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This report summarizes the information presented in the Kingfish MEPDES Permit Application regarding the coastal hydrodynamics in this region of Chandler Bay, and how it pertains to the anticipated dispersion of chemical plumes from diffuser pipes. The specific focus of this report covers the near and far field modeling work for the Recirculating Aquaculture System (RAS) facility proposed for Jonesport, Maine.

This work includes both near field modeling using CORMIX and far field modeling using the TUFLOW-FV hydrodynamic modeling system. The literature on CORMIX is that it should not be used for representing longer term processes in tidally-dominated water bodies or water bodies where flow can recirculate back to the location of the diffuser pipe. The region of Chandler Bay where the diffuser pipes will be located is both tidally influenced and prone to the recirculation of water away from and returning to the general region of the discharge source. The ADCP (Acoustic Doppler Current Profiler[1]) data collected as part of the permit application show strong lateral gradients in tidal flow energy consistent with gyres or eddies, which by definition recirculate water back towards the discharge pipes. We focus less on CORMIX, as user manuals state the model is not meant for use in areas with tidal recirculation such as Chandler Bay.

Model Characteristics.

Here we focus primarily on the far-field modeling work using TUFLOW-FV, and the data sets used to validate the far field modeling. TUFLOW-FV includes two-dimensional (2D), or vertically averaged simulations of the coastal estuarine system as well as a mode of model simulations using full three-dimensional (3D in space) representations of water circulation and related transport processes. The information provided in the Permit Application indicates the 3D version of this model has been used for the results that are presented. The model cross sectional schematic shown in Figure 3-2 (from the KF MEPDES application) indicates two distinct types of model grid cells are used for the 3rd, or vertical dimension. These include adaptive sigma layers for the very surface waters, such that layers can expand and contract vertically with the tidal oscillations. A second, or deeper zone referred to as the z-layer in this figure shows these deeper grid cells maintain a fixed thickness, reported here as 2m. This implies that in areas of the model where water depth is [1]limited, there are very few vertical grid nodes available to represent shear within the water column. In these shallower areas, the model begins to simulate vertically averaged flow, which is not appropriate for representing longer term fate and transport of chemical plumes within the water column.

[1] https://www.whoi.edu/what-we-do/explore/instruments/instruments-sensors-samplers/acoustic-doppler-current-profiler-adcp/ (visited May 2, 2022)

Circulation in coastal water bodies, like Chandler and Englishman Bays are driven by a range of environmental forcing conditions (Figures 2-5). The twice daily, or semi-diurnal tides driven by gravitational forces related to the Moon-Sun-Earth system, provide the most dramatic and obvious water motions (e.g. Figure 3,4, examples from Narragansett Bay (RI)). These also drive the changes in water levels related the flood and ebb stages of the tide cycle (Figure 2). Such flows are often referred to as tidal currents or instantaneous currents and are typically the largest of the estuarine currents by flow magnitude. These can exceed 1 m/s in some estuaries. However, these currents tend to be oscillatory in nature, moving water inward during the flood and outward during the ebb stages of the tide (Figures 2,3). These tidal currents tend not to be the dominant mode of water flow responsible for determining the fate of chemical or biological constituents within the water body.

It is the **residual currents (Figure 5)**, often referred to as the sub-tidal currents, which are most important for longer term flushing/retention processes of chemical plumes, such as those proposed here, from their discharge locations and for predicting the much longer transport pathways this dissolved chemical material will follow. These residual currents are driven by winds and density differences (Figure 5) produced by freshwater runoff from the watershed interacting with higher density shelf waters. The latter produces what are referred to as baroclinically forced residual currents. The classical depiction of residual flow in estuaries involves a mode of 2-layer circulation, where less dense surface water moves ocean-ward and denser (colder, saltier) water moves landward a depth, below the shallow outflow. The Earth's rotation distorts these characteristic residual flow patterns through an apparent force, referred to as the Coriolis force, which acts to deflect water (air) motion to the right of its intended path in the northern hemisphere. The influence in coastal waters is that less dense, shallower outflows tend to follow the western shores. Deeper, denser inflow currents tend to follow deeper bathymetry features and to also be deflected to hug the eastern shores of the water body.

Shallow and deep residual current flow/transport patterns are strongly influenced by both the spring-neap tide cycle and the magnitude, direction, and duration of winds. The Spring tides have the largest tidal range, meaning the biggest difference between high tide and low tide water levels for the semi-diurnal cycle. These produce the largest tidal currents and occur when the gravitational pull of the Moon and Sun are aligned. Neap tides occur when the gravitational pull of the Sun and Moon are acting at 90° angle from each other and produce the smallest tidal range and tidal current magnitudes. Residual currents have been observed to vary in strength over the Spring to Neap cycle.

Wind forcing strongly influences residual transport currents. Winds typically speed up or slow down the background pattern of outgoing surface water and incoming bottom water during events ranging from 3-7 day time periods. Oscillations between prevailing (e.g. sea breeze) winds to short lived wind forcing due passing weather systems can lead to important and dramatic water column mixing and residual flow exchange events.

