Hydrodynamic and Suspended-Sediment Transport Model of Skagit and Padilla Bay System

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Executive Summary

The loss of habitat caused by thousands of kilometers of estuarine shorelines being modified for flood protection and agriculture through the construction of dikes and other artificial structures is regarded as one of the major causes for declining fish stocks. Many estuarine habitat restoration and protection projects are underway at scales ranging from less than a hectare to large swaths encompassing several kilometers of shoreline. These projects strive to restore hydrologic and hydrodynamic functions in the tidal marshlands with the help of shoreline modifications and reconstruction, thereby facilitating the return of natural processes. Despite best intentions, efforts to restore near-shore habitats can result in poor outcomes if water circulation and transport are not properly addressed. Response of natural processes to physical changes are often nonlinear, and land-use constraints can lead to selection of suboptimal restoration alternatives that may result in undesirable consequences, such as flooding, deterioration of water quality, and erosion, that require immediate remedies and costly repairs. A finite-volume hydrodynamic model set up at fine-scale resolution could address the possibility of achieving beneficial restoration outcomes at small local scale while preserving estuary-wide ecosystem integrity, and is therefore essential for feasibility analysis and land-use planning.

While the effects of anthropogenic alterations on fresh and saltwater ecosystems and the plants, fish, and wildlife they support are measurable through direct observations, impacts from climate change induced hydrologic variations are not obvious. For example, results from recent regional models indicate that summer river flows are likely to decline by 30 percent in the Pacific Northwest and the sea-level may rise 10 to 143 cm by 2100. The projected losses in glacial cover are likely to result in increased sediment contributions and landslide inputs. These changes, which likely will affect estuarine vegetation composition and production that in turn will impact salmon population restoration, have to be factored into protection efforts. Through this project, we have created a quantitative, mathematical-modeling-based tool that can inform restoration and management efforts by demonstrating the range of possible implications of future sea-level-rise and other climate change scenarios on estuarine rearing habitat for juvenile Chinook salmon. The model is designed for application to the near-shore environment and can minimize uncertainty about restoration goals, such as recovery of tidal exchange, supply of sediment and nutrients, and establishment of fish migration pathways.

The technology developed through this research consists of applying the Unstructured Grid Finite Volume Coastal Ocean Model (FVCOM) to represent complex estuarine shoreline, associated tidal marshland, and tidal flats. FVCOM is a prognostic, unstructured-grid, finite-volume, free-surface, three-dimensional, primitive-equation, coastal ocean circulation model developed jointly by the University of Massachusetts-Dartmouth and the Woods Hole Oceanographic Institute. The model domain extends from Padilla Bay at the north boundary to Saratoga Passage to the south. It includes multiple intertidal channels while retaining the configuration of the overall study domain. The model was initially calibrated using oceanographic data collected from low- and high-flow periods in 2005 and 2006 and was validated using data collected in 2008 as part of this project. The model simulates three-dimensional baroclinic circulation and has the capability of simulating water-quality kinetics (i.e., eutrophication) and sediment transport. An associated sediment transport model was setup using flow-sediment rating curves developed by the U.S. Geologic Survey (USGS) and sediment deposition estimates based on maintenance dredging records and sediment accretion measurements by Western Washington University. Through this
study, we refined the techniques for incorporating high-resolution light-detection and ranging data into the simulation of estuarine circulation and transport in the intertidal mudflats with wetting and drying marsh features.

The benefits provided by this technology development and key findings of the research conducted through this grant are best described through the examples described below.

- **Hydrodynamics and Circulation – Skagit River Estuary.** The hydrodynamic model was applied to simulate the tidal circulation, salinity stratification, and freshwater plume dynamics in the intertidal region of the Skagit River estuary in Puget Sound. The grid used in the unstructured grid model allowed variable grid resolution in the intertidal zone and in the multiple distributary tidal channels. The model reproduced the tidal currents, salinity stratification, and wetting/drying processes over tidal flats as observed in the field data and provided a good understanding of the overall physical process in the Skagit River estuary. During ebb tide, the freshwater plume generally moved out a considerable distance downstream of the river because of the high discharge of the Skagit River. Salinity intrusion in the main river branch (i.e., the North Fork) reached an upstream distance of approximately river mile (RM) 2 under low-river-flow conditions. During high-river-flow conditions, the salt intrusion point was further pushed out by the strong river plume, approximately 1000 m downstream from the river mouth (i.e., RM 0). Strong stratification and de-stratification processes occur in the estuary during a tidal cycle. While the river plume occupies a significant portion of the tidal flats in Skagit Bay, the heavily diked Fir Island separates the river plumes from the North and South Forks and results in a relatively high salinity and low velocity zone in the bay front of Fir Island. Tidal residual currents in Skagit Bay are in the range of 0.1 to 0.2 m/s in most of the tide flat area under high-river-flow conditions and less than 0.1 m/s in low-river-flow conditions. Strong wind events can change the current directions completely and the salinity distribution in the tidal flats of Skagit Bay. Preliminary modeling analysis indicated that the salinity intrusion length scale in the Skagit River estuary is proportional to the $-\frac{1}{4}$th power. To calculate the salinity intrusion more accurately as a function of river flow, tidal dispersion, and the fortnight timescale of spring-neap cycles, more detailed model simulations and data analysis are required for future studies (Yang and Khangaonkar 2009)

