DEPARTMENT OF
ECOLOGY
State of Washington

Hydrodynamic Model Report

Quartermaster Harbor
Nitrogen Management Study

October 2013
Publication No. 13-03-026

Publication and Contact Information

This report is available on the Department of Ecology's website at
https://fortress.wa.gov/ecy/publications/SummaryPages/1303026.html

The Activity Tracker Code for this study is 08-531.

For more information contact:

Publications Coordinator
Environmental Assessment Program
P.O. Box 47600, Olympia, WA 98504-7600
Phone: (360) 407-6764

Washington State Department of Ecology - www.ecy.wa.gov

- Headquarters, Olympia (360) 407-6000
- Northwest Regional Office, Bellevue (425) 649-7000
- Southwest Regional Office, Olympia (360) 407-6300
- Central Regional Office, Yakima (509) 575-2490
- Eastern Regional Office, Spokane (509) 329-3400

Hydrodynamic Model Report

Quartermaster Harbor Nitrogen Management Study

by

Skip Albertson

Marine Monitoring Unit
Environmental Assessment Program
Washington State Department of Ecology
Olympia, Washington 98504-7710

Water Resource Inventory Area (WRIA) and 8-digit Hydrologic Unit Code (HUC) numbers for the study area:

WRIA
- 15 (Kitsap)

HUC number
- 17110019

This page is purposely left blank

Table of Contents

List of Figures and Tables

Page

Figures

Tables

Abstract

King County, in collaboration with the Washington State Department of Ecology and the University of Washington-Tacoma, began the *Quartermaster Harbor Nitrogen Management Study* in 2009 with the aid of a West Coast Estuaries Initiative Grant from the U.S. Environmental Protection Agency (EPA). The need for the study was driven by observation that dissolved oxygen levels in the harbor during late summer were well below the Washington State marine water quality standard of 7 mg/L. Dissolved oxygen is essential for the survival of fish and other marine life.

This report describes the development and calibration of a hydrodynamic model for Quartermaster Harbor using structured grids with two resolutions, one coarse and the one fine. The target model hindcast prediction skill, as identified in the Quality Assurance Project Plan, was to achieve an average root mean square error (RMSE) of +/-1 psu in salinity, +/-1 deg C in temperature, and within 10% (~ 10 cm/s) of velocity relative to measurements taken in the field. In most estuaries, salinity is the most critical factor to predict because a change of 1 psu has roughly the same effect on density as 5^{o} C change in temperature, and density changes drive the subtidal estuarine flow that most affects water quality.

The average RMSE achieved during the calibration period (all of 2009) at the interior stations (UWT52 – UWT56) for the coarser grid was 0.89 deg C in temperature, 0.85 psu in salinity, 0.63 sigma-t in density, and 8 cm/s in velocity. The average RMSE for the finer grid was 0.93 deg C in temperature, 0.39 psu in salinity, 0.36 sigma-t in density, and 8 cm/s in velocity.

The calibrated model predicts instantaneous flushing times for the inner harbor that vary seasonally and are based solely on physical forcing that range from 20 days to over 100 days. Longer flushing times appear highly dependent on salinity and occur either when salinity is high everywhere due to low summertime riverine inflows internal to the bay, or lowered across the mouth of the bay by the presence of fresher water outside rather than inside the bay (e.g., the Puyallup River).

This physical model will be the basis for a water quality model that will be used to evaluate the influence of nitrogen inputs on dissolved oxygen levels in the harbor.

Acknowledgements

The author would like to recognize Anise Ahmed and Venkat Kolluru for their multiple assistances with the GEMSS model. The support for the development of the hydrodynamic model was provided by a West Coast Estuaries Initiative Grant from EPA. Thanks also to Greg Pelletier for reviewing this report.

Introduction

This report describes the development and calibration of a hydrodynamic model that will be used in tandem with a water quality model planned as part of the *Quartermaster Harbor Nitrogen Management Study* (King County, 2009a). King County was awarded a West Coast Estuaries Initiative grant by Region 10 of the U.S. Environmental Protection Agency (EPA) to conduct the study.

The goal of this study is to support the protection and restoration of Quartermaster Harbor, a high value, coastal aquatic resource at Vashon-Maury Island (VMI) in Puget Sound. Partners working with King County on this grant-funded study include the University of Washington (UW)-Tacoma and the Washington State Department of Ecology (Ecology).

Project Objectives

Over the last seven years, dissolved oxygen levels have been monitored monthly in Quartermaster Harbor by King County. The levels detected were below Washington State marine water quality standards (Figure 1). Dissolved oxygen is essential for fish and other marine life; when levels fall below critical thresholds, marine life can become stressed, killed, or forced to escape to more oxygenated waters if possible. Low dissolved oxygen levels – combined with the high habitat value of Quartermaster Harbor, increased frequency of detection of nitrate-nitrogen in VMI groundwater, and ongoing population growth – make this project a high priority for King County. Quartermaster Harbor has many similarities with South Puget Sound embayments which do not meet state dissolved oxygen standards established for the protection of aquatic life.

Quartermaster Harbor was one of 19 areas of Puget Sound judged to be relatively sensitive to human-caused (anthropogenic) nutrient inputs (Rensel Associates and PTI, 1991). Nitrogen and phosphorus are essential nutrients for marine plants and phytoplankton. Excess nutrients, nitrogen compounds in particular, can lead to excessive phytoplankton and algae growth which can deplete oxygen concentrations when the algae die and are decomposed by bacteria in the water column and sediments. Although phosphorus compounds are important for phytoplankton growth, nitrogen is generally considered to be the limiting nutrient in marine waters of Puget Sound.

The interactions between nitrate, algal biomass (using chlorophyll *a* as a surrogate), and dissolved oxygen in Inner Quartermaster Harbor are illustrated in Figure 1. Algal biomass generally peaks during spring and summer, which coincides with a reduction of nitrate concentrations to below the limit of laboratory detection as a result of algal uptake and growth near the surface of the water column. The minimum oxygen concentrations observed in late summer and fall are associated with the final decline in the summer peaks in algal biomass. These data provide additional evidence that phytoplankton growth in the harbor is limited by nitrogen and that additional inputs of nitrogen to the harbor have the potential to fuel additional growth of algae and additional losses of oxygen when the algae die and are decomposed in the water column and sediments.

The purpose of the hydrodynamic model is to represent the circulation of the harbor in response to tidal forcing, wind, freshwater inputs, and entrance boundary conditions. When coupled to a water quality model, the fate and transport of non-conservative constituents such as nitrogen can be simulated.

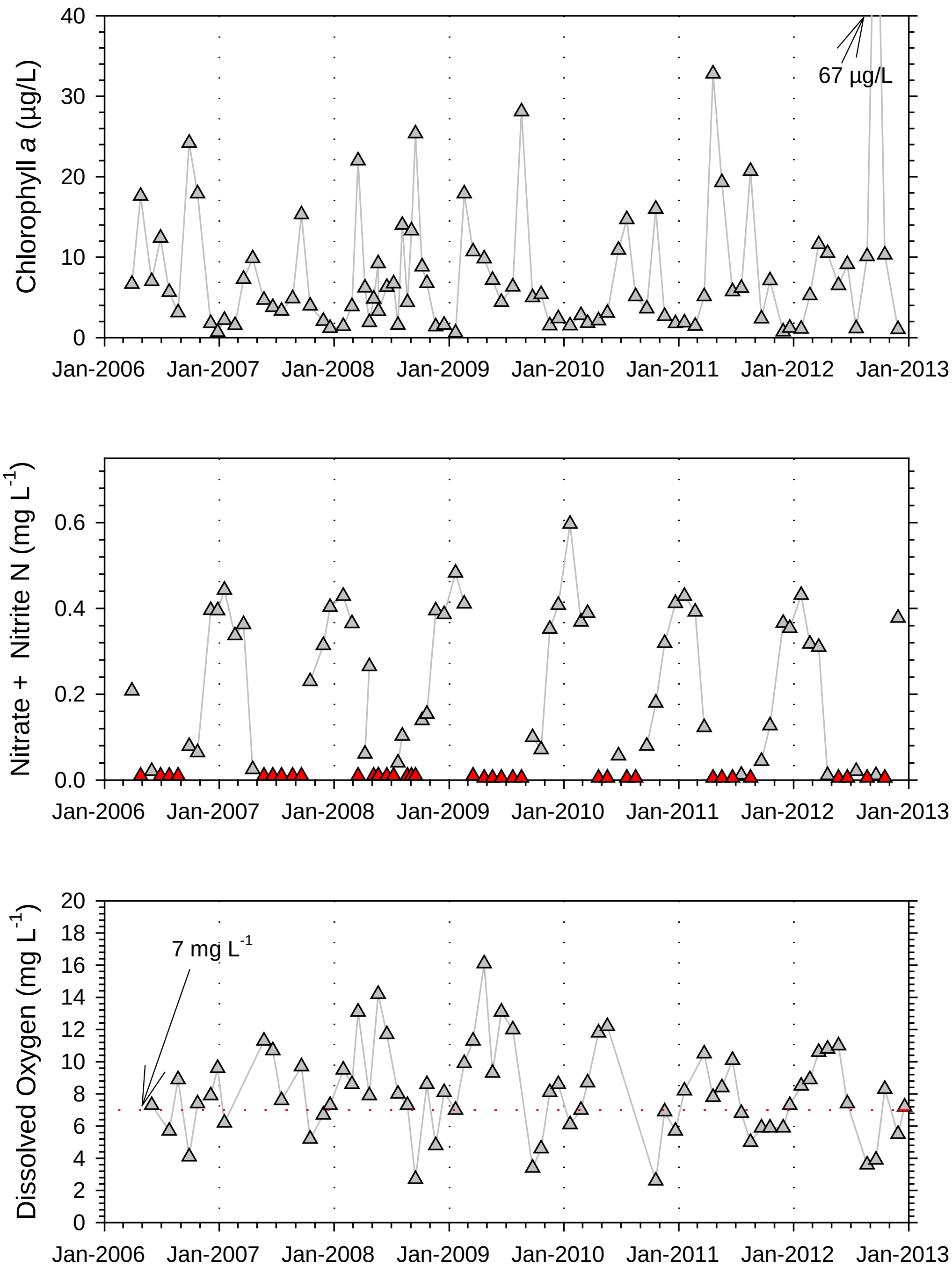


Figure 1. Monthly concentrations of surface water algal biomass (based on measurements of chlorophyll *a*), surface concentrations of nitrate-nitrogen, and bottom water dissolved oxygen concentrations (station MSWH01) in Inner Quartermaster Harbor.

Red fill indicates at or below reporting limits.
Source: King County, unpublished data.

Description of Study Area

Quartermaster Harbor is a shallow estuarine embayment on VMI in the main basin of Puget Sound. It is sheltered from the wind and waves and receives runoff from about 40% of VMI (Figure 2). It comprises approximately 12.1 km^2 (3,000 acres) of water surface area that can be divided by a small strait into an inner and outer harbor. Inner Quartermaster Harbor is especially sheltered; Judd Creek, located in the northwestern portion of the inner harbor, is its largest freshwater inflow.

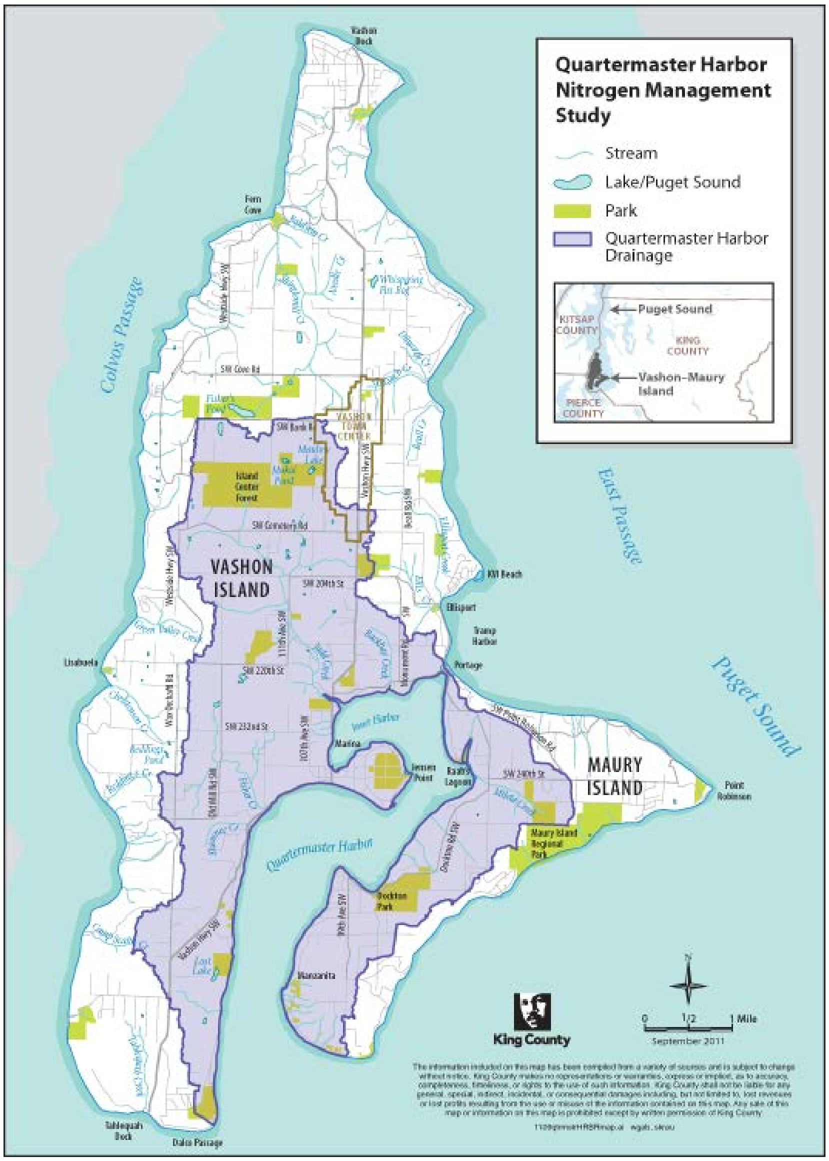


Figure 2. Map of Vashon-Maury Island (VMI) highlighting the drainage area to Quartermaster Harbor.