Accurate model simulations on the fate and transport of chemical plumes into coastal waters must be well validated against residual currents, recorded over a wide range in forcing conditions (spring-neap cycles, prevailing winds, event-scale winds). Data-model validations must characterize both the vertical and lateral (e.g. cross-estuary) changes in residual inflow/outflow patterns. Examples of this are shown for the Narragansett Bay Estuary in Figure 1 from this document. Here map view plots are shown of near surface (red) and near bottom (blue) residual currents from a mid-latitude section of the estuary. ADCPs were deployed at different depths (values shown in frame a) which bracket the ~40 feet depth seen at location of the proposed discharge pipe in Chandler Bay. Data from 30 moored acoustic Doppler current profilers (ADCPs) like this, from all over Narragansett Bay show similar patterns in residual flow. Surface and bottom waters rarely, if ever, move in identical directions for extended periods of time. This shows that vertically averaged circulation models, or 3D circulation models with poor vertical resolution, are not appropriate for simulating long term biochemical transport in estuaries. **As it is the residual currents, not the tidal currents, which control longer term chemical transport, it is essential to document these well, and take care that numerical model simulations are able to match the most basic patterns in the observations (Figures 1-4).** Figures 4b,d illustrate how residual flow simulated within a 3D coastal hydrodynamics model can be validated against time series observations. At this particular shallow water site in the Narragansett Bay estuary, the model has been developed and tuned to recreate a large scale, clockwise retention gyre, which controls water quality in the most impaired section of the estuary.

Data-model validation steps should focus on both the horizontal (e.g. gyres) and vertical patterns in residual circulation/flushing/transport. Vertical differences in residual flow, as pathways for chemical pollutants, are fundamental to most estuaries. Figures 1,2 and 4 (in this document) show how current meter data reveal both horizontal and vertical differences in residual flow for shallower, impacted regions of Narragansett Bay (RI). These plots, along with Figures 3 and 5 (from this document), outline the differences between "tidal" flow and "residual" flow and what it takes to observe these in the estuary. Tidal flows cannot be accurately characterized by 4 data points recorded over a single tidal cycle (Figures 3). Such limited current meter data will not allow for models to validated to the point that they may accurately quantify the patterns in the ebb and flood circulation for even a single tide cycle and cannot possibly provide any information on variability in tidal currents between spring and neap tidal periods. More importantly, just four sets of ADCP data collected over a single tide cycle provides no usable information on spatial-temporal character of residual currents (Figures 1, 2, 4), which are ultimately most important for training models to accurately simulate long term pollution transport/flushing.

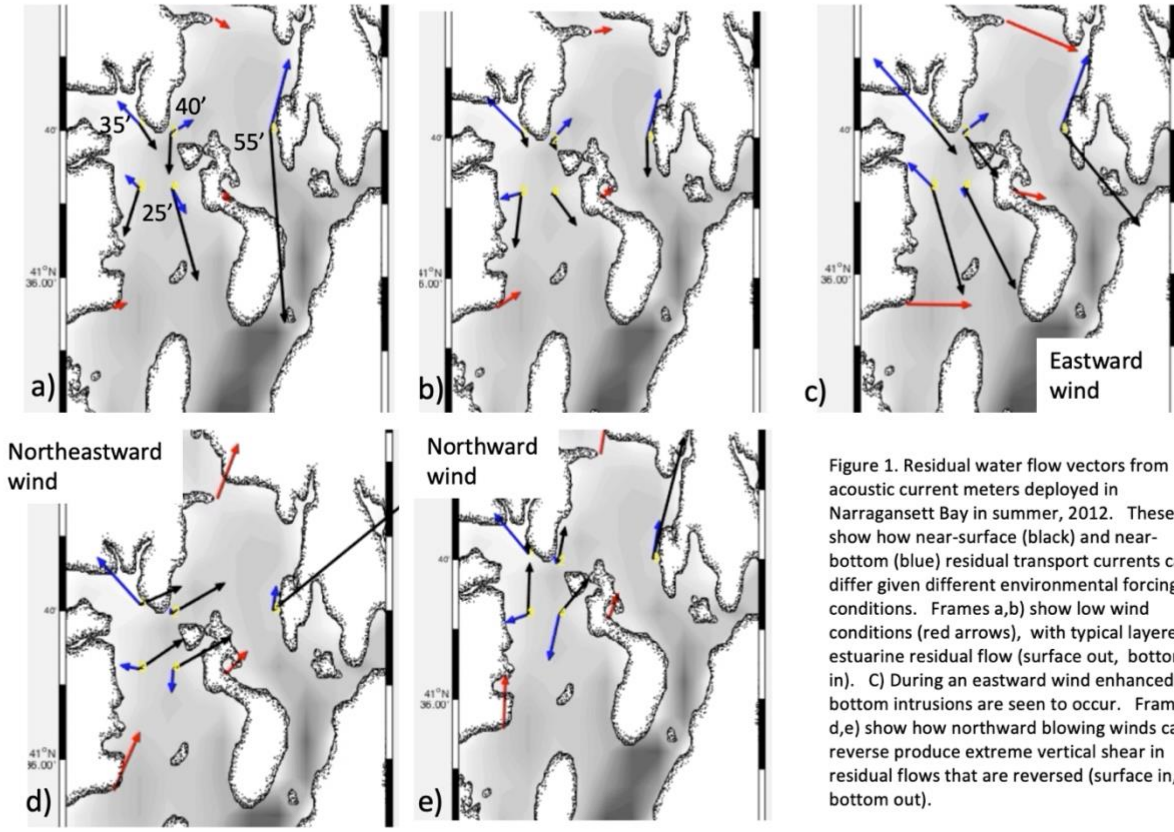


Figure 1. Residual water flow vectors from acoustic current meters deployed in Narragansett Bay in summer, 2012. These show how near-surface (black) and near-bottom (blue) residual transport currents can differ given different environmental forcing conditions. Frames a,b) show low wind conditions (red arrows), with typical layered estuarine residual flow (surface out, bottom in). C) During an eastward wind enhanced bottom intrusions are seen to occur. Frames d,e) show how northward blowing winds can reverse produce extreme vertical shear in residual flows that are reversed (surface in, bottom out).