- **Insight on Estuarine Habitat Restoration Approaches.** Application of this tool on the Skagit River Delta has helped demonstrate that popular solutions for restoring brackish conditions through a few individual or selected freshwater bypass channels as a substitute for a former network of freshwater distributary channels may not be as effective as once believed.

  - The application of the model to generate detailed information on water and particulate motion has alerted planners to the possibility that opening the dikes at localized sites may be ineffective unless fish access and connectivity are restored as well, thereby leading teams to conduct estuary-wide assessments. The methods and techniques developed using the Skagit and Padilla Bay estuaries as test domains are fully applicable to other estuaries around the United States, assuming a site-specific application is conducted to address problems particular to the new location (Khangaonkar et al. 2011).
– Sensitivity tests with the sediment transport model demonstrated that dredging to open previously filled channels that historically supported flowing water and habitat had high potential for re-sedimentation. Restoration actions near a major sediment transport corridor would be at risk from future increased sediment loads and would require periodic dredging to maintain off-channel functionality and sustainability (Lee and Khangaonkar 2009).

• Connectivity between Padilla Bay and Skagit Bay. The model application has provided useful information regarding connection between Padilla Bay and Skagit Bay through sensitivity tests aimed at improving connectivity between the Skagit River and Swinomish Channel, a migratory barrier that exists today. An associated sediment transport model was setup using flow-sediment rating curves developed by USGS and sediment deposition estimates based on maintenance dredging records and sediment accretion measurements. The model then was applied over the period from 1988 through 2010, both with and without proposed restoration alternatives. The results were used to estimate relative changes in sediment transport and deposition in Swinomish Channel resulting from the proposed reconnection to the North Fork Skagit River. The potential for increase in sediment deposition within the Swinomish Channel because of proposed restoration actions was of particular interest. This information will be used to evaluate if such increases in sedimentation can be accommodated by current and ongoing maintenance dredging for the channel.

It is important to note that the technology developed through this effort bridges an important gap between conventional hydraulic engineering tools and classic oceanographic models. The conventional steady-state hydraulic engineering tools commonly used by civil engineers for water-resource planning and flood-plain assessments are not applicable in the coastal or tidal environments. Similarly, oceanographic models historically have mostly focused on large-scale circulation and transport phenomena in deep waters and did not address flood plains and marshes. The use of the FVCOM model in tidal flats and upstream flood-plain reaches is a new development that is an improvement over existing technologies.

In conclusion, the capability for simulating the important near-shore processes and their response to restoration actions and climate change was developed through support from this grant from the U.S. Environmental Protection Agency. These processes include 1) circulation in complex multiple tidal channels, 2) salinity and inundation frequency, 3) wetting and drying of tidal flats, and 4) water quality and sediment transport as part of restoration feasibility. The technology has already been deployed at a number of restoration project sites in Puget Sound and is ready for application to analysis of climate change scenarios and their impact to coastal habitats.
### Acronyms and Abbreviations

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<th>Description</th>
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<tr>
<td>ADCP</td>
<td>acoustic Doppler current profiler</td>
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<tr>
<td>FVCOM</td>
<td>Unstructured Grid Finite Volume Coastal Ocean Model</td>
</tr>
<tr>
<td>NOAA</td>
<td>National Oceanic and Atmospheric Administration</td>
</tr>
<tr>
<td>RM</td>
<td>river mile</td>
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<td>USGS</td>
<td>U.S. Geologic Survey</td>
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1.0 Introduction

The Skagit River is the largest river in the Puget Sound estuarine system. It discharges approximately 39 percent of the total sediment (Downing 1983) and could, at times, account for more than 50 percent of the freshwater flowing into Puget Sound (Cannon 1983). 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. The diked portion of the Skagit River Delta is known as Fir Island, where irrigation practices over the last century have resulted in land subsidence and reduced efficiency of the drainage network. The dikes have also impeded fish passages through the area and greatly reduced nursery habitat for many fish and invertebrate species. Most importantly, the Fir Island dike confined the Skagit River Delta to two conduits (North Fork and South Fork), diverting freshwater away from the dike-front region that was historically a productive brackish marsh that fostered alongshore habitat connectivity. As a consequence, marsh habitat has been lost, and the dike-front region has deteriorated into mud-flat conditions with increased salinity (20 to 25 ppt) devoid of vegetation.

