Development and Calibration of a Model for Tracking Dispersion of Waters from Narragansett Bay Commission Facilities within the Providence River & Narragansett Bay

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1.0 Introduction

Episodic summer hypoxic events are of growing concern for the upper parts of Narragansett Bay, the Providence River and Greenwich Bay. In effort to better understand the processes surrounding these events, a series of buoys have been deployed throughout the bay equipped with sensors to measure important physical and chemical properties including, temperature, salinity, dissolved oxygen, pH and chlorophyll. Monthly surveys of temperature, salinity and oxygen in the Upper Bay have also been conducted during the summer months. In addition, the Narragansett Bay Commission funded an observational program (2001-2002) headed by Microinorganics to characterize spatial variability in circulation and chemical transport within the Providence and Seekonk Rivers during each seasonal period. The data set on currents collected by Kincaid's group with Narragansett Bay Commission funding provides the most detailed spatial images on circulation ever collected for Narragansett Bay.

One of the most striking features of the Narragansett Bay Commission ADCP data surveys is the identification of dominant outflow regions of the Providence River where flushing is expected to be very efficient. In addition, the surveys identified key stagnation regions, where waters are expected to remain unmixed over multiple tidal cycles thereby greatly increasing residence times. The vast majority of estimates for residence time in estuarine systems are based on the assumption of complete mixing. These data suggest the Providence River does not behave in this way, suggesting previous flushing estimates may be inaccurate. These diverse data sets provide clues as to the relative importance of different environmental factors, including tidal range, wind speed, direction and duration, and fresh water input, on the occurrence of hypoxia in Narragansett Bay. However, each data set does not provide both the spatial and temporal scales necessary to fully resolve the system.

The purpose of this study is to use a combination of numerical modeling and new observational data to better calibrate transport models and provide more accurate estimates on flushing rates for Narragansett Bay Commission releases entering the Providence River, either from Fields Point or the Seekonk River. We have conducted a detailed hydrographic survey within the Providence River, which included four months of bottom mounted Acoustic Doppler Current Profiler (ADCP) data from three locations and a 12 hour tidal survey of the currents along three transects of the Providence River (Figure 1). In addition, we have generated a high resolution grid of the Providence River, from the northern tip of Prudence Island to the mouth of the Seekonk River, for the Regional Ocean Modeling System (ROMS) to use to examine the influence of winds, tides and river flow on regional flushing rates.

2.0 Data Collection

RD Instruments Broadband Acoustic Doppler Current Profilers (ADCP) were used in this study to measure water column currents. The ADCP consists of an array of four transducers oriented such that sound beams are transmitted out 90° angles from each other and a known angle from the central axis of the instrument. Sound pulses emitted by the transducers are reflected by particles throughout the water column, such as biological and other particulate matter. The reflected sound pulses are Doppler shifted due to the movement of the particles in the moving water. The ADCP processes the Doppler shifted return echoes to obtain along-beam velocity components which are then combined for each transducer and converted into a three-dimensional (3-D) velocity pattern. Through a process called "range gating" the ADCP listens to the returning sound pulses over uniform time increments. Progressively later time increments correspond to energy returning from greater depths. In this way velocities are resolved into depth cells, or bins. For each energy pulse sent out, or set of energy pulses, which are subsequently averaged, the resulting velocity versus depth profile is called an "ensemble".

2.1 Bottom Mounted ADCPs

Three bottom mounted instruments were deployed in the Providence River from July through October 2005 (Figure 1, Table 1). A 1200 kHz ADCP was deployed on the western side of the Providence River in the small channel near the Edgewood Yacht Club (EYC) in approximately 3 m of water. A 600 kHz ADCP was deployed in the middle of the shipping channel in line with the Edgewood Yacht Club in approximately 11 m of water. A 300 kHz ADCP was deployed north of Conimicut Point in the middle of the shipping channel in approximately 13 m of water. Data were collect at 15 minute intervals with 200 pings per ensemble. The bottom mounts were deployed from the NBC boat, a 25' Parker. Pick-up lines of 1.5 times the water depths were dropped along a north-south line for retrieval by grappling and Notus pingers were attached to each mount.

The data were analyzed using the least-squares harmonic analysis toolbox- T_tide, modified described in Pawlowicz *et al.* (2002), to extract the tidal signal from the data. Data were decomposed into flow into and out of the channel and data gaps were filled using a linear regression. Residual velocity components were calculated by running a 5^{th} order low pass Butterworth filter to remove frequencies higher than 24 hours.