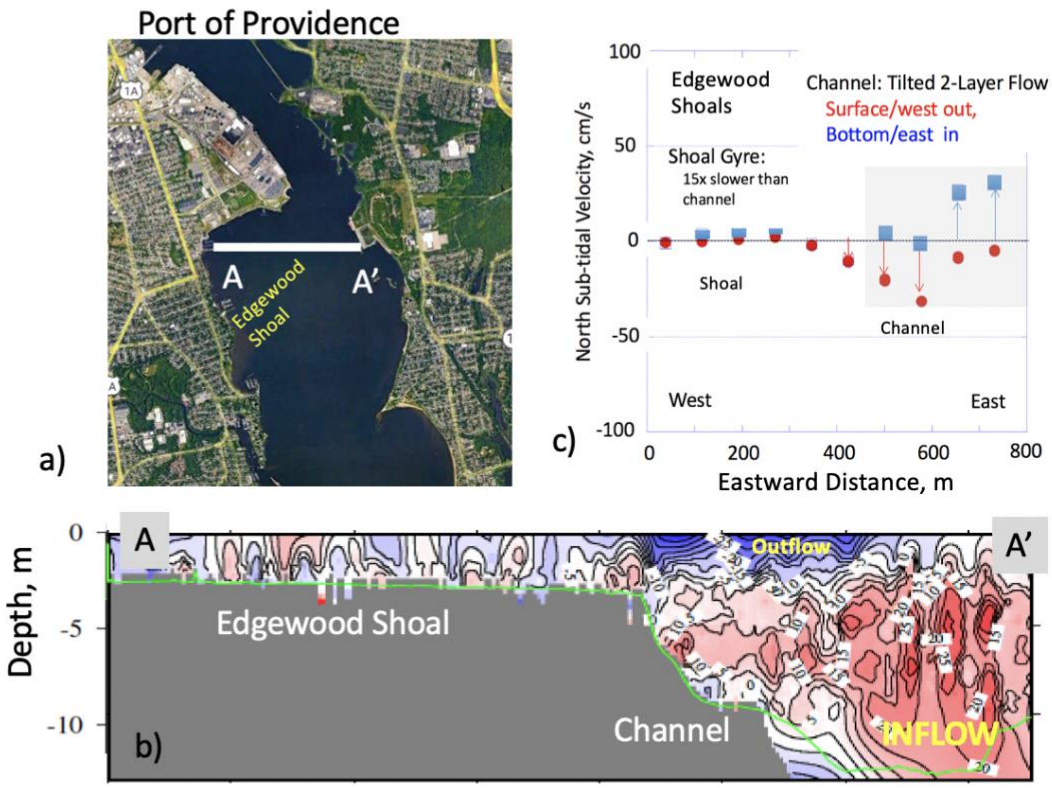
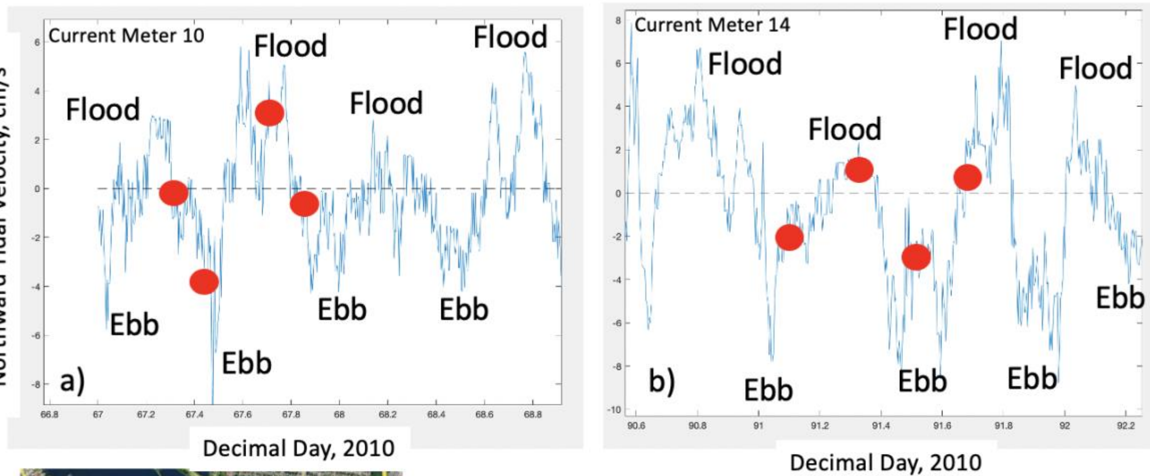


Figure 2. a) Map of tidal and residual circulation study area at Edgewood Shoals in the Providence River (RI). b) Underway ADCP data collected continuously over 16 hours have been used to characterize differences in tidal flow within the shipping channel over flood, ebb and slack conditions. c) By gathering repeated data over these transect lines, over 16 hours (more than a full semi-diurnal tide cycle), we are able to accurately average out the oscillatory inflow/outflow of the tides, revealing residual transport patterns. Data clearly show strong vertical differences in residual transport, even in 2m (6feet) of shoal water, where deep northward residual flow is 5-10 times greater than values at shallower levels.



