Development of a Land Use Planning Tool for Estuarine Habitat Protection, Restoration, and Cumulative Effects Assessment in Northern Puget Sound, WA

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Development of a Land Use Planning Tool for Estuarine Habitat Protection, Restoration, and Cumulative Effects Assessment in Northern Puget Sound, WA

A Final Report Submitted to

The NOAA/UNH Cooperative Institute for Coastal and Estuarine Environmental Technology (CICEET)

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1.0 EXPANDED EXECUTIVE SUMMARY AND KEY FINDINGS

The loss of habitat is regarded as one of the major causes for declining fish stocks. This is caused by thousands of kilometers of estuarine shorelines being modified for flood protection and agriculture through the construction of dikes and other artificial structures. In the Pacific Northwest, especially in the Columbia River and Puget Sound estuaries, a number of local and federally funded projects are planned or already underway that seek to achieve overall estuarine ecological restoration and fish-stock recovery. This requires planning with respect to competing land-use interests (restoration vs. development) and technical feasibility. In other words, an action ideally suited from the perspective of restoration of ecological functions may result in economic losses because of unexpected outcomes, such as flooding during high flow seasons or land mass loss due to erosion. Restoration actions planned without the benefit of tools such as estuarine circulation models and hydraulic and hydrologic analysis packages run the risk of not achieving the desired outcome as estuarine response may be different from that envisioned. The objective of this research, therefore, was to develop a numerical modeling tool and techniques that may be used for planning and designing restoration actions by restoration managers and land-use planners.

The technology developed through this research consists of applying an unstructured grid hydrodynamic model (FVCOM) to represent complex estuarine shorelines, including incorporation of multiple intertidal channels while retaining the configuration of the overall study domain. The model conducts three-dimensional baroclinic circulation and has the capability to simulate water quality kinetics (eutrophication) and sediment transport. Through this study, we refined the techniques for incorporating high-resolution light detection and ranging (LiDAR) data into the simulation of estuarine circulation and transport in the intertidal mudflats with wetting and drying marsh features. The technology also includes a fish-like particle tracking model. The hydrodynamic modeling tool provides an assessment of hydraulic and coastal engineering feasibility, and the fish-like particle tracking model developed in this study allows such parameters as connectivity, migration pathways, and access to be evaluated to help quantify the potential for overall success.

The benefits provided by this technology development are best described through examples. The application of this tool on the Skagit River delta has helped demonstrate that proposed 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 (Yang et al. 2010a). Similarly, applying the model on the Snohomish River estuary has provided a strong indication that the effects of restoration actions are not limited to the immediate local environment, but could extend over the entire tidal prism, affecting the hydrodynamic balance of the entire estuary (Yang et al. 2010b). 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 is restored as well, thereby leading teams to conduct estuary-wide assessments. The methods and techniques developed using Whidbey Basin estuaries as the test domain are fully applicable to other estuaries around the United States, assuming site-specific application to address problems particular to the new location (Khangaonkar et al. 2010).
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 only focused on large-scale circulation and transport phenomena in deep waters and did not address flood plains and marshes. We recognize that the FVCOM model used for tide flats is a new development that is an improvement over existing technologies. In this Cooperative Institute for Coastal and Estuarine Environmental Technology (CICEET) project, the improvement is illustrated through the application of FVCOM model using LiDAR information characterizing finer details of the distributary network and upstream expansion into the flood plain.

While this hydrodynamic simulation tool for estuarine processes in the tidal marshlands is new, it may still be considered relatively mature as the application has already spread to a number of additional sites in the Columbia River and Puget Sound estuaries well beyond the Whidbey Basin CICEET project domain. However, the fish-like particle tracking model, also initiated through this project, is in its infancy. Using qualitative information on fish behavior provided by co-principal investigators (CO-PIs) from the Skagit basin, we developed an algorithm to make improvements over the passive particle motion that is typically used to analyze fish migration pathways. Attempts were made to calibrate the model to interpret fish-monitoring data from the Skagit basin. The approach shows promise in that improvement was seen over passive particles. However, more funding and effort will be needed before the fish-like particle tracking model can be improved to provide more realistic estimates of fish population densities in the estuary.

In conclusion, the capability for simulating the important nearshore processes was developed through support from this CICEET grant. These processes include 1) circulation in complex multiple tidal channels, 2) wetting and drying of tide flats, and 3) 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 growing in popularity as land-use planners begin to see its utility through application to on-the-ground projects. Although the fish-like particle tracking tool, developed as a companion tool, is still in early stages of development, the possibility of incorporating behavior and motility rules has generated considerable interest from a wide group of scientists engaged in fish and oyster larva migration research and others interested in the formation of thin layers of harmful algal blooms.

Potential user communities beyond the immediate project partner institutions (National Oceanic and Atmospheric Administration [NOAA], Skagit River System Cooperative [SRSC], U.S. Geological Survey [USGS], and the Washington State Department of Ecology [Ecology]) now includes Universities (the University of Washington [UW] and Western Washington University [WWU]), local tribes (Nookacskack, Tulalip, and Stillaguamish), and various cities and counties. Other agencies that have supported this work before the CICEET grant provided us letters of support, such as Washington State Department of Fish and Wildlife (WDFW), Washington Sea Grant Program, Northwest Straits Commission, and Island County Planning and Community Development. Nonprofit groups such as the Skagit Watershed Council (SWC), Ducks Unlimited (DU), The Nature Conservancy (TNC), and people for Puget Sound continue to be our partners and potential users of this technology.
2.0 PROJECT DEVELOPMENT

Abstract

Restoration managers and nearshore land-use planners are under perpetual pressure to ascertain whether actions proposed at their project site will result in any measurable benefits. Due to schedule and budget constraints, estuarine and coastal hydrodynamic processes are sometimes neglected or addressed in a simplistic manner in the design and planning of nearshore restoration actions. Consequently, despite best intentions, efforts to restore nearshore habitats can result in poor outcomes and undesirable consequences, such as flooding, deterioration of water quality, and erosion, requiring immediate remedies and costly repairs. This underscores the need to develop hydrodynamic and oceanographic modeling tools suitable for application to coastal mudflat and marshland environments and to bring these tools into day-to-day practice for use by restoration planners and managers to verify coastal engineering feasibility and the success of proposed nearshore restoration projects. Even after completion of a specific restoration activity, the overall success of a project designed to create habitat and refuge for downstream migrating salmon is still dependent on the ability of the juvenile fish to successfully detect and obtain access to the newly restored habitat. The motility and behavior of the migrating fish may be affected by other estuarine features, such as connectivity within the estuarine distributaries’ structure, competing restoration sites within a small region, and ambient environmental parameters, such as water depth, velocity, and salinity and temperature.

In this paper, we describe the development of a numerical tool to assist land-use planners in the Whidbey Basin of northern Puget Sound make sound decisions about the location and configuration of nearshore habitat restoration sites. The tool is based on a three-dimensional (3-D) hydrodynamic model of Whidbey Basin. The hydrodynamic model was calibrated using site-specific data from the Skagit, Stillaguamish, and Snohomish sub-basins. The model was then applied to test various alternative restoration scenarios in the Snohomish Basin to examine the cumulative effects of proposed actions. The recovery of fish stock being one of the major goals, a fish migration pathway tracking model was also developed as part of the overall restoration feasibility assessment tool. The fish migration model is based on the Eulerian-Lagrangian-Agent method and uses environmental cues, such as oceanographic properties of water coupled with basic fish behavior rules affecting fish motion. This paper discusses the validation of the hydrodynamic model, the development and testing of the behavior influenced, and the fish migration model and also compares model predictions to fish catch data from the Skagit Basin.

2.1 Introduction

Puget Sound is a large estuarine system that is under strong development pressure. It suffers from a legacy of unplanned watershed and shoreline development and lacks a comprehensive plan to incorporate future stresses, including population growth and global climate change. Among the most important resources of Puget Sound that are currently threatened are the salmon populations that spawn in the rivers entering this inland fjord. Many populations of Puget Sound Chinook salmon are at historically low levels due to habitat loss caused by coastal land-development activities, including the construction of dikes and levees protecting agricultural and
residential lands from flooding. Other impacts have occurred along shoreline areas because of dredging and filling of intertidal habitats. Therefore, juvenile fish habitat restoration projects are of great concern in the Puget Sound coastal area for land-use planners.