Values for wind speed and direction were obtained from the National Climate Data Center (NCDC) for the T.F. Green station in Warwick, RI. Daily mean values of freshwater discharge in cubic feet per second were obtained for the Blackstone River from the United States Geological Survey stream gauge in Massachusetts.

2.2 Boat Mounted ADCPs

For the boat mounted work, a 1200 kHz broadband ADCP instrument was mounted to the side of the NBC 25' Parker. Data were collected by driving along lines, called "transects" (Figure 1). Energy pulses are sent out on average every 5 seconds. Given an average boat speed of 1 m/s, a velocity ensemble is collected roughly every 5 meters. Therefore, over a complete transect information is obtained on 3-D velocity as a function of both depth and horizontal position. Plots can be made showing velocity contours through a vertical slice of the river oriented along the transect line.

A goal of the hydrographic surveys was to characterize flow patterns within the Providence River during the spring tide. A series of three transect lines (Figure 1) where defined for mapping flow structure in the vicinity of the Fields Point discharge site.   The numbering of the lines is based on the 2000-2001 survey. Line 3 modified was positioned at Sabin Point. Line 2.5 extended between Edgewood Yacht Club to the west and Pomham Rocks to the east. The line ended at the East Providence sewage outfall pipe. Line 2 was positioned near Fields Point and the Save the Bay facility. Each line was surveyed once per circuit, where a circuit is defined as a complete set of transect lines. The ADCP data was collected using standard water mode of 4, with depth bins of 25 cm. A SeaBird SB19 CTD was dragged behind the boat at roughly 1 meter depth for all transects.

Sampling began on July 21, 2005 at 6:30 pm EST, on the southernmost line (3 modified) and progressed northward to lines 2.5 and 2. The first and second circuits coincided roughly with late flood and slack conditions. Circuits 3 through 5 covered roughly early through late ebb conditions. Circuits 6 and 7 covered slack and early flood conditions. Circuits 8 and 9 covered early and late flood conditions. A detailed summary of data collection locations and times is given in table 1.

2.3 Numerical model

The numerical model ROMS (Regional Ocean Modeling System) (Shchepetkin and McWilliams, 1998; 2003; 2005) has been applied to the Providence River with horizontal grid resolution of less than 150 meters (Figure 1). The bathymetry is from the National Geophysical Data Center 3-arc-second Coastal Relief Model smoothed with a single pass of a Shapiro filter. The open southern boundary is located just north of Prudence Island. Sea-level height and velocity were defined at the southern open boundary based on seven harmonics (M_2, N_2, S_2, K_2, O_1, M_4, M_6) determined from an ADCIRC simulation of the western Atlantic (Luettich et al., 1992). Multiple inputs for point sources are incorporated to represent the Blackstone/Seekonk, Pawtuxet, Woonasquatucket, and Moshassuck rivers, as well as the Fields Point WWTF discharges. ROMS incorporates the air-sea flux parameterizations (momentum, sensible heat, and latent heat) which allows simulation of surface heating/cooling (thermal stratification) in the Providence River. This model has been successfully run for 30 days under idealized conditions with a single freshwater source at the head of the Providence River (Figure 2b).

3.0 Results

3.1 Bottom Mounted ADCPs

Tidal analysis of the Providence River bottom mounted ADCP data shows that the most energetic flow at each is in response to tidal forcing, which is in turn dominated by the M2 frequency (Table 3). Tidal amplitudes (M2) are higher in the deep channels near the EYC and Conimicut Point than in the shallows near the EYC. Tidal velocities in both the shallows and deep channel near the EYC were predominantly north-south. Surface and bottom velocities in the shallows varied between +/-200 mm/s (Figure 2). Velocities in the EYC deep channel ranged between +/-350 mm/s (Figure 3). Tidal velocities at the Conimicut Point site flowed northwest to southeast, which follows the orientation of the channel. Peak instantaneous flows vary between +/-400 mm/s to +/-150 mm/s during spring and neap tides (Figure 4).

The influence of winds and river flow on the residual flow in the Providence River was observed in the four months of bottom mounted ADCP data. Surface flows at the EYC shallows site appear to be strongly influence by the North-South components of the winds (Figure 2). In the deep channel near EYC, two layered flow is observed, surface flow out and the bottom flow in (Figure 3). However, strong northward wind events can alter this flow, reducing the outward surface flow and halting the deep in flow, as seen on 8/26 to 8/31, 9/26 and 9/29 (Figure 3). At the Conimicut Point site surface flow is generally out and bottom flow in (Figure 4).