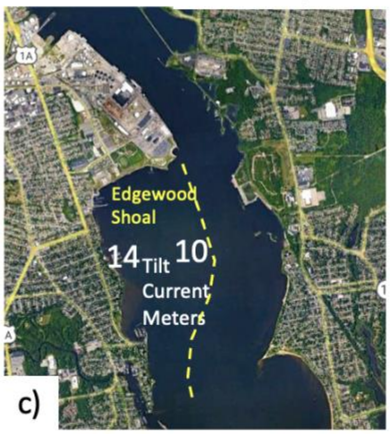
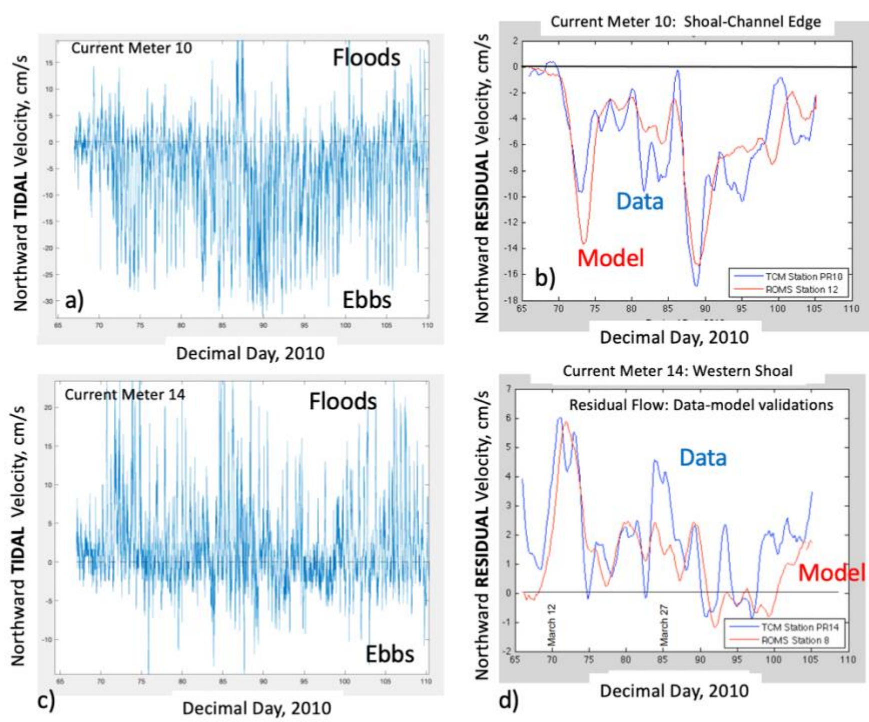


Figure 3. Moored current meters were placed on Edgewood Shoals for 45 days in late Spring of 2010. Northward "instantaneous" or tidal currents are shown over 1-2 days for locations a) Meter 10 near the shoal-channel interface and b) Meter 14 along the western side of the shoal, shown in mapview in (c). These plots show the twice daily, or semi-diurnal inflow and outflow of water associated with tidal floods and ebbs. These moored meters record flow data every 6 minutes. Gathering flow data only 4 times over a tide cycle (as done in the Kingfish Maine permit application) and shown schematically by the red dots in (a) does not provide sufficient temporal information to enable accurate characterize of TIDAL flows on even a single day, and provides no information on RESIDUAL flows which control pollution transport (see Figure 4).

Figure 4. Here we compare the full deployment tidal flow records for current meters (a) 10 and (c) 14 (from FIgure 3), compared with the "sub-tidal" or "residual" flows (frames b, d). In frames b, d the twice daily ebbs/floods are filtered out, to reveal the net trsnsport (residual) flow for b) current meter 10 and d) current meter 14. The current meter data on residual flow are shown as blue lines in b,d. The red lines show how the hydrodynamic model does as recreating these residual flows.

Key Point: To accurately train a model to provide trustworthy predictions for long term pollution transport in an estuarine system, it is imperitive to use spatially-temporally detailed current meter deployments, capable of fully characterizing both tidal and RESIDUAL flows. Using just 4 ADCP measurements from a single day (shown schematically in Fig. 3) cannot inform data-model validations as shown in Fig. 4b,d. .



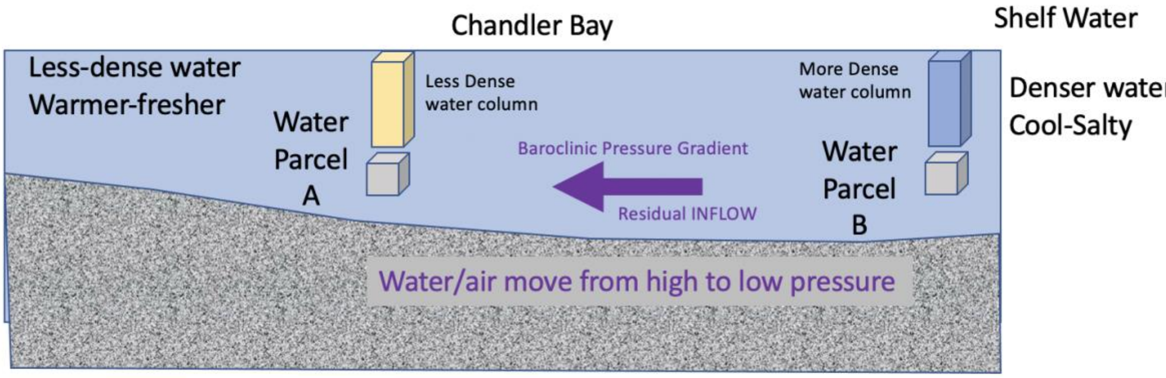


Figure 5. Schematic showing how water density differences between offshore waters and estuarine waters can produce "sub-tidal" or "tidally-averaged" flows that can move pollutants large distances, over extended periods. These currents are called "residual" flows. Consider the pressures felt by two parcels (volumes) of water: Parcel A: within Chandler Bay, Parcel B: outside the mouth of Chandler Bay. The pressure felt at each parcel is dictated by the weight of the water column above each parcel. Because the water column is warmer/fresher above A in summer conditions, Parcel A feels "lower" pressure. Water overtop of Parcel B is cooler and saltier, and exerts higher pressure on Parcel B. Air and water always flow from high pressure towards lower pressure. These basic hydrographic conditions produce these effect, called a baroclinic pressure gradient, in estuaries like Narragansett Bay (RI) (Figures 1-4) and Chandler Bay (ME). Such gradients drive residual currents that strongly control the long term fate of pollutants released to estuaries. Pollutants released in bottom water (like the proposed discharges) will ride these residual currents northward.

