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Sediment Transport into the Swinomish Navigation Channel, Puget Sound—Habitat Restoration versus Navigation Maintenance Needs

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Abstract: The 11 mile (1.6 km) Swinomish Federal Navigation Channel provides a safe and short passage to fishing and recreational craft in and out of Northern Puget Sound by connecting Skagit and Padilla Bays, US State abbrev., USA. A network of dikes and jetties were constructed through the Swinomish corridor between 1893 and 1936 to improve navigation functionality. Over the years, these river training dikes and jetties designed to minimize sedimentation in the channel have deteriorated, resulting in reduced protection of the channel. The need to repair or modify dikes/jetties for channel maintenance, however, may conflict with salmon habitat restoration goals aimed at improving access, connectivity and brackish water habitat. Several restoration projects have been proposed in the Skagit delta involving breaching, lowering, or removal of dikes. To assess relative merits of the available alternatives, a hydrodynamic model of the Skagit River estuary was developed using the Finite Volume Community Ocean Model (FVCOM). In this paper, we present the refinement and calibration of the model using oceanographic data collected from the years 2006 and 2009 with a focus on the sediment and brackish water transport from the river and Skagit Bay tide flats to the Swinomish Channel. The model was applied to assess the feasibility of achieving the desired dual outcome of (a) reducing sedimentation and shoaling in the Swinomish Channel and (b) providing a direct migration pathway and improved conveyance of freshwater into the Swinomish Channel. The potential reduction in shoaling through site-specific structure repairs is evaluated. Similarly, the potential to significantly improve of brackish water habitat through dike breach restoration actions using the McGlinn Causeway project example, along with its impacts on sediment deposition in the Swinomish Navigation Channel, is examined.

Keywords: hydrodynamics; sediment transport; nearshore restoration; dredging; dike alteration; FVCOM; Puget Sound; Salish Sea

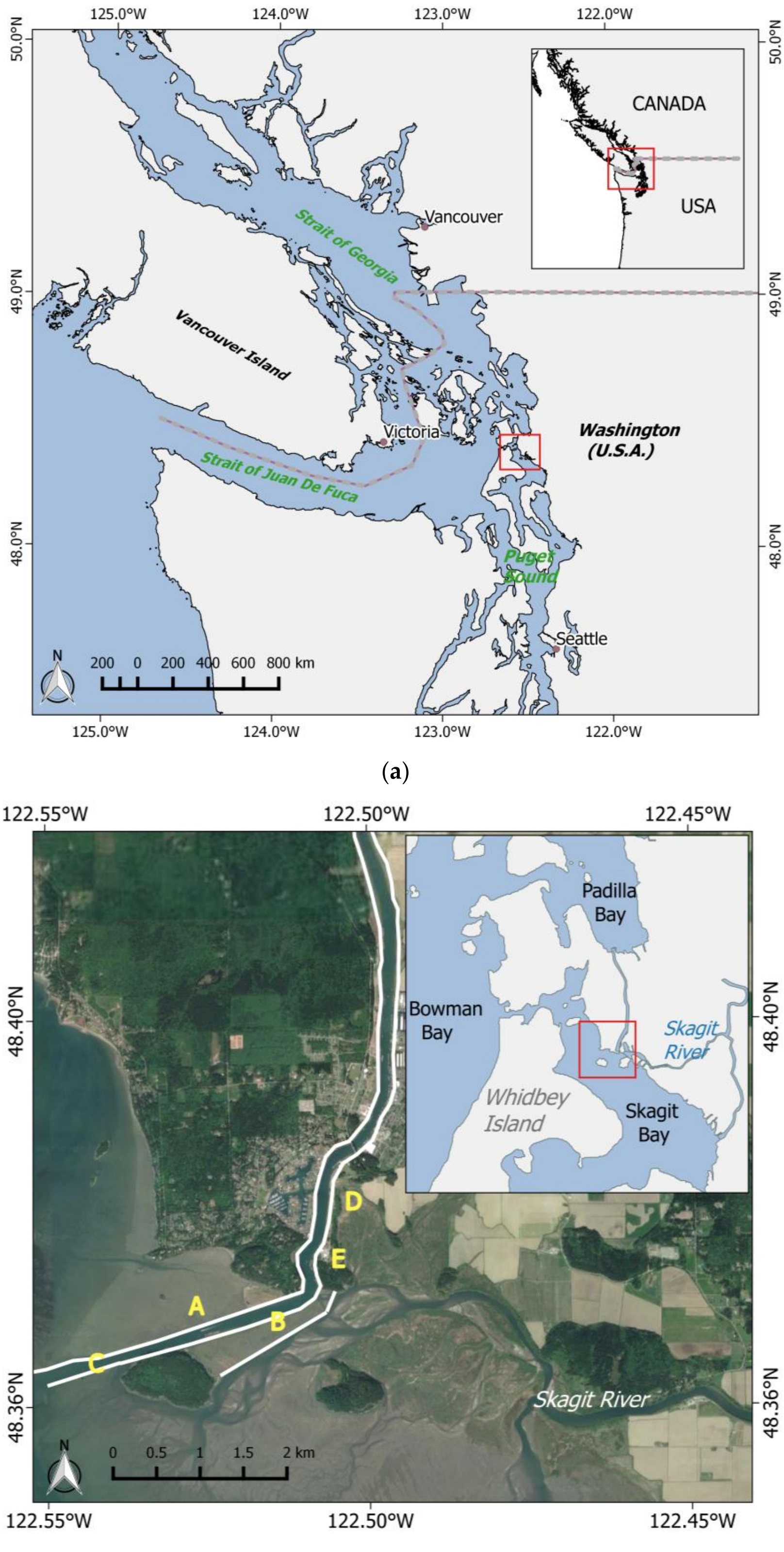
1. Introduction

The Swinomish Navigation Channel is located near the mouth of the Skagit River estuary, which is the largest river in the Salish Sea estuarine system consisting of Puget Sound, Strait of Juan De Fuca, and Georgia Strait (Figure 1a). The Skagit River estuary is a macro-tidal environment with a tidal range of 4 m and fluctuations around −1 to 3 m during spring tide and −0.5 to 2.5 m during neap tide relative to NAVD88. It has mixed semi-diurnal and diurnal tidal forcing and significant diurnal inequalities. The Skagit drainage basin delivers approximately 39 percent of the total sediment discharged to Puget Sound [1] and could, at times, account for more than 50 percent of the freshwater inflow [2]. The Skagit River Delta provides rich estuarine and freshwater habitats for salmon and many other fish and wildlife species. Over the past 150 years, economic development in the Skagit River Delta has resulted in significant losses of fish and wildlife habitat and alteration of habitat sustaining processes, particularly resulting from the construction of dikes and levees for agricultural land use. The dikes have impeded fish passages through the area and greatly reduced nursery habitat for many fish and invertebrate species [3]. The dikes have also diverted freshwater away from the dike-front region that was historically a productive brackish marsh that fostered alongshore habitat connectivity. Therefore, marsh habitat has been lost, and the dike-front region has deteriorated into tide-flat conditions with increased salinity (20 to 25 ppt) devoid of vegetation. In response, several habitat restoration projects/alternatives have been proposed in this basin. The 2006 Skagit Chinook Recovery Plan identified a total of 26 nearshore restoration opportunities in the Skagit delta [4]. These projects strive to restore hydrologic and hydrodynamic functions in the tidal marshlands largely through shoreline modifications such as dike breaching, dike setback, and dike removal. The numeric criteria for restoration-site hydrodynamic performance are species specific, vary from site to site, and are typically categorized in broad rules such as (a) desired minimum inundation depth and frequency (e.g., >0.3 m and >50% of time); (b) salinity range (e.g., 5–15 ppt); and (c) peak velocity (e.g., <0.5 m/s).

A series of engineering activities have also occurred associated with the development of the Swinomish (Navigation) Channel. It is a 11 mile (1.6 km) long, 100-foot (30.5 m) wide, and 12 feet (3.7 m or 4.6 m/NAVD88) deep channel between Skagit Bay to the south and Padilla Bay to the north that was initially completed in in 1936. Once constructed, the project established short and safe route for vessels traveling between inner Puget Sound and the Straits of Georgia and Juan De Fuca (see Figure 1b). For Skagit River, which is the largest of Puget Sound tributaries that supplies approximately 2.8 million tons of sediment per year to the Skagit Bay [5], shoaling in the Swinomish channel has always been an issue. To secure navigability through this corridor, four training structures were constructed to confine flows and impede sediments from entering the Swinomish Channel from the Skagit River North Fork delta. Figure 1b shows the Skagit River Estuary study area along with the Swinomish Channel and the training structures.

In recent years, functionality of the navigation features of the Swinomish Channel has deteriorated due to excessive shoaling. The reliability of the channel is tied to the condition of the navigation training structures designed to minimize shoaling. These dikes have deteriorated and undergone several modifications. Recent condition surveys (2014) indicate that channel depths are less than 5 feet (1.5 m or 2.4 m/NAVD88) below mean lower low water (MLLW) at certain locations in the reach between Skagit Bay and McGlinn Island. The U.S. Army Corps of Engineers (USACE) responsible for maintenance of the navigation channel is currently investigating alternatives to reduce the operations and maintenance (O&M) dredging demands over the next 50 years. Construction of the Swinomish Channel and the associated jetty and dikes have changed this waterway from a highly complex, braided deltaic distributary wetland to a simplified channel bounded by dikes. These changes have also resulted in loss of connectivity between habitat forming processes and functions associated with freshwater flows of the Skagit River and the estuarine transitioning environment of the Swinomish Channel to Skagit and Padilla Bays.

Detailed understanding of the circulation and hydrodynamic conditions in the Skagit River estuary, and its interaction with Padilla Bay to the north and Saratoga Passage to the south are only beginning to emerge through short-duration synoptic measurements of currents, tides, salinities, and temperatures [6–8]. A three-dimensional (3D) hydrodynamic model of the Skagit River estuary including Skagit Bay, the North Fork, the connection to Padilla Bay through Swinomish Channel, and the braided network associated with the South Fork was developed previously to assist with restoration feasibility assessments [9]. The model was developed using the Finite Volume Coastal Ocean Model (FVCOM) code [10], and includes a detailed representation of the tide flat bathymetry, river-training dikes and jetty, Swinomish Channel, and Skagit Bay.