Transition zones between freshwater surface flows and marine water within the bay include the regions at the mouth of Judd Creek, Fisher Creek, and Raab's Lagoon as well as numerous smaller streams. Inner Quartermaster Harbor is shallow, with a maximum depth of about 5 to 6 meters and very little tidal flushing. Outer Quartermaster Harbor water depths range from about 11 to 46 meters with greater tidal flushing. The subtidal sediments are generally dominated by silt and clay, although some shallow areas, especially in the outer harbor, are dominated by sand (University of Washington, 1976; Long et al., 2002).

Historical Information Review

Quartermaster Harbor and the upland areas draining to the harbor have been the subject of water quality and quantity investigations beginning at least as far back as the early 1970s. King County (2010a) provides a review of historical information relevant to this project. Monitoring data used to support the development of the hydrodynamic model were provided by King County and UW-Tacoma as part of monitoring supported at least in part by the EPA grant. Details for these monitoring programs will be provided in separate reports. (King County, 2009a)

Analytical Framework for Modeling

Background

A variety of models were considered for use in this project, including EFDC[1], CH3D-CE-QUAL-ICM, and GEMSS[2] (King County, 2010b). GEMSS was selected because Ecology's South Puget Sound modeling project was using GEMSS (Albertson et al., 2007) and it was seen as an advantage to use a model that the team was both familiar with and that could provide calibrated water quality parameter coefficients from adjacent South Puget Sound and Budd Inlet models (Roberts et al., 2012). This would provide a better starting point for the development of a water quality model of Quartermaster Harbor.

The original GEMSS model application in the region was performed for Lacey, Olympia, Tumwater and Thurston County (LOTT) Wastewater Partnership[3] discharge to Budd Inlet to support National Pollutant Discharge and Elimination System (NPDES) permitting activities (Aura Nova Consultants and J.E. Edinger Associates et al., 1998). J.E. Edinger Associates, Inc. (JEEAI) applied the 3-D hydrodynamic and water quality model, Generalized, Longitudinal-Lateral-Vertical Hydrodynamics and Transport (GLLVHT), to Budd Inlet during studies conducted from 1996-1998, with follow-up work in 1999 and 2000.

JEEAI was subsequently acquired by ERM Group Inc. (ERM). The GLLVHT modeling framework was updated by JEEAI and ERM and is currently called GEMSS. According to the naming convention used at the time of the *LOTT Budd Inlet Scientific Study*, the model was called the "combined model" (for example, combined hydrodynamics and water quality computations) and relied on observed sediment oxygen demand values to compute oxygen uptake at the bottom. During the LOTT study, the sediment diagenesis model, Ocean Margin Exchange Nutrient Diagenesis model (OMEXDIA), was linked to the combined model (the *linked model*), but the combined model without sediment diagenesis was chosen for the final calibration and permitting simulations.

GEMSS is a dynamic model that simulates continuous changes in hydrodynamics with a time step that varies between 10 seconds and 6 minutes in our applications. The conditions in Quartermaster Harbor are dynamically calculated and updated every time step in response to dynamic changes in boundary conditions such as tides, meteorology, and creek inflows. The model was calibrated using the 2009 field data following the approach outlined in the modeling Quality Assurance (QA) Project Plan developed for this study (King County, 2010b).

[1] Environmental Fluid Dynamics Code
[2] Generalized Environmental Modeling System for Surfacewaters
[3] Name has since changed to "LOTT Alliance."

Modeling Approach

As part of a recent *Capital Lake Budd Inlet Dissolved Oxygen Study*, Ecology conducted a rigorous review and testing of the GEMSS modeling framework and of the FORTRAN code for the water quality modules in GEMSS. The level of rigor used for review and testing is comparable to the review and testing used by EPA for their Water Quality Analysis Simulation Program (WASP) modeling framework, and was conducted by the same expert that developed WASP (Robert Ambrose). Significant errors were discovered, and all errors associated with model variables that are used for the present study were corrected.

Representing the complex structure and response to tidal and other forcing in Quartermaster Harbor requires a three-dimensional model. Data compilation and collection supports this model in order to simulate the relevant nitrogen loading and hydrodynamics present in the bay. The structured grids and associated depths developed for this project are shown in Figure 3, with depths shown in the North American Vertical Datum of 1988 (NAVD88) coordinate system. The primary open boundary for the bay is at the southern extreme, toward the bottom of the page.

Horizontal Structure

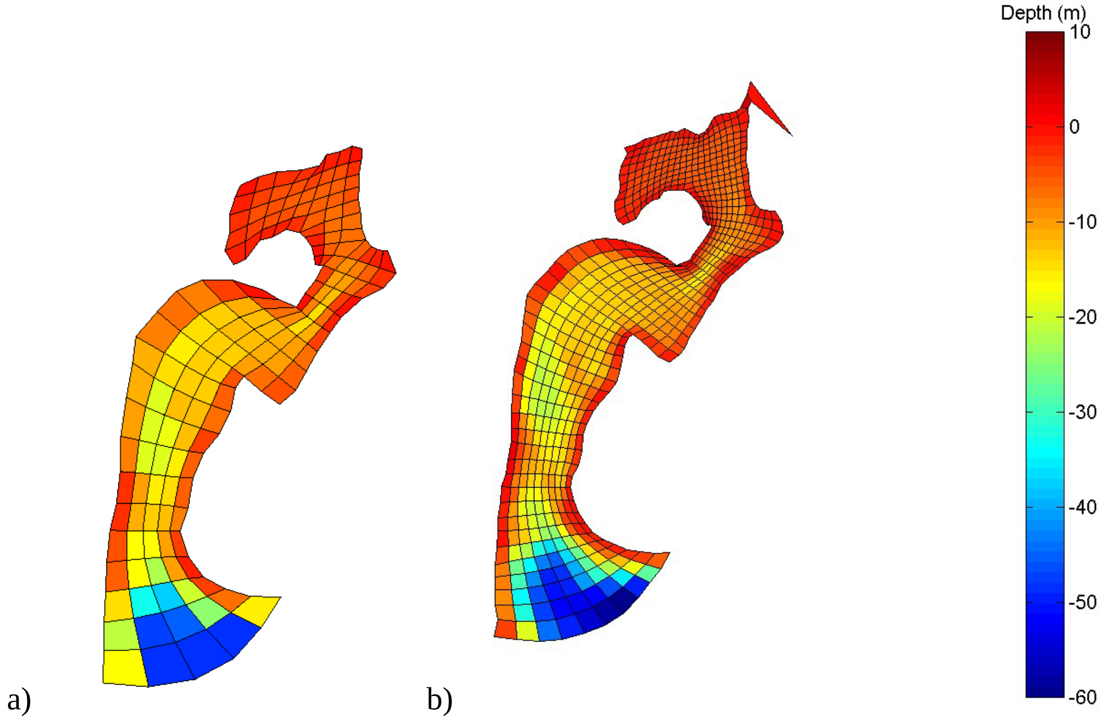


Figure 3. Structured model grids and bathymetry (NAVD88 datum for depth) used with Quartermaster Harbor model for: (a) coarse resolution grid and (b) fine resolution grid. (c) Aerial photo looking west and showing a portion of the Quartermaster Harbor shoreline.

Photo courtesy of Eyes Over Puget Sound.

Vertical Structure

Both coarse and fine resolution grids were developed for this Quartermaster Harbor model study. Both consist of the same vertical layering scheme, although the maximum depth in the coarse resolution grid is less than in the fine resolution grid due to effects of averaging bathymetry over a broader region. Both model resolutions consist of 37 vertical layers (Figure 4 /Table 1). The fine resolution grid has a maximum of 799 horizontal grid cells in each layer for a total of 12,190 grid cells, and the coarse resolution grid has a maximum of 206 horizontal grid cells in each layer for a total of 3,214 grid cells. In both cases, deeper layers contain fewer grid cells. The thickness of each vertical layer varies from 1 m at the surface (thinnest), to 5 m near the bottom layer (thickest) with an exponentially smooth depth-transition zone between these.

During execution, the model adds and subtracts layers as the tide and wind move water around, so a shallow cell can become completely dry under the right conditions. Some of the drying cells occur over the shoals at the approach of the inner harbor and can be seen in the aerial photograph shown in Figure 3c.

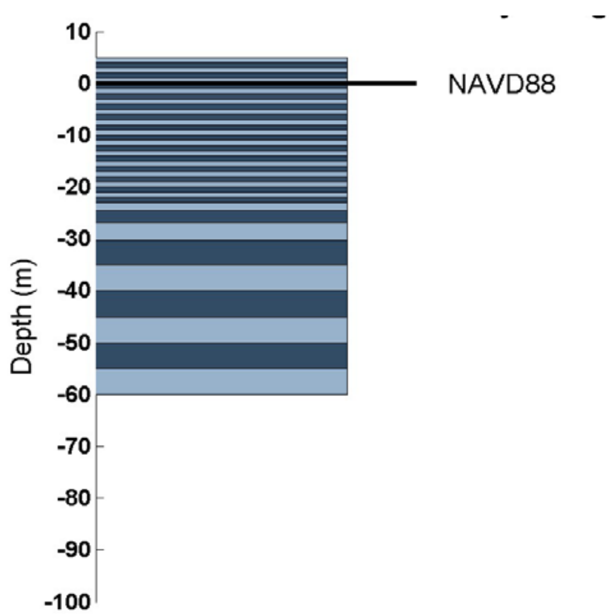


Figure 4. Graphic showing the vertical layering scheme (thickness of each layer) for the Quartermaster Harbor model for all grids.

The coarse resolution model only extends to -50 m (NAVD88).

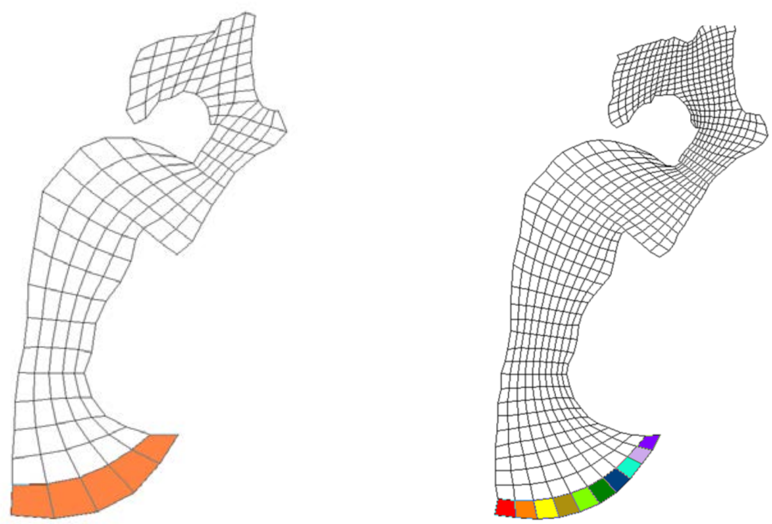
Table 1. Model layer thicknesses and depths for all grids.
The coarse resolution model only extends to -50 m (NAVD88).

Layer	Thickness (m)	Depth of layer bottom in NAVD88 (m)
1	1	4
2	1	3
3	1	2
4	1	1
5	1	0
6	1	-1
7	1	-2
8	1	-3
9	1	-4
10	1	-5
11	1	-6
12	1	-7
13	1	-8
14	1	-9
15	1	-10
16	1	-11
17	1	-12
18	1	-13
19	1	-14
20	1	-15
21	1	-16
22	1	-17
23	1	-18
24	1	-19
25	1	-20
26	1	-21
27	1	-22
28	1	-23
29	1.5	-24.5
30	2.3	-26.8
31	3.4	-30.2
32	4.8	-35
33	5	-40
34	5	-45
35	5	-50
36	5	-55
37	5	-60

Forces Driving Water Circulation in Quartermaster Harbor

Tidal Forcing

During execution, dynamic changes in water surface elevation result from the complex interaction of tidal forces from the moon and sun (the tides), wind, the physical features (shape) of the embayment and to a lesser extent freshwater inputs. Correctly predicting these are a key indicator that hydrodynamic models are correctly calibrated. In the vicinity of Quartermaster Harbor, the National Oceanic and Atmospheric Administration (NOAA) records and publishes water surface elevations at only two stations: in Elliott Bay and Commencement Bay. To measure tide-forcing more exactly for Quartermaster Harbor, well established tools are available that provide detailed estimates of water surface elevations near the open boundary exclusively due to the tides.



a) b)

Figure 5. Open boundary cells for (a) low resolution grid and (b) high resolution grid, showing cells where tidal forcing is applied.

The Puget Sound Tide Channel Model (PSTCM) predicts water surface elevations throughout Puget Sound based on the amplitude and phase of the full suite of tidal constituents (Lavelle et al., 1988; Mofjeld et al., 2002). Finlayson (2005) developed a stand-alone version of the updated PSTCM called PSTides that was used to generate tides for this Quartermaster Harbor model study.

For the coarse resolution grid runs, tidal elevation is input across the five grid cells (Figure 5a, highlighted) in the same manner for all cells along the open boundary, as a plane wave, from segment 200 in PSTides. All vertical elevations are expressed as NAVD88, Ecology's standard datum, unless otherwise specified. Ecology converted PSTides tidal elevations, expressed relative to mean lower low water (MLLW), to NAVD88 using NOAA's VDatum program (nauticalcharts.noaa.gov/csdl/vdatum.htm). Positive elevations indicate locations above the datum and negative elevations below it. For the fine resolution model, tidal forcing was provided from PSTides using segment 199 for the westernmost grid cell and segment 214 for the easternmost grid cell. The forcing for each of the ten boundary grid cells was interpolated between these two segments to obtain a different phasing for each grid cell, as indicated in Figure 5b by using different colors.

Meteorological Conditions

Hourly air and dew point temperature, relative humidity, wind speed/direction, and barometric pressure data used in computing surface heat exchange in the model came primarily from a station located at Dockton in Quartermaster Harbor. There were a number of small gaps in the record from this station that were filled from the next closest meteorological station on the island (Station 28Y near the headwaters of Judd Creek).