An additional concern with the model setup, as shown in Figure 3.2 of the Permit Application, is the vertical grid resolution within the model. The pipes are shown to discharge into 40' of water depth. This area will surely be dominated by strongly layered residual flow, with basic patterns of near-surface residual outflow and deep residual inflow, capable of carrying chemical plumes well northward from the proposed site (Figure 5). The site will also be likely to exhibit the types of vertical variations in horizontal residual flows with differing tides, winds and runoff conditions that are highlighted in Figures 1,2,4. However, the model setup suggests that only 5-6 vertical grid nodes are available to the solution in these areas, which is not sufficient for representing the levels of variability typically mapped in estuaries for residual flows.
It is critical for models attempting to represent long term transport of chemical plumes to allow for vertical shear in residual flow even into the shallower regions of the estuary. The model setup for TUFLOW used in this application becomes a vertically-averaged model within the shallower regions, which is not capable of representing any vertical shear processes. As shown in Figures 2-4, significant differences in the patterns of residual flow occur with depth even in waters depths of 2m. In the shallower regions of the Chandler Bay Tuflow model, the use of 1-2 grid nodes will not allow for accurate representation of these basic styles of pollution transport currents.

The last, and perhaps more significant issue with the TUFLOW modeling for this site, and this particular application of long-term chemical transport involves placement of the open ocean boundary (Appendix A, Figure A1). Best practices in coastal/estuarine ocean modeling typically require the ocean boundary to be far removed from the primary area of model interest. This is because boundaries can exert a strong influence on processes nearby within the model domain, and because boundaries typically do not have sufficient information about estuary-shelf exchange processes. In this case it appears that the solutions, showing plumes staying local to the discharge site, are strongly controlled by an applied boundary condition that does not allow for typical estuarine residual exchange flow. Without removing the ocean boundary much further from the area of interest, and providing more detailed information on both the tidal and residual exchange conditions that are used at that boundary, it is impossible to tell if it is the poorly informed model boundary conditions, rather than the true Chandler Bay exchange physics, which are controlling the predicted transport processes shown in the permit application. Often moored ADCPs deployed for a full Spring-Neap-Spring cycle are used to properly inform the ocean boundaries for estuarine models.

Model Validation

Model-data validation steps for simulations representing long term chemical transport must include consideration of both tidal and residual flows. By far, the easiest flows to represent in models are those related to the tidal forcing. The residual flows tend to be significantly more variable and complex (Figures 1, 2, 4) than tidal flows, and tend to dominate the processes controlling how plumes are either retained within or flushed from the immediate area of discharge. Without model-data validations on residual flows, the accuracy of the simulations in terms of determining how the chemical plume moves either offshore or northward, into the shallower, ecologically sensitive regions of the estuary is impossible to determine.

There are no data shown in the report for sub-tidal or residual flow. In terms of the tidal data shown (Appendix A, Figures A2-A5), the Tuflow model data do not appear to accurately represent some of the tidal flow characteristics seen in ADCP data. Without better representation of tidal flows, it is likely the Tuflow model will not accurately represent residual flow. In order to train a model to simulate residual transport, the choice of current meter data is important. ADCP measurements from a single, incomplete portion of a semi-diurnal tide cycle is not adequate for developing proper characterization of either tidal or residual flows (Figures 3,4). Best practices typically combine both underway ADCP lines done at more stages of the tide cycle and over Spring and Neap conditions, along with moored current meters to provide necessary temporal resolution. The temporal sampling frequency for the underway ADCP lines should be capable of resolving the M4 tidal constituent, related to frictional effects in shallowing estuaries, in order to generate accurate residual flow estimates from the underway ADCP data. Figure 3 shows the characteristic dips in flooding currents from Narragansett Bay produced by the M4 frictional component of the tide (e.g. the dip see in Figure 3a at day 68.7). This temporary stalling of the flood currents tends to occur in shallower, frictionally dominant areas like Chandler Bay. If the M4 is indeed important within sensitive areas of Chandler Bay then the data and models must be designed to properly represent this effect, or simulations will produce errors in the estimated transport/flushing patterns and time scales.

In order to the characterize the time varying patterns in residual flow for validating this aspect of the models, longer term moorings, such as those shown in Figures 1,3,4 are needed. Mooring deployments of at least a Spring-Neap-Spring cycle (~14 days) are needed to provide the model validation steps with enough information to determine residual flow versus environmental forcing relationships (e.g., impacts of winds, runoff and changes in density stratification within/beyond Chandler Bay).

The following statements are made for the fate of the discharged plumes based upon the Tuflow Modeling work for the Kingfish Maine permit application.

1) Plumes will move by offshore flow currents and tidal flow.
2) Plumes will move 3 miles north and 1 mile south.
3) Plumes will not move beyond these limits beyond 7 days (reaches equilibrium).
4) Plumes can impact shore, but always at a dilution factor of 173x.