One interesting feature in the data set is the large wind and rain/runoff event that began on October 8. For most of the sampling period, river flows were low (Blackstone River flow was less than 15 $m^3 s^{-1}$), however, flows peaked to 382 $m^3 s^{-1}$ on October 16. This large runoff event is clearly seen in all three data sets. At the EYC shallow site there is a strong, broad surface outflow observed from October 9-16 (Figure 2). At the

EYC deep channel site the surface outflow peaks within 1 day after peak flows were recorded at the Blackstone River gauge and rapidly tapers off (Figure 3). At the Conimicut site, pulses of strong two layered flow, surface outflow and bottom inflow, are observed on 10/10, 10/12 and 10/17 (Figure 4).

3.2 Boat Mounted ADCPs

The boat mounted ADCP survey from July 21, 2005 shows the complex vertical and lateral structure in the Providence River (Figures 5-8). The twelve hour survey captured all stages of the tide at the three transect lines (Figure 5).

At the Sabin Point line (line 3 modified) the tide begins to ebb along the eastern edge of the channel (Figure 6). During the peak ebb, the strongest currents are observed in the deep channel. As the tide shifts, the flow reverses first in the deep channel. During the peak flood, the weakest inflow is observed along the eastern and western sides of the channel.

At the EYC line (line 2.5) differences in flow between the deep channel and shallows was observed (Figure 7). During the late flood survey, currents are still observed flowing inward in the deep. As the tide shifts, three layers of flow are observed in the deep channel: out flow in the bottom waters and surface water and a plug of mid-depth flowing inward. During the early ebb, stronger outflows are observed in the surface and bottom water of the channel, while weaker outflows are observed in the mid-depth of the channel and along the shallows. The currents begin to flood first in the bottom of the deep channel. Throughout the flood tide, the strongest inflows are observed in the deep channel. Profiles obtained by the Narragansett Bay Commission during the day on July 21, show a stratified water column, in terms of both temperature and salinity, along the EYC line, which supports the observed two layer flow (Figure 9).

Complex flow patterns are also observed at the Fields point line (line 2) (Figure 8). Out flowing currents begin first in the deep channel and surface at the Fields Point transect. The strongest out flows are observed in the surface waters. As the tide shifts, the bottom water begins to flood first. Two layer flow is clearly observed in the early stage of the flood tide- out at the surface and in at the bottom. The strongest in flow is observed at mid-depth of the channel.

3.3 Numerical model

The new Providence River grid has been check for stability and conservation of salt. Analysis of the grid show that the topography of the Providence River after smoothing with a two point Shapiro filter is below the ROMS criteria for steepness. The ROMS Providence River grid was checked for conservation of salt by running the model as a closed system, with no tides and an initial salinity gradient of 0 to 30 from north to south. Figure 10 shows the concentration of salt at various points throughout the Providence River grid over a 110 day model run. The concentration of salt changes rapidly in the first 30 days of model simulation, however, once the model reaches equilibrium the concentration of salt remains constant. Figure 11 shows the time rate of change of salt at a vertical profile at a single point in the Providence River and at the surface along a cross section of the River is zero after the first 30 days of model simulation. This indicates that the salt is conserved by the model.

Data sets collected by MicroInorganics during the Narragansett Bay Commission funded an observational program (2001-2002) have been used for comparison with the model runs. Figure 12 shows the horizontal and vertical distribution of salt for the Providence River model after 30 days under idealized conditions with freshwater sources from the Seekonk River, Pawtuxet River and Fields Point. The results are similar to the salinity distribution observed in the July MicroInorganics surveys.

Numerical simulations have been conducted to determine the strength of the deep return flow towards the head of the estuary given changes in environmental forcing conditions. A cross-section of tidally averaged flow through the Providence River has been examined to determine the changes in the patterns of deep return flow under various environmental conditions (Figure 13). The patterns in the cross-sectional velocities compare well with data collected in the Providence River. These results have set the stage for looking at how flushing and deep return flow (both crucial in the oxygen balance of the Bay) change with expected future changes brought about by climate changes.

The surface velocities from the numerical modeled have been examined to determine circulation patterns in the Providence River. Velocity vectors (shown as arrows in the direction of the flow) are provided for the ebb tide. These results show that higher velocities, indicated by longer arrows, are present in the channel of the Providence River, while very low velocities are observed in the shallow region south of Fields Point (Figure 14). These model results are consistent with the data collected during both the 2001-2002 and 2005 field surveys.