The Dockton meteorological station measured photosynthetically active radiation (PAR) rather than total incoming shortwave radiation; therefore, the hourly total solar radiation data from Station 28Y was used as the input for solar radiation. Small gaps in the solar radiation records at 28Y were filled using total solar radiation data collected at a station located at the University of Washington in Seattle.

Cloud cover data were needed as input to the model to derive the amount of outgoing longwave radiation. Hourly cloud cover data were obtained from SeaTac International Airport.

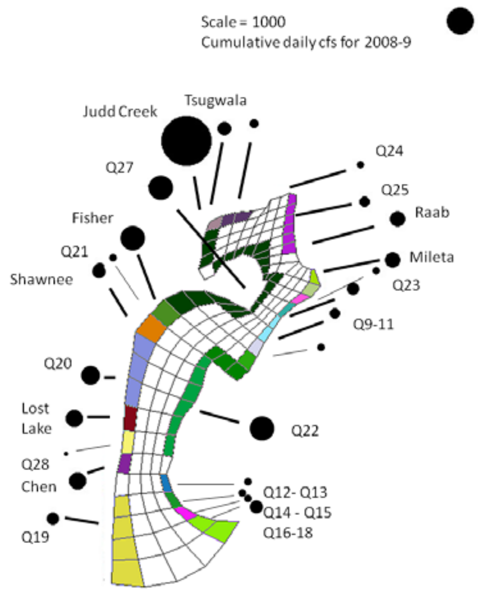
The mean of the recorded daily total precipitation measured at three stations in or near the Quartermaster Harbor drainage basin (Tahlequah 65U, Maury Island 36U, and Judd Creek 28Y) was used as input of freshwater to the harbor surface. Precipitation temperature was specified using the dew point temperature provided in the meteorological input file, and the oxygen concentration of the precipitation was specified as the concentration in pure water at the specified dew point temperature. Wind speed in the inner bay was often observed to be lower than in the outer bay.

Stream Input

Stream inflow and temperature were specified for 28 streams. The two largest tributaries, Judd Creek and Fisher Creek, representing about half of the fresh surface water inflow to the harbor, are monitored for flow, temperature, and other water quality parameters. The data and methods used to estimate inputs from unmonitored freshwater sources are described by King County (2012).

Stream inflows for the model are shown varying by color in Figure 6. They enter into a single grid cell or in a range of cells as indicated by a continuous color over multiple cells along the shoreline. The total annual flow is indicated by the proportionate size of the black circles shown in each diagram.

a) b)



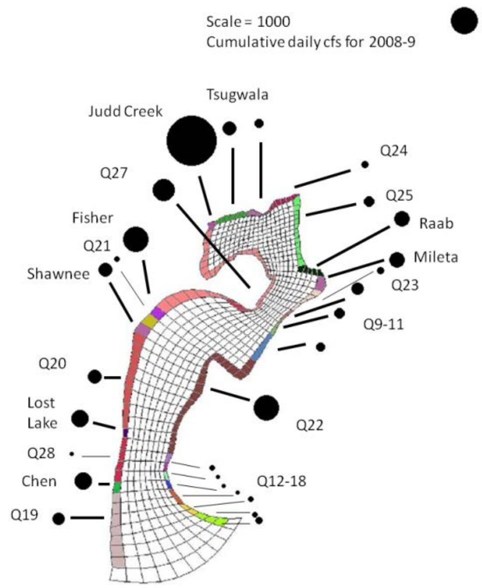


Figure 6. Stream inflow locations shown by cell color with total annual inflow indicated by black circle size for the (a) coarse resolution model and (b) fine resolution model.

Conditions at the Open Boundary

a)  b) 

Figure 7. Data collected from a: (a) mooring positioned at open boundary and (b) ship-based monthly collection.

Conditions of temperature and salinity at the harbor entrance were obtained from a surface mooring (Figure 7a) that recorded data at 15-minute intervals beginning on January 15, 2009 (King County, unpublished data). Availability of the mooring time series at the open boundary determined the choice of 2009 as our calibration period. Spring to summer snowmelt runoff (freshet) to Puget Sound, including inputs from the Puyallup River (Figure 8) located on the opposite side of Commencement Bay east of the harbor entrance, were detected by the surface sensors on this mooring. Freshwater inflow throughout Puget Sound, including the creeks interior to Quartermaster Harbor, was at a minimum in late summer. Salinity variations in the surface sensors on the mooring (Figure 9) illustrate the episodic influence of freshwater inflow to the sound, particularly during spring snowmelt runoff.

These mooring surface results were blended with monthly data collected by UW-Tacoma that reveal more information about the stratification in the mid-depths (Figure 9). To determine the sensitivity to how these data sets were melded, three different versions of data-blending were used: (1) assuming a constant 4-m pycnocline, (2) seasonal varying pycnocline determined from the monthly CTD[4] data, and (3) an exaggerated deep seasonal varying pycnocline to test for sensitivity in matching physical variables. These boundary conditions are not expected to have much effect on the tides, but rather on the subtidal density-driven estuarine flow that is typically seaward on the surface and landward at depth.

[4] Conductivity, Temperature, Depth

Figure 8. Puyallup River plume visible off the southwestern tip of Vashon Island across the mouth of Quartermaster Harbor.

Photo courtesy of Eyes Over Puget Sound.

Colvos Passage is visible on the left side of the photograph, and the west side of the mouth to Quartermaster Harbor is visible on the right side.

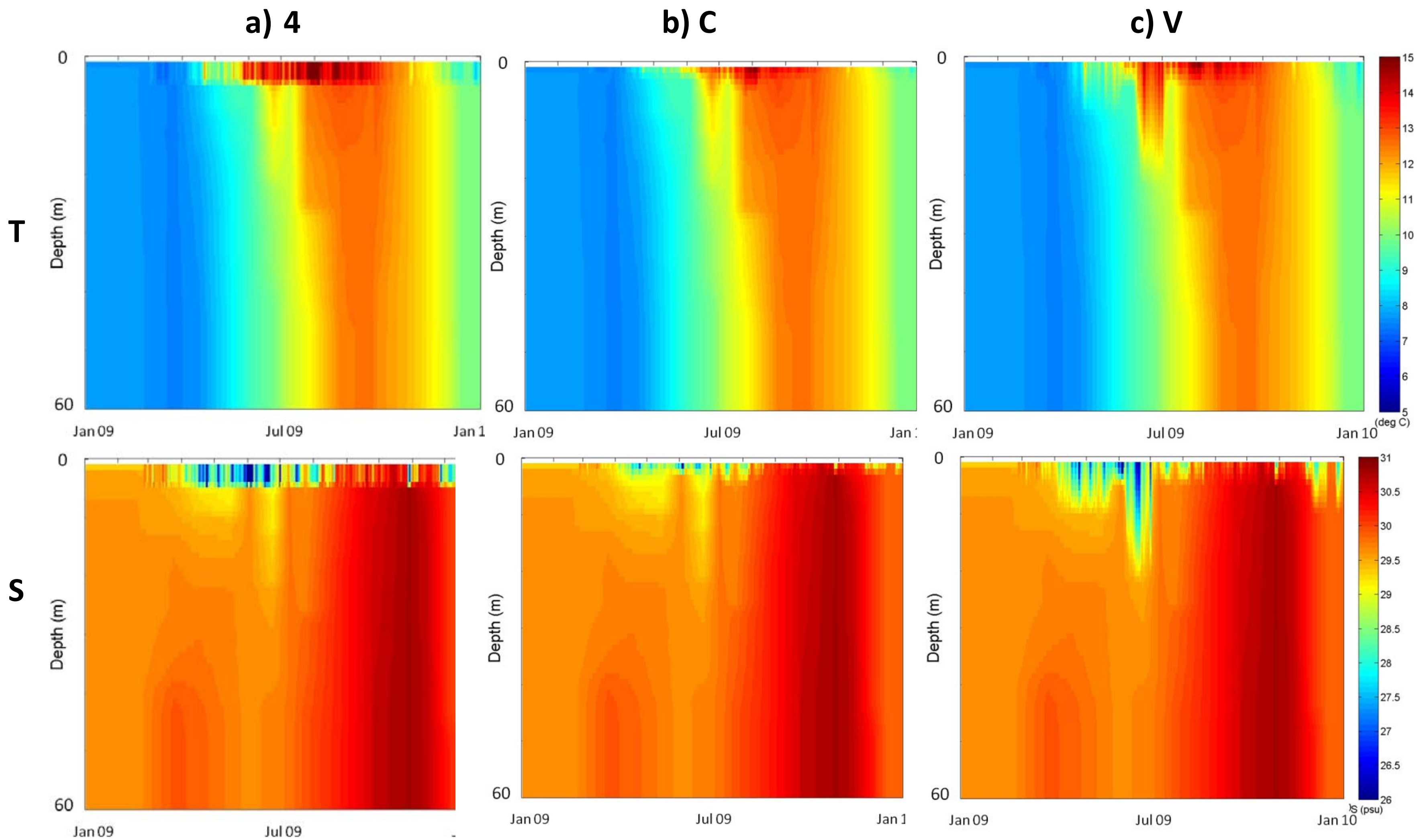


Figure 9. Merged mooring and ship-based boundary conditions for temperature (T) and salinity (S) with (a) fixed 4-m boundary (4), (b) observed seasonal varying pycnocline (C), and (c) exaggerated deep pycnocline depth (V).

Description of Groundwater Approach

Groundwater inflow was estimated by King County (2010a) and applied over two zones as shown in Figure 10. Inflow rates were greater in the inner bay based on the knowledge that the shallow or principal aquifer intersects with the harbor in this area.

a) b)

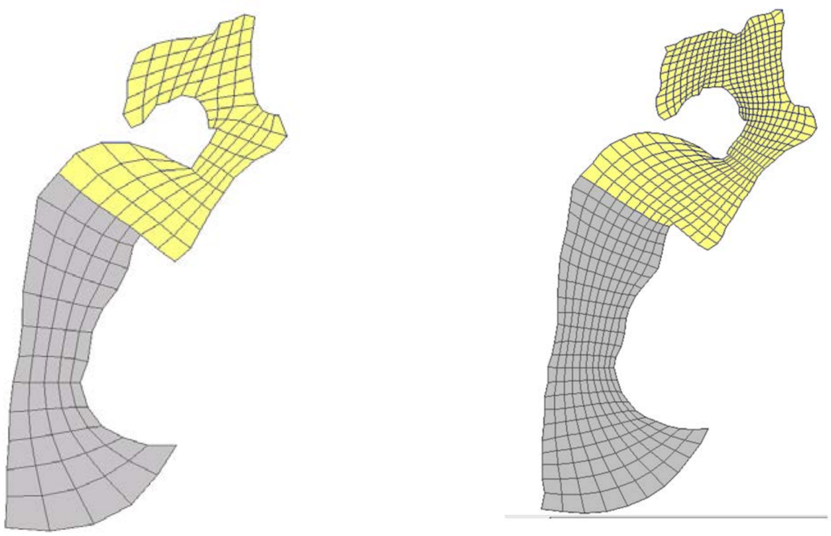


Figure 10. Groundwater inflow zones for the (a) coarse resolution grid and (b) fine resolution grid.

Groundwater flow is greater in the inner bay (gold) than in the outer bay (silver).

Calibration Methods

The following section presents the calibration approach for the Quartermaster Harbor modeling project. The calibration period adopted for the study was January 1 to December 31, 2009, based on the availability of boundary condition and calibration data. Hydrographic field data were collected at roughly monthly intervals throughout 2009 by UW-Tacoma along the deepest channel (thalweg, roughly a north-south line) at stations shown in Figure 11a and in Table 2.

Current meter data were collected at hourly or sub-hourly intervals for a month as shown in Table 3, by the King County Department of Natural Resources (KCDNR) in the fall of 2009 at four locations along an east-west line as shown in Figure 11b. The four current meters consisted of two varieties: Sontek and (Teledyne) RD Instruments (RDIs). The Sonteks were deployed closest to the east and west shoreline, and the RDIs were deployed toward the center channel.

The measure of success used was to compare model results within the bay to collected field data by using standard methods, such as root mean square error (RMSE), to demonstrate that an acceptable level of accuracy has been reached. The target accuracy, as identified in the QA Project Plan, was to achieve an average RMSE of +/-1 psu in salinity, +/-1 deg C in temperature, and +/-10% (~ 10 cm/s) of full-scale velocity relative to measurements taken in the field. In most estuaries, salinity is the most critical parameter because a change of 1 psu has roughly the same effect on density as 5 deg C, and density changes drive the subtidal estuarine flow that most affects water quality.

The mean bias metric shows whether a parameter is consistently under-reported or over-reported by the model. Since the bias values achieved are typically lower than the RMSE, the model is determined to not be significantly biased overall.

a) b)

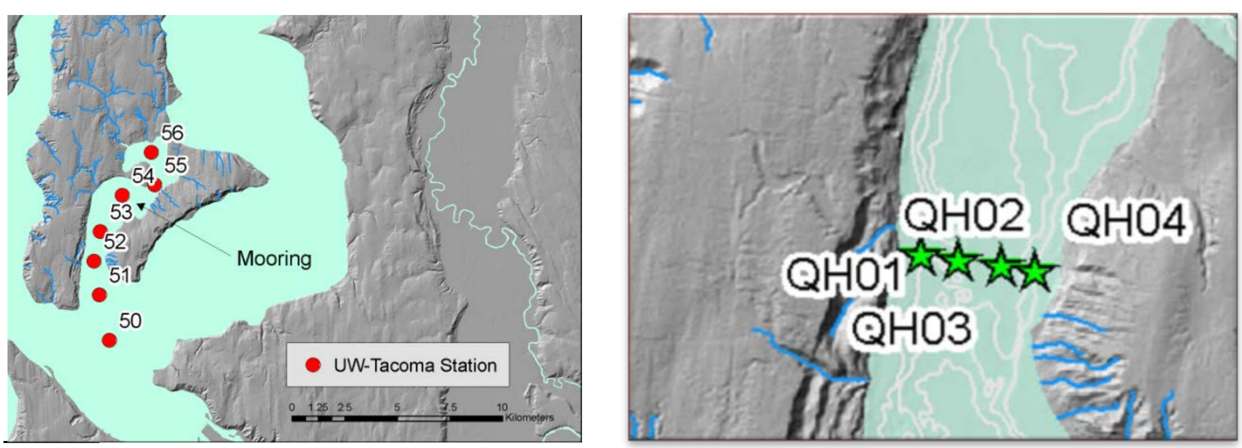


Figure 11. Station location for field data collection of (a) CTD hydrographic data and (b) current meter data.