(b)

Figure 1. Study area showing, (**a**) Northern Puget Sound area and (**b**) Swinomish Channel near the mouth of Skagit River estuary, located in Whidbey Basin, Puget Sound, Washington. (A) North Dike; (B) McGlinn Island to Goat Island Jetty; (C) South Jetty; (D) McGlinn Island to Mainland causeway, (E) McGlinn Island.

In this paper, we present the refinement and calibration of the model using oceanographic data collected from the years 2006 and 2009 with a focus on the sediment and brackish water transport from the river and Skagit Bay tide flats to the Swinomish Channel. The primary objective is to develop the model for use in the design of repair and modifications to structures to improve the reliability of the Swinomish Channel. However, the availability of the model also allows examination of potential opportunities for achieving the desired dual outcome of (a) reducing sedimentation and shoaling in the Swinomish Channel and (b) providing a direct migration pathway and improved conveyance of freshwater into the Swinomish Channel. A sensitivity test style application of the model is presented using two dike modification scenarios for a comparative assessment. The feasibility of achieving desired outcome of reduction in shoaling through site-specific jetty repairs is analyzed. Similarly, potential to increase sediment deposition due to dike breach restoration scenarios at McGlinn Causeway project site is also examined.

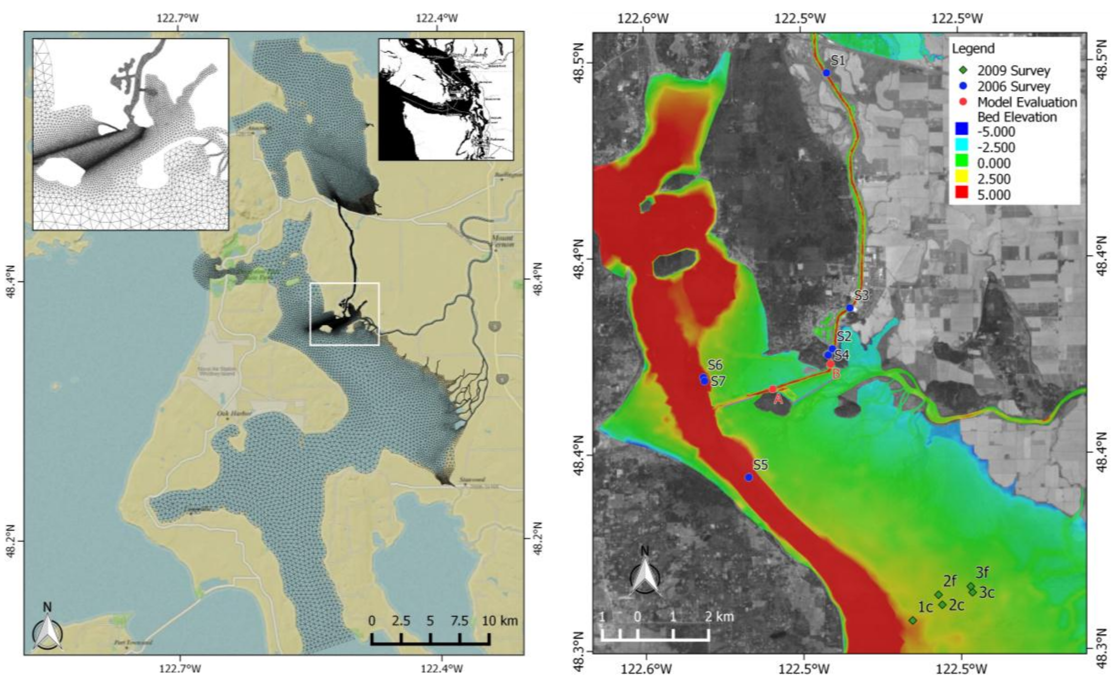
Despite best intentions, efforts to restore near-shore habitats can result in poor outcomes for area land uses and local community infrastructure if water circulation and sediment transport are not properly addressed. Response of natural processes to physical changes are often nonlinear, and land-use constraints can lead to selection of restoration alternatives that may result in undesirable consequences for the built environment, such as flooding, deterioration of water quality, and erosion, that require immediate remedies and costly repairs. In the case of Swinomish Channel, the projects could lead to increased sedimentation and maintenance dredging. Through this case study, we demonstrate the feasibility and importance of using large-scale (estuary-wide) 3D hydrodynamic and sediment transport models with local refinements down to fine scale (10 m dike sections) for assessment of and design shoreline modification projects. While FVCOM hydrodynamic model has been used extensively over the world its application for sediment transport and use for habitat restoration are relatively new. The contribution of this paper is the demonstration that FVCOM-sediment transport module may be used effectively in support of nearshore restoration and shoreline modification assessment to address feasibility concerns related to sedimentation along with other hydrodynamic processes.

2. Materials and Methods

For this study, we selected data from a survey in 2006 during which numerous stations in the Swinomish Channel region pertinent to this assessment were available. Oceanographic data was collected at several locations in Skagit Bay and the Swinomish Channel by U.S. Geological Survey (USGS) from 1 May 2006 to 31 May 2006 [8]. Additional data was also collected in 2009, as part of an Office of Naval Research sponsored effort to study sediment transport over tidal flats when Woods Hole Oceanographic Institute (WHOI) [11] conducted an extensive field campaign with fixed and shipboard observations. This study was designed for high-resolution measurements of current profiles, salinity, temperature, and acoustic and optical back scatter. Suspended sediment concentrations (SSC) measured from the surface and bottom layers were used to calibrate optical and acoustic sensors. This data and the associated sediment transport model from WHOI study were selected for use in this assessment. The approach was to first improve the model grid and domain coverage, upgrade the bathymetric representation using latest surveys and calibrate the hydrodynamic model to data from the 2006 USGS survey. Following hydrodynamic calibration, conduct the model setup for Year 2009 conditions corresponding to WHOI data collection period and complete the sediment transport model validation.

2.1. Hydrodynamic Model of the Skagit River Estuary with the Swinomish Channel

An improved version of the hydrodynamic model of the Skagit River estuary by Yang and Khangaonkar [9,11] was used in this study. The model uses finite volume community ocean model (FVCOM) code [12] and solves the three-dimensional momentum, continuity, temperature, salinity, and density equations in an integral form by computing fluxes between non-overlapping, horizontal, and triangular control volumes. A 30-layer sigma-stretched coordinate system was used in the vertical plane with unstructured triangular cells in the lateral plane. The model employs the Mellor Yamada level-2.5 turbulent closure scheme for vertical mixing [12] and the Smagorinsky scheme for horizontal mixing [13]. The original model of Skagit River estuary was improved through grid refinement and domain expansion to allow better characterization of the exchange between Skagit Bay and Padilla Bay through the Swinomish Channel. The high-resolution grid refinement focused primarily on the marsh habitat and tidal flat regions, including restoration sites. To simulate the tidal-wave propagation and salinity intrusion properly in the multi-channel and tide-flat area, finer grid cells were specified in the intertidal channels, the marshlands near the habitat restoration sites, and between the tributary sloughs. The prior model domain of Skagit Estuary was expanded to include Padilla Bay through the connection of the Swinomish Channel to Skagit Bay. Like Skagit Bay, a large tide flat important for providing near-shore fish habitat exists in Padilla Bay. To represent the Padilla Bay tide flats accurately, we obtained detailed bathymetric data that had been compiled by Western Washington University (WWU) based on historical data collected by the National Oceanic and Atmospheric Administration (NOAA) by the National Ocean Service and the historic U.S. Coast and Geodetic Survey. Bathymetric data collected for the Padilla Bay National Estuarine Research Reserve was applicable to the Fidalgo Bay region. A navigation channel appearing to be a dredged extension of the Swinomish Channel exists in the shallow tide flats region in Padilla Bay and has also been incorporated in the model geometry. The model grid was constructed with details to resolve such key features as well as other main tidal channels in Padilla Bay. The intertidal bathymetry near the mouth of the North Fork of Skagit River was updated using a combination of Lidar data and boat-based surveys conducted by USACE and USGS in 2012 and 2014. Figure 2a below shows the Skagit River estuary model with a closeup of the Swinomish Channel region. The updated model grid has 26,248 nodes, 59,329 elements and 30 sigma-layers.



(**a**) (**b**)

Figure 2. (**a**) The Skagit River estuary model grid with expanded domain covering Padilla Bay to the north and Saratoga Passage to the South with the Swinomish Channel connecting the two basins; (**b**) the locations of May 2006 (blue circles), WHOI study mooring stations during June of 2009 [13] (green diamonds), and for scenario evaluation (red circles).

As a first step, the performance of the model with the refined grid in the Swinomish Channel region was tested against the data from the Swinomish Channel region collected in 2006 by USGS [8]. Skagit River inflow data were obtained from a USGS stream gage about 25 km upstream of the estuarine mouth, at Mt. Vernon, WA, USA. Wind data were obtained from University of Washington Weather Research and Forecasting results. We used spatially uniform wind magnitude and direction for wind forcing. Tidal elevations at the model open boundaries at Saratoga Passage, Deception Pass/Bowman Bay, Guemez Channel/Anacortes, and Chucknaut/Padilla Bay were obtained from a harmonic tide prediction software (XTIDE) based on NOAA's National Oceanic Service algorithms (http://www.flaterco.com/xtide/). Figure 3 shows a comparison of observed and simulated currents at two of the Swinomish Channel locations along with tides and salinity. Model performance was evaluated using error statistics such as absolute mean error (*AME*), root-mean-square error (*RMSE*) and model skill (*SS*) (Table 1). The *AME* and *RMSE* of time series with *N* elements are defined as

$$AME = \frac{1}{N}\sum\left|(X_{\text{mdl}} - X_{\text{obs}})\right| \tag{1}$$

$$RMSE = \sqrt{\frac{\sum(X_{\text{mdl}} - X_{\text{obs}})^2}{N}} \tag{2}$$

Model skill metric was adopted from Willmott [14] and is defined as

$$SS = 1 - \frac{\sum(X_{\text{mdl}} - X_{\text{obs}})^2}{\sum\left(\left|X_{\text{mdl}} - \overline{X_{\text{obs}}}\right| + \left|X_{\text{obs}} - \overline{X_{\text{obs}}}\right|\right)^2} \tag{3}$$

where X_{mdl} and X_{obs} are the values from the model and observations, and an overbar represents a time average.