Preliminary analysis of the biological component of ROMS which includes nutrients, phytoplankton, zooplankton, carbon and oxygen has been conducted. The biological model was run in one dimension (vertically) to see how the biology responds to variations in stratification, sunlight and nutrients. A series of model runs were conducted to examine the sensitivity of the model result to changes in parameterization of the biological equations. The results of the model were compared to MERL nutrient loading experiments for the highest nutrient levels (Oviatt, et. al, 1986). A comparison of two model runs (default parameters and mixed parameters based on results of the sensitivity analysis) are shown in Figure 15 with the experimental results. The model results are consistent with the experimental results for the phytoplankton and zooplankton, however, the model did not capture the observed variability in oxygen. More information on the sensitivity analysis can be found in the Summer Undergraduate Research Fellowship Program in Oceanography (SURFO) 2005 Technical Report (http://espo.gso.uri.edu/~surfo/publications.html#c).

4.0 Future Work

We will further analyze the bottom and boat mounted ADCP data. The ROMS model will be run under the summer 2005 conditions and compared to the ADCP and CTD data. The model will be run under variable wind and river flow conditions to determine residence times in various regions of the Providence River. We will work with Jim Kremer, Scott Nixon and Mark Brush on continue to improving the results of the 1-D biological model.

5.0 References

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Table 1. Location of bottom mounted ADCPs.

Station	Location	Inst. Frequency (kHz)	Depth (m)	Size of Bins (m)	Dates of Deployment
Edgewood Shallow	41°46.594'N 71°23.022'W	1200	3	0.25	7/7-10/24/2005
Edgewood Deep Channel	41°46.497'N 71°22.352'W	600	11	0.50	7/12-10/24/2005
Conimicut Point Channel	41°43.426'N 71°21.226'W	300	13	1.00	7/7-10/31/2005

Table 2.

Line #	File #	Transect Name	Start Time (UTC)	Latitude	Longitude	End Time (UTC)	Latitude	Longitude	Tide
3 mod	0	Sabin Point	23:49:00	41 46.013	71 23.081	0:01:20	41 46.008	71 22.193	Late
2.5	1	Edgewood Yacht Club	0:06:33	41 46.557	71 23.231	0:34:10	41 46.463	71 22.098	Flood
2	3	Fields Point	0:50:48	41 47.039	71 22.977	0:57:33	41 46.941	71 22.305	
3 mod	4	Sabin Point	1:11:01	41 46.000	71 23.063	1:22:02	41 45.960	71 22.259	Slack
2.5	5	Edgewood Yacht Club	1:35:53	41 46.520	71 23.246	1:50:41	41 46.499	71 22.324	
2	6	Fields Point	2:03:45	41 47.065	71 22.709	2:09:34	41 46.958	71 22.331	
3 mod	7	Sabin Point	2:24:09	41 46.316	71 23.042	2:34:27	41 45.981	71 22.239	Ebb
2.5	8	Edgewood Yacht Club	2:50:03	41 46.545	71 23.254	3:05:00	41 46.449	71 22.124	
2	11	Fields Point	3:23:34	41 47.048	71 22.730	3:29:41			
3 mod	12	Sabin Point	3:42:59	41 46.250	71 22.839	3:56:40	41 45.990	71 22.290	
2.5	13	Edgewood Yacht Club	4:11:40	41 46.535	71 23.241	4:26:49	41 46.554	71 22.600	Ebb
2	14	Fields Point	4:40:46	41 47.079	71 22.756	4:47:43	41 46.905	71 22.329	
3 mod	15	Sabin Point	5:00:05	41 46.002	71 23.070	5:11:16	41 45.986	71 22.479	
2.5	16	Edgewood Yacht Club	5:24:34	41 46.563	71 23.225	5:40:28	41 46.534	71 22.542	Ebb
2	19	Fields Point	6:10:20	41 47.079	71 22.740	6:16:52	41 46.947	71 22.304	
3 mod	20	Sabin Point	6:56:52	41 46.012	71 23.070	7:07:14	41 45.978	71 22.307	Slack
2.5	21	Edgewood Yacht Club	7:34:19	41 46.557	71 23.227	7:48:16	41 46.459	71 22.143	
2	22	Fields Point	8:07:07	41 47.056	71 22.760	8:13:01	41 46.950	71 22.315	
3 mod	23	Sabin Point	8:27:56			8:37:17	41 45.984	71 22.279	Early
2	24	Fields Point	8:55:36	41 47.094	71 22.751	9:01:22	41 46.918	71 22.407	Flood
2.5	26	Edgewood Yacht Club	9:17:17	41 46.552	71 23.253	9:32:26	41 46.446	71 22.134	
3 mod	27	Sabin Point	9:56:43	41 46.011	71 23.091	10:06:11	41 45.993	71 22.272	Flood
2.5	28	Edgewood Yacht Club	10:26:44	41 46.542	71 22.396	10:41:19	41 46.554	71 22.261	
2	29	Fields Point	10:57:54	41 47.081	71 22.744	11:02:46	41 46.946	71 22.302	
3 mod	30	Sabin Point	11:18:47	41 45.994	71 23.076	11:27:34	41 45.994	71 22.281	Flood
2.5	31	Edgewood Yacht Club	11:45:43	41 46.552	71 23.256	12:00:09	41 46.459	71 22.111	
2	32	Fields Point	12:14:10	41 47.052	71 22.758	12:21:15	41 46.954	71 22.312	