Similarly, a series of engineering activities that took place over a period of approximately 100 years starting in the late 1800s and culminating in 1937 also have affected the natural processes of freshwater and sediment transport to the Padilla Bay located north of Skagit Bay. Historically, Swinomish Slough, connecting Skagit and Padilla Bays in Northern Puget Sound, was a significant migratory corridor for juvenile Skagit River Chinook salmon seeking rearing habitat in Padilla Bay. Construction of the Swinomish Slough navigation 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 resulted in loss of connectivity between habitats in the Skagit River, Swinomish Channel, and Padilla Bay.

Figure 1.1 shows the study area consisting of the main stem of the Skagit River, North Fork and South Fork branches, Skagit Bay, Fir Island, Jetty (river training dike), Swinomish Slough navigation channel, and Padilla Bay. The study area is located within the Whidbey Island Basin at the northeast corner of Puget Sound. There are three large rivers that enter Whidbey Basin and supply the greatest amount of freshwater and sediment to the system. Further, Whidbey Basin is critical to the recovery of endangered Puget Sound salmon because of the large number of salmon populations that spawn in the rivers entering Whidbey Basin. Considerable effort is underway in Whidbey Basin to develop ecosystem recovery plans with near-shore habitats being a focus of conservation efforts. As a first step toward developing an integrated assessment tool, we constructed a hydrodynamic model of the Skagit Basin. The model domain was expanded subsequently to Padilla Bay to the north and other parts of Whidbey Basin. For this study, the model grid was developed with attention to the importance of simulating near-shore processes, such as circulation in complex multiple tidal channels and wetting and drying of tide flats, so that questions that arise as part of restoration feasibility studies in Skagit and Padilla Bay projects could be addressed adequately. The expectation is that the hydrodynamic model application would help evaluate whether proposed restoration actions, such as removing a tide gate, breaching a dike, dredging drainage channels, installing culverts, etc., would result in a desired hydrodynamic response. Desirable hydrodynamic responses include inundation with tide, suitable velocities, flushing, optimum salinity levels, etc. Feasibility from an engineering perspective looks at potential impacts from the proposed
actions, such as increased flooding, sedimentation, backwater effects, and perhaps unexpected erosion and pond formations.

In particular, the model developed through this grant would be a tool that could be used to evaluate the estuarine response and feasibility of proposed projects for current conditions as well as for future changes associated with climate change and sea-level-rise.

**Figure 1.1.** Skagit River Estuary and Padilla Bay Study Area in Puget Sound, Washington
2.0 Project Development

2.1 Project Objectives

The overall project objective is to develop a practical tool that can predict ecological consequences and likely impacts to the landscape from sea-level rise and river flow and sediment load alteration. The approach is to accomplish this by developing and linking a spatially explicit hydrodynamic and sediment transport models of Padilla Bay and Skagit Bay, which will inform a mechanistic wetland elevation dynamics and vegetation unit model and models of tidal channel geomorphology and juvenile salmon abundance and distribution. Following model calibration and validation, the models will be run under various sea-level-rise, river-flow, and sediment-load scenarios. Results can inform restoration goals and strategy revisions and adaptive management responses depending on how much marsh progradation or erosion occurs over the next century. The study will characterize high- or low-risk restoration sites based on likely vulnerability or resilience to climate change.

The specific project objectives were as follows.

Phase I. Development of Hydrodynamic Model of Skagit and Padilla Bay
- Develop a three-dimensional hydrodynamic model for the study domain (Saratoga Passage, Skagit Bay, and Padilla Bay including Swinomish Channel)
- Design and assist with oceanographic and sediment field data-collection program
- Perform hydrodynamic model calibration.

Phase II. Incorporation of Sediment Loading, Transport, and Model Validation
- Develop an offline linked associated sediment transport model
- Perform sediment transport model validation.

Phase III. Model Application
- Conduct model application to restoration scenarios
- Conduct model application and sensitivity tests to restoration and climate change scenarios

2.2 Development of Hydrodynamic Model for Skagit and Padilla Bay

2.2.1 Model Setup and Boundary Conditions

The hydrodynamic model used in this study is the Unstructured Grid Finite Volume Coastal Ocean Model (FVCOM) developed by Chen et al. (2003). FVCOM solves the three-dimensional momentum, continuity, temperature, salinity, and density equations in an integral form by computing fluxes between non-overlapping, horizontal, and triangular control volumes. This finite-volume approach combines the advantages of finite-element methods for flexibility in handling complex shorelines and the superior capability of finite difference methods for simple discrete structures. 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; Khangaonkar and Yang 2011a,b; Yang and Khangaonkar 2009; Yang et al. 2010a,b).