Primary conclusion from this initial effort was that grid resolution and bathymetry in the Swinomish Channel region were sufficient to reproduce observed currents for use in sediment transport modeling. Error statistics are shown in Table 1 below. Note that his preliminary application was conducted using 10 layers. To improve salinity predictions and near-bed shear stress, a 30-layer model setup was selected for the setup and calibration of the sediment transport model presented in the next section.

Table 1. Hydrodynamic model calibration error statistics, May 2006.

Station	Water Surface Level, m			Velocity, m/s			Salinity, ppt		
	AME [1]	RMSE [2]	SS [3]	AME	RMSE	SS [3]	AME	RMSE	SS [3]
S1	–	–		u [3]:0.20; v:0.29	u:0.24; v:0.32	0.85 0.84	–	–	
S2	–	–		u:0.32; v:0.34	u:0.37; v:0.42	0.60 0.52	–	–	
S3	–	–		–	–		2.40	3.16	0.40
S4	0.31	0.38	0.96	–	–		1.73	2.24	0.42
S5	0.32	0.39	0.95	u:0.34; v:0.22	u:0.42; v:0.26	0.55 0.77	–	–	
S6	0.26	0.32	0.94	–	–		–	–	

[1] *AME* = absolute mean error, [2] *RMSE* = root mean square error, [3] *SS* = skill score, *u* and *v* are velocity components in the *x* and *y* (east and north) directions respectively.

Not included in this table are model bias values for currents that were relatively small and varied from −0.02 m/s to 0.08 m/s for "*u*" and "*v*" components at stations S1, S2, and S5.

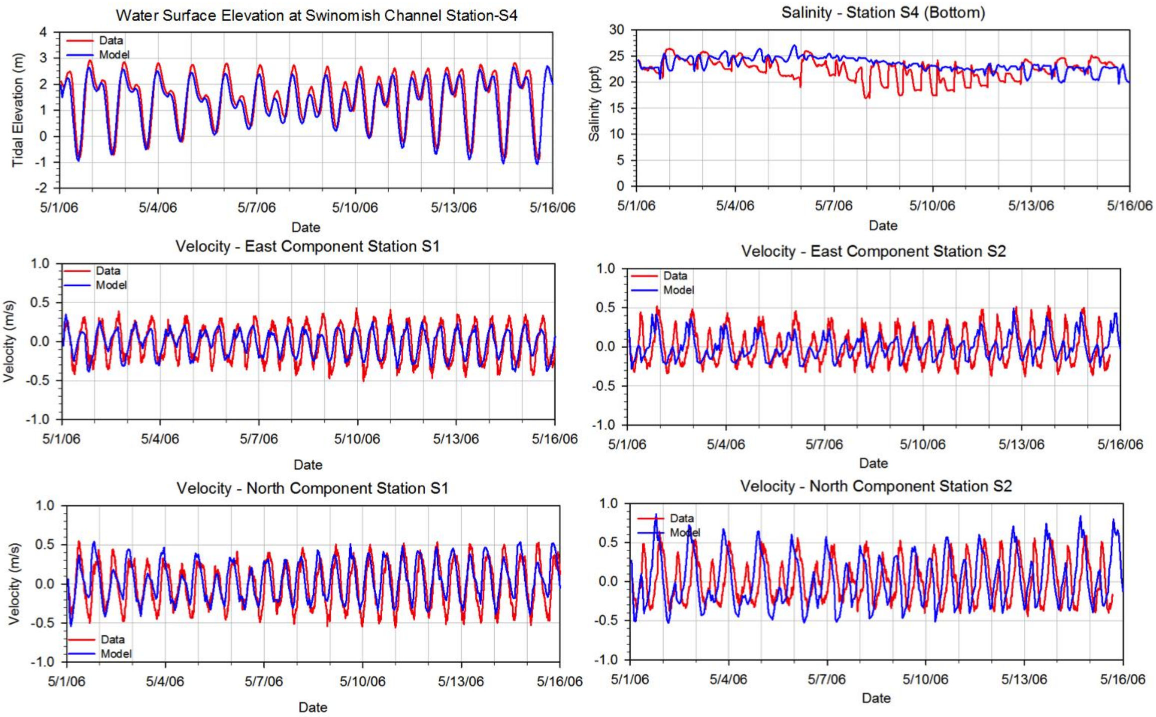


Figure 3. Comparison of observed tide, salinity, and currents in the Swinomish Channel (Figure 2b) shown as example at stations S1, S2, and S4 during May of 2006 as part of hydrodynamic model setup and calibration.

2.2. Sediment Transport Model of the Skagit River Estuary with the Swinomish Channel

2.2.1. Skagit River Sediment Load and Deposition Characteristics

USGS maintains a permanent monitoring gage at Mt. Vernon, Washington (USGS 12200500) on the mainstream of Skagit River, located at River Miles (RM) 15.7. Strong daily flow variation in river flow is observed and is attributed to daily peaking mode operations at the upstream hydropower projects. To facilitate analysis over a long period representative of current conditions, a 24 year record of flow data was extracted from the Mt. Vernon gage archives. During this period, the highest flow recorded was 142,000 cubic feet per second (cfs) (4024 m^3/s) that occurred in November of 1990, and the lowest flow was 3600 cfs (102 m^3/s) recorded in October of 2006. The average flow during this period was 16,462 cfs (467 m^3/s). Figure 4 shows a Skagit River flow hydrograph from 1988 to 2010.

Using a combination of total suspended solids (TSS) grabs and turbidity measurements for fine sediment (i.e., silt- and clay-sized particles smaller than 0.0625 mm) and fine- to medium-sized sand (0.0625–0.5 mm), USGS developed a suspended sediment-rating curve for the Mt. Vernon site by Curran et al. [15] as follows:

$$S = 1 \times 10^{-5} \times Q^{2.32} \qquad Q < 27{,}400 \text{ cfs } (776 \text{ m}^3{\cdot}\text{s}^{-1}) \tag{4}$$

$$S = 3 \times 10^{-13} \times Q^{3.74} \qquad 27{,}400\ (776 \text{ m}^3{\cdot}\text{s}^{-1}) < Q < 66{,}100 \text{ cfs } (1872 \text{ m}^3{\cdot}\text{s}^{-1}) \tag{5}$$

$$S = 4.53 \times 10^{-2} \times Q^{1.41} \qquad Q > 66{,}100 \text{ cfs } (1872 \text{ m}^3{\cdot}\text{s}^{-1}) \tag{6}$$

where S = sediment load in tons/day, and Q = Skagit River flow at Mt. Vernon in cubic feet per second (cfs).

Based on this 24 year record, the Skagit River averages a sediment discharge of nearly 4 million tons/year sediment, at an average TSS concentration of 162 mg/L. A time series of TSS at Mt. Vernon estimated using the above regressions is also presented in Figure 4 for the period 1988 to 2010.

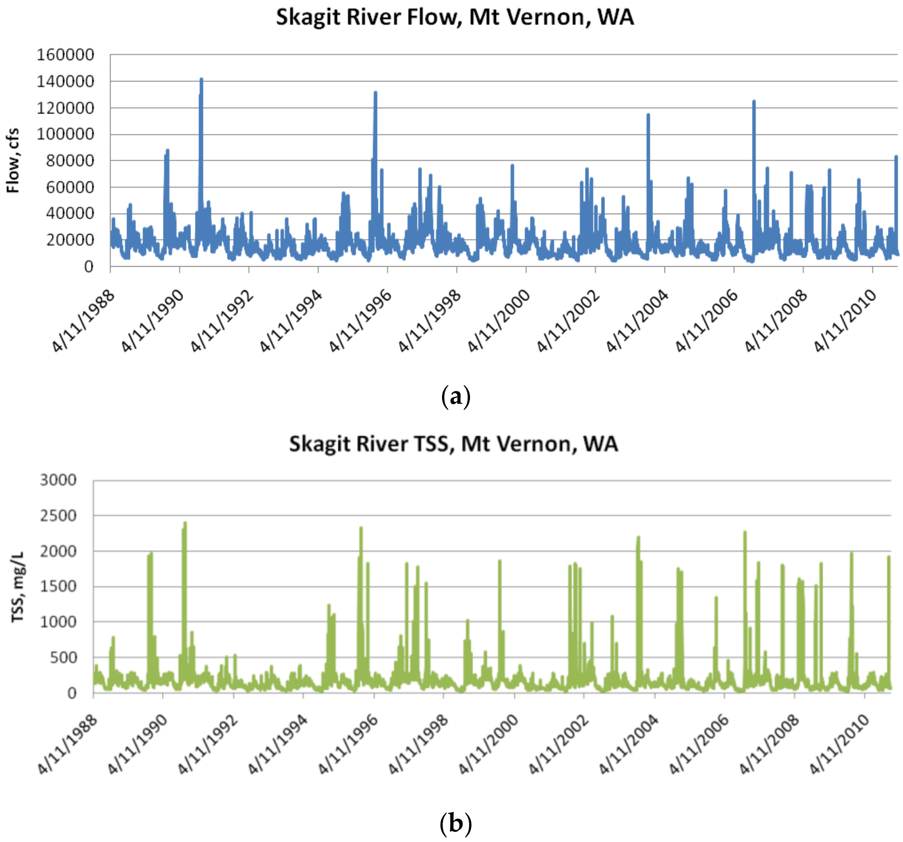


Figure 4. Skagit River daily (**a**) average flow and (**b**) estimated TSS at Mt. Vernon, Washington.

