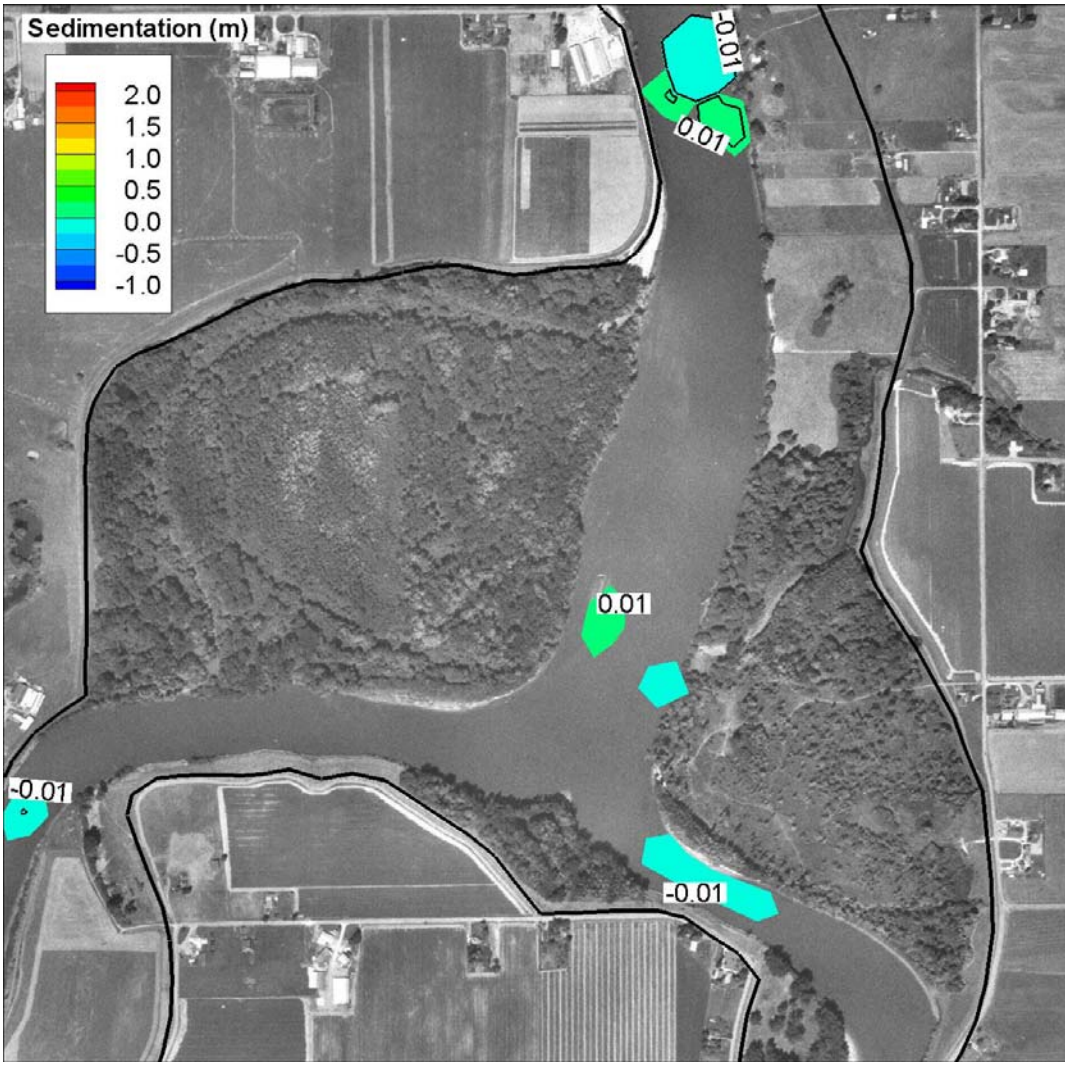

FIGURE 5-9
Sedimentation Distribution of Alternative 3—Low Flow Condition

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6.0 Summary and Conclusions

A hydrodynamic and sediment transport model was developed for the Cottonwood Island Restoration Feasibility Study. The objective of this study was to evaluate whether the proposed restoration of Cottonwood Island is feasible with respect to hydrodynamic and sediment-transport processes at the restoration site. The goal of the proposed restoration at Cottonwood Island is to restore the hydraulic connection and flow through a historic "west channel" around the west bank of Cottonwood Island. Proposed actions include dike setback, dredging, and channel modifications. Hydrodynamic feasibility assessment, therefore, focuses on the capability of the proposed restoration to provide the required access through re-connection, to maintain desirable juvenile fish habitat, and to minimize potential re-sedimentation in the restored west channel.

