Tidal mixing rates and residence times from data and modeling for Willapa Bay,

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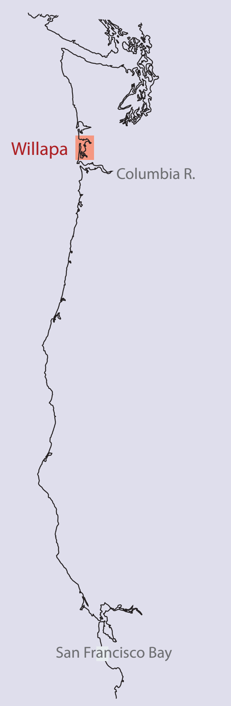
A three-dimensional circulation model of Willapa Bay, Washington is used, in concert with three years of hydrographic data, to determine tidal mixing rates and residence times throughout the bay during low-to-moderate riverflow conditions. The model is an implementation of GETM (Generalized Estuarine Transport Model), a finite-difference model developed for systems like Willapa with substantial intertidal area.

The model reproduces tidal velocities throughout the bay to 5-20%, and also—a more stringent test—reproduces empirical estimates of the effective horizontal diffusivity K, a direct measure of the strength of large-scale tidal mixing. K is found (in the absence of riverflow-driven exchange, which is weak relative to tidal mixing in summer) to vary from 1200 $m^2\ s^{-1}$ at the mouth to 20-50 $m^2\ s^{-1}$ in the upstream reaches of the bay.

These diffusivities are equivalent to residence times of ~ 8 d for the upper reaches of the bay but only a few tidal cycles for an equally sized region near the mouth: thus while tidal stirring appears to be an efficient mechanism of ocean-estuary exchange over much of the bay's volume, long retention times are possible in some subregions.

Background

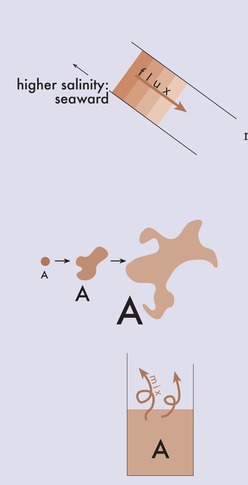


Willapa Bay is the largest, after the Columbia River, of the coastal-plain estuaries of Washington and Oregon. Like the other estuaries on this coast it experiences strong tides, and roughly half its area and volume are intertidal. River input can be strong in winter but is close to zero during much of the summer growing season. Banas et al. (2004) found that except during high winter flows, the river-driven gravitational circulation is not nearly as important to the circulation of the bay as tidal stirring and mixing.

Most of the nutrients that fuel primary production in Willapa come not from the rivers but from wind-driven coastal upwelling—thus the rate at which tidal stirring draws new ocean water into the bay and mixes it upstream is a fundamental control on estuarine ecology. Mapping this tidal exchange process is the goal of this poster.

The horizontal diffusivity K

is the parameter we use to measure exchange rates. It can be defined and used several different ways:



$$\frac{\partial}{\partial t}\int a s\, \partial x = aK\frac{\partial s}{\partial x}$$

K relates the flux of a spread-out tracer (like salt) to the local concentration gradient of that tracer.

$$K = \frac{1}{2}\frac{\partial A_{patch}}{\partial t}$$

K also describes the rate at which the surface area of a patch of tracer (like dye) spreads over time.

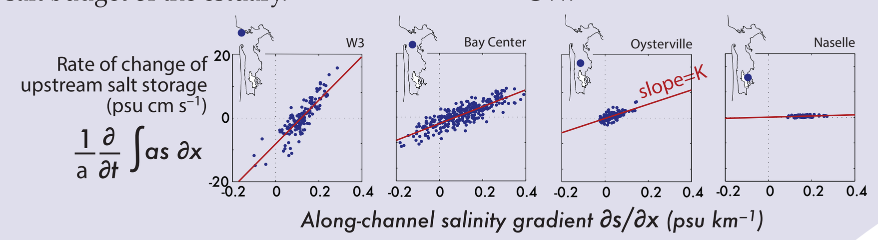
$$\tau_{1/2} = \frac{A_{box}}{2K}$$

For a box of a given size (say, a subregion of the estuary), K can be used to determine the half-life of a tracer diffusing out of that box. This is one definition of the estuarine residence time.