In addition to the sediment load, the USGS study by Curran et al. [15] also provided grain size distribution information based on analysis of water column grab samples also collected at Mt. Vernon gage. Their results indicate that more than 50% of sediments have a grain size smaller than 0.0625 mm. This class of sediment belongs to silt and clay class and is often transported as suspended or wash load. The remaining sediment is distributed in various grain sizes. However, only about 3% of the total sediments are in 0.5–1 mm range and are transported as bedload.

Based on examinations of available data on TSS in combination with bed sediment properties and bed elevations, estimates of sediment load and channel erosion or accretion in the Skagit and Padilla Bay system have been developed. USACE conducted a Flood Hazard Mitigation Study [16], during which considerable bed sediment information was collected. The sediment types in the forks and the upstream reaches were primarily medium to coarse sand. The mean bed sediment diameters in the North and South Forks were 0.46 and 0.6 mm, respectively. The mean diameter in the Cottonwood Island region near the confluence of North and South Forks and the upstream reach was reported as 0.6 mm. Examination of past surveys performed by West Consultants [17] indicates that a significant accretion has occurred throughout the North Fork reach below the confluence near Cottonwood Island from 1975 to 1999. The average accretion rate in the North Fork reach RM 4.5 to 8.85 was 2 cm/year. Average accretion rate in the South Fork reach was 1.25 cm/year.

Very little information is available on the accretion rates in Skagit and Padilla Bay tide flats. WWU established a network of 23 Surface Elevation Table (SET) sites in Padilla Bay during the summer of 2002. Data collected from the SETs through 2006 revealed a bay-wide mean surface elevation change of -0.15 ± 0.15 cm/year relative to the subsurface datum indicating sediment erosion and loss of sediment through most of Padilla Bay except three sites near the mouth of the Swinomish Channel where deposition of 0.13 cm/year was noted [18]. This indicates that most of the sediment delivered by Skagit River remains within Skagit Bay and is not transported to Padilla Bay through the Swinomish Channel. As part of this study, a sediment trap was established near the mouth of Skagit River. This well-known depositional area recorded a bed elevation change of 8 cm/year based on a 15 day deployment from 18 November 2008 to 3 December 2008, during which the average river flow was 12,000 cfs (340 m^3/s).

Coastal Geological Services conducted a sedimentation study of Swinomish Channel. Shoaling rate analysis was conducted to assess the rates and patterns in which the Swinomish Channel bed was filling up because of sediment loads from connecting water bodies and surrounding uplands [19]. Their analysis based on examination of pre-and post-dredging records showed an average bed accretion rate of 28 cm/year during the period from 2004 to 2008 in the Swinomish Channel. This value is representative of the sedimentation rate of area at the mouth and sedimentation rates at other locations in the channel were even higher. Previous estimates of sediment deposition rates in the study domain are summarized in Table 2. A shoaling analysis conducted by USACE in the southern reach of the Swinomish Channel based on annual channel conditions surveys from 2008 to 2015 indicates that approximately 34,000 cubic yards (25,995 m^3) per year on average are deposited in the channel that require dredging.

Table 2. Sediment accretion estimates in the Skagit River Estuary and Padilla Bay. (*g.d.w.* stands for gram dry weight, and *s.d.* stands for standard deviation).

Source	Description	Study Results	Representative Sediment Accretion Rate Estimate cm/Year
Khangaonkar et al. [20]	Preliminary estimate of sediment accretion rate using annual average sediment load (3,962,084 tons/year based on average of load from 1988 to 2010)	Skagit Bay and Swinomish Channel: Uniform distribution and deposition of sediments in Skagit Bay study area of (1.6×10^8 m^2, porosity of 0.4, and density of 2650 kg/m^3)	Skagit Bay study domain including Swinomish Channel ≈2 cm/year
Rybczyk, J. [21]—EPA STAR Grant project (unpublished data)	Sediment Trap and Feldspar five marker horizons/grids at Skagit Bay Nearshore site: N 48°21′25.1″, W 122°28′33.8″. Accretion rate was noted over the markers during a 15 day period (11/18/08 to 12/3/08)	Skagit Bay Marsh: Mean accretion in sediment trap = 5.15 *g.d.w.* ± 2.3 (*s.d.*) = 334.6 g/m^2 in 15 days Bed elevation change 0.33 ± 0.23 (*s.d.*) cm/15 days	Skagit Bay nearshore Station—Accretion from the 15-day sample in 2008, ≈8 cm/year
Kairis and Rybczyk [18]	Rate of elevation change derived from the linear regression of surface elevation changes at multiple sites in Padilla Bay from 2002 to 2010	Padilla Bay: Most sites in Padilla show erosion except the three below 12 (b)—0.13 cm/year 14 (b) —0.12 cm/year 8–0.16 cm/year	Padilla Bay sediment accretion rates at selected sites ≈0.13 cm/year
Coastal Geological Services [19]	Swinomish Channel Sedimentation Study—Shoaling rate analysis using dredging records	Swinomish Channel: Analysis of dredging and survey records from two periods 2001–2003 and 2004–2008	Swinomish channel average accretion rate based on 2004–2008 records ≈28 cm/year
USACE [22] Skagit River Flood Risk Management General Investigation	Sediment Budget and Fluvial Geomorphology. Examination of Skagit River bed elevation changes	Skagit River, North Fork and South Fork: Comparison of surveyed cross sections between 1975 and 1999.	Average accretion rate based on 24 year record, Skagit River (RM 10.1 to RM 18) ≈1.75 cm/year N.F. Skagit River (RM 4.5 to RM 8.85) ≈2 cm /year S.F. Skagit River (RM 5.8 to 9.25) ≈1.25 cm/year

2.2.2. Skagit River Sediment Transport Model Setup

The Skagit River Sediment Transport Model setup and validation was conducted using data collected by WHOI from 2009. The monitoring stations are shown in Figure 2b (green diamond). As described in Ralston et al. [11], instrument frames for high-resolution sampling within about 1 m of the bed were deployed at five locations in the intertidal zone. Near-bed instruments included pulse-coherent acoustic Doppler profilers (pcADPs), acoustic backscatter sensors (ABSs), acoustic Doppler veloci-meters (ADVs), conductivity-temperature (CT) sensors, and optical backscatter sensors

(OBSs), as well as upward-looking acoustic Doppler current profilers (ADCPs) and pressure sensors. Surface buoys at each station had CTs and OBSs for near-surface water properties, and two of the buoys had meteorological instrument packages for wind, air temperature, and barometric pressure. Near-bottom and near-surface water bottle samples were obtained to calibrate the optical and acoustic backscatter sensors, including samples collected at the instrument frames. Water samples were filtered, dried, and weighed to determine TSS, which were correlated with shipboard and moored acoustic and optical backscatter [13].

The sediment transport model used in this study is based on the Community Sediment Transport Model of Warner et al. [23]. Its capabilities include the ability to couple with wave models, multiple sediment classes, suspended and bedload computations, bed slope, morphology, and sediment density effects. Suspended sediment transport calculations are conducted through source and sink terms through vertical settling and exchange with bed layer. Exchange with bed is conducted using erosion flux formulation of Ariathurai and Arulanandan [24]. Bed load computations are conducted using the Meyer–Muller method [25]. The model was set up using three sediment classes consisting of fine silt, silt, and fine sand based on sediment samples collected from the tide flats. Bed roughness was set uniform with "z_0" of 1.5 mm and one sediment bed layer. Table 3 below provides a listing of the sediment model parameters used in this application.

Table 3. Sediment properties and model input parameters.

Model Parameter	Fine Silt	Silt	Fine Sand
Settling velocity, m·s^{-1}	0.1	1.0	10.0
Mean diameter, mm	0.014	0.04	0.14
Erosion rate, kg·m^{-2}·s^{-1}	1.2×10^{-5}	1.2×10^{-4}	1.2×10^{-3}
Critical stress for erosion, N·m^{-2}	0.05	0.08	0.15
Porosity	0.65	0.60	0.55
Fractional composition (river load and Initial sediment bed)	0.15	0.45	0.40

SSC at the river boundary was specified using a modified version of the USGS rating curve from Curran et al. [15] of the form

$$C = C_o \cdot \left(\frac{Q_r}{Q_{ro}} \right)^{1.4} \quad (7)$$

where C is the SSC (mg·L^{-1}), C_o is a reference concentration (165 mg·L^{-1}), Q_r is the discharge (m^3·s^{-1}), and Q_{ro} is the mean annual discharge (470 m^3·s^{-1}). This rating curve also matches the rating curve used by Ralston et al. [11].

2.3. Hydrodynamic and Sediment Model Validation

Simulated hydrodynamic and sediment properties such as velocity, salinity and TSS were compared with measured data from the 2009 WHOI study [11]. ADCP data were available at stations 3c, 2f and 1c for bottom velocity comparison (Figure 5). We compared the east (u) and north (v) bottom velocity components with model results. The bottom and surface current magnitudes predicted by the model appear to match the measured data reasonably well (SS of 0.52 to 0.85). However, the model seems to underpredict the bottom velocity at station 1c. This discrepancy may be because the station is located near the edge of the tide flat and model grid bathymetry may not have accurately captured the local channel depths and slopes. The effect of wetting and drying on tidal flats are included in the model simulation. This creates higher velocity in the tidal channels as they drain, but zero velocity when dry. This is seen in the time series at stations 3c and 2f, which show higher velocities and gaps indicating periods during which the associated cells became dry.