The model grid cells are identified by indices I (east-west), J (north-south), and K (shallow and deep). The grid cell indices nearest to each station are identified in Table 2 for both the coarse resolution (I-Lo & J-Lo) and the fine resolution (I-Hi & J-Hi) grid.

Table 2. Hydrographic (CTD) stations in terms of model grid coordinate in the high (Hi) and low (Lo) resolution versions.

Station	Location	Depth (m)	I-Hi	J-Hi	I-Lo	J-Lo
UWT51	Boundary (south)	51.03	28	22	26	21
UWT52	South inner	17.2	29	29	27	24
UWT53	South mid	21.31	29	35	27	27
UWT54	North mid	13.16	29	46	27	33
UWT55	North inner	14.63	33	53	29	37
UWT56	Inner bay (north)	5.88	27	69	25	44
Dockton	Mooring (time series)	4.45	38	45	31	32

Turbulence Closure

One of the most important factors to achieving a good calibration is the choice of the turbulence closure schemes; there are several options available in the GEMSS model. Some of these schemes might work better in the open ocean, or in an open reach. For an enclosed bay like Quartermaster, the best result used 0-Equation vertical momentum dispersion with a Von Karman mixing length and Prandtl Number of 10. The momentum dispersion coefficient was with the Okubo formulation: Ax (= Ay) = Axo * L ^ n. Ax0=Ay0=0.00584 m^2/sec and n=1.1.

Calibration Results

Overall, the model is considered to be acceptable for the purpose of this project and predicting the response of critical bottom dissolved oxygen concentrations in inner Quartermaster Harbor to variations in nutrient loading and concentration since the model met the objectives set forth in the QA Project Plan.

Using RMSE as an aid to model calibration is similar to the approval used in other recent studies in South Puget Sound (Pelletier et al., 2011). The RMSE determinations were made for all physical variables in this report. From the current meters, there are u (east-west) velocity, v (north-south) velocity, and speed, which is the magnitude of the u-v vector and is a derived variable. From the hydrographic (CTD) data, there are temperature (T), salinity (S), and density (D), which is also a derived variable determined from temperature and salinity.

Comparison of the Model to KCDNR Current Meter Profiles

The availability and duration of current meter data is shown in Table 3. The RMSE for each current meter location is calculated for the entire deployment as well as for a specific day when all current meters were deployed (Oct. 1, 2009). This is because a storm or wind event that was detected by some current meters and not others could have caused those locations deployed during the storm to have a larger RMSE because of the storm event.

Table 3. Current meter type, deployment location, depth, high resolution and low resolution grid indices, and deployment period.

Station	Instrument*	Location	Depth(m)	I-Hi	J-Hi	I-Lo	J-Lo	Start time	Stop time
QH01	ADP-Sontek 1500	West	8.13	27	32	25	26	9/23/09 15:00	10/21/09 12:54
QH02	ADCP-RDI 300	Midwest	14.55	29	32	26	26	9/18/09 11:45	10/20/09 23:51
QH03	ADCP-RDI 300	Mideast	15.65	31	32	28	26	9/18/09 12:25	10/13/09 14:37
QH04	ADP-Sontek 1500	East	8.82	33	32	29	26	9/23/09 15:00	10/21/09 12:54

* Manufacturer and MHz

In addition to tidal forcing, wind can have a dramatic effect on water currents measured in the bay. Over the monthly duration of the current meter deployment, all four meters show a dominant north-south tidal current pattern. Since the orientation of the bay is primarily north-south, only the v-component of the velocity is first used to make an initial field-data to model comparison; this is easiest to see over a tidal cycle or two (Figure 12).

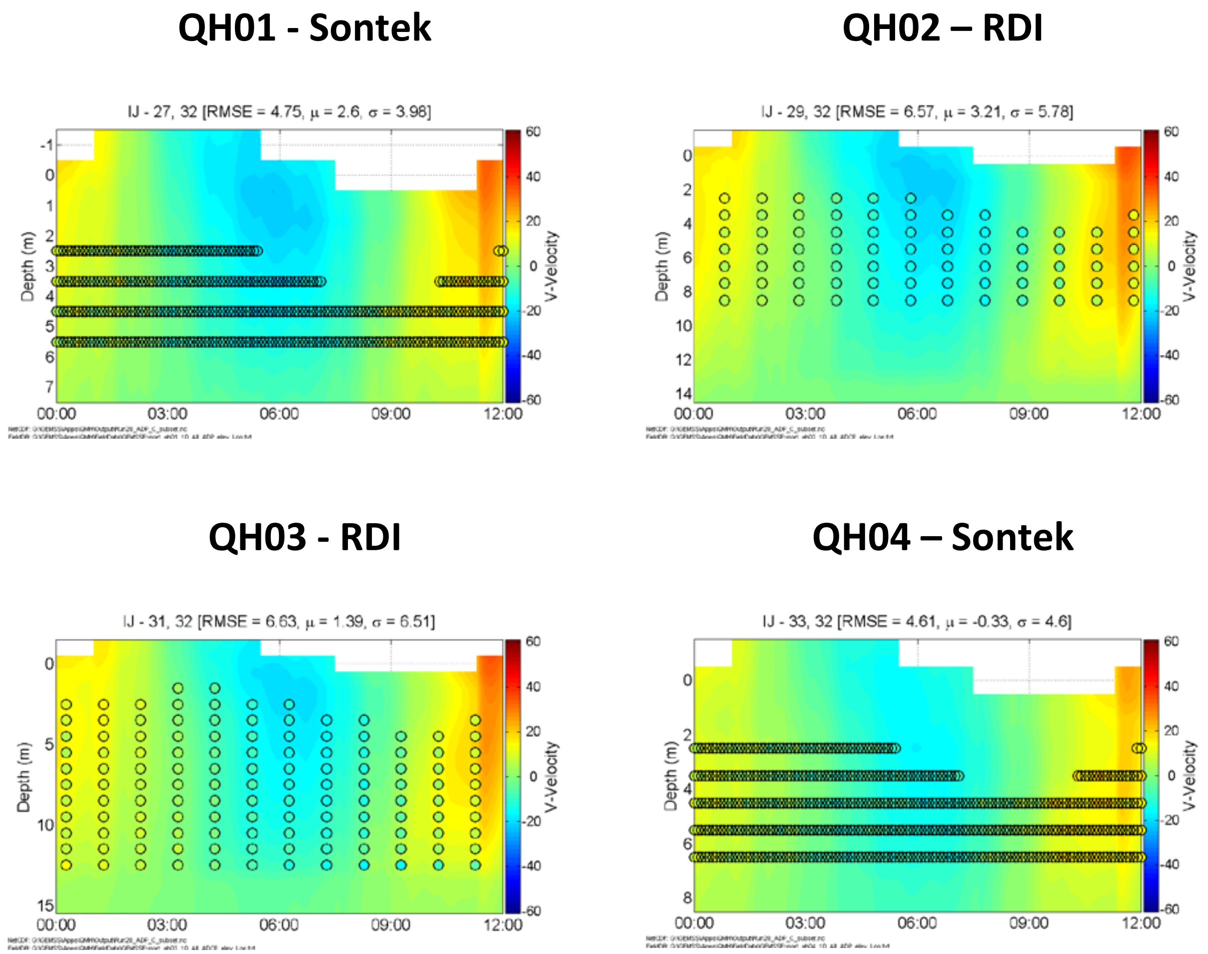


Figure 12. A comparison based on the fine resolution model of measured (circles) to modeled (background contour) of north-south (v) water currents over all depths and stations from midnight to noon on Oct. 1, 2009.

Closed circles are field data; background contour is from the model.

Another analysis is made over the entire collection period for each current meter (shown in Table 3) by summarizing all the results in a compass rose and comparing the field data to the model in this way (Figure 13). These show that field data (the top row from west to east) are slightly more variable and that the model is slightly more “stiff” (i.e., it does not have as many instances of wind coming from atypical directions, as was observed).

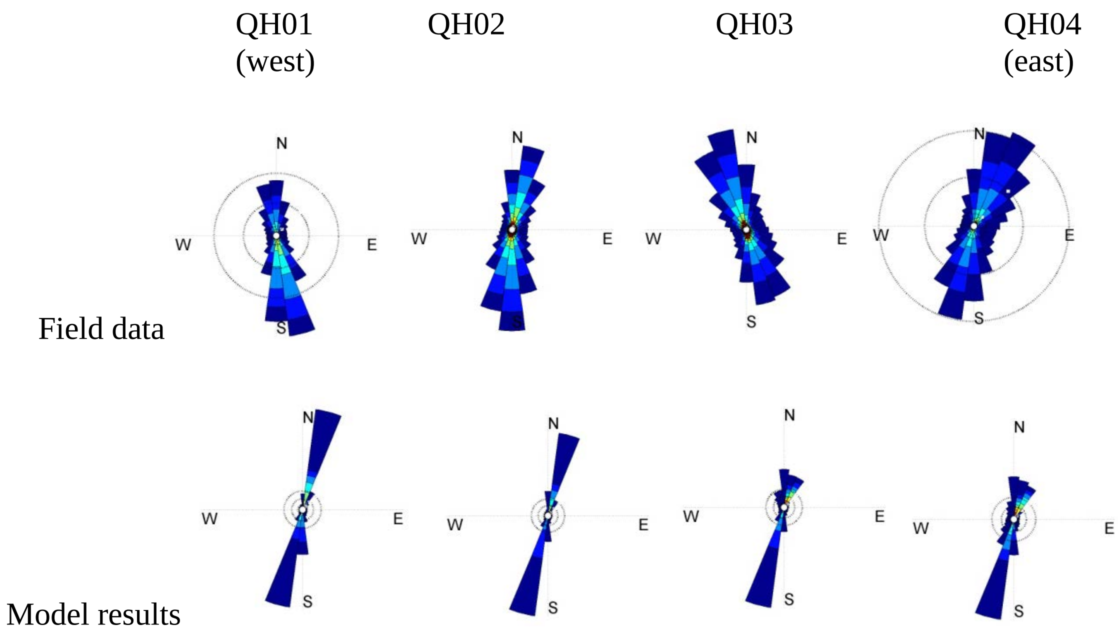
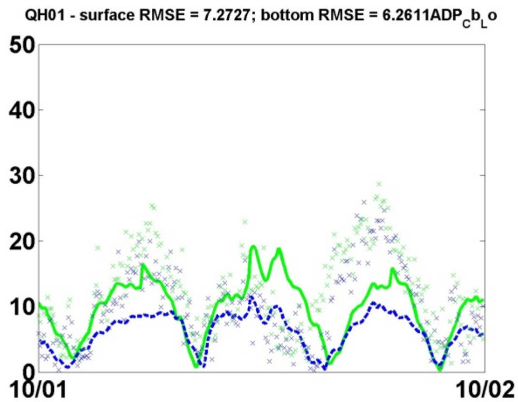
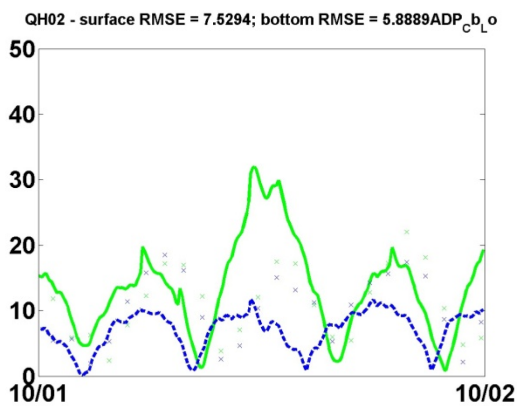


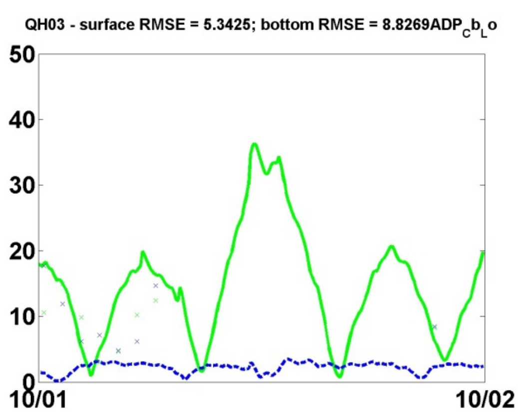
Figure 13. Compass roses of field data and fine resolution model results from west to east across the mouth of Quartermaster Harbor.

A final comparison is made between the speed or magnitude of velocity along the semi-major axis of a tidal ellipse, and that is compared with model results (Figure 14) as a time series. These plots show that the field data (dots) are more chaotic than the model, which is better-behaved.