Calculating K from data

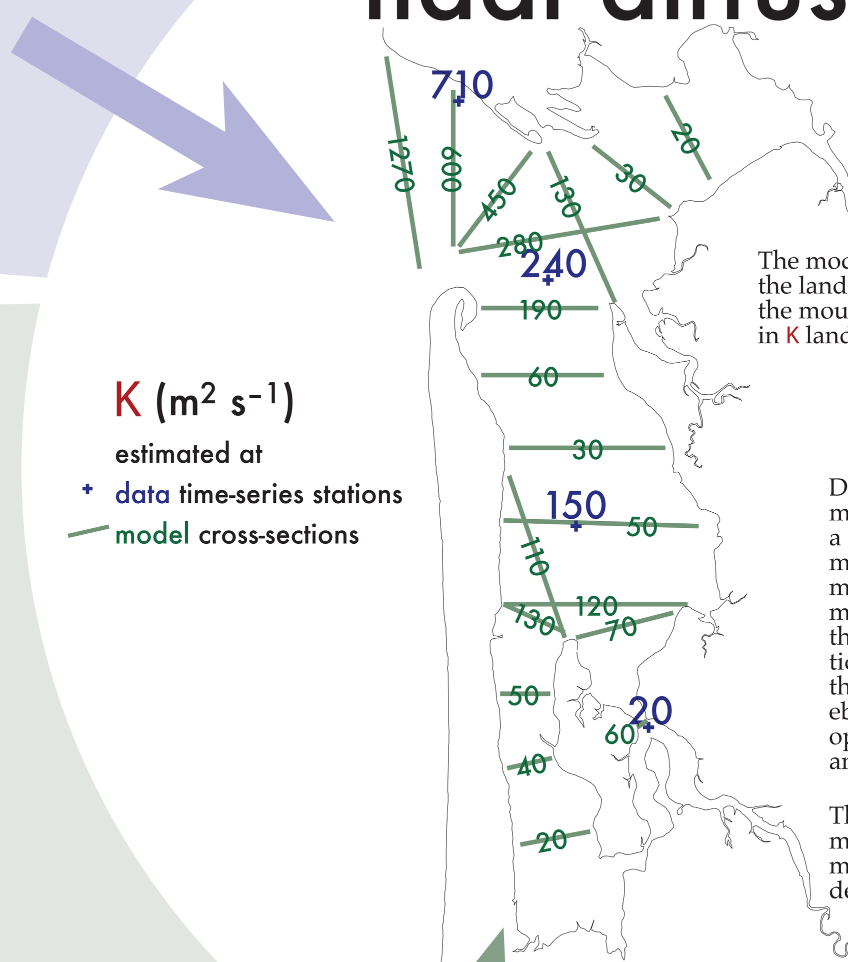
In low-riverflow conditions, when the river-driven salt fluxes through the estuary are small, the first definition of K above is a good approximation to the tidally-averaged salt budget of the estuary.

Banas et al. (2004) evaluated this budget equation at each of four CTD time-series stations maintained by Jan Newton / WA Dept of Ecology and the Hickey group at UW.



These four empirical tidal diffusivities are an important benchmark for testing the mixing behavior of the model.

A map of tidal diffusivities



The model matches observations within a small factor in the landward reach of the estuary, and very closely near the mouth. Both model and data show a strong decrease in K landward of the mouth as well.