In general, many of these efforts to restore nearshore habitats for salmon are hindered by a lack of information on how best to assess the feasibility of various restoration and protection options. Implications of proposed changes on key resources, such as salmon, and existing and alternate land uses are not easy to determine based on best professional judgments only. The stakeholders from various agencies involved in Puget Sound nearshore restoration activities agree on the need for more information to help the planning and decision-making process through oceanographic circulation and transport modeling tools. However, there are currently no integrated ecosystem analysis tools particularly applicable to fish-habitat restoration activities that are easily accessible to assess the individual or cumulative impacts of multiple restoration projects.

A key area of concern in the Puget Sound estuary is the Whidbey Basin. Whidbey Basin is a large region located in the northeast corner of Puget Sound and encompasses the water body sheltered by Whidbey Island. Figure 1 shows the location of the Whidbey Basin study area in relation to the greater Puget Sound and Salish Sea region. 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 nearshore habitats being a focus of conservation efforts. As a first step toward developing an integrated assessment tool, we constructed a hydrodynamic model of Whidbey Basin, integrating all of the sub-estuaries into a single domain. The model grid was developed with attention to the importance of simulating nearshore processes, such as circulation in complex multiple tidal channels, and wetting and drying of tide flats, such that questions that arise as part of restoration feasibility studies in Whidbey Basin projects would be adequately addressed. The hydrodynamic model application helps 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.
Figure 1. Oceanographic Regions of Puget Sound and the Northwest Straits (Salish sea), including the inner sub-basins—Hood Canal, Whidbey Basin, Central Basin, and South Sound.
However, hydrodynamic or coastal engineering feasibility alone does not guarantee success from the perspective of fish stock recovery and habitat restoration. From a fisheries perspective, the success of such a restoration effort in addition to flows is also controlled by other factors, such as connectivity, and the ability of the downstream migrating fish to find and use the newly restored habitat. To help facilitate the integration of the fish migration pathway and nearshore habitat restoration activities, a fish-like particle (i.e., fish surrogate) tracking tool was also developed as part of this project. The ability to track and predict the behavior of migrating fish in the presence of artificial structures in Puget Sound is of interest not only for assessing the potential benefits but also for evaluating potential impacts or obstructions that migrating fish may face from newly proposed development projects in the region.

A standard mathematical method integrating oceanographic information calculated by the hydrodynamic model with biologically sound fish-sensory and behavior rules to predict fish migration pathways does not exist and remains a challenge (Steel et al. 2001). Researchers have previously attempted to reproduce trajectories of larvae-stage fish using individual-based particle tracking models (Hinckley et al., 1996; Scheibe and Richmond, 2002, and Engie and Klinger, 2007). In these studies, the larvae were treated as passive neutrally buoyant particles, and only the effects of water quality variables on the mortality of larvae or juvenile fish were considered. A common dissatisfaction expressed by stakeholders is that fish are not passive and that motility and swimming behavior needs to be taken into account. An agent-based mathematical model describing fish behavior as a function of cues provided by aquatic environment information was first proposed by Anderson (1988). Based on this model, researchers have developed an individual-based fish tracking model using an Eulerian-Lagrangian-Agent method (ELAM) (Goodwin et al. 2006). Much of the work thus far has been on tracking of juvenile fishes around the engineering structures, such as hydraulic dams, in connection with the design of downstream fish-passage systems. In these efforts, the focus has been on hydraulic agents, such as hydrostatic pressure, velocity, and shear strain. In estuarine settings, the out-migrating salmon have many choices to consider, and the fish appear to make decisions about the duration of residence, use of available habitat, and departure from the nearshore marsh refuge areas in the brackish environment to the larger open-ocean conditions. The model therefore requires the mathematical capabilities to guide the movement of fish-like particles in response to different stimuli (agents), such as salinity, temperature, type of habitat, and fish life-cycle-stage parameters such as age, size, and species type.

In response to this need, through this CICEET grant, a preliminary attempt was made to develop a 3-D Fish-like Particle Tracking Model (FPTM3D). The model was designed to mimic the preferential movement of individual fish based on an Eulerian-Lagrangian-Agent Method (ELAM) that mechanically decodes and predicts 3-D movement trajectories of individual fish responding to selected abiotic agents. For simplicity, in this preliminary phase of the work, only hydrostatic pressure, salinity, and habitat variables were considered as agents. The ELAM framework consists of 1) the Eulerian hydrodynamic model to calculate the hydrodynamic variables, 2) the Lagrangian particle-tracking model to calculate the movement of fish-like particles, and 3) the agent model to calculate the fish behavior. The Lagrangian fish tracking model was externally coupled with the Finite Volume Coastal Ocean Model (FVCOM) of Whidbey Basin, which provides it with the required computed hydrodynamic variables (velocity, water depth, salinity, and temperature).
2.2 Objectives

The overall objective of this project is to develop a practical tool that will enable land-use planners to effectively address their concerns with respect to planning coastal development and restoration projects. The proposed approach includes the use of 1) hydrodynamic and constituent transport model and 2) a Lagrangian fish-like particle tracking model that land-use planners or scientists can use to predict the movement of fish-like particles. The results may then be used to assess the feasibility of success for a specific restoration project with respect to the potential use of restored habitat by downstream migrating fish in addition to hydrodynamic and coastal engineering feasibility.

The specific objectives are as follows.

- Develop a 3-D hydrodynamic model for Whidbey Basin using oceanographic data for model validation.
- Develop a 3-D Lagrangian fish-like particle tracking tool based on biologically sound fish behavior model.
- Validate the fish-like particle tracking model for the ideal test cases.
- Apply the fish-like particle tracking model using the juvenile salmon migration data for Skagit delta collected during a selected year (2002).
- Engage stakeholders in the development and evaluation of the land-use planning tool to confirm that it is accessible, applicable, and useful in local land use planning and work with national networks to export the tool to other coastal estuaries.
- Develop planning tool documentation, user information, and training materials to enable dissemination of the land-use planning tool beyond the range of the Whidbey Basin and Puget Sound.

2.3 Method

2.3.1 Development of Hydrodynamic Model for Whidbey Basin

Model Setup and Boundary Conditions

The 3-D hydrodynamic model used in this study is FVCOM developed by Chen et al. (2003). FVCOM solves the 3-D momentum, continuity, temperature, salinity, and density equations in an integral form by computing fluxes between non-overlapping, horizontal, and triangular control volumes. This finite-volume approach combines the advantages of finite-element methods for flexibility in handling complex shorelines and the superior 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.

Model grid development covered the entire Whidbey Basin and Padilla Bay. The high-resolution grid refinement was focused primarily on the marsh habitat and tidal flat regions, including restoration sites located in the Skagit Bay, Port Susan Bay, and Snohomish River. For computational efficiency, a relatively coarse grid was developed in the Saratoga Passage and Possession Sound area. 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. To minimize the effects of the open-boundary conditions on the area of interest, the model boundaries were extended into Possession Sound, Deception Pass, and Padilla Bay of Puget Sound. The determination 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 the 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 LiDAR 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 43,810 elements and 25,070 nodes in the horizontal plane. Ten uniform vertical layers were specified in the water column in a sigma-stretched coordinate system. Figure 2a shows the Whidbey Basin model domain extending from Point Possession at the south boundary to Padilla Bay at the north boundary. The model grid is plotted, showing a tight coverage of the nearshore boundaries, including the tide flats, the major distributaries, and the connection between Skagit Bay and Padilla Bay via the Swinomish Channel.

The open boundary conditions specified at the north and south end of the domain were tidal elevations corresponding to model validation periods and were obtained using the XTIDE program (Flater 1996) based on National Oceanic Service algorithms. Tidal elevations were specified from the Glendale station located near the entrance of Possession Sound, at Yokeko Point near Deception Pass, and at Anacortes at the Guemes Channel, which are available through the NOAA tide-prediction network. Another open boundary condition along the Padilla Bay entrance between Guemes Island and Samish Island was specified as the average tidal elevation between Anacortes and Chuckanut stations, which is also available from the predictions. The salinity open-boundary condition was specified with a constant value of 32 ppt, which represents the intrusion of the 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 is likely not significant in comparison to the effect of salinity. The temperature effect on the density-induced currents thus was not simulated in this study. 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 (KPAE) station near the study area.
Figure 2a. Unstructured Hydrodynamic Model Grid of Whidbey Basin.