The model results on the limited dispersion distance of the plume over 7 days, the specific northward and southward transport distances and the concentration values quoted for the different coastline impacts of the plume are governed by the residual flow forcing that is within the model boundary conditions. Without knowing more about the ocean boundary conditions used within the TUFLOW model, and how this compares to actual residual flow conditions in this area of Chandler Bay from actual moored observations, it is not possible to determine the accuracy or usefulness of these model predictions. Based on these patterns, however, it appears likely the model is not accurately representing typical background estuarine-shelf exchange processes (e.g. deep intrusions) at either the ocean boundary or the site of the discharge pipes. Because the discharge is continuous from the pipes, the plumes will likely alternate between periods of being retained in the area of the discharge via recirculating gyres or moving efficiently northward with residual deep intrusions. With regard to the former, a compounding effect will likely occur as receiving water that has recirculated back to the discharge site gets additional doses of chemically influenced water from the discharge pipe. This compounding effect will be strongly dependent on residual circulation and flushing processes, and important in determining longer term plume impacts through chemical concentrations within both the near and far field areas. Quantifying these far field impacts is only possible with numerical models that are shown to accurately represent the basic features of residual flow patterns within deeper and shallower regions of Chandler Bay.

A final point is that tracking far field impacts of the discharge plumes which are riding residual currents within simulations matching the basic patterns in the observations, will be highly likely to move well northward from the release site. It is very important to run the simulations much longer than 7 days, as the integrating effects of continued deep northward transport of plume material is likely to take months to begin to approach an equilibrium state.

A summary of key points is as follows:
The TUFLOW ocean boundary is too close to the region model interest (the discharge sites).

There is no information given in the report to determine how well the TUFLOW model is doing at representing residual flows, which are critical to producing accurate and trustworthy simulations of long-term chemical transport in an estuarine system like Chandler Bay, Maine.

The ADCP data shown within the report are: a) not adequate for characterizing the range of tidal flows over a single tide cycle, or over the range of known tide cycles (spring, neap) and b) not adequate for calculating residual flows along the transect lines. Moreover, the ADCP data that are provided do not appear to closely match up with predicted tidal flows within the models. It would be helpful if the modeling report was clearer on what velocity information is being shown. It is also difficult to tell if the comparisons are for a specific depth or shown as vertically averaged values.

Moored and underway current meter data is needed to provide better information on spatial and temporal characteristics of residual flows, which ultimately control longer term flushing and transport processes. These data sets must be compared with TUFLOW simulations to better determine whether models are providing useful, believable representations of longer term far field transport and chemical plume fate/impacts.

Specific predictions on limited spatial dispersion patterns for the plumes and specific dilution factors at specific locations and times, cannot be evaluated for accuracy based on the information provided within the Near/Far Field Modeling Report of the Permit Application. It is highly likely that deep residual intrusion currents, capable of carrying plume products far northward into the estuary, are not being properly represented in the TUFLOW models. Given the limited vertical resolution of the 3D model grid, it is highly likely the vertical structure of residual flow in this section of Chandler Bay is not adequate for resolving coastal exchange flows. Moreover, the limited vertical resolution within the shallower regions, particularly within the coves and along the shorelines, does not allow the model as constituted to represent details of vertical shear within residual transport flows. Such vertical resolution errors can result in water level estimates that roughly match observations, while at the same time producing inaccurate estimates for long term transport and dispersion of chemical plumes.

Appendix A: Figures from the Kingfish Maine Permit Application, Near and Far Field Modeling.