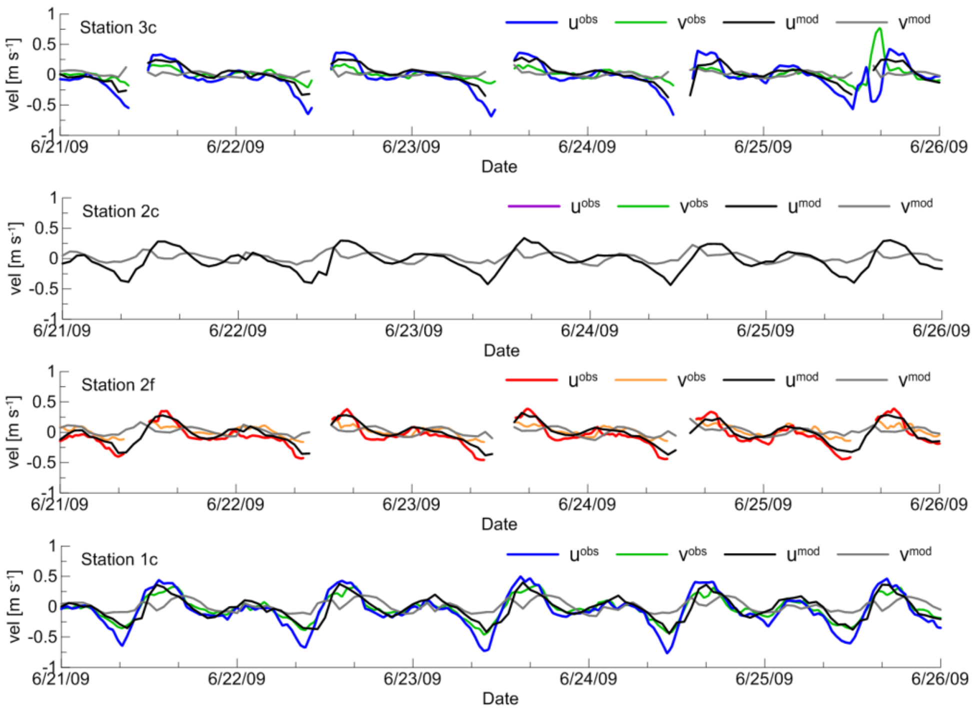


Figure 5. Comparison of bottom currents in Skagit tidal flats shown at stations 3c, 2c, 2f and 1c during June of 2009 as part of sediment model setup and calibration. (u^{obs} = observed east velocity component, v^{obs} = observed north velocity component, u^{mod} = modeled east velocity component and v^{mod} = modeled north velocity component).

Figure 6 shows the time series comparison of bottom stress at stations 2c, 2f and 3c. The model reasonably captures periodic peaks of bottom stress during peak ebb and low tidal conditions. The model underpredicts bottom stress at low tide for station 2c but it performs quite well for stations 3c and 2f. During this period, bottom velocity peak at 0.5 m/s creates high bottom stress and conditions suitable for high seabed erosion. These results indicate that accurate description of local bathymetry in an environment undergoing morphological change is important for accurate model predictions.

Examination of bottom shear stress was of major importance in the validation process due to its direct influence on sediment erosion and deposition process and corresponding measurable response in TSS concentration. The bed shear stress is calculated within FVCOM at each time step from the instantaneous bottom layer flow velocity using a logarithmic profile representation of the boundary layer. The formulation of bed shear stress is as follows:

$$\tau_b = \rho C_d |u_*|^2 \tag{8}$$

where ρ is sea water density, C_d is the bottom drag coefficient and $|u_*|$ is the critical shear velocity, which is related to bed roughness.

Figure 7 shows the comparison of observed TSS in Skagit Bay tide flats at stations 3c and 1c. The high bottom stress during peak ebb current periods over the tide flats results in significant increase of bed shear and corresponding increase in TSS, varying from 200 to 400 mg/L for stations 3c and 1c, respectively, as shown in Figure 7. Also shown in the plot are variations of bottom and surface salinity influenced by a combination of tidal circulation and river plume. The strong response of salinity due to freshwater plume can be seen at station 3c. The bottom salinity can be as low as 5 ppt during low tidal periods. Further offshore, station 1c shows that the influence of freshwater plume is weaker and higher salinities are noted.

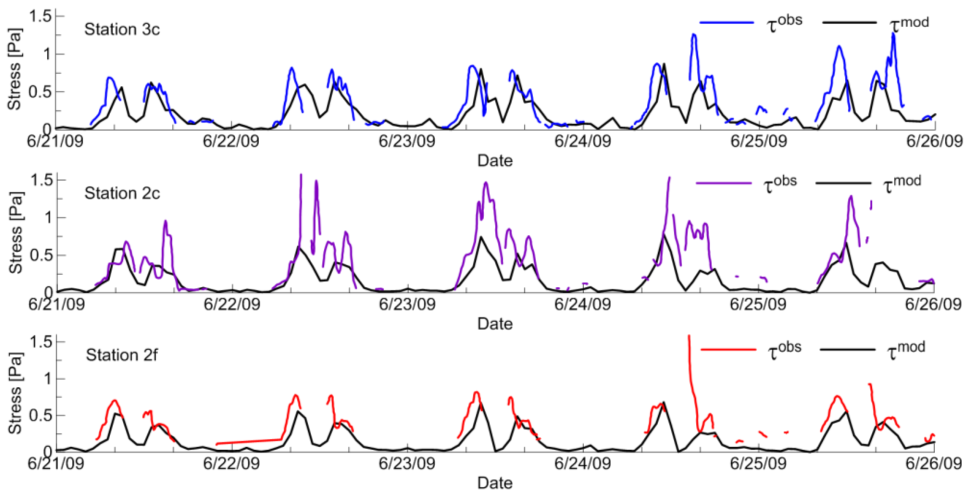


Figure 6. Comparison of observed bottom stress in Skagit tidal flats shown at stations 3c, 2c and 2f during June of 2009 as part of sediment model setup and calibration. (τ^{obs} = observed bottom shear stress and τ^{mod} = modeled bottom shear stress).

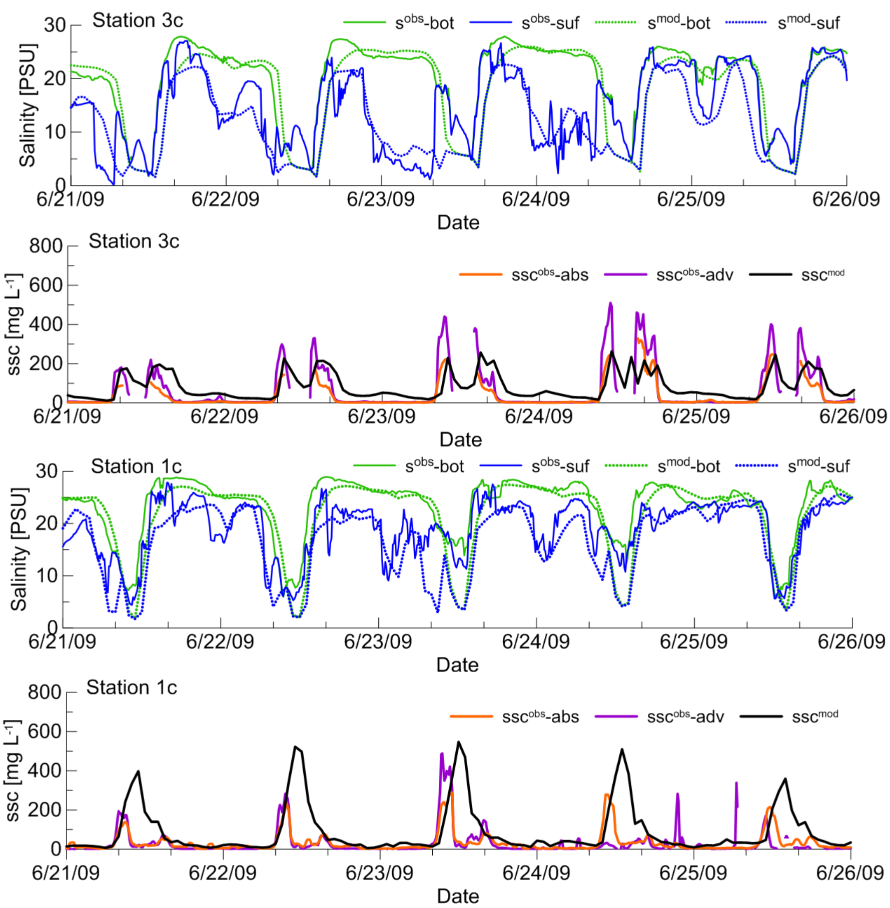


Figure 7. Comparison of observed salinity (s^{obs}-bot = observed bottom salinity, s^{obs}-suf = observed bottom salinity, s^{mod}-bot = modeled bottom salinity and s^{mod}-suf = modeled surface salinity) and SSC (ssc^{obs}-abs = observed acoustic backscatter sensor suspended sediment, ssc^{obs}-adv = observed acoustic Doppler velocitymeter suspended sediment and ssc^{mod} = modeled suspended sediment) in Skagit tidal flats at stations 3c and 1c.

2.4. Application to Dike Repair and Restoration Scenarios

We conducted two sensitivity tests using the model to examine hypothetical scenarios involving modifications to the existing jetties and dikes near the mouth of north fork of Skagit River and compared the hydrodynamics and sediment transport response to baseline (existing conditions). A 20 day (10 June 2009 to 30 June 2009) simulation of hydrodynamics and sediment transport was conducted for baseline, and two scenarios with dike modification during the WHOI field data collection period. The predictions of time averaged salinity, bottom shear stress, and TSS distributions simulated near McGlinn and Goat Island locations of interest for the respective scenarios were compared with the baseline condition as part of this assessment. A close-up of the baseline grid is shown in Figure 8 along with bathymetry used in baseline scenario developed using bathymetric information from the 2014 channel and Lidar surveys.