The upstream end of the model domain is extended up to the USGS stream gages, which are not affected by tides, to specify the upstream model boundary condition. At the upstream river boundaries, the daily fresh-water inflows from three major rivers were specified. The data were from the USGS gauge stations (12200500, 12167000, and 12150800) in the Skagit, Stillaguamish, and Snohomish basins, respectively. River inflows in Whidbey Basin for three separate model validation periods are presented in Figure 2b.
Field Data Collection for Hydrodynamic Model Validation

The field-data for validating the hydrodynamic model included velocity profiles, salinity and temperature profiles, and water surface elevations for several 2-week long periods near habitat restoration sites in the Skagit Bay, Port Susan Bay, and Snohomish Basin, respectively. A 2-week, data-collection program encompassing a complete neap-spring tidal period was set up and conducted as part of the previous restoration projects in the study area. Specifically, in Skagit Bay, data were collected for a 2-week period from 6/6/2005 to 6/23/2005 (SK1 and SK2). Similarly, near the mouth of the Stillaguamish River in Port Susan Bay, data were collected from 10/10/2005 to 10/26/2005 (PS1 and PS2), and 10/12/2006 to 10/28/2006 (SN1, SN2, SN3, SN4) covers the data-collection period for the Snohomish Basin.

Model validation was conducted by comparing predicted oceanographic properties, such as water surface elevation and velocity time histories, salinity profiles, and time series data by applying the Whidbey Basin model corresponding to the field data-collection period. Details on model calibration efforts at the respective basins are presented in Yang and Khangaonkar (2009) and Yang et al. (2010 a, b).
Validation of Hydrodynamic Model

For this study, as described in the previous sub-section, the Whidbey Basin-wide model was validated against observed data in each sub-basin. Specifically, the predictions of the hydrodynamic model were compared with the measured water surface elevation, velocity, and salinity data at stations SK1, SK2, PS1, PS2, SN1, SN2, SN3, and SN4, covering a wide range of tidal characteristics (station locations are shown in Figure 2a). The stations are mostly located near the restoration project sites, the mouths of three major rivers (Skagit, Stillaguamish, and Snohomish). The model validation periods are as follow:

- Skagit River and bay (SK1, SK2)—6/6/2005 ~ 6/23/2005
- Stillaguamish River and Port Susan bay (PS1 and PS2)—10/10/2005 ~ 10/26/2005
- Snohomish River and basin (SN1, SN2, SN3, SN4)—10/12/2006 ~ 10/28/2006

Because of the existence of large tidal mudflat regions 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 MLLW 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 Whidbey Basin, such as the diurnal inequality of tides, fresh water discharge plumes, and salinity intrusion at the river mouths. The statistical errors were calculated for a quantitative estimation of model calibration. The absolute error and root-mean-square error (RMS) are provided in Table 1. Overall, the model errors for tide are within 8% of the tidal ranges from MLLW to MHHW. 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 surface freshwater plume and bottom salt water during the tidal cycle. Overall, the model is considered sufficiently validated for application to restoration feasibility assessment and fish-like particle tracking analyses.

<table>
<thead>
<tr>
<th>Calibrated Variables</th>
<th>Statistical Errors</th>
<th>Snohomish Basin</th>
<th>Port Susan</th>
<th>Skagit Bay</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RMS</td>
<td>SN1</td>
<td>SN2</td>
<td>SN3</td>
</tr>
<tr>
<td>Tide Elevation (m)</td>
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<td>0.16</td>
<td>0.23</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td>Absolute Error</td>
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<td>0.18</td>
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<tr>
<td>Velocity (m/s)</td>
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<td>0.07</td>
</tr>
<tr>
<td></td>
<td>Absolute Error</td>
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<td>0.11</td>
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<tr>
<td>Salinity (ppt)</td>
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<tr>
<td></td>
<td>Absolute Error</td>
<td>1.59</td>
<td>4.80</td>
<td>4.90</td>
</tr>
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</table>

Figure 3(a, b, c) provides an example of the comparison of predicted water-surface elevation, velocity, and salinity with measurements at validation stations in Skagit Bay (SK2), Port Susan...
(PS2), and the Snohomish River (SN1), respectively. Similar fit to data were obtained at other stations.

Figure 3a. Comparison of the Predicted Water Tide Elevation, Salinity, and Velocity with Observed Data at Skagit Bay Station SK2.
Figure 3b. Comparison of the Predicted Water Tide Elevation, Salinity, and Velocity with Observed Data at Port Susan Bay Station PS2.
2.3.2 Development of Eulerian-Lagrangian-Agent Fish Tracking Model

*Fish Surrogate Tracking Model Framework*

A 3-D FPTM3D was developed for this study. The model is based on ELAM, first proposed by Anderson (1988). The model mechanically decodes and predicts 3-D movement trajectories of individual fish responding to abiotic stimuli. As depicted in Figure 4, the ELAM framework consists of 1) the Eulerian hydrodynamic model, 2) the Lagrangian particle tracking model, and 3) the agent-based behavior model. The eulerian framework describes the hydrodynamics and dispersion of physical properties in the water column at each computational node at discrete time intervals. The variables, including velocity and salinity, are externally computed by FVCOM.
These computed variables are fed into the Lagrangian particle-tracking model. The Lagrangian framework tracks the position of individual fish surrogates throughout a computational domain using a Eulerian frame of reference. An individual fish surrogate preserves its own fish identity, such as age and size. The agent-based behavior model computes the movement (speed and direction) of individual fish surrogates responding to perceived stimuli. The strengths of stimuli are estimated from the agent values at the fish location (e.g., pressure, salinity, habitat characteristics) interpolated using the values at the model nodes surrounding the surrogate fish.

The computed motion (translation only) of the surrogate fish is imported into the Lagrangian particle tracking model. The Lagrangian particle tracking model is central to the ELAM-based framework for this study. The algorithm solves a set of nonlinear systems of differential equations to track the particle position under the influence of a 3-D velocity field externally generated by the Eulerian hydrodynamic model. The explicit Runge-Kutta multistep method is used to solve the discrete integral form of the equation at every time step. At the solid boundary, the particles are reflected back to the interior water domain to simulate fish movement. This is similar to what might happen when a fish encounters a solid boundary, and it is necessary to confirm that the surrogate fish does not exit the computational domain through a solid boundary.

A 3-D fish swimming vector is estimated through input from fish behavior rules for each surrogate fish at every model time step. The speed is generally limited by the size of the fish and initial orientation. Once the speed and direction is determined, the swim vector is decomposed into Cartesian components \((u_f, v_f, w_f)\). The resultant fish swim vector is a vector sum of fish-movement vector components \((u_f, v_f, w_f)\) and water-flow vector components \((u_w, v_w, w_w)\) interpolated to a fish location from the previous time step (see Figure 5). Using the resultant fish swim vector, the current fish location \((x_t, y_t, z_t)\) at time \(t\) is updated from the previous fish location \((x_{t-1}, y_{t-1}, z_{t-1})\) after the time interval \((\Delta t)\).

The new fish location is calculated by:

\[
x_t = x_{t-1} + (u_w + u_f) \cdot \Delta t \tag{1}
\]

\[
y_t = y_{t-1} + (v_w + v_f) \cdot \Delta t \tag{2}
\]

\[
z_t = z_{t-1} + (w_w + w_f) \cdot \Delta t \tag{3}
\]
Figure 4. Eulerian Lagrangian Agent Model (ELAM) Framework.

Figure 5. Illustration of Individual Fish Movement in a Eulerian Mesh.
The sensory system for a typical fish consists of several types of receptors, including chemoreceptor, mechanoreceptor, thermoreceptor, and electromagnetic receptor (Atema et al., 1988; Coombs, 1999; Kanter and Coombs, 2003). Modeling full-fledged fish behavior is therefore very complex, and mathematical formulations are at best gross simplifications and approximations based on observed behavior. Yet this improvement, however small over passive particle transport, is likely to make a difference in being able to simulate fish populations in an estuary.