Table 3. Tidal components for the bottom mounted ADCPs.

Component	**Frequency (cph)**	**Edgewood Shallows**	**Edgewood Channel**	**Conimicut Point**
K1	0.0418	8.30	20.97	6.62
N2	0.0790	10.29	31.35	22.83
M2	0.0805	61.90	138.29	90.97
S2	0.0833	17.25	27.63	21.88
K2	0.0836	4.69	7.52	5.95
M4	0.1610	32.49	38.73	23.93

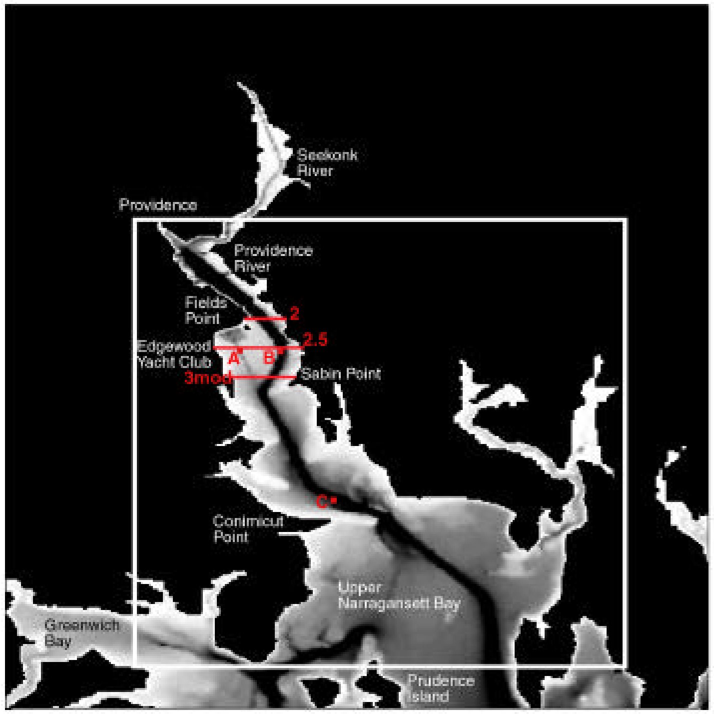


Figure 1. Map showing the study area of Providence River, RI. Locations of three bottom mounted ADCPs used in this study are shown (red dots): A- Edgewood Yacht Club Shallows, B- Edgewood Yacht Club Deep Channel, and C- Conimicut Point Deep Channel. The underway survey lines are also shown (red line). Bathymetry is represented in grey scale (darker grey=deeper water). The white box represents the ROMS model domain.