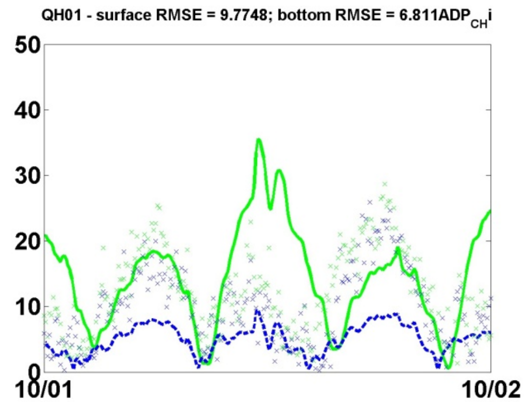
Coarse Resolution (model to data comparison)

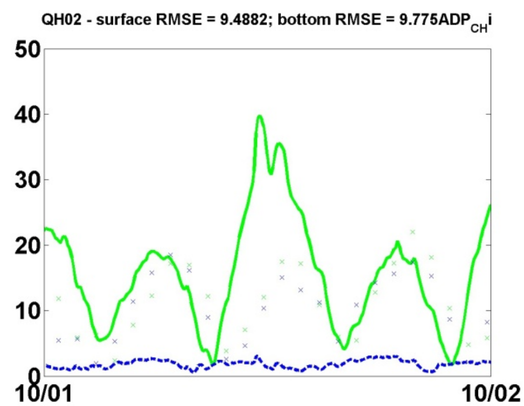


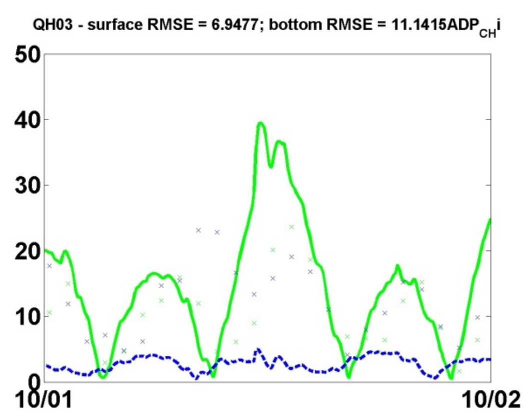


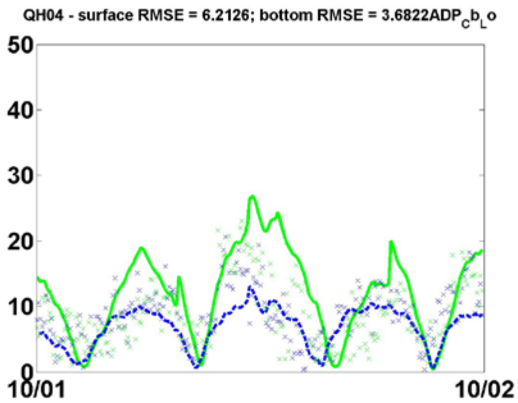


Fine Resolution (model to data comparison)









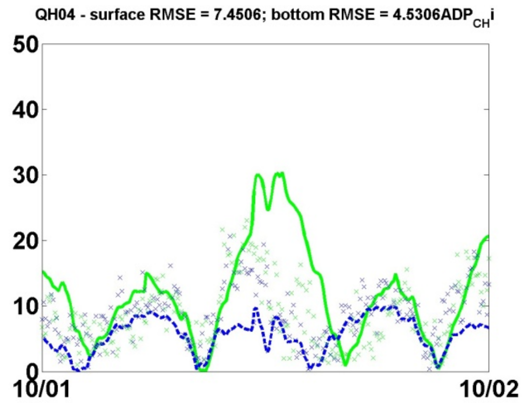


Figure 14. A comparison of near-surface (green) and near-bottom (blue) water velocity magnitude/speed (y-axis scale is cm s^{-1}) in the model (solid) to field data (dots) time series.

A summary of the RMSE for each station over the entire deployment period (different for each current meter as shown in Table 3) and on Oct. 1, which was a typical day common to all, is shown in Table 4. The grand mean RMSE for speed, taken from both bottom and surface depths, is actually slightly lower in the coarse resolution model. Perhaps this is due to noise-averaging effects over the larger grid cells. At the surface, RMSE errors range from 5.3 cm/s at QH03 on Oct. 1 to 9.8 cm at QH01. Near the bottom, it ranges from 3.7 cm/s at QH04 to 12.6 cm/s at QH03. This indicates that the location of QH03 is a relatively sensitive location to changes in environmental conditions. The errors along the bottom range from a low of 3.7 cm/s at QH04 on Oct. 1, to a high of 12.6 cm/s at QH03 over the entire period.

Table 4. Model to field data RMSE (cm/sec) for surface (Surf) and bottom (Bot) current meter results in the coarse (lo) and fine (hi) resolution models for the entire period of record (2009) and the single shared day of Oct. 1, 2009 (Oct1).

Station	Surf_lo	Bot_lo	Surf_hi	Bot_hi	Surf_lo_Oct1	Bot_lo_Oct1	Surf_hi_Oct1	Bot_hi_Oct1
QH01	6.79	5.80	9.08	6.53	7.27	6.26	9.77	6.81
QH02	6.92	6.96	8.21	11.03	7.53	5.89	9.49	9.78
QH03	9.24	12.64	8.62	11.65	5.34	8.83	6.95	11.14
QH04	7.22	3.66	7.83	4.07	6.21	3.68	7.45	4.53
Mean	7.54	7.26	8.43	8.32	6.59	6.16	8.42	8.06
Median	7.07	6.38	8.41	8.78	6.74	6.08	8.47	8.29
Grand Mean	7.40		8.38		6.38		8.24	

Plus or minus 10% of full scale would be within 10 cm/s absolute since full-scale velocities range from -50 cm/s to 50 cm/s.

Comparison of the Model to UW-Tacoma Hydrographic Profiles

The available cast times for hydrographic data in 2009 are shown in Table 5. The RMSE for each CTD station location (Figure 11a) is calculated for the entire calibration year (2009). Results are calculated for temperature, salinity, and density, with the final calibration after making sensitivity tests for the importance of wind, evaporation, and the stratification imposed at the open boundary.

Table 5. UW-Tacoma hydrographic survey dates and time-of-day by station within 2009.

Date in 2009: Station	2/17	3/24	4/16	5/15	6/23	7/24	8/24	9/26	11/12
UWT51	18:39	19:19	19:21	19:34	18:05	19:03	20:55	15:56	16:31
UWT52	18:41	19:22	19:34	19:44	18:07	19:14	20:57	15:57	16:32
UWT53	18:43	19:24	19:37	19:50	18:09	18:28	20:58	16:03	16:33
UWT54	18:46	19:26	19:43	19:59	18:12	18:19	20:59	16:02	16:34
UWT55	18:48	19:28	19:47	20:15	18:13	17:59	21:02	16:00	16:38
UWT56	18:50	19:30	19:49	20:28	18:16	17:50	21:03	15:59	16:40

Sensitivity Analysis Using the Computationally Fast Low Resolution Grid

Sensitivity analyses were made using the lower resolution grid because a large number of runs could be made overnight, which is significantly faster execution than is possible for the higher resolution grid. The objective was to find the best combination of stratification to apply at the open boundary, as well as to investigate sensitivity to wind and evaporation effects since meteorological data, particularly wind speeds, were provided primarily from a single location in the harbor.

As before, the overall success of the model was evaluated by comparing its predictions to field data. Although the model is forced with field data near its outward boundary, conditions in the inner bay can be very different, and the ability of the model to match these measurements speaks to the prediction skill of the hydrodynamic and thermodynamic equations that constitute the model. The boundary stratification that achieved the best fit was not the best fit everywhere. Wind was the most sensitive parameter to vary once the tides were fixed. The results for sensitivity are summarized in Table 6. The best overall fit was achieved using the boundary condition developed using the observed variation in the seasonal pycnocline (Table 6b), which is most sensitive to the salinity in the inner bay. The windless condition matched the field data better in the inner bay at stations 55 and 56.

Table 6. Temperature (T) and salinity (S) coarse resolution grid model results (RMSE/Bias).

a - With 4-m pycnocline at the open boundary.

Run	Station 52, T	Station 53, T	Station 54, T	Station 55, T	Station 56, T	Station 52, S	Station 53, S	Station 54, S	Station 55, S	Station 56, S
Wind & Evap	0.59 / -0.12	0.60 / 0.20	0.78 / 0.19	1.20 / 0.44	1.34 / -0.19	0.40 / 0.09	0.44 / 0.13	0.79 / -0.25	1.15 / 0.04	1.60 / -1.29
No Wind	0.57 / -0.10	0.58 / 0.14	0.80 / 0.21	1.23 / 0.52	1.36 / -0.12	0.40 / 0.10	0.42 / 0.20	0.76 / -0.22	1.12 / 0.12	1.51 / -0.97
No Evap	0.59 / -0.12	0.60 / 0.19	0.78 / 0.19	1.19 / 0.43	1.34 / -0.20	0.41 / 0.08	0.44 / 0.13	0.80 / -0.26	1.15 / 0.03	1.62 / -1.31
No Wind or Evap	0.57 / -0.10	0.58 / 0.13	0.80 / 0.20	1.21 / 0.50	1.35 / -0.13	0.40 / 0.09	0.42 / 0.20	0.76 / -0.23	1.13 / 0.11	1.53 / -1.21

b - With observed seasonally-varying pycnocline at the open boundary.
(best salinity RMSE in bold).

Run	Station 52, T	Station 53, T	Station 54, T	Station 55, T	Station 56, T	Station 52, S	Station 53, S	Station 54, S	Station 55, S	Station 56, S
Wind & Evap	0.65 / -0.15	0.60 / 0.15	0.68 / 0.02	1.17 / 0.35	1.34 / -0.29	0.48 / 0.14	**0.43 /** 0.17	**0.67 /** -0.13	1.12 / 0.09	1.54 / -1.23
No Wind	0.63 / -0.14	0.63 / 0.10	0.71 / 0.08	1.19 / 0.42	1.35 / -0.23	**0.47** / 0.15	0.45 / 0.24	0.69 / -0.14	**1.11 /** 0.17	**1.47 /** -1.14
No Evap	0.65 / -0.16	0.60 / 0.15	0.68 / 0.02	1.16 / 0.35	1.34 / -0.30	0.48 / 0.14	0.44 / 0.17	0.68 / -0.13	1.13 / 0.09	1.56 / -1.24
No Wind or Evap	0.64 / -0.14	0.63 / 0.09	0.71 / 0.08	1.18 / 0.41	1.35 / -0.24	0.48 / 0.14	0.45 / 0.24	0.70 / -0.14	1.11 / 0.16	1.49 / -1.16

c - With exaggerated deep pycnocline at the open boundary.

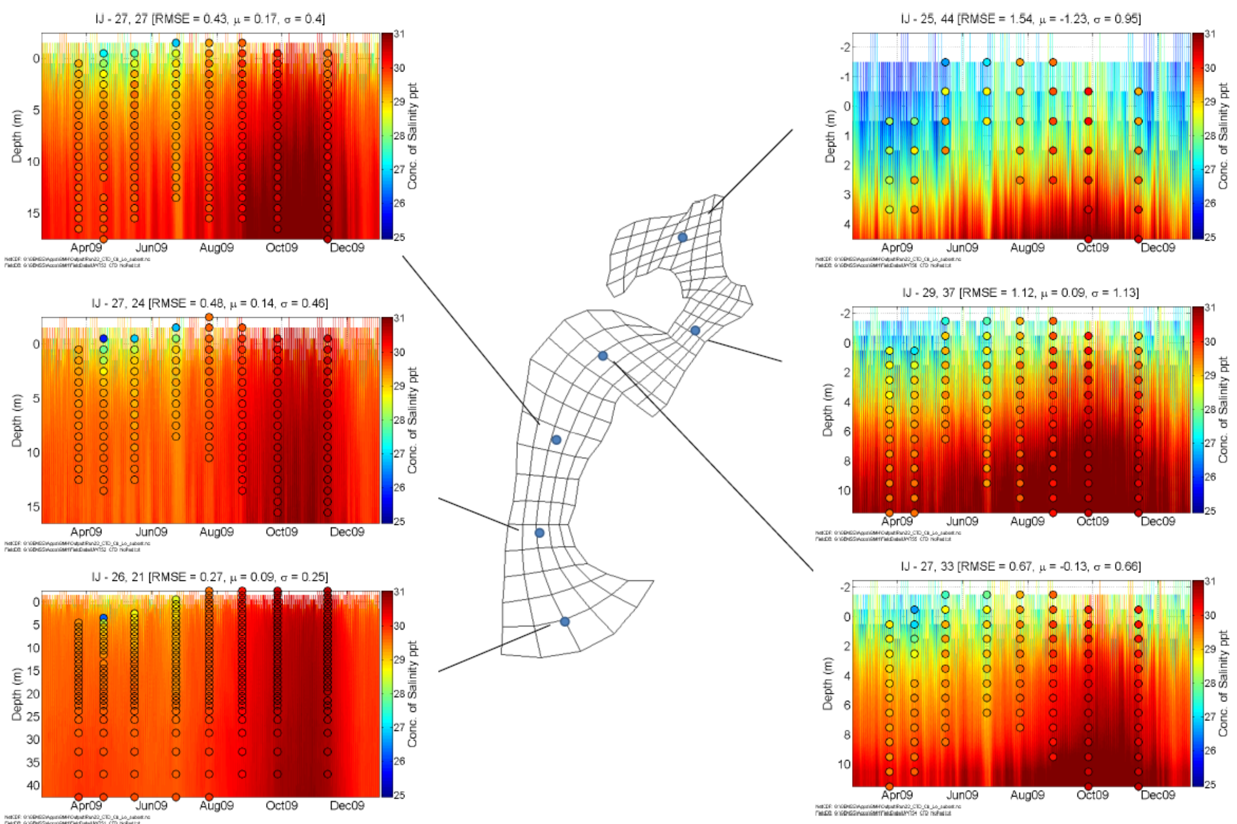
Run	Station 52, T	Station 53, T	Station 54, T	Station 55, T	Station 56, T	Station 52, S	Station 53, S	Station 54, S	Station 55, S	Station 56, S
Wind & Evap	0.56 / -0.09	0.63 / 0.21	0.82 / 0.17	1.21 / 0.43	1.30 / -0.19	0.40 / 0.06	0.45 / 0.11	0.79 / -0.27	1.13 / 0.01	1.59 / -1.29
No Wind	0.55 / -0.07	0.63 / 0.15 /	0.83 / 0.19	1.25 / 0.52	1.32 / -0.12	0.40 / 0.07	0.43 / 0.18	0.77 / -0.24	1.11 / 0.10	1.52 / -1.20
No Evap	0.56 / -0.09	0.62 / 0.20	0.82 / 0.17	1.20 / 0.42	1.30 / -0.21	0.40 / 0.06	0.45 / 0.11	0.80 / -0.27	1.13 / 0.01	1.61 / -1.31
No Wind or Evap	0.55 / -0.07	0.63 / 0.15	0.83 / 0.18	1.24 / 0.50	1.31 / -0.13	0.40 / 0.07	0.43 / 0.18	0.77 / -0.24	1.12 / 0.09	1.52 / -1.19

Salinity results are discussed first because they are the most important to density, and density drives the estuarine flow. The best overall fit was obtained with the seasonally-varying pycnocline shown in Figure 9b.