Model grid development covered the entire Skagit Bay and Padilla Bay, and included portions of Saratoga Passage. 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 tidal mud-flat area, finer grid cells were specified in the tidal channels, the marshlands near the habitat restoration sites, and between the tributary sloughs. The existing model domain of Skagit Estuary developed by Pacific Northwest National Laboratory during previous projects was expanded to include Padilla Bay through the connection of Swinomish Channel to Skagit Bay. Similar to Skagit Bay, a large tide flat critical for providing near-shore fish habitat exists in Padilla Bay. To represent the 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 (Figure 1.1). Bathymetric data collected for the Padilla Bay National Estuarine Research Reserve was applicable to Fidalgo Bay. 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 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.

Accurate specification of land geometry and bottom bathymetry is one of the most important factors affecting the accuracy of model prediction of tidal circulation in estuaries. Because of the complexity of this braided estuary and the presence of a large tidal mud flat and surrounding tidal marshlands, high-resolution and accurate bathymetry data were used in the model setup combining light-detection and ranging and Digital Elevation Model data maintained by University of Washington. The river bathymetry data were obtained from the U.S. Army Corps Engineers. The hydrodynamic model consists of 16,430 elements and 9500 nodes in the horizontal plane. Ten uniform vertical layers were specified in the water column in a sigma-stretched coordinate system. Figure 2.1 shows the Skagit-Padilla Bay model domain extending from Saratoga Passage at the south boundary to Padilla Bay at the north boundary. The model grid is plotted, showing a tight coverage of the near-shore boundaries, including the tide flats, the major distributaries, and the connection between Skagit Bay and Padilla Bay via the Swinomish Channel. Bathymetry incorporated into the model also is shown in Figure 2.1.

Two open boundaries are specified in Padilla Bay. One is located at the mouth of Padilla Bay, and the other is along the waterway between Guemes Island and Fidalgo Island. Because of strong tidal currents in Skagit Bay and large freshwater flows from the Skagit River, the Skagit plume travels further south into Saratoga Passage, past the mouth of Skagit Bay where the existing Skagit Bay model open boundary is located. To accurately simulate the longitudinal dispersion of the Skagit River plume and to reduce the southern open-boundary effect on interior computational domain, the southern open boundary was moved further down into Saratoga Passage in the south. The open-boundary conditions specified at the north and south ends of the domain were tidal elevations corresponding to model validation periods and were obtained using the XTIDE program (Flater 1996), which is based on National Oceanic Service algorithms. Tidal elevations were specified from the Greenbank station located in Saratoga Passage, at Yokoko Point near Deception Pass, at Anacortes at the Guemes Channel, and at Chuckanaut Bay. This tidal information is available through the NOAA tide-prediction network. The open-boundary condition
along the Padilla Bay entrance between Guemes Island and Samish Island was specified as the average tidal elevation between the Anacortes and Chuckanut stations. Figure 2.2 shows locations of the tide stations along with the water surface elevation time series corresponding to the 2008 model validation period. [Model calibration during the earlier development phases for low- and high-flow conditions recorded in 2005 and 2006 was reported previously and is not repeated here (Yang and Khangaonkar 2009, Lee et al. 2010)].

Figure 2.1. Unstructured Hydrodynamic Model Grid of the Skagit River and Padilla Bay Domains along with Associated Model Bathymetry
The salinity open-boundary condition was specified with a constant value of 30 ppt, which represents the intrusion of Pacific coastal ocean waters. Historical observations indicated that temperature variations in the study area were less than 5°C during the simulation period, which were much smaller than the salinity variations of 20 ppt near the project. Therefore, the effect of temperature on density likely is not significant in comparison to the effect of salinity. Wind stress was specified at the water surface. The wind stress was applied uniformly across the entire model domain using the wind data measured at NOAA’s National Weather Service site at the Everett/Paine Field station near the study area.