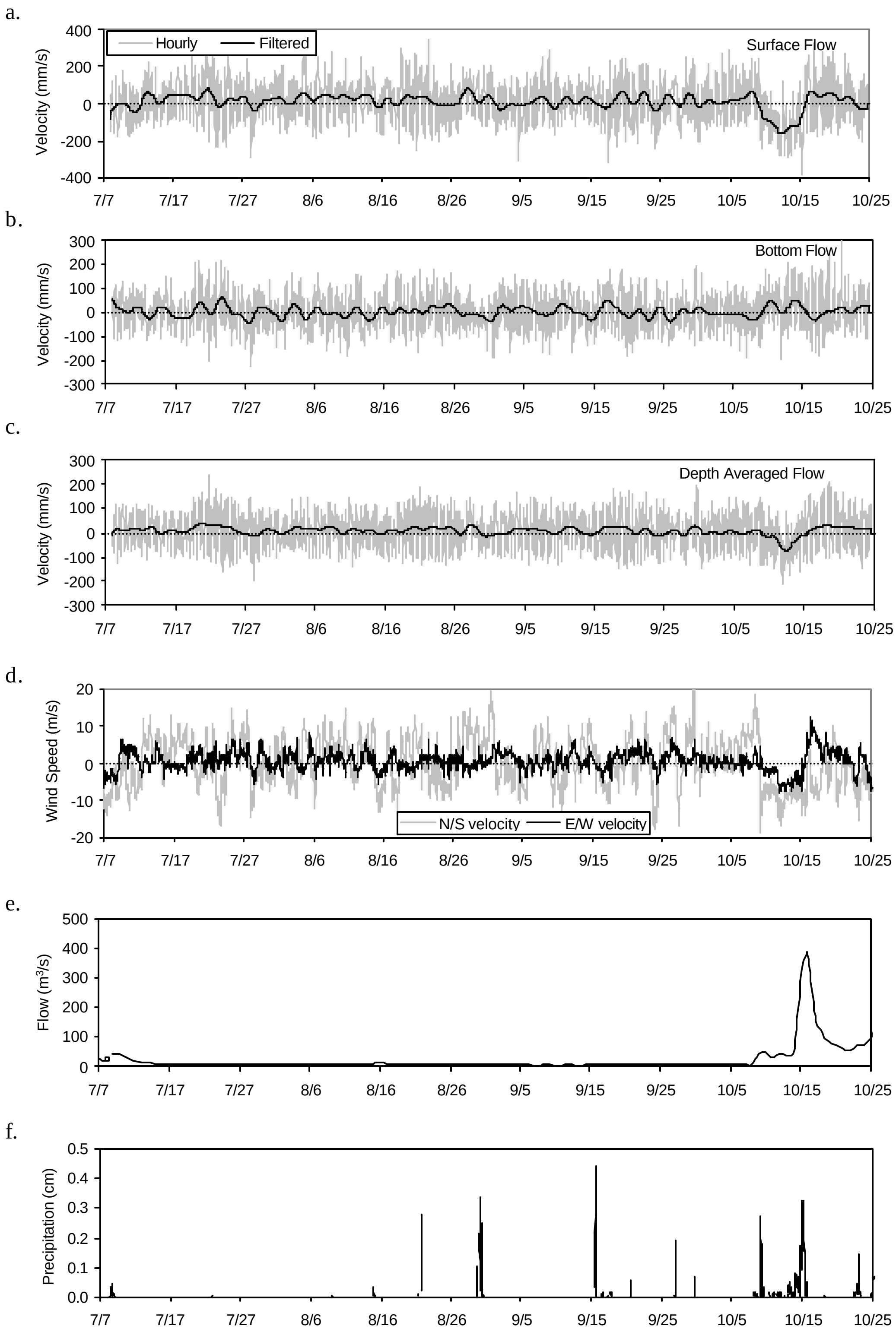


Figure 2. Bottom mounted data from Edgewood Yacht Club Shallows (1200kHz ADCP), (a) near-surface inflow (+) and outflow (-), (b) near-bottom inflow and outflow, (c) depth averaged inflow and outflow, (d) T.F. Green wind velocity (northward and eastward are positive), (e) Blackstone River flow and (f) T.F. Green precipitation.