The water temperatures predicted by the model use a mass and energy balance that considers each cell in the grid as a well-mixed single element. The temperature is affected by meteorological conditions such as solar radiation, wind speed, channel depth and morphology, temperature of incoming and outgoing surface and subsurface flows, as well as water clarity. All the resultant hydrographic parameters respond to estuarine flow, which results over many ebb-flood tidal cycles but is much slower and conveyor-belt-like (seaward at the surface and landward at depth). The estuarine flow is density-driven flow that is driven by mixing caused by tide and wind.

Based on these sensitivity results, the moderate seasonally-varying stratification is used with wind and evaporation fully modeled for the final runs. The low resolution and high resolution model final results for the study, based on these boundary conditions and the turbulence closure scheme discussed earlier, are shown in Figure 15 for salinity, Figure 16 for temperature, and Figure 17 for density.

a)



b)

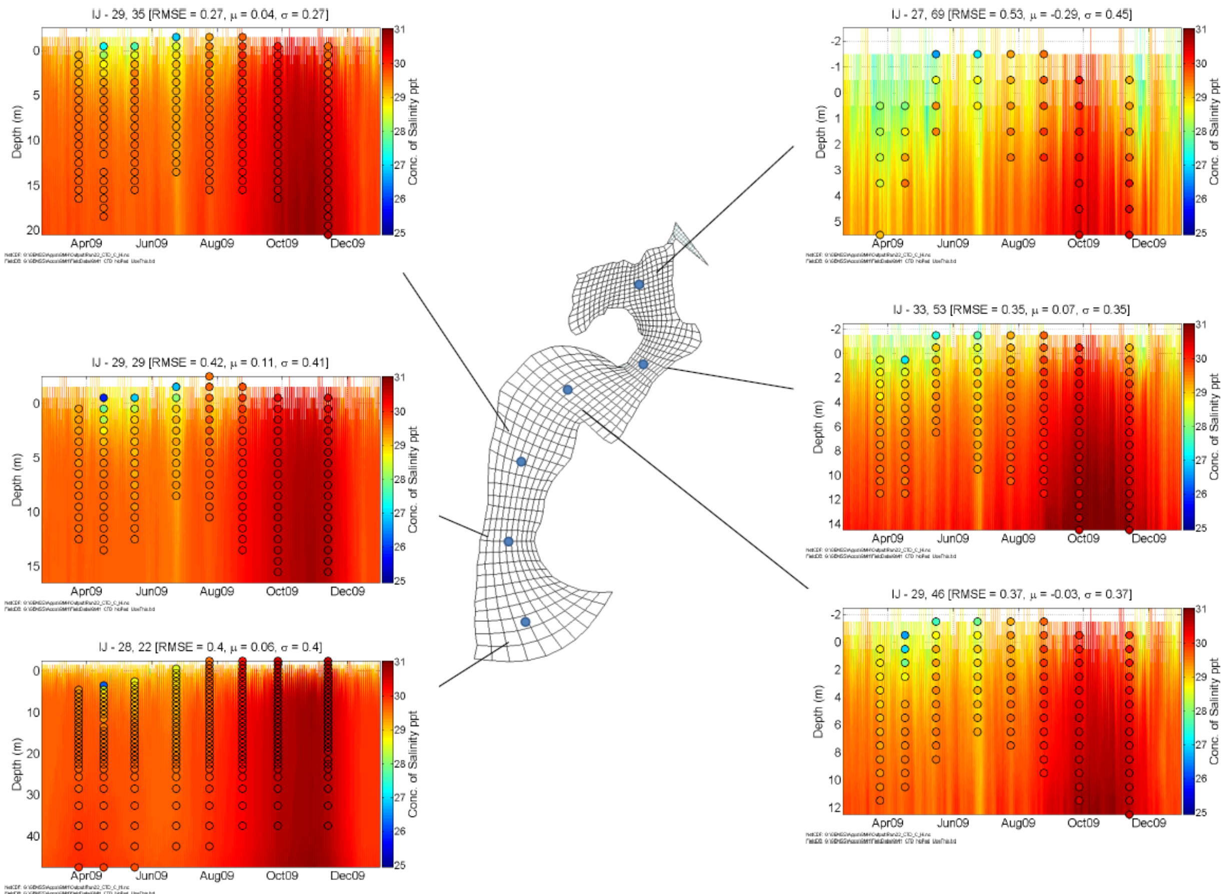
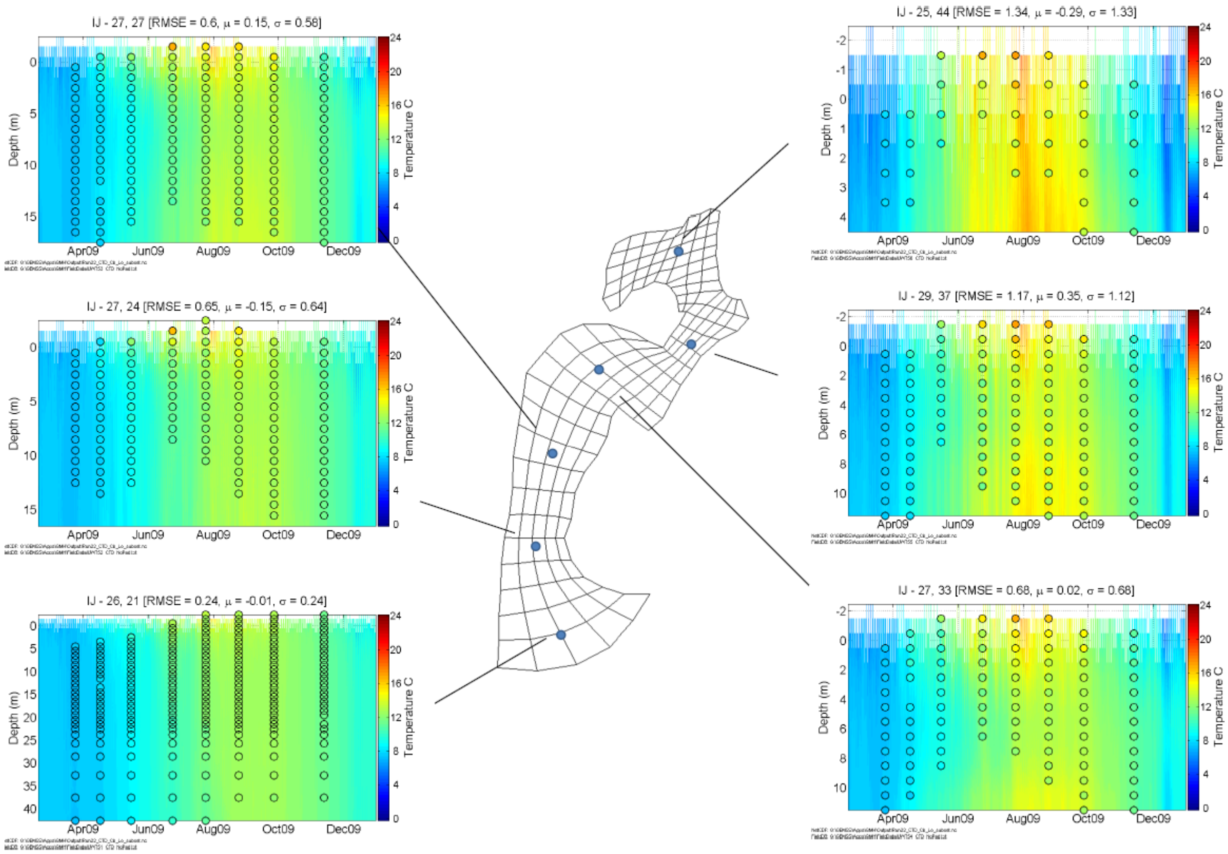


Figure 15. Measured (color inside circles) and predicted (contour) salinity (psu) in Quartermaster Harbor during the model calibration period (2009) from (a) coarse resolution and (b) fine resolution model grids.

a)


IJ - 27, 27 [RMSE = 0.6, μ = 0.15, σ = 0.58]
IJ - 27, 24 [RMSE = 0.65, μ = -0.15, σ = 0.64]
IJ - 26, 21 [RMSE = 0.24, μ = -0.01, σ = 0.24]
IJ - 25, 44 [RMSE = 1.34, μ = -0.29, σ = 1.33]
IJ - 29, 37 [RMSE = 1.17, μ = 0.35, σ = 1.12]
IJ - 27, 33 [RMSE = 0.68, μ = 0.02, σ = 0.68]
Depth (m)
Temperature C
Apr09
Jun09
Aug09
Oct09
Dec09

b)

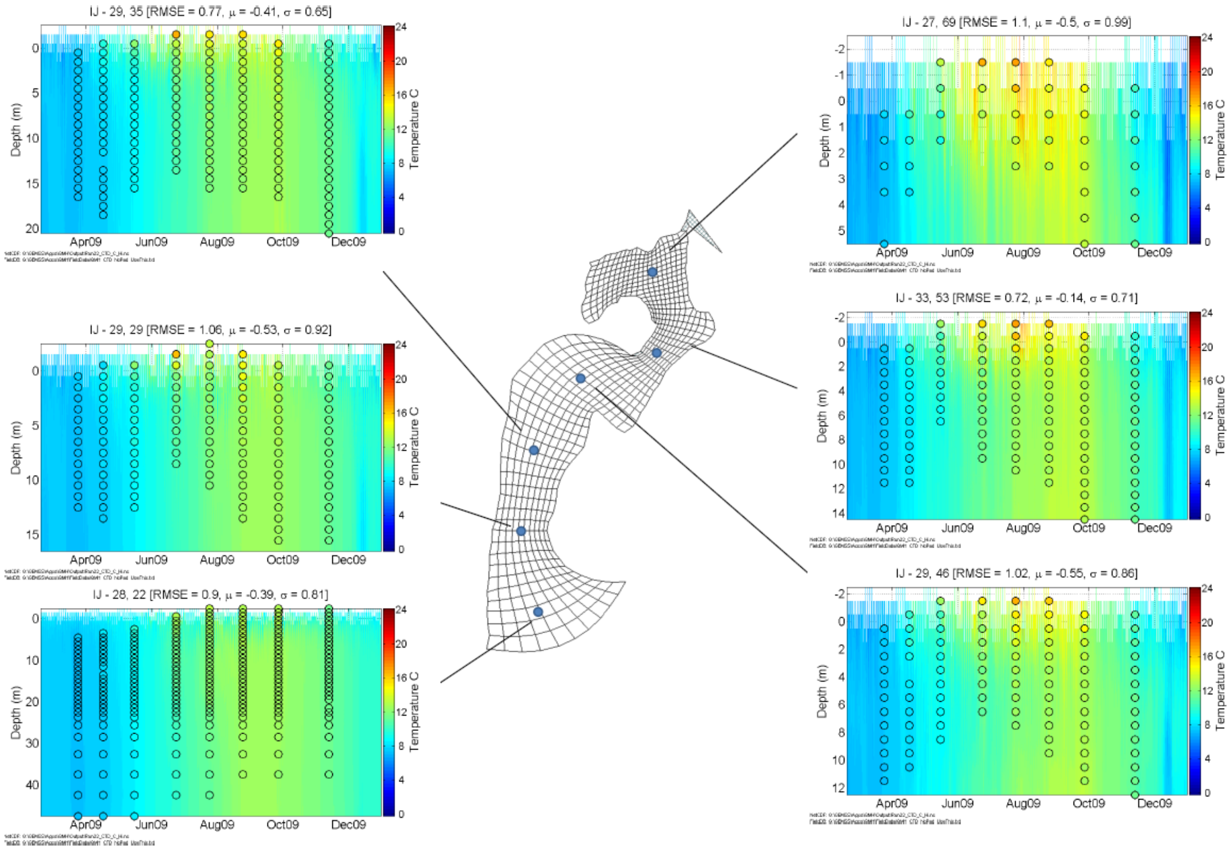
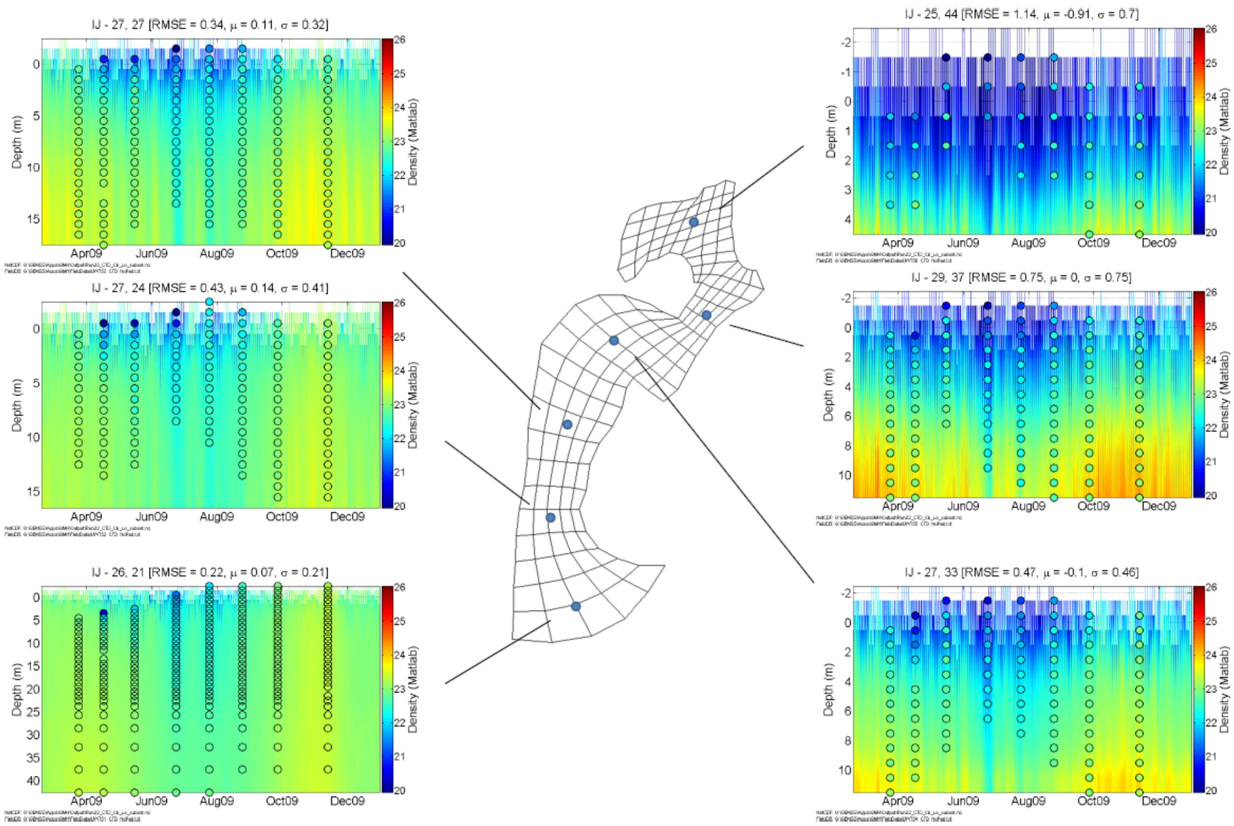