Fish swimming can be defined as the interaction of muscles and neurons responding to stimuli (Terzopoulos et al., 1995; Ijspeert and Kodjabachian, 1999). These stimuli in the mathematical framework are provided through agents (environmental parameters such as salinity, temperature, velocity shear, and habitat information). Environmental properties are computed using the hydrodynamic model at the nodes and centroids of meshes in the Eulerian framework at each time step. The FPTM3D code interpolates the hydrodynamic model results to the surrogate fish location at every model time step. Habitat information, which is fixed and specified at the habitat nodes, is also conveyed to the surrogate fish, assuming that a fish can sense the habitat once it is within a certain range. The sensory range of the fish is specified using a parameter defined as the length scale of fish sensory ovoid (SFS) (see Figure 5). Theoretically, the mesh size (length of a cell) and model time step should be smaller than the SFS and fish motion time scale during an event. Practically however, it may not be possible to accomplish this high computational resolution because of computational costs. In general, the resolution of a Eulerian model grid cell in coastal hydrodynamic modeling is much larger than the SFS. To overcome this limitation, gradients of oceanographic properties (agents) and distances between surrogate fish location and surrounding nodes are used to estimate a behavior and a strength of response. The FPTM3D code selects SFS for each fish at every time step using the following rule.

\[ SFS = \max (SFS_f, SFS_g) \]  

where SFS\(_f\) is the length scale of a real fish sensory system, and SFS\(_g\) is the length scale of a model fish sensory system defined by the size of the grid cell surrounding the fish.

In the agent-based behavior model, the fish encounters agents (A\(_j\)) that affect its fitness and behaviors, such as drive and motility. Based on observations, typical environmental agents known to affect migrating juvenile salmon are salinity, temperature, velocity gradients, prey and predator, and habitat characteristics (Brett, 1952; Smith et al., 2006; Keefer et al., 2008). As the fish moves through its aquatic environment, during each discrete time interval \(\Delta t\), it may encounter different agents and undergo different exposure durations. During the encounter, the fish may quickly or slowly acclimatize to the agents. It is hypothesized that the fish’s ability to perceive a stimulus to exceed the threshold is relative to the acclimatized stimulus level from past experiences. The detection of agents exceeding threshold is mathematically formulated as follows:

\[ I_j(t) - I_{a,j}(t-1) > k_j \]
where $I_j(t)$ is the instantaneous strength (intensity) of agent $j$ at the current time step, $I_{a,j}(t-1)$ is the acclimatized strength of agent $j$ at the previous time step, and $k_j$ is the threshold value for agent $j$. The acclimatized strength of an agent is represented by a weighted average:

$$I_{a,j}(t) = (1-m_j)I_j(t) + m_jI_{a,j}(t-1) \quad (6)$$

where $m_j$ is the memory coefficient ranging from 0 to 1. The memory coefficient allows the model to set the weight that must be placed on acclimatization from the previous exposure. This may also be viewed as adaptation to change.

Once a fish perceives the strength of agent (stimuli) exceeding a threshold value for each agent, an event is allowed to occur. This event is specific to a tactical behavior and provides the fish information to estimate the probability of obtaining the intrinsic utilities resulting from the behavior. The event is specified by the following formulation:

$$e_j(t) = 0, \text{ if } I_j(t) - I_{a,j}(t-1) < k_j = 1, \text{ if } I_j(t) - I_{a,j}(t-1) \geq k_j \quad (7)$$

where $e_j(t)$ is the boolean measure of event for each agent index $j$.

The probability of obtaining the intrinsic utility ($u_j$) as a result of behavior is also stated by a weighted average:

$$P_j(t) = (1-m_j)e_j(t) + m_jP_j(t-1) \quad (8)$$

where $P_j(t)$ is the probability of each event specific to agent $j$.

The choice of behavior is controlled by complex neurological processes. For simplicity, our model is based on a game theory framework adopted by Anderson (2002). In his framework, it is assumed that the fish has a preference-ordering of behaviors and makes a choice among the behaviors based on overall utility. Associated with each behavior is its own intrinsic utility ($u_j$). There is also a bioenergetic cost ($C_j$) carrying out the behavior. A fish chooses a behavior that has a maximum expected overall utility involved in potential choices. The calculation of overall utility and the selection of a behavior are expressed mathematically as follows.

$$U_j(t) = P_j(t)u_j - C_j(t), B_x > B_y \leftrightarrow U_x > U_y, U_x = \max[U] \quad (9)$$

where, $B_x$ and $B_y$ are the behaviors associated with agents $x$, $y$.

**Testing of the ELAM Model Formulation Algorithms**

The mathematical formulation of the fish behavior model was tested using three idealized descriptions of agents: 1) Gaussian distribution of free shear strain, 2) sinusoidal variation of pressure, and 3) impulse of high salinity. No bioenergetic costs were included in these tests. The memory coefficient values were set to 0.98, 0.94, and 0.90, and the intrinsic utility values were 0.70, 0.99, and 0.99 for shear strain, pressure, and salinity, respectively.

The strength of the free shear-strain stimuli were assumed to be scaled by a logarithmic function as follows (Goodwin, 2006).
where $S_0$ is a reference strain value. The strengths for the pressure and salinity stimuli are assumed to be linearly proportional to their magnitudes. Results of the model algorithm tests are illustrated in Figure 6. In the plot, the stimuli $(I_i(t) - I_{a,j}(t-1))$ were normalized by the average depth (3 m) for the pressure and the peak values (1s$^{-1}$, and 10 ppt) for free shear strain and salinity. The normalized threshold values ($k_j$) for stimuli $(I_i(t) - I_{a,j}(t-1))$ were set to 0.4, 0.0667, and 0.2 for shear strain, pressure, and salinity, respectively. As shown in Figure 6, the stimuli peak at the high gradient points (times when there is highest rate of change) of agent functions (strain, salinity, and pressure). For example, a sharp peak of response to stimuli occurs when a pulse of high salinity occurs (as given by the salinity function). The probability of obtaining the intrinsic utility is off in the peak phase from the stimuli function because it is estimated by weighted average with time. The utility is scaled by multiplying intrinsic utility values by the probability. The behavior is then chosen by comparing the utility values. A behavior can continue for a period following an event because of acclimatization based on previous experience. A series of sensitivity tests indicates that the shape of perceived stimulus is sensitive to the memory coefficient. Therefore, the memory coefficient must be calibrated carefully in the real application.
Figure 6. Illustration of Mathematical Model for Fish Behavior.
Testing of FPTM3D Fish-like Particle Tracking Model for Idealized Channel Case

The fish surrogate particle tracking model FPTM3D was tested to evaluate the response to three agents (pressure, salinity, and habitat) in a long rectangular open channel (10,000 m long × 100 m wide × 4 m deep) with a small side channel (50 m long × 10 m wide × 4 m deep) in steady flow as shown in Figure 7. The side channel is representative of freshwater inflow with a brackish environment and with habitat suitable for rearing. The model domain has 20 triangular elements across the channel and 5 layers vertically. The model mesh provides the computational domain for the Lagrangian particle tracking model. A constant ambient velocity was assumed. The integration time step was set to 1 min. Two inflow salinity conditions were selected to investigate the fish responses to low and high salinity plumes discharged from the side channel. The salinity plumes were designed to be 2-D in the horizontal plane, assuming no vertical variation. The objective of this setup was to mimic an idealized juvenile fish-rearing channel with favorable environmental conditions, such as the presence of a freshwater source, less turbulent water, and availability of suitable habitat. Sensitivity analyses were conducted for the selected three agents by varying model parameters and environmental conditions. The model parameter values, including memory coefficient and intrinsic utility values, were selected from the literature (Goodwin et al., 2006). The model setup parameter conditions for the scenarios tested are summarized in Table 2.

Table 2. Numerical Experiment Conditions for the Ideal Channel Case.

<table>
<thead>
<tr>
<th>Test Case</th>
<th>Agent ( (A_j) )</th>
<th>Threshold ( (k_j) )</th>
<th>Memory Coefficient ( (m_j) )</th>
<th>Intrinsic Utility ( (u_i) )</th>
<th>Ambient Condition</th>
<th>Default Fish Velocity ( (V_{fd}/V_{fm}) )</th>
<th>Behavior</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>pressure</td>
<td>1.0</td>
<td>0.0, 0.94, 1.0</td>
<td>0.99</td>
<td>2</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Case 2</td>
<td>[S(t) - S(t-1)]</td>
<td>0.05, 0.01</td>
<td>0.90</td>
<td>0.99</td>
<td>0.2, 0.5, 1.2</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Case 3</td>
<td>habitat(500)</td>
<td>0</td>
<td>0.98</td>
<td>0.99</td>
<td>0.2, 1.2</td>
<td>10</td>
<td>0</td>
</tr>
</tbody>
</table>

*Note—fish length \( (L_f) \) is 5 cm and maximum fish speed is \( L_f \) m/sec. \( S(t) \) is the salinity at time \( t \). \( V_a \) is the ambient velocity, and \( V_{fd} \) and \( V_{fm} \) are the default and maximum fish swimming velocities, respectively.