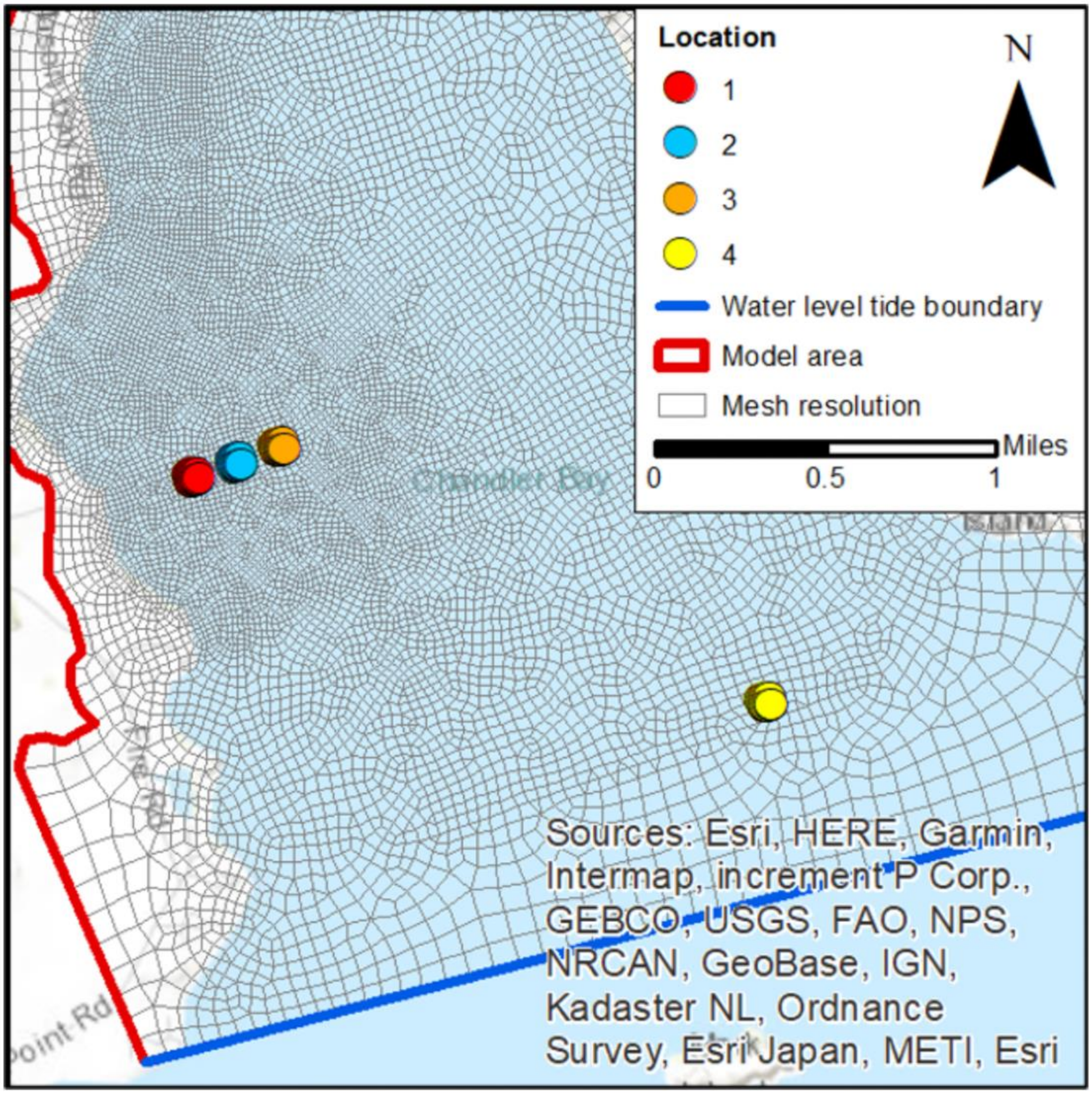


Figure 5-1: Proposed diffuser locations within Chandler Bay

Figure A-1. Depiction of the TUFLOW model grid, showing how closely this essential ocean boundary is to the region of model interest, or the discharge site.

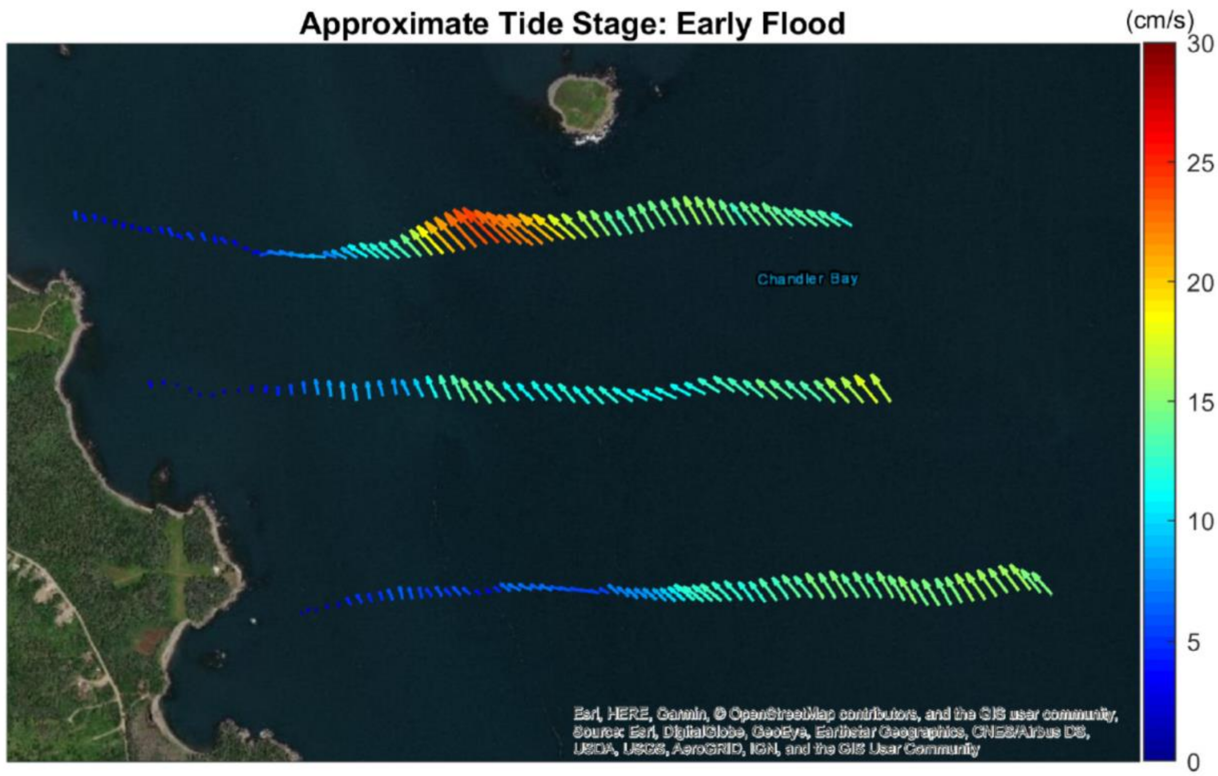


Figure A2. ADCP data were collected at three transects, over 4 stages of one tide cycle. This frequency of sampling does not allow for adequate characterization of the tidal or residual flows in this area. The data also do not allow for determining patterns in residual estuary-shelf exchange at the ocean boundary, just south of this location. Work done in Narragansett Bay suggest that hourly data along transects is needed to accurately average out the semi-diurnal flow energy to reveal the residual flow patterns/energies.