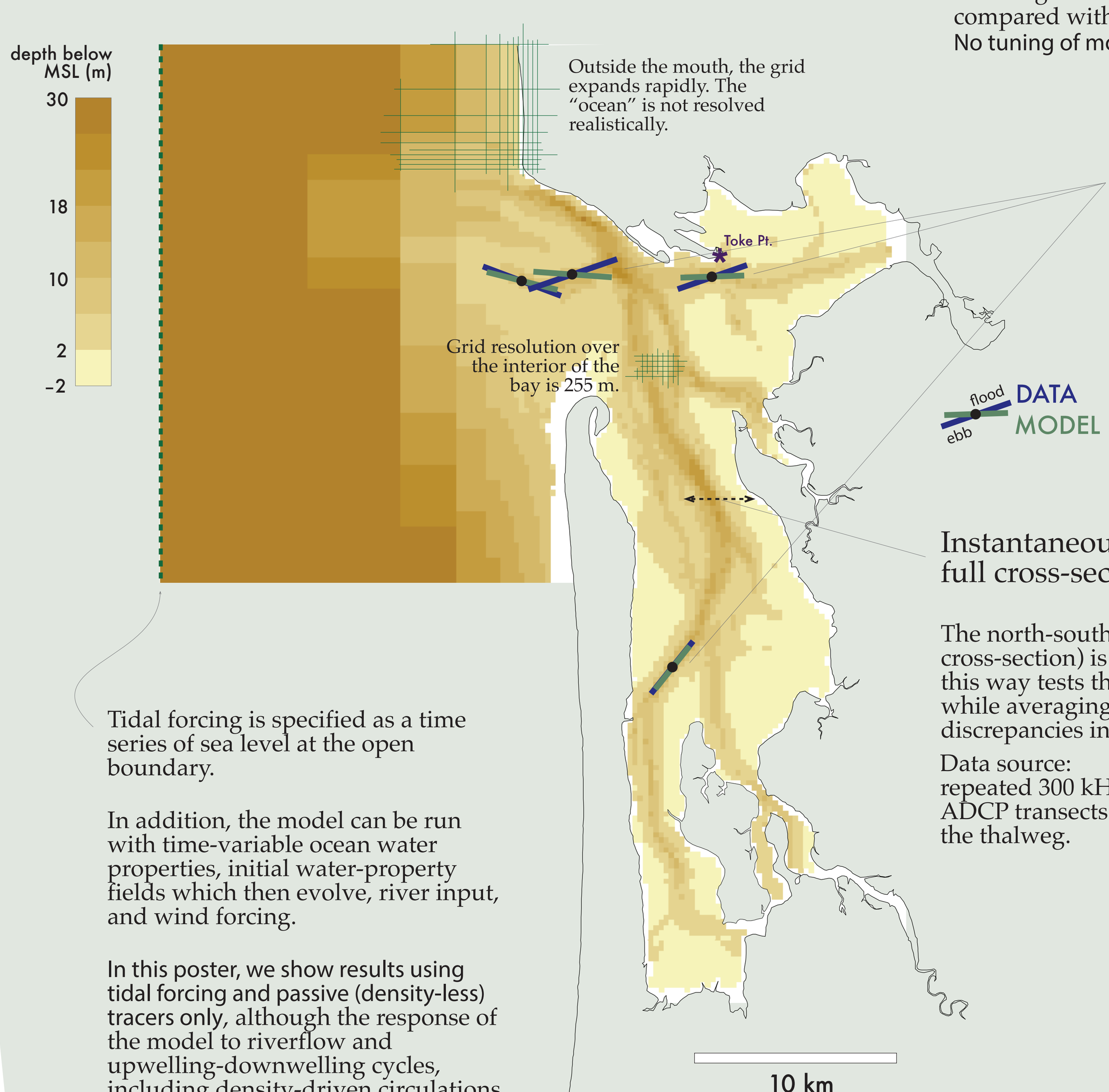
Direct comparison of horizontal mixing rates with empirical results is a stringent test for a circulation model, since it requires that the model reproduce not only the overall magnitude of tidal currents but also the small asymmetries in the tide—asymmetries between sides of the channel, between flood and ebb—that cause net dispersion, as opposed to a simple sloshing back and forth.

This level of validation of tidal models is not often done in estuary modeling, for lack of a method for determining K from data.

The model

…is an implementation of GETM (Generalized Estuarine Transport Model), a new finite-difference, primitive-equation model with high-order advection schemes, many choices of turbulence closure including the k-ε scheme used here, and a stable, accurate wetting and drying algorithm.

GETM is open-source and still under development: more information can be found at `http://bolding-burchard.org/getm.`



Outside the mouth, the grid expands rapidly. The "ocean" is not resolved realistically.

Grid resolution over the interior of the bay is 255 m.

Tidal forcing is specified as a time series of sea level at the open boundary.

In addition, the model can be run with time-variable ocean water properties, initial water-property fields which then evolve, river input, and wind forcing.

In this poster, we show results using tidal forcing and passive (density-less) tracers only, although the response of the model to riverflow and upwelling-downwelling cycles, including density-driven circulations, is already being investigated.