The upstream end of the model domain is extended up to the USGS stream gage (#12150800), which is not affected by tides. There are no major rivers entering Padilla Bay except for small stream runoff from Joe Leary Slough and Indian Slough. The average annual flows for Joe Leary Slough and Indian Slough are 19.5 cfs and 8.2 cfs, respectively. These two sloughs are included as tributary inflows in the model. The River inflow into Skagit Bay during model validation periods is presented below in Figure 2.3.
2.2.2 Field Data Collection for Hydrodynamic Model Validation

Battelle assisted WWU to develop a comprehensive field data-collection program for the validation of the hydrodynamic model. The goal of this field data-collection program was to collect synoptic oceanographic data in the Skagit-Padilla-Snohomish Channel system so that model validation could be conducted simultaneously for the Padilla Bay and Skagit Bay regions of the model study domain. Physical data proposed for collection included tidal elevations (pressure gage); currents (acoustic Doppler current profiler [ADCP], S4, and ADV instruments), and conductivity, temperature, and depth time series and vertical profiles. A two-week data-collection program encompassing a complete neap-spring tidal period was set up and conducted. A layout of the field data program is shown in Figure 2.4.

2.2.3 Validation of Hydrodynamic Model

Model validation was conducted by comparing predicted oceanographic properties, such as water surface elevation and velocity time histories and salinity time series, to measured data by applying the Whidbey Basin model that corresponded to the field data-collection period. Specifically, the predictions of the hydrodynamic model were compared with the measured water surface elevation, velocity, and salinity data at stations T2, T5, M4, M5, and M6, covering the full neap-spring range of tidal characteristics for the period November 18, 2008 to December 4, 2008. Because large tidal mud-flat regions existed in the study domain, wetting and drying processes of the intertidal zone were included in the model. The inundation areas were shown to match well with the mean lower low water lines in NOAA’s nautical chart. 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 successfully reproduced the hydrodynamic characteristics in the study domain, such as the diurnal inequality of tides, fresh water discharge plumes, and salinity intrusion at the river mouths. Overall, the model errors for tide are within 8 percent of the tidal ranges from mean lower low water to mean higher high water. Errors for velocity are mostly within 0.15 m/s. The signatures of neap-spring tidal cycle and diurnal inequality were observed in the collected data as well as model results. Errors for salinity are also in the acceptable range of 0.12 ~ 5.7 ppt. The model captured the interaction between the surface freshwater plume and the bottom salt water during the tidal cycle. Overall, the model is considered sufficiently validated for application to restoration feasibility assessment.

Figure 2.5 shows a comparison of measured tide and simulated water surface elevation at stations T2 and T5 in Padilla Bay and Skagit Bay regions, respectively.
ADCP data were available from the Skagit Bay station M5, so that station was used as the primary location for velocity comparisons. Figure 2.6 shows an example comparison of measured current components in the surface middle and bottom layers to model predictions.

Although the ADCP data is relatively noisy, the current magnitudes predicted by the model appear to match the measured data reasonably well through the month of November 2008. Figure 2.7 shows a comparison example of model results to measured salinity and temperature data. Station M6 is in the direct path of the freshwater plume from the South Fork of the Skagit River, and a strong response to the ebb tidal period is evident when the Skagit River plume extends out. The salinity response at Skagit Bay station M5 is relatively subdued as it is shielded from the North Fork freshwater plume by the presence of the Swinomish Channel dikes and the net transport of the water to the north.

Figure 2.8 and Figure 2.9 show plan views of predicted velocity vectors and salinity contours during typical ebb and flood tidal conditions, respectively.
Figure 2.6. Comparison of Predicted Currents to Measure ADCP Data at Station M5 in the Middle of Skagit Bay
Figure 2.7. Comparison of Predicted Salinity and Temperature to Measured Data at Stations M4, M5, and M6, Respectively
Figure 2.8. Surface Currents in the Study Area during High and Low Tide Periods, Respectively, during November 2008
2.3 Development of Suspended-Sediment Transport Model for Skagit and Padilla Bay

A comprehensive sediment transport model including suspended load transport, bed-load transport, and geomorphological simulation capability such as shoreline change and channel migration is beyond the scope of this study. For the purpose of assisting in restoration feasibility analysis and sensitivity tests, we have limited the sediment transport model scope to suspended-sediment transport, deposition, and erosion processes only.

2.3.1 Sediment Deposition Characteristics of Skagit Bay, Swinomish Channel, and Padilla Bay

Numerous studies have examined available data on total suspended solids (TSS) to estimate sediment load from the Skagit River and, in combination with bed sediment properties and bed elevations, have developed estimates of channel erosion or accretion in the Skagit Bay and Padilla Bay systems. The U.S. Army Corps of Engineers conducted a Flood Hazard Mitigation Study (Pentec Environmental 2002) during which considerable bed sediment information was collected. The sediment types in the forks and
the upstream reach were primarily medium to coarse sand. 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 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 (2001) 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 at RM 4.5 to 8.85 was 2 cm/year. The 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 sites in Padilla Bay during the summer of 2002. Data collected from these sites 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 for three sites near the mouth of Swinomish Channel where deposition of 0.13 cm/year was noted (Kairis and Rybczyk, 2010). This information indicates that most of the sediment delivered by the 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 November 18 to December 3, 2008 during which the average river flow was 12,000 cfs.