Figure 7. Model Grid for Idealized Channel Test Cases.
Case 1—Pressure

The model was tested to evaluate the response of a surrogate fish to pressure (water depth) change. Only the pressure agent was considered in the fish behavior rules for this test. A sensitivity analysis for the memory coefficient was also conducted as part of this analysis. The threshold value for an event occurring was set to 1.0 m. That is, when the pressure exceeded 1.0 m of water depth, a response from the fish was expected. The response that would provide benefit would be to move upward towards lower pressure. Initially, the surrogate fish was located vertically at a depth of 3.0 m below the water surface and at the coordinate (4900.5 m, 50.5 m) as depicted in Figure 8. The ambient channel flow was assumed a constant with a velocity of 2 Lf/sec flowing in the downstream direction. The vertical and horizontal trajectories of the surrogate fish are presented in Figure 8, corresponding to three different memory coefficients. Horizontal trajectories are identical because the fish surrogate is passively transported by the same ambient velocity, and there are no stimuli in this test that would cause a behavior response of turning to the left or right.

Vertically, the fish surrogate with \( m_j = 1 \) did not respond to a pressure change. The acclimatized strength of the agent is always set to that from the previous time step. For this case, the probability of obtaining the intrinsic utility is always the same with the initial value set to a small nominal value. Therefore, no behavior occurs regardless of an event occurring.

For the case of \( m_j = 0 \), the fish surrogate moved upward 0.25 m initially and stayed at the 2.75 m depth during the downstream transportation. For this case, the acclimated strength of the agent was a small background value. Exposure to the stimuli of 3 m depth greater than the threshold of 1-m-depth pressure caused an immediate upward movement response. After that event, however, the fish surrogate did not acclimatize, and the agent strength from the previous exposure was no longer considered. As formulated in Eq. (6), the acclimated strength of agent \( (I_{a,j}(t)) \) is always the strength of agent \( (I_j(t)) \) at the current time step when \( m_j = 0 \). This leads to a zero stimulus value \( (I_j(t) - I_{a,j}(t-1)) \), which is always smaller than the threshold value \( (k_j = 1 \text{ m}) \), and no further upward movement occurs.

The fish surrogate with a typical memory coefficient \( m_j = 0.94 \) responded to a pressure change. It moved upward up to the water surface at a specified vertical speed \( (0.1 \text{Lf/sec}) \) during a passive transportation by the ambient flow \( (V_a = 2 \text{L}_f/\text{sec}) \).
Figure 8. The Vertical and Horizontal Trajectories of a Fish Surrogate Responding to Pressure Change. The trajectories with three memory coefficients ($m_j=0.0, 0.94, 1.0$) are shown in the vertical movement plot.
Case 2—Salinity

The model was also tested to assess surrogate fish response to a salinity agent. Two discharge plume scenarios were tested including the low (10 ppt) and high (15 ppt) salinity plume discharged from the side channel. The ambient salinities were 15 ppt and 10 ppt, respectively. The salinity of the discharge plume varies gradually from the source.

Two different fish behavior rules were assumed for this test. The first rule is that the fish perceives salinity variation ($|S(t)-S(t-1)|$). The second rule is that the fish also perceives absolute salinity ($S(t)$). The behavior response to both stimuli is identical, which is to seek a lower salinity within the fish sensory range.

Figure 9 presents horizontal trajectories of fish surrogates with low (0.01 ppt) and high (0.05 ppt) threshold values for the low salinity plume. The default fish swimming speed was $0.2L_f \text{ m/s}$ (i.e., 0.01 m/s for a fish of length 0.05 m) in the downstream direction. There was no ambient flow. The low threshold value was sufficient to be exceeded by the stimulus perceived by the surrogate fish within a default fish movement scale ($0.01 \text{ m/s} \times 60 \text{ sec}=0.6 \text{ m}$) during the model time step (60 sec) at the plume boundary. The salinity varies 0.25 ppt across about 3-m plume contour lines at the plume boundary. The fish surrogate responded to the salinity variation at the plume boundary, moving toward the low salinity source by crossing the salinity contour lines. After about 135 minutes, the fish surrogate found the low salinity source and remained at the source node. In this simulation, events did not always occur at each time step, but the surrogate continued its movement toward the lower salinity point because of the memory effect on utility. This memory effect would eventually diminish with time if no event occurs. The dissipation rate would be inversely proportional to the memory coefficient value. In contrast, the high threshold value of 0.05 ppt was always above the stimuli encountered by the surrogate fish as it traversed the plume, and as a result, there was no event, no behavior response, and the surrogate fish continued downstream without detecting the plume.

Figure 10 shows the impact of ambient velocities (0.2, 0.5, 1, and $2*V_{fm}$ where $V_{fm}$ is the maximum fish swimming speed) on the trajectories of surrogate fish in a low salinity plume. The ambient flow is similar to the typical hydraulic condition that the migrating juvenile fish may encounter in its natural environment. In this situation, we assume that the surrogate fish is passively transported downstream by ambient current until it encounters the plume boundary. Once the surrogate fish perceives less saline water, it moves toward the source of fresh water with the maximum swimming speed ($V_{fm}=5 \text{ cm/s}$). The resulting velocity is a vector sum of fish swimming velocity and ambient velocity. Therefore, in the high-ambient velocity condition ($1*V_{fm}$ and $2*V_{fm}$), the fish surrogate is swept downstream without being able to detect the plume. In the low-ambient velocity condition ($0.2*V_{fm}$), the fish surrogate is able to sense salinity gradients in a timely manner, change direction towards the low salinity source, and arrive at the desired destination. In the presence of moderate velocity condition ($0.5*V_{fm}$), the fish surrogate ended up near the plume boundary at the side channel entrance but could not find the entrance. These test results indicate that the ambient velocity relative to fish swimming speed (or size) is an important parameter hindering the ability of the migrating juvenile fish to find a safe rearing habitat channel. The results also indicate that the probability of reaching the side channel would be affected by the initial location/distance from the river bank.
In Figure 11, the trajectories of surrogate fish in response to a high-salinity plume are plotted. These results are in contrast to the simulation for a low-salinity plume. The low-salinity plume is favored by the surrogate fish, but the high-salinity plume serves as a barrier to downstream migrating fish. In the absence of ambient current, and when a high threshold criterion is activated, the surrogate fish is unaffected by the salinity plume, and it moves downstream, crossing the plume with the default migration speed. When the low threshold is activated, the surrogate fish moved back upon encountering the plume boundary to the low-salinity region until the acclimated stimulus effect dissipated. After the acclimated stimulus effect dissipated, the fish surrogate moved downstream and turned towards the rearing channel until it once again hit the plume and bounced back again. This process was repeated and resulted in a net movement to the channel bank. The net downstream movement along the channel bank then forced the surrogate fish to enter the plume. Once inside the plume, the fish became acclimatized to the high-salinity environment. This acclimation effect remained until the fish surrogate sensed the high gradient of salinity (around x=5000 m). In this high-salinity gradient region, the surrogate fish escaped the plume quickly and moved downstream. During the process of moving back and forth at the upstream plume boundary, the swim direction was determined by the numerical ordering of mesh numbers of the surrounding nodes if the salinity values were identical as in this test case (10 ppt of ambient salinity). In a real life application, there would be an extremely low chance of this happening. It is likely that the surrogate fish may go around the plume toward the other side of the bank.
Figure 9. Horizontal Trajectories of Fish Surrogate Responding to Salinity Fluctuation with High and Low Threshold in Low Salinity Plume. No ambient velocity was assumed.
Figure 10. Impact of Ambient Velocities on Horizontal Trajectories of Fish Surrogates Responding to Salinity Fluctuation in Low-Salinity Plume.
Figure 11. Horizontal Trajectories of Fish Surrogates Responding to Salinity Fluctuation with High and Low Threshold in High-Salinity Plume. Ambient velocity was assumed to be zero.