Model validation

For model validation, NOAA tidal-height data from Toke Point (∗) for particular time periods was used for the seaward boundary condition (convenient, but a source of 5-10% inaccuracy) and the resulting model tidal currents compared with observations. No tuning of model parameters was done. Standard values were used for bottom roughness z_0 and the k-ε turbulence parameters. Even with this very simple modeling strategy, the model reproduces tidal currents with errors of 5-20%.

Depth-averaged M2 (semidiurnal) tidal velocities at four locations, Oct 1998.

flood / ebb
DATA
MODEL

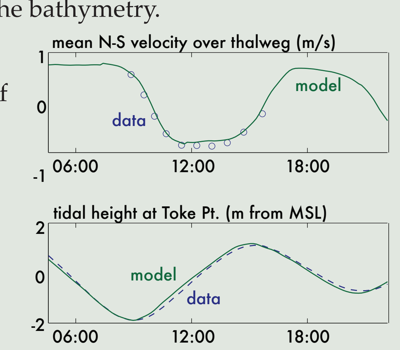
Note that while data and model current amplitudes agree closely, the real flow follows bends in the channel near the mouth that the flow in the model doesn't seem to feel. This is probably because model bathymetry is smoother and channel edges less abrupt than in the real bay.

Data source: Army Corps Seattle District (see Kraus 2000).

Instantaneous tidal velocity averaged over a full cross-section of the thalweg, May 5, 2000.

The north-south velocity component (normal to the cross-section) is shown. Integrating over the channel in this way tests the overall tidal transports in the model while averaging out point-by-point errors caused by discrepancies in the bathymetry.

Data source: repeated 300 kHz ADCP transects of the thalweg.