Coastal Geological Services conducted sedimentation study of Swinomish Channel. Shoaling-rate analysis was conducted to assess the rates and patterns in which Swinomish Channel bed was accreting as a result of sediment loads from connecting water bodies and surrounding uplands (Coastal Geological Services 2010). Their analysis, which was based on an 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.

Previous estimates of sediment deposition rates in the study domain are summarized in Table 2.1.

### 2.3.2 Review of Skagit River Flow and Suspended-Sediment Load Data

USGS maintains a permanent monitoring gage at Mt. Vernon, Washington (USGS 12200500) located at RM 15.7 on the main stem of the Skagit River. Strong daily variation in river flow is observed and is attributed to daily peaking mode operations at upstream hydropower projects. To facilitate analysis over a long period but to be representative of current conditions, a 24-year record of flow data was extracted from the Mt. Vernon gage archives. During this 24-year period, the highest flow recorded was 142,000 cubic feet per second (cfs), which occurred in November of 1990. The lowest flow of 3600 cfs was recorded in October 2006. The average flow during this period was 16,462 cfs. Figure 2.10 shows Skagit River flow hydrograph data for the period from 1988 to 2010.
Table 2.1. Sediment Accretion Estimates in the Skagit River Estuary and Padilla Bay

<table>
<thead>
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<th>Source</th>
<th>Description</th>
<th>Study Results</th>
<th>Representative Sediment Accretion Rate Estimate cm/yr</th>
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<tr>
<td>Pacific Northwest National Laboratory (2011) McGlinn Causeway Feasibility Study</td>
<td>Preliminary estimate of sediment accretion rate using annual average sediment load (3,962,084 tons/yr based on average of load from 1988 to 2010)</td>
<td>Skagit Bay and Swinomish Channel: Uniform distribution and deposition of sediments in Skagit Bay study area of (156154694 m², porosity of 0.4, and density of 2650 kg/m³)</td>
<td>Skagit Bay study domain including Swinomish Channel ≈ 2 cm/yr</td>
</tr>
<tr>
<td>WWU (2011) – EPA STAR Grant project (unpublished data)</td>
<td>Sediment Trap and Feldspar five marker horizons/grids at Skagit Bay Near-shore site: N48° 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) River Flow = 12,000 cfs</td>
<td>Skagit Bay Marsh: Mean accretion in sediment trap = 5.15 g d.w. ± 2.3 (s.d.) = 334.6 g/m<strong>2</strong> in 15 days Bed elevation change 0.33 ± .23 (s.d.) cm /15 days</td>
<td>Skagit Bay near-shore station near marsh - accretion from the 15-day sample in 2008 ≈ 8 cm/yr</td>
</tr>
<tr>
<td>Kairis and Rybczyk (2010)</td>
<td>Rate of elevation change derived from the linear regression of surface elevation changes at multiple sites in Padilla Bay from 2002 to 2010</td>
<td>Padilla Bay: Most sites in Padilla show erosion. Three sites show small deposition rates 12 (b) - 0.13 cm/yr 14 (b) - 0.12 cm/yr 8 - 0.16 cm/yr</td>
<td>Padilla Bay sediment accretion rates at selected sites ≈ 0.13 cm/yr</td>
</tr>
<tr>
<td>U.S. Army Corps of Engineers (2008) Skagit River Flood Damage Feasibility Study</td>
<td>Sediment Budget and Fluvial Geomorphology. Examination of Skagit River bed elevation changes</td>
<td>Skagit River, North Fork and South Fork: Comparison of surveyed cross sections between 1975 and 1999</td>
<td>Average accretion rate based on 24 year record Skagit River (RM 10.1 to RM 18) ≈ 1.75 cm/yr N.F. Skagit River (RM 4.5 to RM 8.85) ≈ 2 cm /yr S.F. Skagit River (RM 5.8 to 9.25) ≈ 1.25 cm/yr</td>
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</table>
Using a combination of total suspended-sediment grabs and turbidity measurements, USGS developed a suspended-sediment-rating curve for the Mt. Vernon site (Curran et al. 2011) as follows.

\[
S = \begin{cases} 
0.000001*Q^{2.32} & \text{Q < 27,400} \\
0.0000000000003*Q^{3.74} & \text{27,400 < Q < 66,100} \\
0.0453*Q^{1.41} & \text{Q > 66,100}
\end{cases}
\]

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

Sediment load converted to suspended-sediment concentration in mg/L is presented in Figure 2.11.