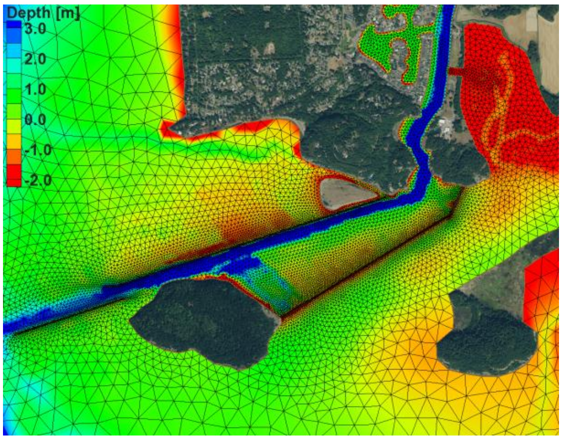
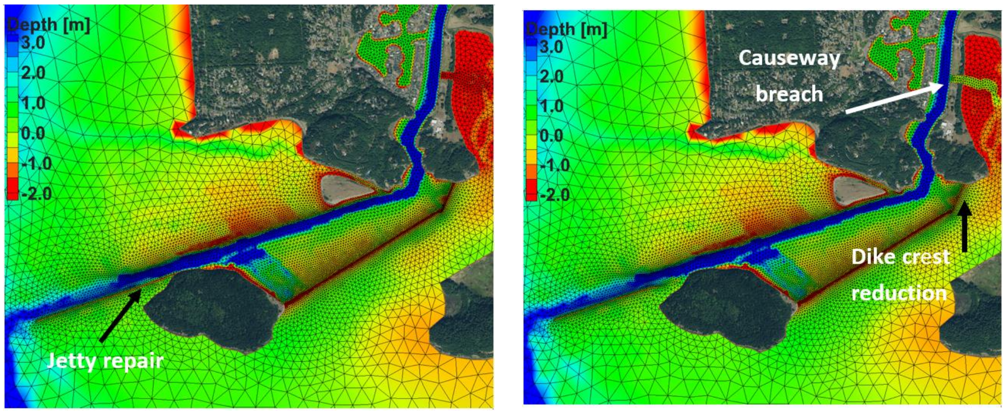


Figure 8. Close-up of the model grid and bathymetry used in baseline (or existing conditions) simulation. Note—color contours indicate depths (negative elevations) relative to NAVD88 datum.

We then modified the baseline grid to generate the following two scenarios of interest shown in Figure 9:

- SCN-1, South Jetty Repair: Recent surveys by USACE indicate that South Jetty of the Swinomish Channel (see Figure 1, C location) that extends southwest from Goat Island along the southern bank of the Swinomish Channel has structurally degraded (jetty elevations reduced from ≈1.9 m to as low as −1.1 m), allowing leakage flow and transport from adjacent flats to the Swinomish Channel. In SCN-1, the South Jetty is repaired by re-setting the elevations of the dike crest nodes back to 1.9 m (NAVD88), thereby restoring the functionality of the South Jetty. The main objective of this scenario is to evaluate if this repair would result in improvement (reduction) in sediment transport into the Swinomish Channel. SCN-1 South Jetty Repair location is shown in Figure 9a.
- SCN-2, McGlinn Causeway Restoration: This habitat restoration proposal involves breaching of the causeway between McGlinn Island and mainland (see Figure 1, D location) and reduction of the crest elevations of the north section of the McGlinn Island to Goat Island Jetty (see Figure 2b). The restoration design calls for reduction in the crest elevation (from ≈3.0 m) to 1.33 m (NAVD88) corresponding to mean sea level ($MSL = 0$) at the north section of the Goat Island jetty allowing a direct connection between the North Fork of the Skagit River and the Swinomish Channel during high tides. The causeway breach was incorporated by reducing the elevation of 2.5 m of the causeway to an elevation of −0.3 m (NAVD88). In addition to providing better connectivity and restoring historic pathways for upstream and downstream fish migration, the objective of this scenario is to examine the potential benefits in the form of reduction in salinity and improved brackish water habitat. SCN-2 McGlinn Causeway Restoration locations, consisting of causeway breach and reduction of the Jetty crest elevations, are shown in Figure 9b.

Also of interest are potential impacts that each scenario may impose on the overall estuarine functions and on their respective beneficial objectives. For example, the existing condition with the breach in the Swinomish Channel South Jetty likely results in some improvement to connectivity and brackish water benefits and its repair may eliminate the access and affect salinity levels along the channel. Similarly, McGlinn Causeway restoration actions while conveying habitat restoration benefits may impact/increase sediment transport or deposition in the Swinomish Channel, resulting in increased dredging and maintenance. The sensitivity analysis presented below using identical forcing and sediment loading conditions allows an assessment of relative merits and impacts to beneficial uses of both scenarios.



(**a**) (**b**)

Figure 9. Modified model configuration used for (**a**) SCN-1 South Jetty Repair and (**b**) SCN-2, McGlinn Causeway Restoration. Note—color contours indicate depths (negative elevations) relative to NAVD88 datum.

3. Results

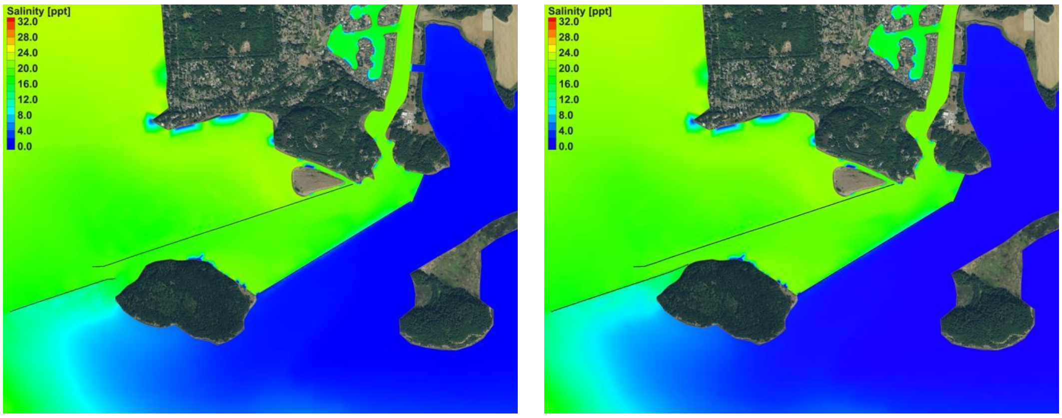
A qualitative assessment of the sensitivity of sediment transport and salinity to the proposed restoration and repair scenarios is presented below.

3.1. Assessment of Jetty Repair Scenario, SCN-1

In SCN-1 with the Jetty repairs in place, salinity distribution appears to show only small nearfield effects near the repaired Jetty (see Figure 10) due to blockage of transport south of the Jetty. The magnitude of freshwater transported through the gap in the degraded portion of jetty was relatively small and does not appear to cause noticeable impacts to salinity gradients in the Swinomish Channel at the plotted scale of 0 to 32 ppt. A difference-plot was added at the end of this section to highlight the relative differences in time averaged concentrations. Small increases in salinity between McGlinn and Goat Island and small decreases in salinity at the southern part of Jetty Island are noticeable.

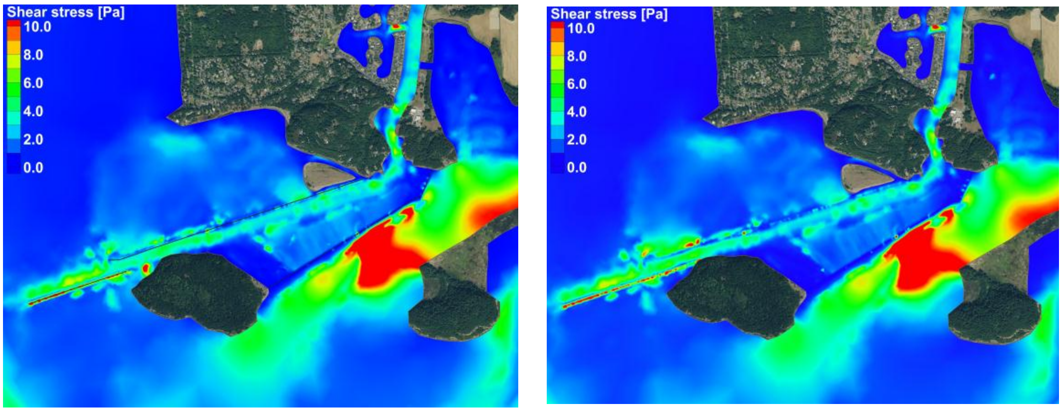
Bottom shear stress also shows local effects mostly near the Goat Island region (see Figure 11). Repairing the jetty creates slightly higher velocities and bottom shear stress along the Swinomish Channel. In baseline simulation, bottom shear stress is noticeably higher in the jetty gap region. Interestingly, higher bottom shear stress is noticeable over the tidal flat just north of the Swinomish Channel North Jetty. Repaired jetty confines the tidal flow to the Swinomish Channel and prevents exchange to the south to Skagit Bay tidal flats via the breach. This likely increases the velocities and exchange over the north side tidal flats and therefore results in slightly higher bed shear.

Repairing the jetty decreases total suspended sediment transported into the Swinomish Channel. However, the volume and sediment fluxes affected by the jetty repair are relatively small and beneficial effects of preventing a large volume of TSS into the Swinomish Channel are not noticeable in the time averaged contour plots as shown in Figure 12.



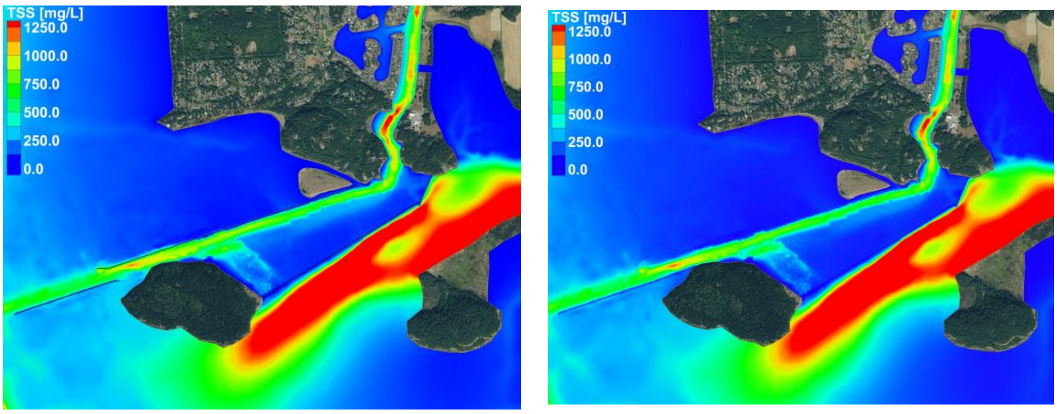
(**a**) (**b**)

Figure 10. Time averaged salinity distribution (20 days) for (**a**) baseline conditions and (**b**) Jetty Repair Scenario, SCN-1.