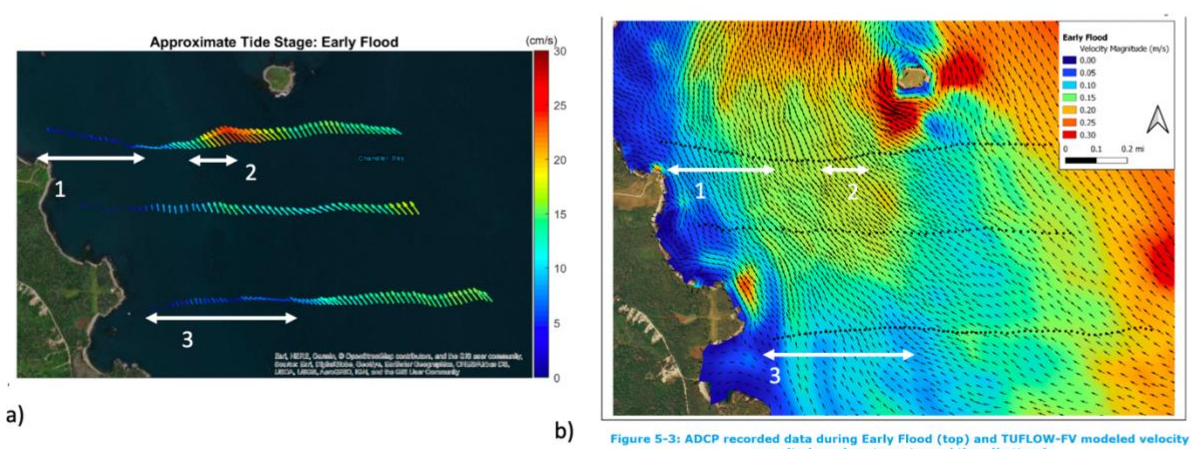
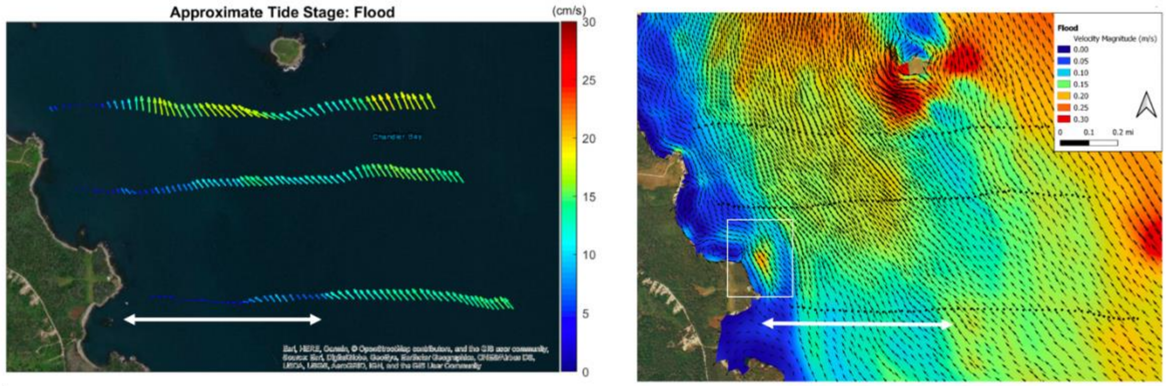


Figure 5-3: ADCP recorded data during Early Flood (top) and TUFLOW-FV modeled velocity magnitude and vectors at equal time (bottom)

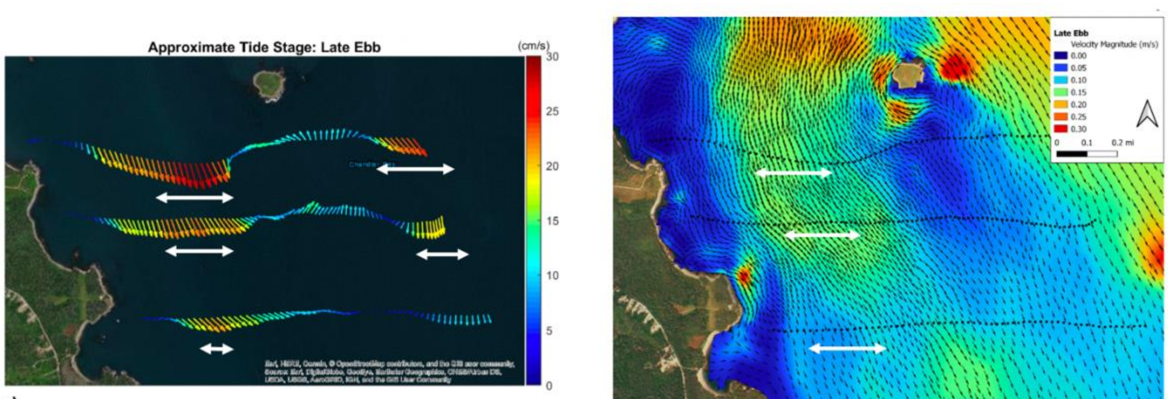
A3. The TUFLOW modeled tidal or instantaneous flows do not appear to match well with the ADCP observations. The model does not appear to capture the width of the stagnation zone (blue color arrows at sites 1 and 3), or the location of the tidal jet (site 2).



a) b)

Figure 5-4: ADCP recorded data during Flood (top) and TUFLOW-FV modeled velocity magnitude and vectors at equal time (bottom)

A4. At the mid-flood stage of the semi-diurnal tide, the model simulations do not appear to represent basic aspect of the observed tidal flows. The white arrow highlights how the model misses the width of the tidal stagnation zone (blue colors in the data figure (a)). The comparison also shows the data does not appear to represent a strong feature that is seen in the model (white box), or the high energy region just off the coast, north of the southern ADCP transect line.



a) b)

Figure 5-5: ADCP recorded data during Late Ebb (top) and TUFLOW-FV modeled velocity magnitude and vectors at equal time (bottom)

A5. During late ebb conditions, the data-model mismatch is particularly striking. None of the Tuflow transects do not represent many basic aspects of measured tidal flows along the ADCP transects. The model significantly underestimates the spatial structure and magnitude of the outflow jet along all three transect lines (white arrows).