Based on this 24-year record and an average TSS concentration of 162 mg/L, the average sediment discharge the Skagit River is nearly 4 million tons/yr.
It is a common misconception that largest amount of sediment is transported mostly during storm-induced flow events. It is true that major geomorphologic changes such as erosion and enlargement of steep, incised channels may occur during extreme fluvial events. Although sediment concentrations are an order of magnitude higher during storm-event-generated flows, their duration is relatively short. It turns out that, in many rivers, modest flow regimes transport greater quantity of sediment material over time because such events occur more frequently (Wolman and Miller 1960).

In practice, 2-year return-frequency flows are used to represent effective flows or channel-forming flows. Flows at this magnitude or higher are referred to as storm-event generated flows in this document. The hydrological record of Skagit River shown in Figure 2.10 includes 21 storm-event flows that are greater than the 2-year return-frequency flow. The 2-year return-frequency flow was specified to be 64,640 cfs based on Beamer et al (2000). The non-storm period (with flows below 64,640 cfs) occurred 92 percent of the time from 1988 to 2010, and had an averaged 15,475 cfs at a TSS concentration of 138 mg/L. The non-storm load accounts for 68 percent of total sediment delivered by the Skagit River to Skagit Bay.

In addition to the sediment load, sediment grain size is an important parameter that controls the nature of sediment transport. Heavier sediments are transported as bed-load while finer-grain-size sediments with corresponding lower settling velocities tend to remain in suspension because of turbulence and are transported as suspended-load. The USGS study (Curran et al. 2011) also provided grain-size distribution information based on analysis of water column grab samples collected at the Mt. Vernon gage. Their results indicate that more 50 percent of sediments have a grain size smaller than 0.0625 mm. Sediment this size belongs to the silt and clay class and is often transported as suspended-load or wash-load. The remaining sediment is distributed in various grain sizes. However, only ~3 percent of the total sediments are in 0.5 to 1 mm range and are transported as bed-load.

2.3.3 Suspended-Sediment Model Setup

Based on available bed sediment size characterization information, the bed sediments are dominated by medium to coarse sand size classes (0.4 mm to 0.6 mm) in the North and South Forks of the Skagit River, and are likely part of the bed-load transport. For this study we have selected a single representative grain size of 0.06 mm (the median grain size in the silt/clay class) based on Curran et al. (2011) for conducting suspended-sediment transport, deposition, and erosion calculations. Initial conditions for suspended-sediment concentration and sediment bed layer thickness were set to zero.

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 is proportional to the sediment size. The critical shear stress (τc) for the erosion of mean sediment particles (0.06 mm) was calculated based on the approach described by Julien (1998) to be 0.11 pa. 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 median sized 0.06 mm particle was specified as 2.66 mm/s using Stokes law. The sediment erosion rate calculations were based on pickup function described in Van Rijn (1984).

Sediment concentration on the open boundaries was set to zero. Sediment concentration for the river inflow boundary was provided by the TSS time series shown in Figure 2.11.
2.3.4 Suspended-Sediment Model Application and Validation

To simulate long-term sediment load transport, distribution, and deposition in the study domain, we have adopted the approach of superposition of sediment loads from storm events over a baseline average (non-storm) condition. The computations were conducted in the two steps described below.

- **Step 1 – Baseline Average Condition.** A 30-day baseline average model simulation was conducted using the calibration period tidal and meteorological forcing from November 1-11, 2011, but using a constant river flow of 15,475 cfs, which corresponds to the non-storm period average. The sediment load was set to 138 mg/L, which also represents the 23-year average without the storm-event flows.

- **Step 2 – 21 Storm Events (from 1988 to 2010).** Using the same 30-day period tides and meteorological conditions, a 30-day period model simulation was conducted in which the average river flow was replaced with a 30-day river hydrograph straddling the storm-event flow. A corresponding TSS concentration was specified at the river boundary. The TSS concentration was varied each day with changing river flow. This was conducted independently for each of the 21 storms.

In addition to hydrodynamic information discussed earlier (i.e., water surface elevations, currents, salinity, and temperature), the model provides TSS concentration at all nodes. Figure 2.12 shows examples of predicted sediment plumes during ebb and flood periods from the upper layers of the model, which occupies the top 33 percent of the water column.

![Ebb](image1.png)  ![Flood](image2.png)

**Figure 2.12.** Skagit River Daily Average TSS Concentration at Mt. Vernon, Washington

Similarly, the model also recorded bed sediment thickness at the end of each 30-day model run. The cumulative sediment bed thickness for the 23 year period was obtained by superposition of 21 individual storm-event flow model runs (covering the 8 percent of the duration) plus the baseline average flow condition result scaled up by remainder of the period (duration of 92 percent).
Figure 2.13 shows a cumulative sediment deposition map corresponding to the 23-year simulation. The predicted sediment thickness was divided by the number of years of simulation needed to generate the deposition rate estimates.