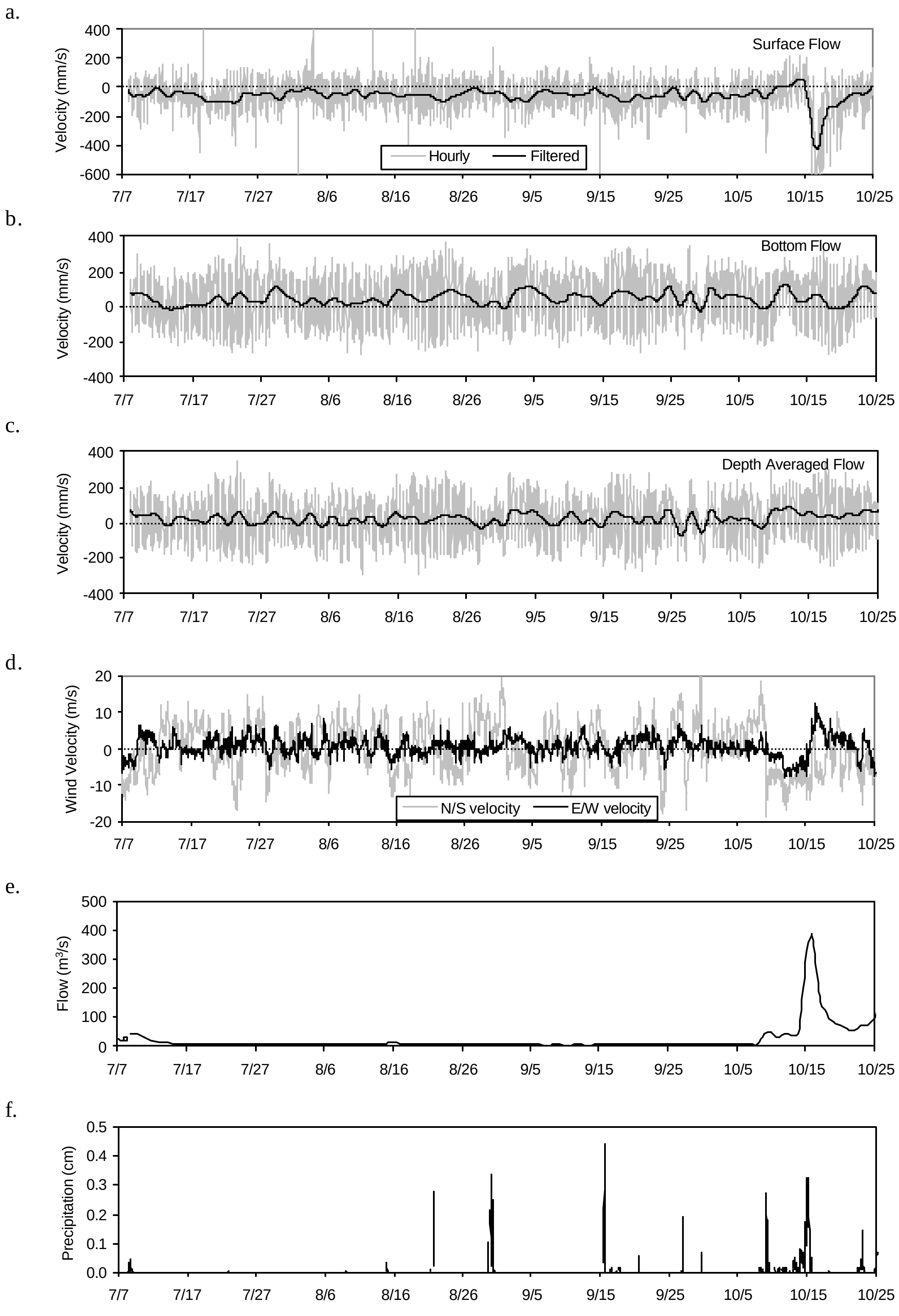


Figure 3. Bottom mounted data from Edgewood Yacht Club Deep Channel (600kHz ADCP), (a) near-surface inflow (+) and outflow (-), (b) near-bottom inflow and outflow, (c) depth averaged inflow and outflow, (d) T.F. Green wind velocity (northward and eastward are positive), (e) Blackstone River flow and (f) T.F. Green precipitation.