The hydrodynamic and sediment transport model for the Cottonwood Island site was developed by refining the Skagit Bay model that was developed previously for the Rawlins Road Restoration Study for SWC. The model was constructed using the finite-volume unstructured hydrodynamic model, FVCOM, developed by the University of Massachusetts. The model was driven by a combination of tides, river discharges, and surface-wind stresses and was validated using tide elevation, current, and salinity data measured at Skagit Bay and the North Fork station for the period of 6/6/2005 to 6/21/2005. The wetting and drying process in Cottonwood Island and the over-bank of the river channel was successfully simulated by the model. The validated model was used to simulate flood inundation, river currents, bed shear stress, suspended sediment concentration, and sedimentation in the study area for the existing conditions using six representative flood hydrographs and low-flow conditions. Then, the model was applied to evaluate the hydrodynamic and initial morphological response to three restoration scenarios in the Cottonwood Island study area. The potential effect on sediment transport in the Cottonwood Island area under the restoration scenario was evaluated for proposed restoration alternatives based on the predicted erosion and sedimentation patterns relative to the existing conditions.

The existing model results showed that the hydrodynamic behavior in the Cottonwood Island area is mainly controlled by levee, channel geometry, and bathymetry. The tidal influence was not significant for most flow conditions, except during low flow. The simulation result for the existing conditions demonstrated that the observed sandy deposits blocking the west channel entrance might be caused by sedimentation of sand materials eroded from upstream reaches of the river. Also, the model results showed that the sedimentation rate in the west channel is small. It is noted, however, that long-term sedimentation was not estimated in this study and could be important in terms of maintenance dredging needs.

Restoration alternatives considered in this study were as follow.

- Alternative 1: Dike setback and reconnection of west channel.
- Alternative 2: Dike setback with dredging of west channel.
- Alternative 3: Dredging of west channel only (no dike setback).

In Alternative 1, the dike was retuned to the original location, and the channel was reconnected. The dike setback without any dredging did not significantly affect hydrodynamics and sedimentation compared to existing conditions. Alternative 2 included dredging of the west channel in addition to dike setback. While widening and deepening of the channel provided encouraging results, it also showed that the dike setback was negligible. Alternative 3 provides the required performance and is attractive because it achieves the objectives without the complications associated with dike setback. However, the model results also indicated a possibility of re-sedimentation and blocking of the west channel following restoration actions.

The specific conclusions of the study based on the results of hydrodynamic and sediment transport modeling for the existing and restored conditions are as follows:

- The Cottonwood Island study area is partially or completely inundated by 10-yr (112,000 cfs) and 25-yr (142,000 cfs) flood flows. Under average flow (16,500 cfs) and low-flow conditions (8,000 cfs), the west channel remained dry. The 1-yr (52,000 cfs), 2-yr (74,000 cfs), and 5-yr (94,000 cfs) flood flow can fill water in the west channel.

- The highest sedimentation was predicted to occur near the upstream entrance of the west channel. The sedimentation pattern produced matches the historic behavior observed, which led to sedimentation and eventual closure of the entrance of the west channel.

- The simulation of Alternative 1, with dike setback action, provided a surprising result in that hydrodynamics and sedimentation in the Cottonwood Island area were not significantly changed by dike setback. In other words, based on existing topography in which the main channel is constrained upstream and downstream of the project site, the dike-setback alternative provides little benefit.

- The potential for restoring the connection to the west channel by removing sediment deposits and dredging the west channel were demonstrated through Alternative 2.

- Alternative 3 appears to be the most attractive option because it provides the required performance of restoring flow and connection to the west channel for most flow conditions. Also, it does not require dike setback. It reduces the re-sedimentation at the entrance of west channel in some degree compared to other alternatives under a high-flow condition. In a low-flow condition, no significant sedimentation was predicted near the entrance.

- Simulation results show that the west channel can be successfully restored in habitat functionality regarding flow connectivity of the off-channel slough in a low-flow condition by dredging the channel up to an optimal elevation for juvenile fish habitat below the low-water level. However, in the long term, there is potential for blocking the opening at the head of the west channel. Based on the simulation results, sediment re-deposition may occur near the west-channel entrance as long as the sediments are supplied from upstream.

- The optimal flow velocity (< 0.3 m/s) for juvenile salmon can be achieved in the restored west channel for most flow conditions by designing appropriate channel depth and elevation.

- After restoration, maintenance dredging may be required to verify west-channel functionality and sustainability. It may be necessary consider modeling or monitoring activities necessary to estimate the channel sedimentation rate and the frequency of dredging after restoration for proper maintenance.

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