Figure 2.13. Estimates of Sediment Deposition Rates Near the Mouth of the North Fork of the Skagit River Showing the Swinomish Channel and Padilla Bay (based on model simulation results from 1988 to 2010)

These results are approximate, and may best be viewed as model sensitivity analysis results. Bed-load is not included, and the model allocates all sediment loads to the median sediment class of 0.06 mm silt/clay fraction. Results may be improved by including bed-load computations, and simulating multiple grain sizes between 0.06 mm to 0.6 mm size classes.
3.0 Application to Simulate Climate Change Scenarios

Future climate simulations based on the Intergovernmental Panel on Climate Change emissions scenario (A1B) downscaled to the Pacific Northwest have shown that hydrology of Skagit River, the largest source of fresh water to Puget Sound, Washington, will be affected. Reduced summer flows coupled with a future sea-level rise are expected to alter estuarine circulation processes. However, there is considerable uncertainty about the extent and magnitude of resulting estuarine response because of the oceanographic complexity associated with Skagit sub-basin within the Puget Sound inland fjord setting. Alteration of the circulation and net and transport and reduction in brackish tidal marsh habitat are of concern because of the potential impacts to coastal fisheries and habitat. Higher salinity in the river distributaries could also affect drinking water and agricultural water supplies. The Skagit River has undergone extensive hydraulic modifications with the construction of flood control dikes and river training structures. River flow that historically occurred through multiple channels is now restricted to two diked forks.

For this effort, the model of Skagit and Padilla Bay was embedded within the intermediate-scale FVCOM model of the greater Puget Sound and Georgia Basin (Khangaonkar et al. 2011), which is also affected by sea-level rise and altered freshwater loads over a larger scale. Simulated salinity intrusions from future scenarios were compared with existing baseline conditions. Also, potential large-scale changes to the seasonal net transport through the basin, north through Swinomish Channel to Padilla Bay or to the south through Saratoga Passage were characterized through a series of sensitivity tests.

The results of this effort, limited to hydrodynamics and salinity computations, are summarized in Khangaonkar et al. (2014).
4.0 Results and Discussion

A hydrodynamic and sediment transport model was developed for the Skagit Bay and Padilla Bay interconnected water bodies including Swinomish Channel and portions of Saratoga Passage of the Whidbey Basin. The hydrodynamic model has been calibrated over the years through a combination of multiple prior projects with improvements to grid resolution and bathymetry, further validated as part of this effort, and is considered well established. However, the sediment transport model was our first attempt at simulating sediment deposition in the system using the FVCOM hydrodynamic solution for the combined Skagit Padilla Bay domain. Considerable improvement is needed to improve our ability to simulate movement and transport of sediments and evolution of the Skagit Delta. This includes refining the model resolution, updating the domain with recent bathymetry, and adding factors such as bed-load transport, multiple grain size, and geomorphological modeling to predict channel migration and bank erosion. The sediment transport model also has not been calibrated or validated against data from robust, long-term TSS monitoring and a bed-thickness data set. Therefore, the sediment transport modeling results must be treated as preliminary and best viewed as sensitivity test results. Yet these preliminary results provide valuable insight into sediment transport properties in the Skagit River estuary and bay system.

The primary objective of the modeling component of this project was to provide information related to sediment delivery and deposition to a mechanistic wetland elevation dynamics and vegetation unit model, and models of tidal channel geomorphology and juvenile salmon abundance and distribution. The final result—a baseline sedimentation rate map of the study domain—is one such output of the model as shown in Figure 4.1.

![Figure 4.1. Summary of Preliminary Estimates of Sediment Deposition Rates Near the Mouth of the Skagit River](image.png)
Specific conclusions are described below.

- The bed sediments routinely sampled and characterized by different groups as part of various studies consistently report grain sizes in the medium sand size class (0.4 mm to 0.6 mm). Our results based on review of new data from the USGS and modeling analysis indicate that these sediments remain in the system as part of the bed-load fraction. The majority (i.e., 97 percent) of discharged sediments of the load in the suspended mode is transported to Skagit Bay.

- Most of the sediment appears to be transported via the Skagit River North Fork conduit, likely because North Fork carries larger fraction of the total water flow.

- Model simulations show that very small fraction of Skagit River sediments are transported to Padilla Bay. This is validated by field data collected by WWU that shows most of the stations in Padilla Bay indicate erosion.

- The deposition rate of about 7 cm/yr matches the accretion rate of 8 cm/yr measured by WWU at that site.
5.0 References