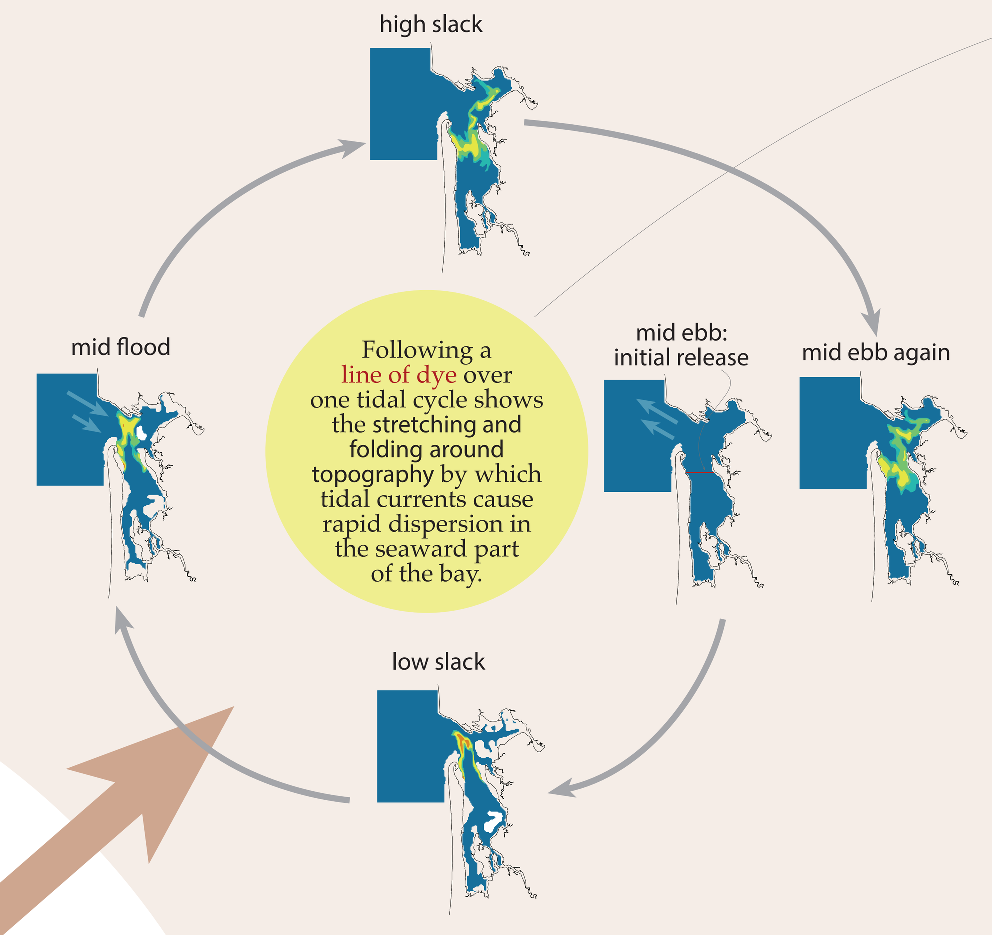


As a final model validation, horizontal tidal diffusivities were calculated in the model by the same method by which they were calculated from data: the slope between the local along-channel salinity gradient and the flux of salt through a number of cross-sections.

(Results are not sensitive to the initial salinity pattern assumed.)

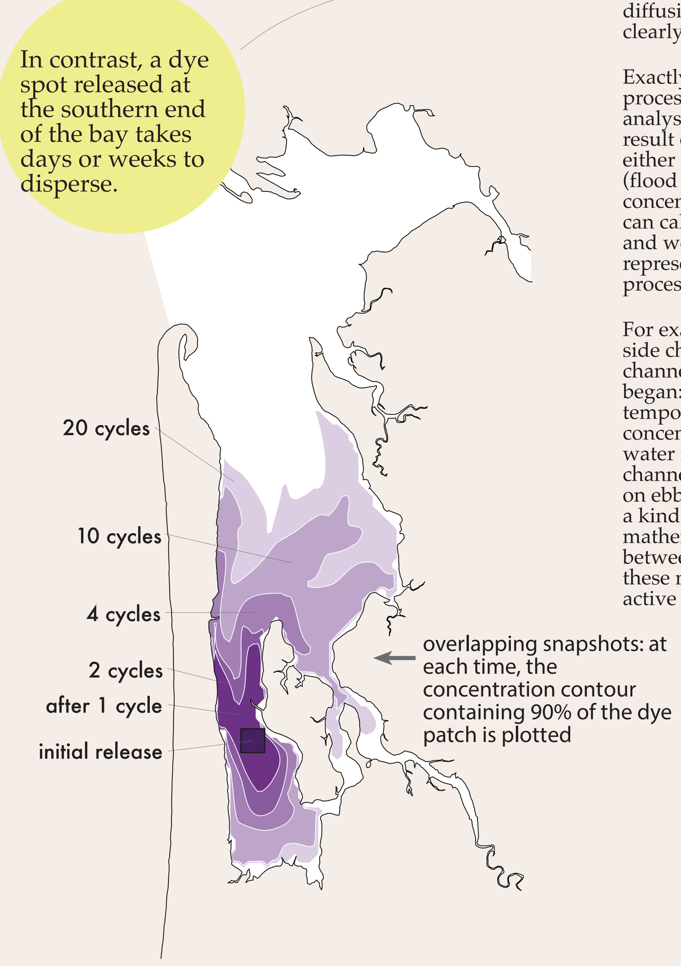
For this all other model results shown in this poster, idealized tidal forcing—a simple semidiurnal tide, whose range (2.4 m) matches the rms tidal range at Toke Point—was used to simplify analysis.

What does this look like?



Following a line of dye over one tidal cycle shows the stretching and folding around topography by which tidal currents cause rapid dispersion in the seaward part of the bay.

In contrast, a dye spot released at the southern end of the bay takes days or weeks to disperse.



overlapping snapshots: at each time, the concentration contour containing 90% of the dye patch is plotted