Figure 16. Measured (color inside circles) and predicted (contour) temperature (deg C) in Quartermaster Harbor during the model calibration period (2009) from (a) coarse resolution and (b) fine resolution model grids.

a)


IJ - 27, 27 [RMSE = 0.34, μ = 0.11, σ = 0.32]
IJ - 27, 24 [RMSE = 0.43, μ = 0.14, σ = 0.41]
IJ - 26, 21 [RMSE = 0.22, μ = 0.07, σ = 0.21]
IJ - 25, 44 [RMSE = 1.14, μ = -0.91, σ = 0.7]
IJ - 29, 37 [RMSE = 0.75, μ = 0, σ = 0.75]
IJ - 27, 33 [RMSE = 0.47, μ = -0.1, σ = 0.46]
Depth (m)
Density (Matlab)
Apr09
Jun09
Aug09
Oct09
Dec09

b)

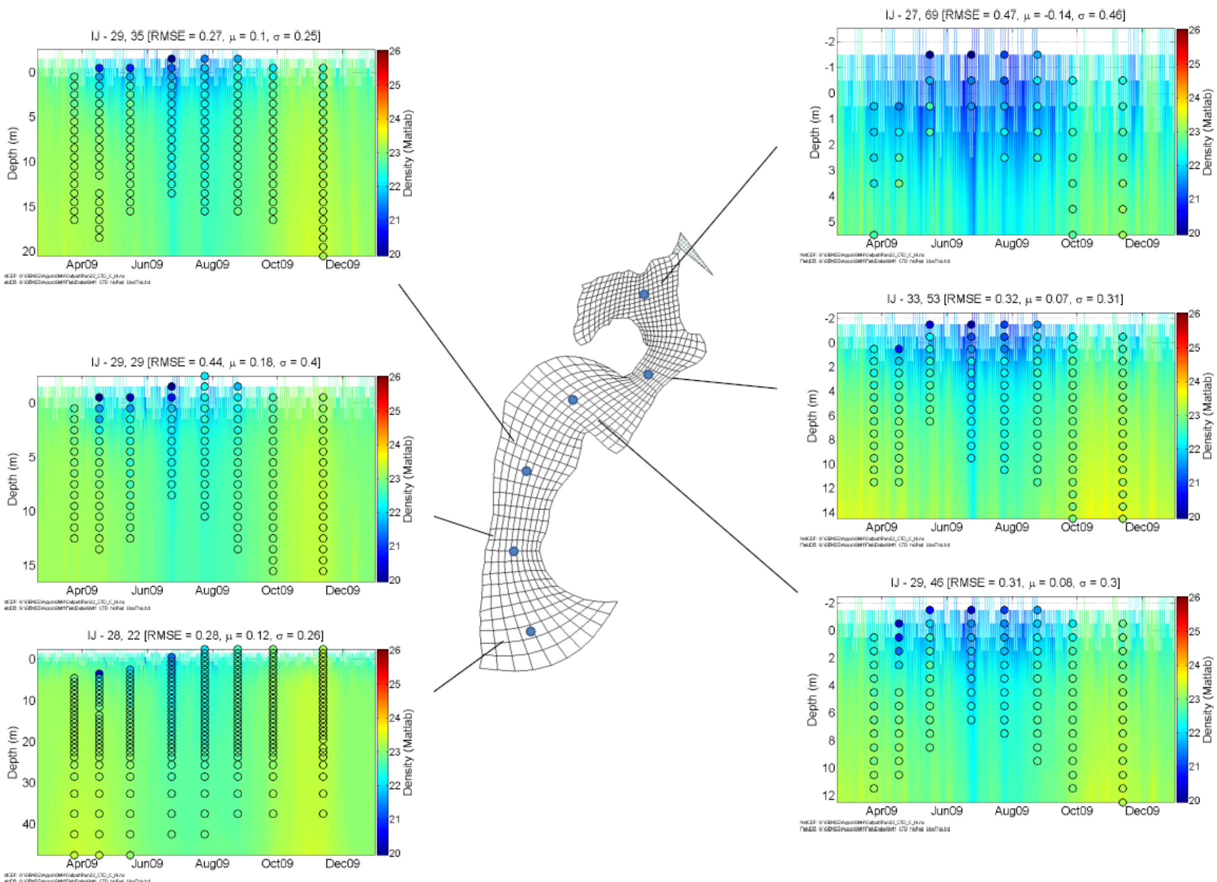


Figure 17. Measured (color inside circles) and predicted (contour) density (sigma-t units) in Quartermaster Harbor during the model calibration period (2009) from (a) coarse resolution and (b) fine resolution model grids.

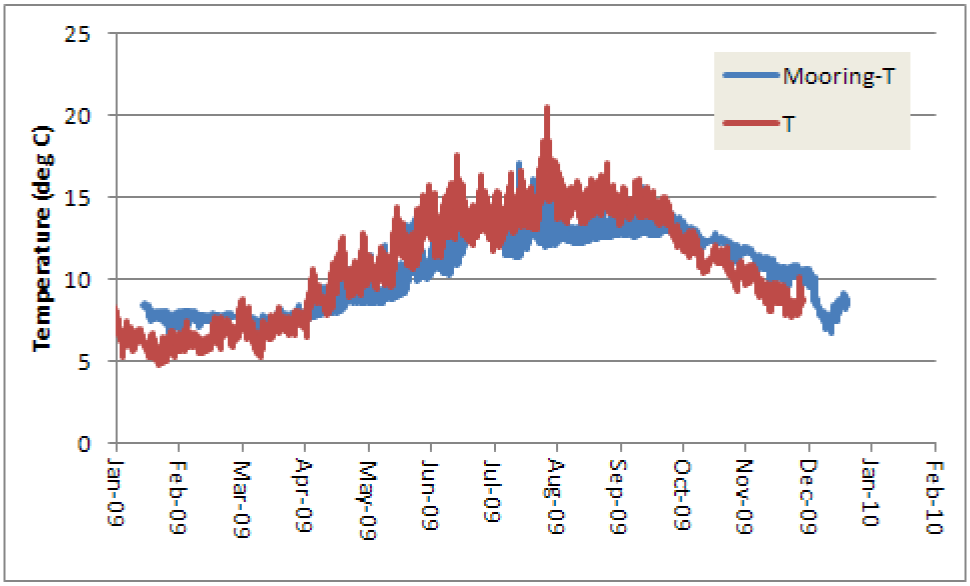
Note that the coarse resolution model has its largest errors within the inner bay, where it over-predicts stratification.

Table 7. Final results for temperature (T, deg C), salinity (S, psu), and density (D, sigma-t) by station for the fine (Hi) and coarse (Lo) resolution model grids.

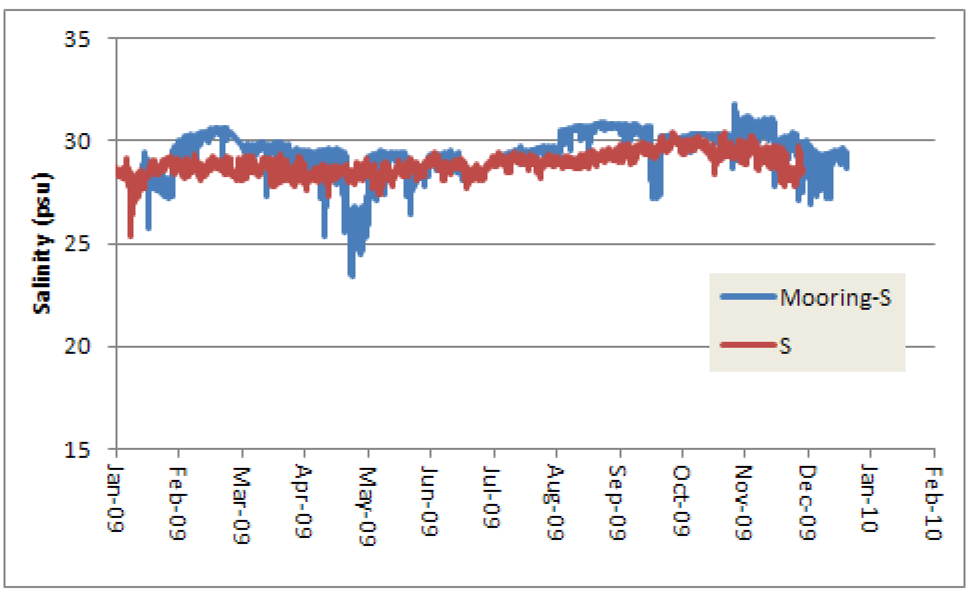
Station	T Hi	T Lo	S Hi	S Lo	D Hi	D Lo
UWT51	0.90	0.24	0.40	0.27	0.28	0.22
UWT52	1.06	0.65	0.42	0.48	0.44	0.43
UWT53	0.77	0.60	0.27	0.43	0.27	0.34
UWT54	1.02	0.68	0.37	0.67	0.31	0.47
UWT55	0.72	1.17	0.35	1.12	0.32	0.75
UWT56	1.10	1.34	0.53	1.54	0.47	1.14
Mean	0.93	0.89	0.39	0.85	0.36	0.63

The average RMSE achieved during the calibration period (all of 2009) at the interior stations (UWT52 – UWT56) for the coarser grid is 0.89 deg C in temperature, 0.85 psu in salinity, 0.63 sigma-t in density, and 8 cm/s in velocity. The average RMSE of the finer grid is 0.93 deg C in temperature, 0.39 psu in salinity, 0.36 sigma-t in density, and 8 cm/s in velocity. The slightly better temperature results for the coarser model may be the benefit of averaging thermodynamics over a broader area. Salinity is more important to density, and those results are better with the finer model grid.

Data from a mooring near Dockton provide a final test for the accuracy of the model predicting temperature and salinity time series at 15-minute intervals over the entire year. Those results can be seen in Figure 18. The Dockton salinity sensor (shown with a blue line) was slightly more sensitive to changes than the near-shore grid cell that contains the sensor in the model. The nearshore location tucked into a cove may explain why the model salinities appear less responsive than the field data (Figure 18b).



a)



b)

Figure 18. Temperature (a) and salinity (b) comparison of Dockton mooring data to fine resolution model output.

Estimates of Flushing Time with the Model

The calibrated model run for 2009 can be used to determine seasonal changes in flushing time based on conditions (e.g., tidal, wind-forcing, and riverine input) prevalent during the year. This was done at monthly intervals by initializing the entire bay with dye tracer (Figure 19a) and calculating how long it took to flush based on remaining concentrations of dye after a period of time has elapsed. A flushing time estimation based on the e-folding time of remaining dye concentration in each grid cell for October is shown in Figure 19b, as one example.

Instantaneous monthly flushing times predicted by this model for the inner harbor (defined by a line from Raab's Lagoon to Jensen Point, see Figure 2) is shown in Figure 20a. These vary seasonally and are based solely on physical forcing. They range from 20 to over 100 days and appear highly dependent on either seasonally high salinities that occur in the late summer with concurrent low inside-the-bay stream inflows, or transitory depressed salinity across the mouth of the bay. This secondary type of longer flushing time aligns with the presence of fresher water across the bay's mouth.

The influence of the Puyallup River discharge is suggested by U.S. Geological Survey (USGS) data shown in Figure 20b. The presence or absence of the plume is indicated from the mooring results shown near the surface in Figure 20c.

Residual Flow

The flushing times shown in Figure 20a are related to subtidal or residual flow and can be estimated by time-averaging east-west (u) and north-south (v) velocities over an appropriate timescale to de-tide the results. The seaward flow in Quartermaster Harbor is generally in the –v (southward) direction. Comparing modeled residual flows to those collected by current meters is a very stringent test of any model (Pers. comm., Mitsuhiro Kawase, UW). Estimates of residual flow transport for both the model and current meter results are shown in Table 8. These were calculated for the deployment period of each current meter, as shown in Table 3, for both the high and low resolution models.

Calculating net transport from ADCP[5] data can also be very difficult (Pers. comm., Parker MacCready, UW) since ADCPs often miss the surface layer due to side-lobe interference. The difference between surface-outgoing and compensating flow at depth is normally the river inflow, but because these Doppler current meters cannot resolve the top 10% (or bottom 10%) of the water column such a validation is impractical, especially when density profiles suggest more of the vertical stratification is in the top few meters of water. It is encouraging that despite this, the transition (slope) of the net profile is smooth and linear from near-surface to bottom during this period, indicating that not a lot of exchange was missed outgoing at the surface.