Case 3—Habitat

Figure 12 demonstrates the capability of model and surrogate fish in searching for favorable habitat location. The favorable habitat is located at the end of the side channel. It is assumed that the fish surrogate can locate the exact coordinate of habitat searched when it is within a certain range from the habitat location (habitat type is predefined in the model mesh properties). Here, the range was arbitrarily set to 500 meters. As shown in Case 1, the ambient velocity affects the trajectories. In the low-ambient velocity (0.2*\(v_{fm}\)) case, the surrogate fish orients itself towards the habitat location and swims towards it in a straight line until it encounters a bank. The fish then follows the channel bank in the downstream direction until the entrance of the side channel is found. It is noted that in the Lagrangian tracking algorithm, a surrogate fish is reflected back into the model domain upon encountering a solid boundary. In the moderate-ambient velocity (1.0*\(v_{fm}\)) case, the fish surrogate is swept away further downstream before it manages to enter into the side channel. However, in the high-ambient velocity (2.0*\(v_{fm}\)), the fish surrogate shoots past the channel and fails to find the habitat.
Figure 12. Impact of Ambient Velocities on Horizontal Trajectories of Fish Surrogates in Searching for Habitat Location.

2.4 Application of FPTM3D to Simulate Fish Migration in Skagit Bay

2.4.1 Monitoring of Skagit Bay Chinook Salmon Population

The outmigration population of juvenile Chinook salmon in the lower Skagit River were used along with juvenile Chinook density data in the Skagit delta estuary, the Swinomish Channel, and Skagit Bay for a validation analysis of the CICEET Fish Migration Pathway tracking tool. The year 2002 was the best year for this analysis because of the completeness of fish catch records in three factors: space, time, and habitat type/area compared to other years available.

Juvenile Chinook salmon timing and abundance data were used in two ways. The first way we used juvenile Chinook data was to represent the population of juvenile Chinook salmon entering the hydrodynamic model domain where the Skagit River meets the Skagit delta estuary. The
population of fish entering the system is one important independent variable influencing juvenile Chinook timing and abundance in all areas downstream.

The second way was to represent the juvenile Chinook salmon using the dispersed habitat downstream of the area where juvenile Chinook salmon enter the hydrodynamic domain, specifically in the area of the Skagit delta estuary, the Swinomish Channel, and Skagit Bay. For this purpose, we used data from 43 different sites throughout the Skagit delta estuary, Swinomish Channel, and Skagit Bay.

A complete description of the juvenile Chinook salmon data used for this analysis is found in Appendix A.

### 2.4.2 Hydrodynamic Simulation for Year 2002

The year 2002 was selected to apply the FPTM3D tool for Skagit Bay based on completeness of the fish catch data and the study domain coverage. The FPTM3D tool requires a hydrodynamic model solution generated by the FVCOM model. In preparation, the hydrodynamic solution corresponding to the period for collecting fish data (year 2002) was generated with inflow and boundary conditions corresponding to 2002. The river hydrograph used in this simulation is presented in the Figure 13.

![Figure 13. Skagit River Flow During Year 2002.](image)

Predicted 2-D velocity and salinity distributions at the surface layer corresponding to flood and ebb tides on February 8 and 9, 2002, are shown in Figures 14 a and b as an example. The areas without velocity vectors in the model domain indicate regions where the model elements are dry (water depths less than 0.2 m). Strong velocities along the deep channel moving toward the north were predicted and are consistent with a qualitative understanding of the system. Velocities near the bayfront of Fir Island were generally small because of the shallow water
depths in the mudflat region. During ebb tide, strong currents were present from the North and South Fork Skagit River channels entering the Bay because of the combination of ebb currents and the out-flowing freshwater plume of the Skagit River. Distinct ebb currents along the deep channel in the west side of the bay were predicted, as shown in the surface 2-D velocity plot.

A large freshwater plume typically occupies the region from the mouth the Skagit River during the entire tidal cycle. Simulations showed that during flood tide, the freshwater plume was confined to the river mouth area and pushed north a couple of miles. During ebb tide, the freshwater plume appeared to have moved south, pushed by the southerly directed ebb currents, all the way to the deep channel on the west side of the bay. Freshwater discharged from the South Fork was shown to be distributed throughout the multiple channels present at the mouth of the South Fork. Results also show that salt water intrusion could reach upstream into the network of tidal channels in the South Fork during flood tide. During ebb tide, a mixed-water mass with salinities in the range of 5 to 15 ppt occupies the bayfront of the South Fork. Salinities in the bayfront region between the South Fork and North Fork were shown to be generally high, with values greater than 15~20 ppt.

Figure 14a. Surface Velocity and Salinity Distribution—Skagit Bay, Flood Tide
2.4.3 Comparison of Fish Tracking Model Results with Skagit Bay Data

Two sets of simulations were conducted in the Skagit Bay region of Whidbey Basin to test the fish tracking model (FPTM3D) in a real estuarine setting. Fish-catch data for migrating juvenile salmon collected by SRSC in the Skagit bay were processed and used for model setup as well as for comparison with predicted results. Two simulations were conducted: 1) *Simulation 1*—passive particle tracking and 2) *Simulation 2*—fish-like particle tracking. In *Simulation 1*, fish properties were turned off. Therefore, particles behaved like neutrally buoyant tracers. In *Simulation 2*, two agents, namely “hydrostatic pressure” and “habitat attraction,” were turned on.

The parameter values used in this simulation are summarized in Table 3. The model parameter values, such as memory coefficient and intrinsic utility, were set at values the same as in the ideal test cases (section 2.3) based on the literature values (Goodwin et al., 2006). It is assumed that juvenile salmon prefer to reside in the surface layers (lower pressure). The search for habitat is given a high priority by setting the threshold parameter for habitat search to zero. The growth of juvenile salmon is expressed as a function of time as follows.

\[ L = L_0 \cdot \exp(rt) \]  

(11)

where \( L \) is the fish length at current time, \( L_0 \) is the initial fish length, \( r \) is the growth rate, and \( t \) is the time. The initial juvenile salmon length ranged from about 40 mm in the early months (February through April) to 70 mm in a later month (July). The size distribution with time was based on the median size data from the fish caught at the upstream boundary near Mt. Vernon.

![Surface Velocity and Salinity Distribution—Skagit Bay, Ebb Tide](image)
The fish growth rate was set to 0.046 day\(^{-1}\) for use in the growth equation. The peak phase difference (approximately 14 days) between the upstream fish migration data and the monthly fish population density data at the sampling locations in the South Fork distributaries was used to estimate the growth rate with the assumption that juvenile salmon with an initial size of 40 mm leaves the habitat after growing up to 80 mm. This growth rate value is regarded as a calibration parameter at this initial application stage as many other important parameters, such as the death rate, which balances fish-population density, are not considered. In this setup, the growth was arbitrarily limited to 100 mm in size to prevent continuous numerical growth.

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Agent ((A_j))</th>
<th>Threshold ((k_i))</th>
<th>Memory Coefficient ((m_j))</th>
<th>Intrinsic Utility ((u_i))</th>
<th>Swimming Speed ((V_{id}/V_{im}))</th>
<th>Behavior</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation 1</td>
<td>none</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Simulation 2</td>
<td>pressure habitat</td>
<td>0.1 m</td>
<td>0.94</td>
<td>0.99</td>
<td>0.2</td>
<td>tactical</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0</td>
<td>0.98</td>
<td>0.99</td>
<td>1.0</td>
<td>strategic</td>
</tr>
</tbody>
</table>

The number of particles released at the upstream boundary was determined by scaling down the downstream migrating fish data at the same location. The estimated total population of downstream migrating wild Chinook was about five million in the year 2002. The procedure for collecting data for downstream fish migration and the method for estimating population based on the weekly catch data are described in Appendix A. The ratio for the estimated fish population to the number of particles used in the FTMP3D model \((F:P\,\text{ratio})\) was 100, optimized to reduce the computational time while confirming the release of sufficient particles to represent the population migrating during different tidal cycles. As shown in Figure 15, the peak 2002 migration in Skagit River occurred in April, during which the fish-count numbers reached as high as 663,000 per week. The total number of particles released in the FTMP3 tracking model was about 50,000. The weekly fish-catch number was converted to an hourly number for the continuous release simulation.