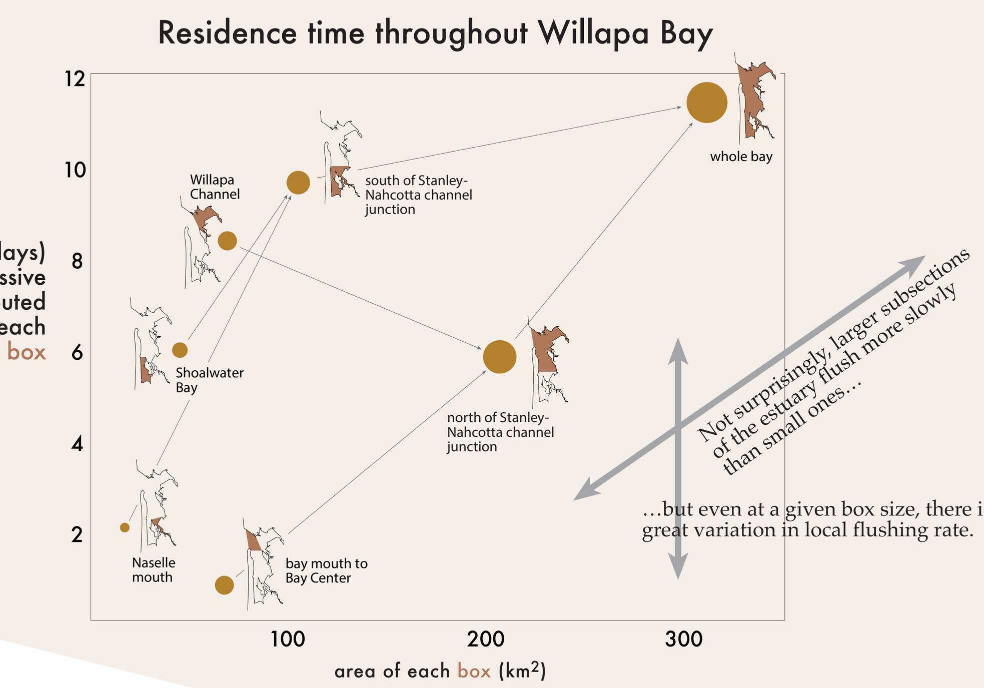
Tidal currents are ~40% weaker in the southern bay than at the mouth, but this is not enough to explain the difference in diffusion rates: local channel geometry is clearly important.

Exactly how channel geometry shapes this process is the subject of the next stage of this analysis. In general, tidal dispersion is the result of correlations between asymmetries, either in space (across the channel) or in time (flood vs. ebb) in flow velocity, tracer concentration, and cross-sectional area. We can calculate these correlations individually and weigh their relative influence: each represents a qualitatively distinct mixing process.

For example: water may become trapped in side channels on flood, and re-enter the main channel in a different position from where it began: this shows up mathematically as a temporal correlation between tracer concentration and velocity. Alternatively, water may preferentially flow down one channel on flood and out a parallel channel on ebb, so that the pair of channels becomes a kind of circulating pump: this shows up mathematically as spatial correlations between concentration and velocity. Both of these mechanisms, and others, appear to be active in the seaward reach of the bay.

Finally, we can use this formula (see "Background" on the left) to convert these diffusivities into local and bay-wide residence times.

$$\tau_{1/2} = \frac{A_{box}}{2K}$$



Two biological applications

1. Larval transport and retention. When the larvae of ocean-spawning or -developing species like Dungeness crab arrive at the mouth of the estuary (Roegner et al. 2003), what portion of the estuary does advection and dispersion make available to them before they settle?

Or: there is strong anecdotal evidence (J Ruesink and A Trimble, pers. comm.) that natural settlement of oyster larvae—which requires retention in the water column for several weeks after spawning—is possible in the southern reaches of the bay but not the northern, with the dividing line close to where, in our model results, the tidal diffusivity changes from < 100 $m^2\ s^{-1}$ to 200-1000 $m^2\ s^{-1}$. Is this tidal dispersion pattern the explanation? The question is central to the problem of the recovery of Willapa's native oyster population, now largely centered within Shoalwater Bay in the southern estuary.

2. Controls on primary production. Do phytoplankton blooms within Willapa arise primarily from in situ growth fueled by upwelled nutrients, or from offshore blooms advected into the bay? An equivalent question: what controls the strong gradients in biomass observed over the length of the estuary and between channel and shoals, patterns of tidal dispersion and advection, or point-by-point balances between light, benthic grazing, and benthic nutrient supply?

To answer these questions we are adding nonconservative tracers, representing chlorophyll, to GETM: these tracers have a specifiable, depth-dependent loss or production rate which represents the sum of local factors affecting phytoplankton growth. This work is being done in collaboration with J Newton (DOE), J Ruesink (UW Biology), B Dumbauld (WDFW) and many others in a Wash SeaGrant-supported project.

Acknowledgements

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