[5] Acoustic Doppler Current Profiler

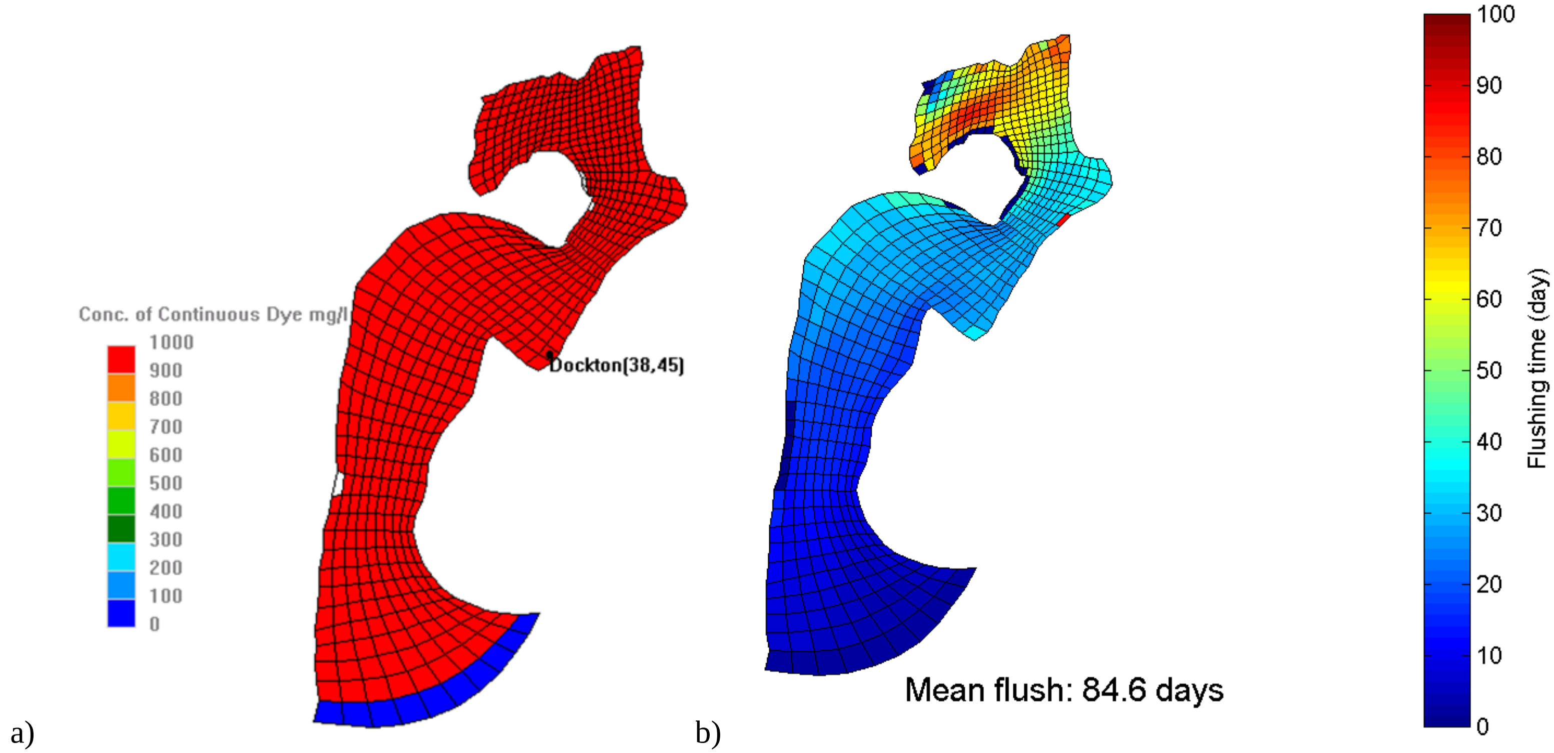


Figure 19. Predicted flushing times for the inner bay based on e-folding time of flushed dye tracer after being initialized uniformly throughout the model (October 2009 shown).

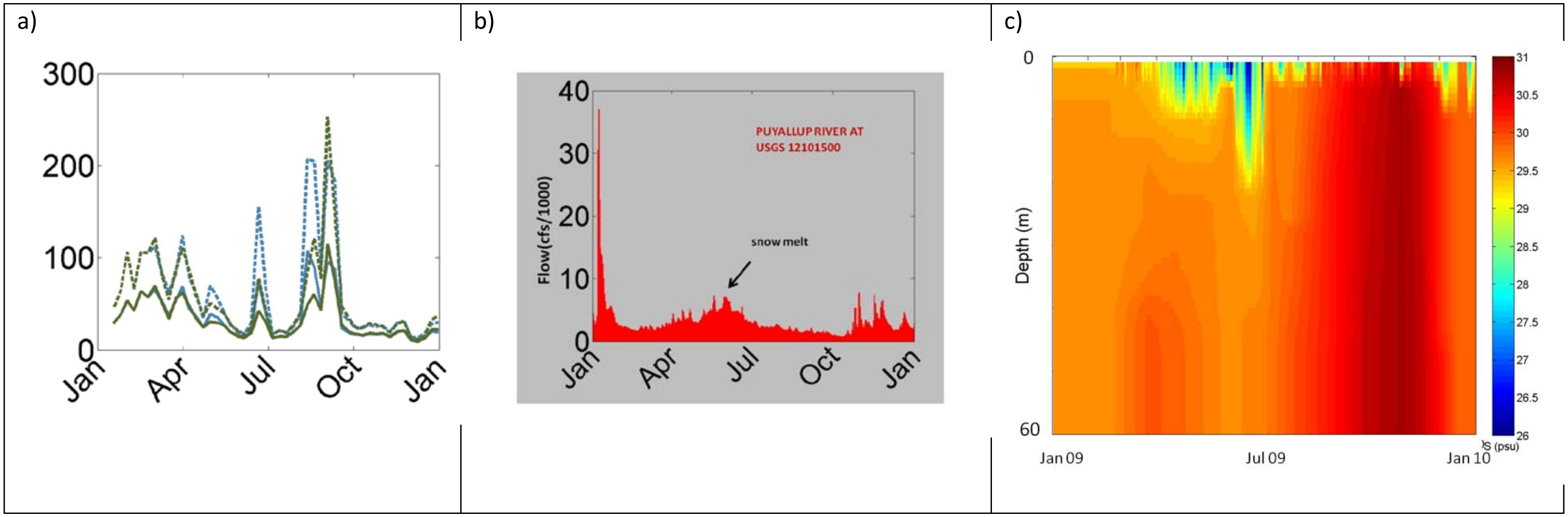


Figure 20. (a) Predicted flushing times over the year 2009, (b) Puyallup River flow, and (c) salinity at the open boundary to the Quartermaster Harbor model based on the exaggerated pycnocline depth blending at the open boundary (Figure 9c).

Table 8. Residual flow vertical profiles for each current meter location (QH01, QH02, QH03, & QH04) for the fall current meter deployments and an equivalent period in the model.

Station	Location	Seaward flux (m^3/s) current meter	Landward flux (m^3/s) current meter
QH-01	west	10	10
QH-02	mid-west	16	14
QH-03	mid-east	35	35
QH-04	east	6	6
Current meter total	all	67	65
Coarse model	all	94	97
Fine model	all	64	64

The volume of Quartermaster Harbor at high tide (MHW) is about 184 x 10^6 m^3, and at low tide (MLLW) is 143 x 10^6 m^3. The current meter results indicate that the estuarine outflow over the period of deployment is about 65 m^3/s. The model results range from 64 m^3/s over all ten cross-channel grid cells in the current-meter transect for the high resolution model, to 97 m^3/s over all five cells in the low resolution model along the same transect (Table 8). That exchange flow corresponds to a flushing period of roughly 25 days along the ADCP transect, which is consistent with the flushing period of model grid cells in that location for October (Figure 19b). Grid cells within the inner harbor flush much slower than this, and that accounts for the longer flushing time reported in Figure 20a, because that time was calculated from the mean flushing time of neutrally buoyant dye tracer for grid cells within that region.

The combined river inflow during the period of current meter deployment in early fall was about 0.6 m^3/s, which means there was approximately a hundred-fold increase in the exchange flow along the ADCP transect line, which is largely a function of mixing processes in the bay's interior. This ratio of exchange-to-river-inflow is slightly higher than reported in Budd Inlet (Pers. comm. Greg Pelletier, Ecology) and may be affected by wind coming from the north helping to push surface water out of the bay at this time of year. Although the model results agree (almost too) well with the data, the model range (100-150% of the field data) is a more realistic evaluation of agreement.

Conclusions and Recommendations

The hydrodynamic model meets the criteria of the modeling Quality Assurance Project Plan.

The difference between the accuracy of the coarse resolution model and the fine resolution model is most noticeable in the inner bay of Quartermaster Harbor. The calibrated model predicts instantaneous flushing times for the inner harbor that vary seasonally and are based solely on physical forcing that range from 20 to over 100 days. Longer flushing times appear highly dependent on salinity and occur either when salinity is (1) high everywhere due to low summertime riverine inflows internal to the bay or (2) lowered across the mouth of the bay by the presence of fresher water outside rather than inside the bay (e.g., the Puyallup River).

The development of the GEMSS water quality model of the harbor, based on the coarse resolution hydrodynamic model, will be presented in a separate report.

References

Albertson, S., J. Bos, K. Erickson, C. Maloy, G. Pelletier, and M. Roberts, 2007. Quality Assurance Project Plan: South Puget Sound Water Quality Study Phase 2: Dissolved Oxygen. Washington State Department of Ecology, Olympia, WA. Publication No. 07-03-101. https://fortress.wa.gov/ecy/publications/SummaryPages/0703101.html

Aura Nova Consultants, Brown and Caldwell, Inc., Evans-Hamilton, Inc., J.E. Edinger and Associates, Washington State Department of Ecology, and A. Devol, University of Washington Department of Oceanography, 1998. Budd Inlet Scientific Study Final Report. Prepared for Lacey, Olympia, Tumwater, Thurston Alliance (LOTT) Wastewater Management District. 300 pp.

Finlayson, D.P., 2005. Combined bathymetry and topography of the Puget Lowland, Washington State. University of Washington, Seattle, WA. http://www.ocean.washington.edu/data/pugetsound/

King County, 2009a. Quality Assurance Project Plan for Quartermaster Harbor Nitrogen Management Study. A Targeted Watershed Grant under the 2008 Puget Sound Initiative. Prepared in cooperation with University of Washington Tacoma and Washington State Department of Ecology. King County Water and Land Resources Division, Seattle, WA. http://www.kingcounty.gov/environment/watersheds/central-puget-sound/vashon-maury-island/quartermaster-nitrogen-study/QMH-documents.aspx

King County, 2009b. Water Quality Status Report for Marine Waters, 2005-2007. King County Department of Natural Resources and Parks, Seattle, WA.

King County, 2010a. Initial Assessment of Nutrient Loading to Quartermaster Harbor. Prepared by Curtis DeGasperi, King County Water and Land Resources Division, Seattle, WA.

King County, 2010b. Modeling Quality Assurance Project Plan for the Quartermaster Harbor Nitrogen Management Study. Prepared by King County in collaboration with the Washington State Department of Ecology and the University of Washington-Tacoma. King County Water and Land Resources Division, Seattle, WA.

King County, 2012. Quartermaster Harbor Nearshore Freshwater Inflows. Prepared by Curtis DeGasperi and Eric Ferguson, King County Water and Land Resources Division, Seattle, WA.

Lavelle, J.W., H.O. Mofjeld, E. Lempriere-Doggett, G.A. Cannon, D.J. Pashinski, E.D. Cokelet, L. Lytle, and S. Gill, 1988. A Multiply-Connected Channel Model of Tides and Tidal Currents in Puget Sound, Washington and a Comparison with Update Observations. NOAA Technical Memorandum ERL PMEL-84.

Long, E.R., M. Dutch, S. Aasen, K. Welch, J. Hameedi, S. Magoon, R.S. Carr, T. Johnson, J. Biedenbach, K.J. Scott, C. Mueller, and J. Anderson, 2002. Sediment Quality in Puget Sound: Year 3, Southern Puget Sound. Washington State Department of Ecology, Olympia, WA. Publication No. 02-03-033.
https://fortress.wa.gov/ecy/publications/SummaryPages/0203033.html

Mofjeld, H.O., A.J. Venturato et al., 2002. Tidal datum distributions in Puget Sound, Washington, based on a tide model. Seattle, WA, NOAA/Pacific Marine Environmental Laboratory: 39.

Pelletier, G., A. Ahmed, B. Sackmann, M. Roberts, and R. Ambrose, 2011. Poster: Calibration of a three-dimensional model of water quality in South Puget Sound. Washington State Department of Ecology, Olympia, WA. Publication No. 11-03-059.
https://fortress.wa.gov/ecy/publications/SummaryPages/1103059.html

Rensel Associates and PTI, 1991. Nutrients and phytoplankton in Puget Sound. Prepared for U.S. Environmental Protection Agency, Region 10, Seattle, WA. PTI Environmental Services, Bellevue, WA.

Roberts, M.L., A. Ahmed, and G. Pelletier, 2012. Deschutes River, Capitol Lake, and Budd Inlet Temperature, Fecal Coliform Bacteria, Dissolved Oxygen, pH, and Fine Sediment Total Maximum Daily Load Technical Report: Water Quality Study Findings. Washington State Department of Ecology, Olympia, WA. Publication No. 12-03-008.
https://fortress.wa.gov/ecy/publications/SummaryPages/1203008.html

University of Washington, 1976. Quartermaster Harbor Marine Park Study. Volumes 1 and 2. Prepared for King County Division of Parks and Recreation. College of Forest Resources, University of Washington, Seattle, WA.

Appendix. Acronyms and Abbreviations

ADCP	Acoustic Doppler Current Profiler
CTD	Conductivity, Temperature, Depth (probe)
Ecology	Washington State Department of Ecology
EPA	U.S. Environmental Protection Agency
GEMSS	Generalized Environmental Modeling System for Surfacewaters (model)
KCDNR	King County Department of Natural Resources
LOTT	Lacey, Olympia, Tumwater, and Thurston County wastewater agency
NAVD88	North American Vertical Datum of 1988
NOAA	National Oceanic and Atmospheric Administration
PSTCM	Puget Sound Tide Channel Model
QA	Quality Assurance
RDI	(Teledyne) RD Instruments, Inc.
RMSE	Root mean square error
UW	University of Washington
UWT	University of Washington at Tacoma
VMI	Vashon-Maury Island
WASP	Water (Quality) Analysis Simulation Program (EPA)

Units of Measurement

deg C	degrees centigrade
cm/s	cubic meters per second, a unit of flow
g	gram, a unit of mass
km^2	kilometers squared, a unit of length equal to 1,000 square meters
m	meter
m^3/s	cubic meters per second
mg/L	milligrams per liter (parts per million)
mL	milliliters
psu	practical salinity units