(**a**) (**b**)

Figure 11. Time averaged bottom shear stress distribution (20 days) for (**a**) baseline conditions and (**b**) Jetty Repair Scenario, SCN-1.



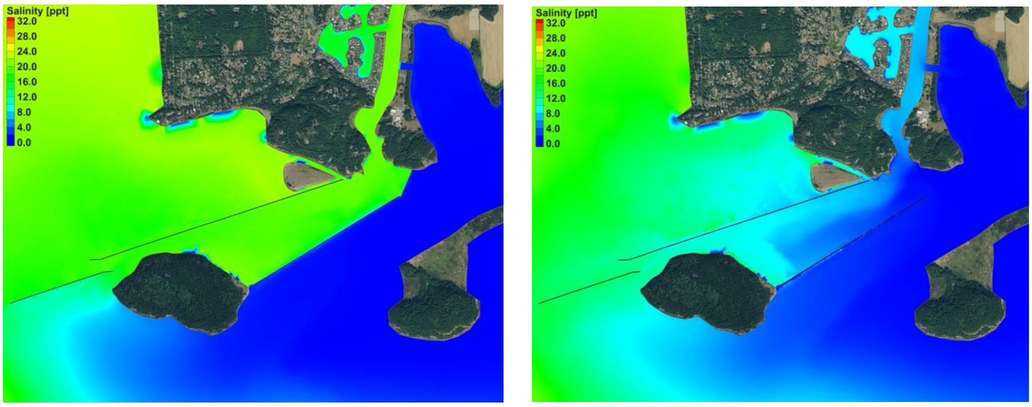
(**a**) (**b**)

Figure 12. Time averaged total suspended sediment (TSS) distribution (20 days) for (**a**) baseline conditions and (**b**) Jetty Repair Scenario, SCN-1.

The difference plot at the end of this section shows the difference between baseline conditions and SCN-1 for shear stress and TSS.

3.2. Assessment of McGlinn Causeway Restoration Scenario, SCN-2

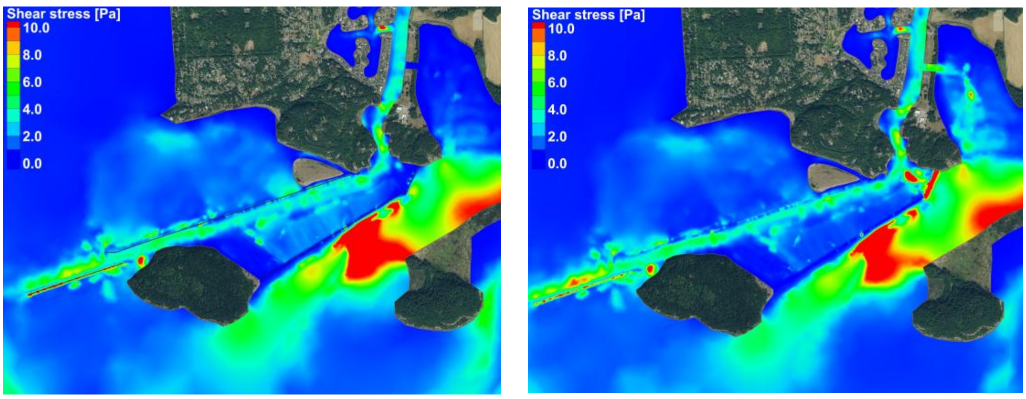
The SCN-2 scenario with breaching of the causeway and reduction in crest elevation of the north section of the Goat Island jetty results in large freshwater volume fluxes from the Skagit River into the Swinomish Channel. As shown in Figure 13, there is a dramatic reduction in salinity levels in the Swinomish Channel and the influence extends from Goat Island all the way up north into the Swinomish Channel towards Padilla Bay. Difference plot at the end of the section shows salinity in SCN-2 can be up to 20 ppt lower than baseline. While salinity reduction is dominant during ebbs, the causeway breach continues to push freshwater into the Swinomish channel during flood tide periods.



(**a**) (**b**)

Figure 13. Time averaged salinity distribution (20 days) for (**a**) baseline conditions and (**b**) McGlinn Causeway restoration, SCN-2.

Significant changes to bed shear stress are noted for SCN-2 as shown in Figure 14. High bottom shear stress is found near the locations of Jetty and Causeway modifications. The lowering of the Jetty and Causeway crest elevations results in transport of the Skagit River water over the structures directly into the Swinomish Channel at the two locations. This results in high velocities bed shear relative to baseline at the locations with modifications. Interestingly, significant decrease in bed shear stress is noted at a tidal flat between the Goat Island Jetty and the South Jetty of the Swinomish Channel. Furthermore, some increase of bottom shear stress is noted near the existing breach of the South Jetty at Goat Island because of modified tidal flow and circulation in this scenario. Note, in SCN-2, the breach is retained as in baseline conditions without repairs.

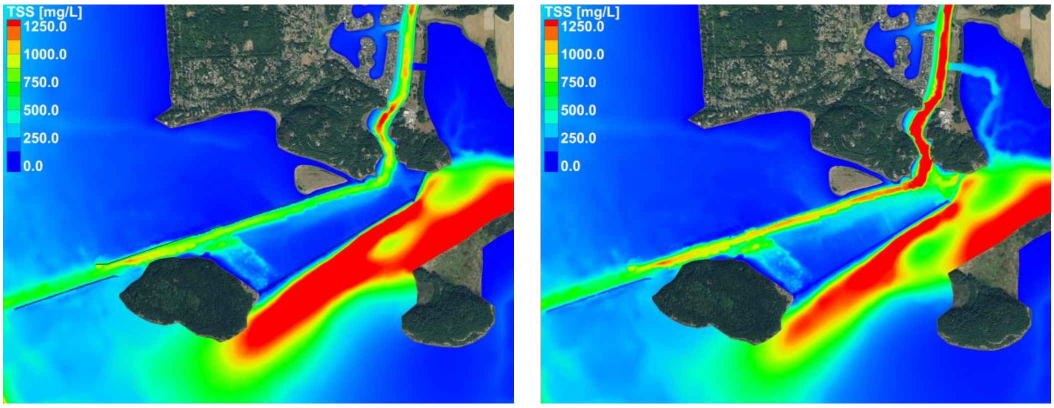


(**a**) (**b**)

Figure 14. Time averaged bottom shear stress distribution (20 days) for (**a**) baseline conditions and (**b**) McGlinn Causeway restoration, SCN-2.

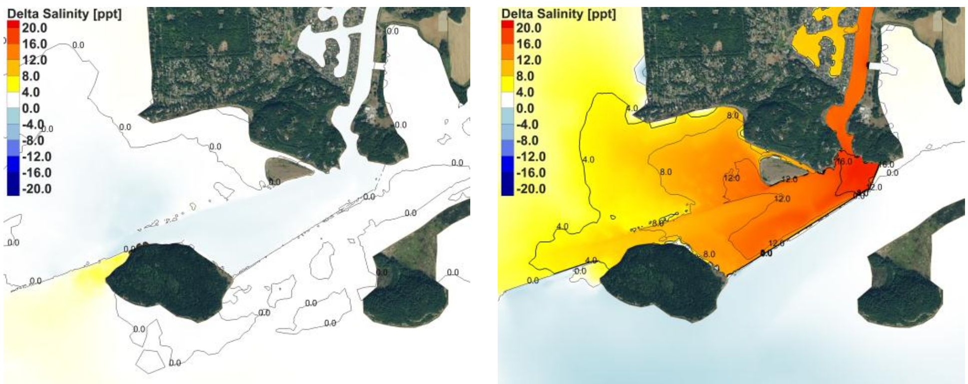
Figure 15 shows that there is a significant increase in TSS concentration in the Swinomish Channel north of Goat Island.

Figure 16 is a difference-plot showing the time averaged horizontal distribution difference between baseline conditions and SCN-1 for (a) salinity (c) shear stress and (e) TSS. In this area, TSS concentration may increase by more than 500 mg as shown in Figure 16f. In contrast, a reduction in TSS concentration is found on the Skagit Bay side south of Goat Island Jetty. This implies that significant TSS from North Fork Skagit River was transported via modified sections into the Swinomish Channel.

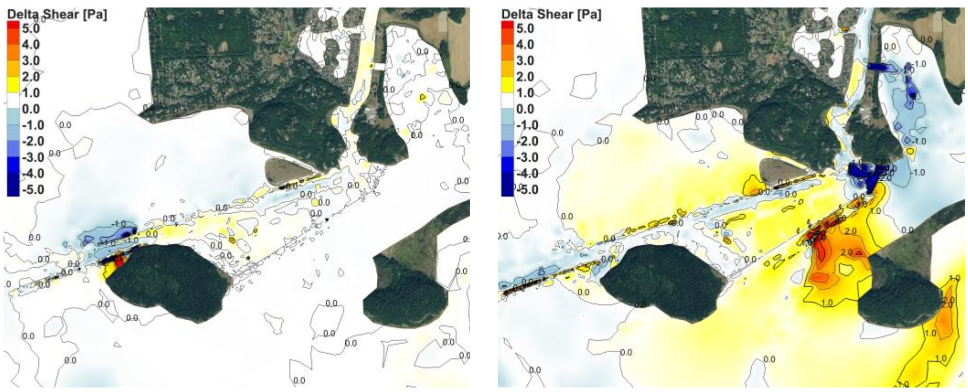


(**a**) (**b**)

Figure 15. Time averaged total suspended sediment (TSS) distribution (20 days) for (**a**) baseline conditions and (**b**) McGlinn Causeway restoration, SCN-2.