Figure 16 shows the juvenile salmon habitat locations investigated for this study along the Skagit Bay. These habitats consisted of numerous blind channels and pocket estuaries with a large range in size and shape. For the current stage of model development, which is only in its preliminary stage, refinement of the existing model grid to the small habitat scale was considered impractical. A simplification was adopted that parameterized the sensing and searching process of juvenile salmon using habitat over larger areas. This was accomplished by clumping together a collection of sites. In the FPTM3D model setup, the properties of habitats were allocated to the nearest nodes within an attraction radius. The attraction radius of habitat was set to 25 m, equivalent to half the effective diameter of the averaged habitat area \((i.e., \, d=\sqrt{4\cdot A/\pi} \,\text{m})\) over the entire Skagit Bay study domain. Qualitatively, the algorithm works as follows: once a fish particle drifts into the attraction radius, the fish particle swims toward the habitat coordinate with a swimming speed proportional to the fish length. The resulting velocity is a vector sum of fish swimming velocity and ambient flow velocity. Therefore, the probability of success for a fish finding the desired habitat depends on a swimming velocity relative to the flow velocity. If the fish particle arrives near the habitat location within a certain range \((5 \,\text{m})\), it is assumed that the
fish particle has reached the habitat destination. The fish particle is then instructed to remain there until it grows up to a threshold size (80 mm). Habitat locations were grouped for analysis into nine segments according to geographic location and hydraulic connectivity of the stream channels. For example, Segment 2 includes habitats located in South Fork distributary channels. This segmentation was created to facilitate the counting of the number of particles entering into those polygons representing the habitat region.

Figure 17 shows the comparison of model results for tracking passive and fish-like particles with juvenile salmon migration data collected at various sampling locations in the Skagit Bay. The monthly averaged numbers of particles entering into the segments were compared with the monthly averaged fish population data for each habitat region. A one-to-one comparison is not possible because of the inherent simplification used to represent the habitat scale and features, but this comparison is expected to provide some useful information about the feasibility and the capability of the fish-like particle tracking model to reproduce actual fish-catch data. Despite some discrepancy in the quantitative prediction of fish population against the data, the fish-like particle tracking model (Simulation 2) reproduced some basic features of spatial distribution of the migrating juvenile salmon population that the passive particle tracking model (Simulation 1) did not. The results of Simulation 1 showed a relatively high population in Segments 1, 2, and 3. Among them, the highest fish population occurred in Segment 1. In Segment 2, the peak in population was observed in August, which is quite off from the data peak occurring in April.

Habitats in Segment 1 are mostly located near the entrance or inside the channel connecting Skagit Bay to Port Susan Bay. Depth-averaged net water transport occurs through this channel from Skagit Bay to Port Susan Bay. The vertically averaged net flux to Port Susan Bay seems to result in the highest population in Segment 1 because passive particles are vertically well mixed and remain longer because of a low flushing rate. On the other hand, Simulation 2 shows the highest population in Segment 2 with better agreement with data. The peak population number is significantly off from the data peak, but the peak times are relatively close to each other. This improvement illustrates a capability of FPTM3D to enable fish-like particles to search the habitats and stay until they grow up to a certain size. Other notable difference from the passive particle model result is the relatively small population predicted in Segment 1, which matches with data. This result is attributed to the fact that the fish-like particles prefer the surface layers and are quickly transported away from Skagit Bay by stronger surface currents that are not in a favorable direction for transport into Segment 1.

In the numerical experiments described here, we find that the passive particle tracking is not appropriate for predicting estuarine fish populations, and the fish-like particle tracking shows a potential for significant improvement in predicting the juvenile salmon migration pathways as well as population densities.

Further improvements of the ability to match observed fish data can be made in several ways: 1) improvement of fish behavior rules in model algorithm, 2) refinement of model grid to more accurately represent geometrical and hydraulic characteristics of habitats, 3) incorporation of statistical variation of fish data, and 4) a variety of sensitivity analyses to find adequate model parameter values.
Our numerical experiments examined only the influence of habitat and pressure agents on the population distribution in Skagit Bay. The response to the salinity front may be also important in terms of forcing juvenile salmon to stay in the fresh water region until they are adapted to saline water before migration to the open ocean. This is associated with the residence time of fish-like particles in the estuary. More detailed information about the behavior and adaptation rules are needed for incorporation into the model.

Another modification that would likely improve simulation results would be to refine the estimate of the habitat attraction radius. The attraction radius is a lumped parameter affecting how many fish particles are able to find a habitat. In the current model run, the average effective diameter of all fish habitat sizes was used as the parameter value. This parameter value does not seem to be sufficiently effective in representing how juvenile salmon find habitats. Inherently, this parameter has a high level of uncertainty because the process of how a fish searches and finds the desired habitat is itself not yet well enough understood to allow parameterization. Further sensitivity analyses by varying the attraction radius parameter value are recommended. Ultimately, further refinement of the model grid resolving the habitat scale with proper hydraulic characteristics will provide improvement without having to lump parameters. Instead of a lump parameter, new agents, such as flow velocity and water depth, can be introduced to attract juvenile fish into the habitat. This approach would better match the realistic behavior of migrating juvenile salmon observed in natural rivers and estuaries.

The discrepancy in Segment 4 seems to be primarily caused by the smaller number of particles transported to the North Fork at the bifurcation of the Skagit River into the North and South Forks. This biased transport is likely caused by the coarse grid and relatively large time step (60 sec) in the fish-tracking model. The flow direction at the immediate upstream of the bifurcation tends to convey many more particles to the South Fork. Refining the grid and time step will be important to improve the results in Segment 4.

Some disagreement with data, particularly in terms of quantitative prediction, also indicates that statistically based estimates of growth rate, death rate, and size distribution of fish data are needed. In the current study, we estimated the growth rate based on the peak time difference between the upstream and downstream migration data. However, this growth rate seems significantly overestimated. A more accurate growth rate distribution, depending on size and habitat, is necessary. At the same time, the death rate of juvenile salmon, also depending on size and habitat, is essential for balancing the population levels. Better estimates of these two parameters will likely provide significant improvements in quantitative prediction capability.

Also, due to budgetary and schedule constraints, a detailed calibration of the model requiring extensive iterative model runs adjusting the model parameter values could not be completed within this project. Sensitivity analyses are recommended for future phases to optimize parameter values within the uncertainty range based on data. A number of simplifications of fish properties and population distribution were made, such as assuming a single fish size at a given release period and specifying uniform fish properties for an entire population at an upstream boundary. Further improvements in model algorithm and input parameters are also possible and should be considered as activities for the next phases of this project.
Figure 15. Number of Particles Released at the Upstream Boundary of the Skagit River.
Figure 16. Juvenile Salmon Habitat Locations Identified Along Skagit Bay. Habitat regions were divided into nine segments based on distributaries and geographic location. Yellow dots are fish sampling sites, and green dots are habitat sites representing blind tidal channel complex.
Figure 17. Comparison of Passive and Fish-Like Particle Tracking Model Results with Fish Migration Data.
3.0 STATE OF THE TECHNOLOGY

The technology developed through this effort includes two parts. Part 1 is the technique of simulating detailed hydrodynamic behavior in the nearshore tidal marshlands. It is an important technological development that has become possible through a combination of the finite volume hydrodynamic modeling technique and availability of computational resources. The use of FVCOM model over tide flats, using LiDAR information to characterize finer details of the distributary network, and upstream expansion into the flood plain is recognized as an improvement over existing technologies and a new development. Part 2 of technology development through this CICEET project is the fish-like particle tracking model, an effort which may best be characterized as in its early stages of development. Using qualitative information on fish behavior provided by CO-PIs from the Skagit basin, we developed an algorithm to improve over passive particle motion that is typically used for fish migration pathway analysis. The approach shows promise in that improvement was seen over passive particles.

The technology (hydrodynamic and particle tracking model) has already been deployed at a number of restoration project sites in Puget Sound and is growing in popularity as land-use planners begin to see its utility through application to on-the-ground projects. Although the fish-like particle tracking tool, developed as a companion tool, is still in early stages of development, the possibility of incorporating behavior and motility rules has generated considerable interest from a wide group of scientists engaged in fish and oyster larvae migration research and others interested in the formation of thin layers of harmful algal blooms.

4.0. NEXT STEPS

The project partners and CO-PIs have mutually agreed to continue progress on developing the tool and technology further. As an ad-hoc group, the Whidbey Basin (CICEET) project team expects to meet periodically to discuss completion of the fish-like particle tracking tool and potential application at other sites around the Puget Sound region. They will also extend the technology to other regions of the United States through future NOAA and NSF grants.
5.0 LITERATURE CITED


APPENDIX A.

Data regarding the outmigration population of juvenile Chinook salmon in the lower Skagit River and timing data were used with juvenile Chinook timing and density data in the Skagit delta estuary, Swinomish Channel, and Skagit Bay for a validation analysis of the CICEET Fish Migration Pathway tracking tool. The year 2002 was the best year for this analysis because of the completeness of fish catch records in three factors: space, time, and habitat type/area, compared to other years available.

Space refers to the number and distribution of sites within the hydrodynamic model domain that were sampled. In 2002, we sampled 44 different sites in a consistent season-long fashion. Time refers to the frequency and number of times that fish catch data were collected at each site. In total, we collected 497 individual fish catch records at the 44 different sites in 2002 (Figure A1). Habitat type/areas refer to four different habitats that juvenile Chinook occupy during their estuarine/nearshore residency period: Skagit Bay shoreline, pocket estuaries, Skagit delta estuary, and Swinomish Channel.

Juvenile Chinook salmon timing and abundance data were used in two ways. The first was to represent the population of juvenile Chinook salmon entering the hydrodynamic model domain where the Skagit River meets the Skagit delta estuary. The population of fish entering the system is one important independent variable influencing juvenile Chinook timing and abundance in all areas downstream.

The second way was to represent the juvenile Chinook salmon using the dispersed habitat downstream of the area where juvenile Chinook salmon enter the hydrodynamic domain, specifically in the area of the Skagit delta estuary, Swinomish Channel, and Skagit Bay. For this purpose, we used data from 43 different sites throughout the Skagit delta estuary, Swinomish Channel, and Skagit Bay.

Data Representing Juvenile Chinook Salmon Population Entering the Skagit Delta Estuary, Swinomish Channel, and Skagit Bay Nearshore

Washington State Department of Fish and Wildlife (WDFW) estimates the population size of juvenile Chinook salmon migrating downstream in the Skagit River annually using a combination of mainstem traps (screw and scoop) located in the lower river upstream of the bifurcation of channels in the delta (Figure A.1). The fish particles entering the hydrodynamic model domain where the Skagit River meets the Skagit delta estuary are meant to represent the timing and abundance of juvenile Chinook salmon outmigrating the Skagit River in 2002.

Weekly juvenile Chinook salmon catch and length data from the year 2002 are reported in Seiler et al. (2003). These data were summarized in an Excel spreadsheet for validation analysis of the CICEET Fish Migration Pathway tracking tool. Only screw-trap data were used because screw-trap fish catch results are less biased due to selective fish size than scoop-trap catch results.
Weekly juvenile Chinook catch per hour data were used and scaled by the number of hours in each week (24 hours by 7 days each week). Then these data were further scaled by a constant to make the weekly estimates fit estimates of the population of juvenile Chinook salmon by Seiler et al. (2003) for each population group (wild and hatchery). The wild Chinook population size was 5 million migrants; therefore, the weekly estimates were scaled by the constant 113.839155. The hatchery population size was 600,000 released (page 38 of Seiler et al. 2003); therefore, the weekly estimates were scaled by the constant 91.9064.

Data Representing Juvenile Chinook Salmon Rearing Within the Skagit Delta Estuary, Swinomish Channel, and Skagit Bay Shoreline

Juvenile Chinook salmon timing and density results from 43 sites located downstream of the WDFW mainstem trap site in the year 2002 were used in a validation analysis of the CICEET Fish Migration Pathway tracking tool. Juvenile Chinook results from these sites are a function of the juvenile Chinook population entering the system (which is represented by data from the WDFW mainstem trap and described above).

Fish Catch Sampling Methods
Two different sizes of beach seines and fyke traps were used to capture juvenile Chinook salmon, depending on the habitat type sampled.

Fyke traps were used in blind channel habitat in the Skagit delta estuary. Fyke trapping methods followed those of Levy and Northcote (1982) and used nets constructed of 0.3-cm mesh knotless nylon with a 0.6 m by 2.7 m diameter cone sewn into the net to collect fish draining out of the blind channel site. Overall net dimensions (length and depth) varied depending on the blind channel’s cross-sectional dimensions. All nets were sized to completely block fish access at high tide. A fyke trap net was set across the mouth of the blind channel site at high tide and “fished” through the ebbing tide, capturing fish as they moved from the channel as it dewatered. The juvenile Chinook catch was adjusted by a trap recovery efficiency (RE; data not shown) estimate derived from mark-recapture experiments using a known number of marked fish released upstream of the trap at high tide. RE estimates are unique to each site and are related to hydraulic characteristics of the site during trapping (e.g., change in water surface elevation during trapping or water surface elevation at the end of trapping). Four to eight different mark and recapture tests were done at each site to develop either an average RE at the site or a regression model to convert the “raw” juvenile Chinook catch to an estimated population within the habitat upstream of the fyke trap on any sampling day. Average RE for the seven fyke sites ranged from 18 to 71%. The RE adjusted Chinook catch was divided by the topwidth channel area of the blind channel network upstream of the trap to calculate a juvenile Chinook density for each fyke trap set. The topwidth channel area was measured in the field.

Shallow intertidal shoreline areas in Skagit Bay, Swinomish Channel, or large distributaries in the Skagit delta estuary were sampled with small beach seines. These habitat areas were typically less than 1.2 m deep and had relatively homogeneous habitat features (water depth, velocity, substrate, and vegetation). Small beach seine-net dimensions were 24.4 m × 1.8 m and made of 0.3-cm-mesh knotless nylon net. The net was set in “round haul” fashion by fixing one
end of the net on the beach while the other end was deployed by wading “upstream” against the water current, hauling the net in a floating tote, and then returning to the shoreline in a half circle. Both ends of the net were then retrieved yielding a catch. The Chinook catch was divided by set area to calculate a Chinook density for each beach seine set. The average set area was 96 square meters. Three beach seine sets were made per site on each sampling day.

The deeper intertidal-subtidal fringe areas of the Skagit Bay shoreline were sampled with a large beach seine. These habitat areas were typically 2 to 5 meters deeper than the areas seined by the small beach seine, requiring a longer and deeper net. Large beach seine dimensions were 37 m × 3.7 m and made of 0.3-cm-mesh knotless nylon net. The net was deployed by fixing one end of the net on the beach while the other end was set by boat across the current, a distance of approximately 60% of the net’s length. After the net was held open against the tidal current for a period of four minutes, the boat end was brought to the shoreline edge, and both ends were retrieved, concentrating the catch in the net’s middle. Three sets per site were made on each sampling day. Tow time, set width, and water surface velocity were measured for each beach seine set to calculate a set area for each beach seine set. The Chinook catch was adjusted by set area to calculate a Chinook density for each beach seine set. The average set area for large net beach seine sites in Skagit Bay is 486 square meters.

For each beach seine or fyke trap set, we counted the number of juvenile Chinook salmon. We measured the fork length of all fish when 20 individuals or less were caught. For catches larger than 20 individuals, we randomly selected 20 individuals for length samples.

Three results were calculated for each date of sampling at each site: 1) juvenile Chinook density, 2) average juvenile Chinook fork length, and 3) log average juvenile Chinook fork length. Using the daily Chinook density results, the following were calculated for each site: monthly average juvenile Chinook density and cumulative Chinook density (described below).

**Cumulative Juvenile Chinook Salmon Density**

The season-long density of juvenile Chinook salmon was estimated at each monitoring site. We term this fish density statistic the *cumulative Chinook density*. The cumulative Chinook density was estimated for different periods, depending on the habitat type/area, because the juvenile Chinook rearing period varies by this factor. The period February 1 through August 15 was used for Skagit delta estuary and Swinomish Channel sites. The period February 1 through October 31 was used for Skagit Bay shoreline sites. The period February 1 through June 30 was used for pocket estuary sites.

The cumulative Chinook density (fish*days*ha⁻¹) was calculated as

\[ C = \sum_{m=F}^{L} D_m n_m \]

where \( D_m \) is the average monthly density, \( n_m \) is the number of days in the month, and \( F \) and \( L \) are the first and last months (\( m \)) sampled, respectively.
**References**


Figure A1. Location of Sites Where Juvenile Chinook Salmon Catch Results Were Collected in 2002 for Validation Analysis of the CICEET Fish Migration Pathway Tracking Tool.