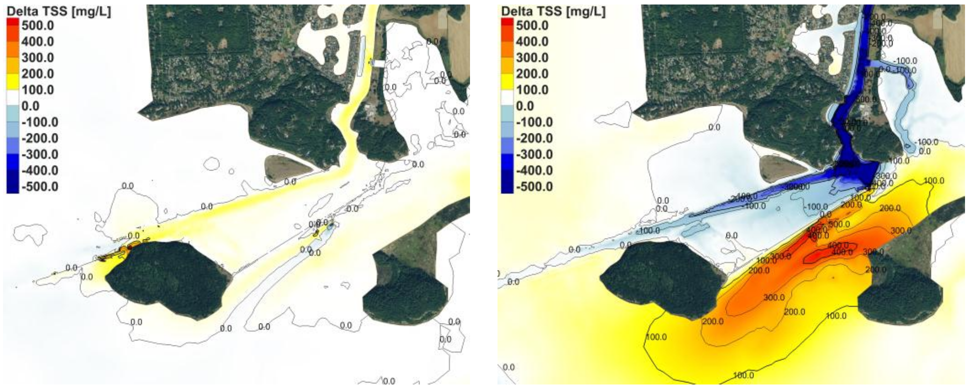


(**a**) (**b**)



(**c**) (**d**)

Figure 16. *Cont.*



(**e**) (**f**)

Figure 16. Time averaged horizontal distribution difference between baseline conditions and SCN-1 for (**a**) salinity (**c**) shear stress and (**e**) TSS; time averaged horizontal distribution difference between baseline conditions and SCN-2 for (**b**) salinity (**d**) shear stress and (**f**) TSS. The positive sign of the color bar means that the baseline concentrations are higher than the selected scenario.

4. Discussion

To facilitate quantitative comparison of scenarios, we selected two stations near the proposed project sites in the Swinomish Channel. Station A was selected near the South Jetty breach-repair location near Goat Island. It is the region where high TSS was predicted in SCN-2 and is marked in Figure 2b (red circles). We also selected another station, station B, at the mouth of north section of the Swinomish Channel where high salinity fluctuation was noted in SCN-2 simulations.

Quantitative comparisons of simulated hydrodynamic parameters are shown in Figure 17 for baseline, SCN-1, and SCN-2 scenarios at these two stations. The percentage difference between the two scenarios relative to baseline conditions for salinity, shear stress and TSS are shown in Table 4. Negative percentage implies that the magnitude of the simulated variable in the scenario is lower than the baseline. On the other hand, positive percentage implies that the magnitude of the simulated variables is higher compared to the baseline result.

Figure 17 shows that the proposed project scenarios do not have a significant effect on water surface elevations. Plots of water surface elevations at both sites are nearly identical for baseline conditions as well as the two project scenarios.

Because of jetty repairs in SCN-1, the time series plots of simulated variables shown in Figure 17a (blue lines) respond and deviate a little from the existing conditions (black lines). Eliminating the leakage of brackish water flow into the Swinomish results in small increase in salinity (7%, 3%). However, the effect on velocities and therefore shear stress in the Swinomish Channel was minimal (−0.2%, −0.1 %). Correspondingly, near-bed or bottom TSS response (−2% and −3%) and depth averaged TSS (−5%) was also small but consistent with the expectation that the Jetty repairs will result in reduction of TSS, and, therefore, reduced sediment deposition in the Swinomish Channel. These results indicate that the Jetty repair scenario SCN-1 would result in relatively small changes in salinity and TSS in the Swinomish Channel relative to baseline conditions.

In contrast, as shown in Figure 17b (red lines), all variables showed a strong response to the McGlinn Causeway Restoration scenario SCN-2 as implemented in this model sensitivity test. McGlinn Causeway breach and Goat Island Jetty crest elevation reduction results in an immediate reduction in salinity through dilution by large volume fluxes of Skagit River freshwater that enters the Swinomish Channel directly. The salinity in the Swinomish Channel at stations A and B is reduced significantly (−44% and −81%) from typical values of ≈20 ppt to <5 ppt. This low-level salinity environment (<15 ppt) are very suitable for fish migratory pathways in estuaries [3,26,27] and can increase fish return rate into Skagit River. For example, Greene et al. [28] suggested that freshwater and nearshore environmental conditions are the main controlling factors of the survival rate of Skagit River Chinook salmon.

Bed shear stress increased in this scenario but was generally <5% and results in an increase of bottom TSS varying from an increase of 6% near station A to a high value of 37% at station B. It appears that this increase in depth averaged water column TSS (11% and 87%) is mostly due to suspended sediment load from the North Fork of Skagit River that is transported through the Jetty and the Causeway openings created in SCN-2 during ebbs. Upon entering the Swinomish Channel, the suspended sediments are mostly transported to north of the Swinomish Channel. Net tidally averaged transport through the Swinomish Channel is to the north towards Padilla Bay.

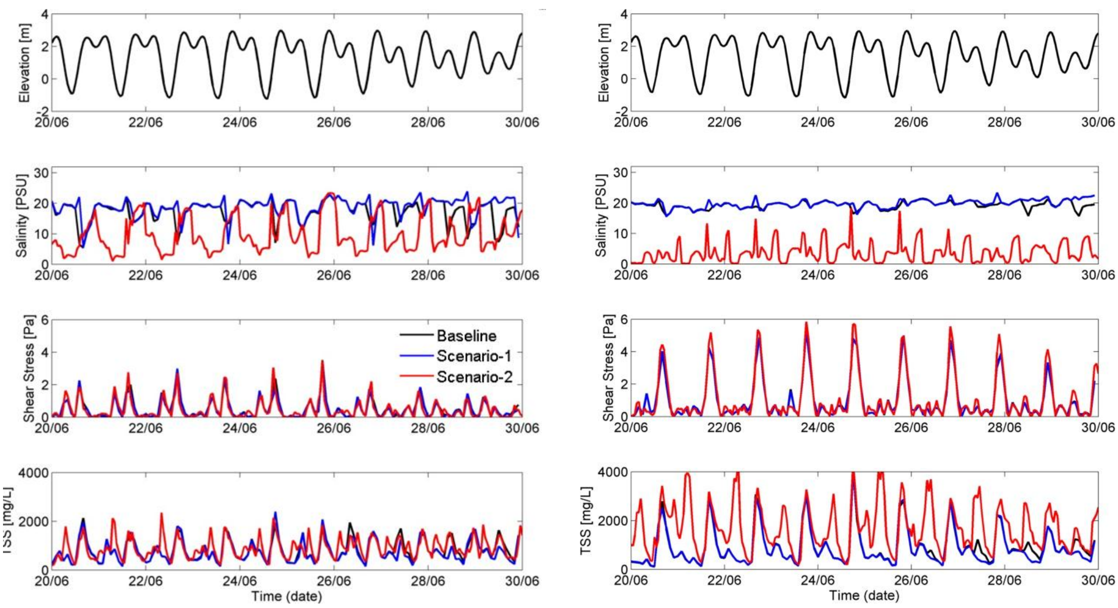


Figure 17. Comparison of time series of salinity, bed shear stress and TSS at (**a**) station A and (**b**) station B (Figure 2b) for baseline, Jetty Repair Scenario, SCN-1, and McGlinn Causeway restoration, SCN-2.

Table 4. Percentage difference of two scenarios with the baseline for salinity, shear stress and TSS at two mooring stations.

Mooring	Salinity		Shear Stress		Bottom TSS		TSS	
	SCN-1	SCN-2	SCN-1	SCN-2	SCN-1	SCN-2	SCN-1	SCN-2
A	7	−44	−0.2	2	−2	6	−5	11
B	3	−81	−0.1	4	−3	37	−5	83

Bottom TSS corresponds to TSS concentration in the lower 3% of water column.

5. Conclusions

In this study, the FVCOM hydrodynamic model was used to examine the sensitivity of estuarine conditions to selected modifications of the structures near the mouth of North Fork of Skagit River estuary. Repairing the existing structures for reduction of sedimentation and dredging may conflict with interests related to creation of migration pathways and brackish water habitat desirable for restoration of salmon populations through restoration of natural tidal functions. A modeling based sensitivity analysis allows a relative and quantitative comparison of potential estuarine response and effectiveness of repair on channel maintenance to allow for a comprehensive evaluation of impact or benefit.

A hydrodynamic model capable of resolving nearshore structures such as dikes and jetties was implemented for the Skagit River estuary. The model was validated using oceanographic data collected in 2006 and 2009. In addition to water surface elevation, velocities, and salinities, the data also included bed shear stress and TSS measurements. The baseline condition corresponding to calibration period was then used to evaluate the system response to two scenarios (1) Jetty Repair Scenario, SCN-1 and (2) McGlinn Causeway restoration, SCN-2. SCN-1 prevents leakage of flow and TSS into the Swinomish Channel, while SCN-2 provides direct migration pathways and improved conveyance of freshwater into the Swinomish Channel.

The results of sensitivity tests show that SCN-1 successfully eliminated the leakage flow and transport of Skagit Bay waters into the Swinomish Channel. However, it turned out that associated volume fluxes were relatively small and beneficial effects (reduction in TSS) as well as potential negative effects (increase in salinity) from fish habitat goals were small. In other words, the estuary and Swinomish Channel response to SCN-1 was not strong. In contrast, SCN-2 was very effective in providing a direct connection (direct migration pathway) and increased freshwater transport into the Swinomish Channel. The peak reduction in salinity by almost 81% and continued northward transport are also very positive responses towards fish habitat restoration goals. However, the restoration design (Jetty crest and Causeway Breach invert elevations and lengths) is such that it allows significant Skagit River sediments to be carried into the Swinomish Channel in suspension. Given that increase in bed shear stress associated with SCN-2 is <4%, an increase in TSS of 11%–83% could result in impacting sediment deposition in the Swinomish Channel. Given the promising response of SCN-2 towards fish habitat restoration goals, further examination/alteration of SCN-2 design aimed towards reducing sediment transport into the Swinomish Channel, while maintaining connectivity and brackish water habitat benefit, is recommended. In addition, other alternatives to modification of existing federal navigation structures should also be examined for a more complete examination of reductions in sedimentation and increased fish migration pathways.

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Conflicts of Interest: The authors declare no conflict of interest.

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