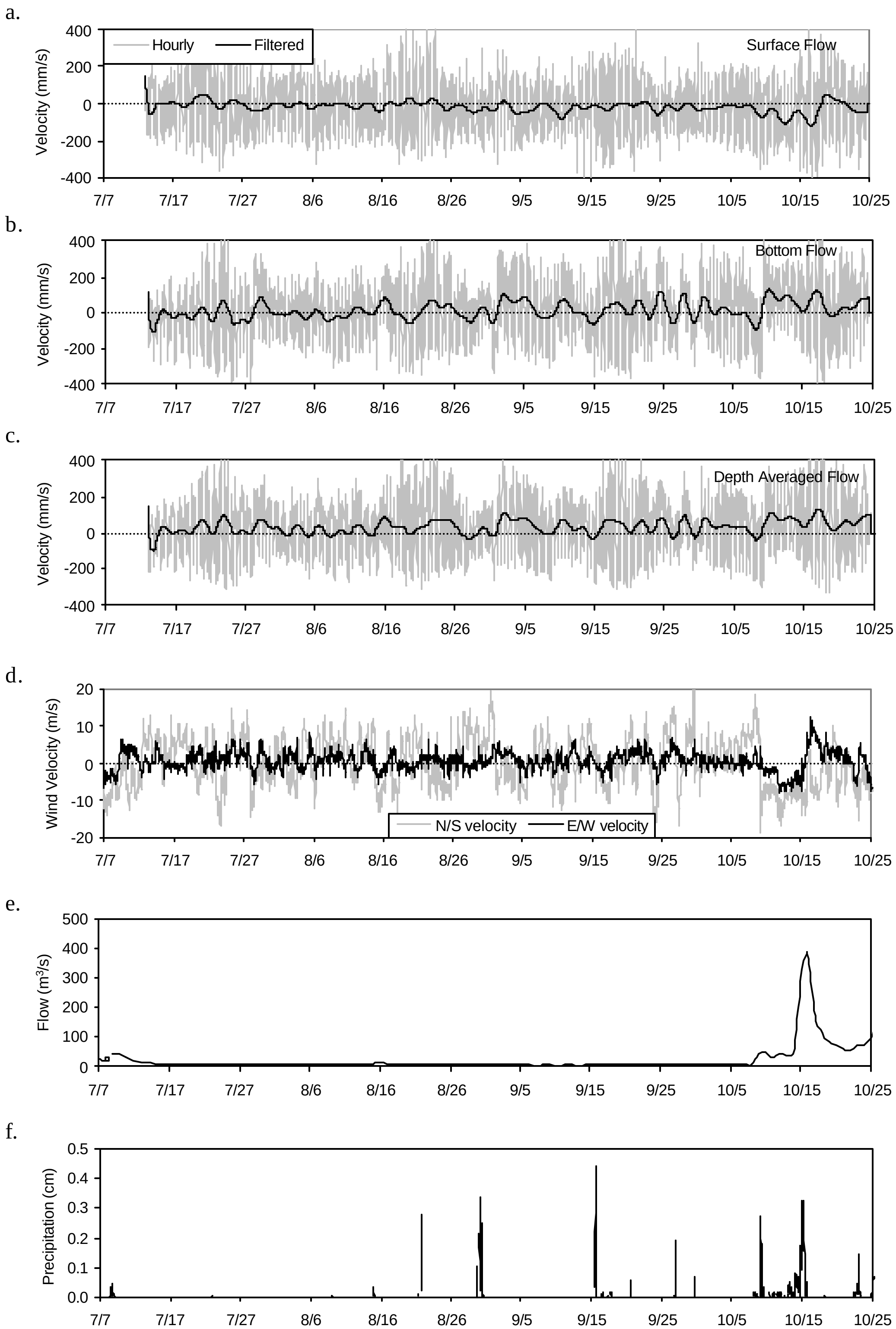


Figure 4. Bottom mounted data from Conimicut Point Channel (300kHz ADCP), (a) near-surface inflow (+) and outflow (-), (b) near-bottom inflow and outflow, (c) depth averaged inflow and outflow, (d) T.F. Green wind velocity (northward and eastward are positive), (e) Blackstone River flow and (f) T.F. Green precipitation.

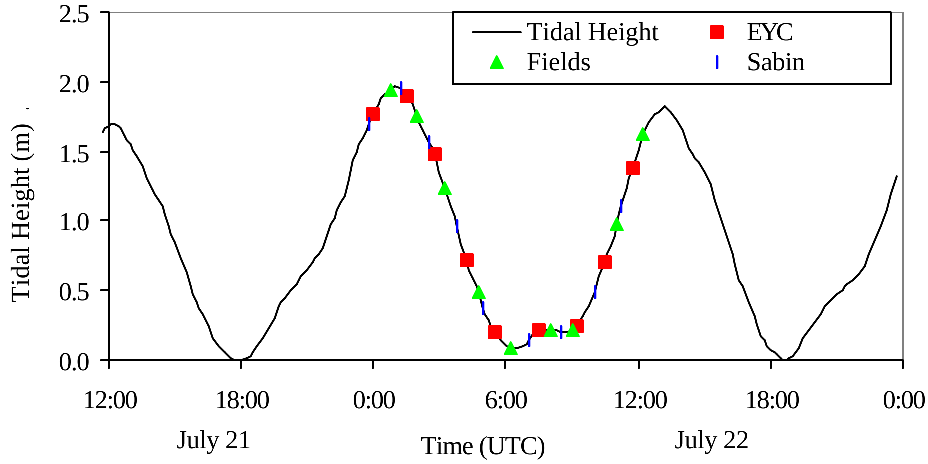


Figure 5. Predicted tidal heights in the Providence River during the tidal survey, points represent when each line was surveyed with respect to the tide: - Blue diamonds - Sabin Point (line 3modified), Red squares – Edgewood Yacht Club (line 2.5) and Green triangles – Fields Point (line 2).

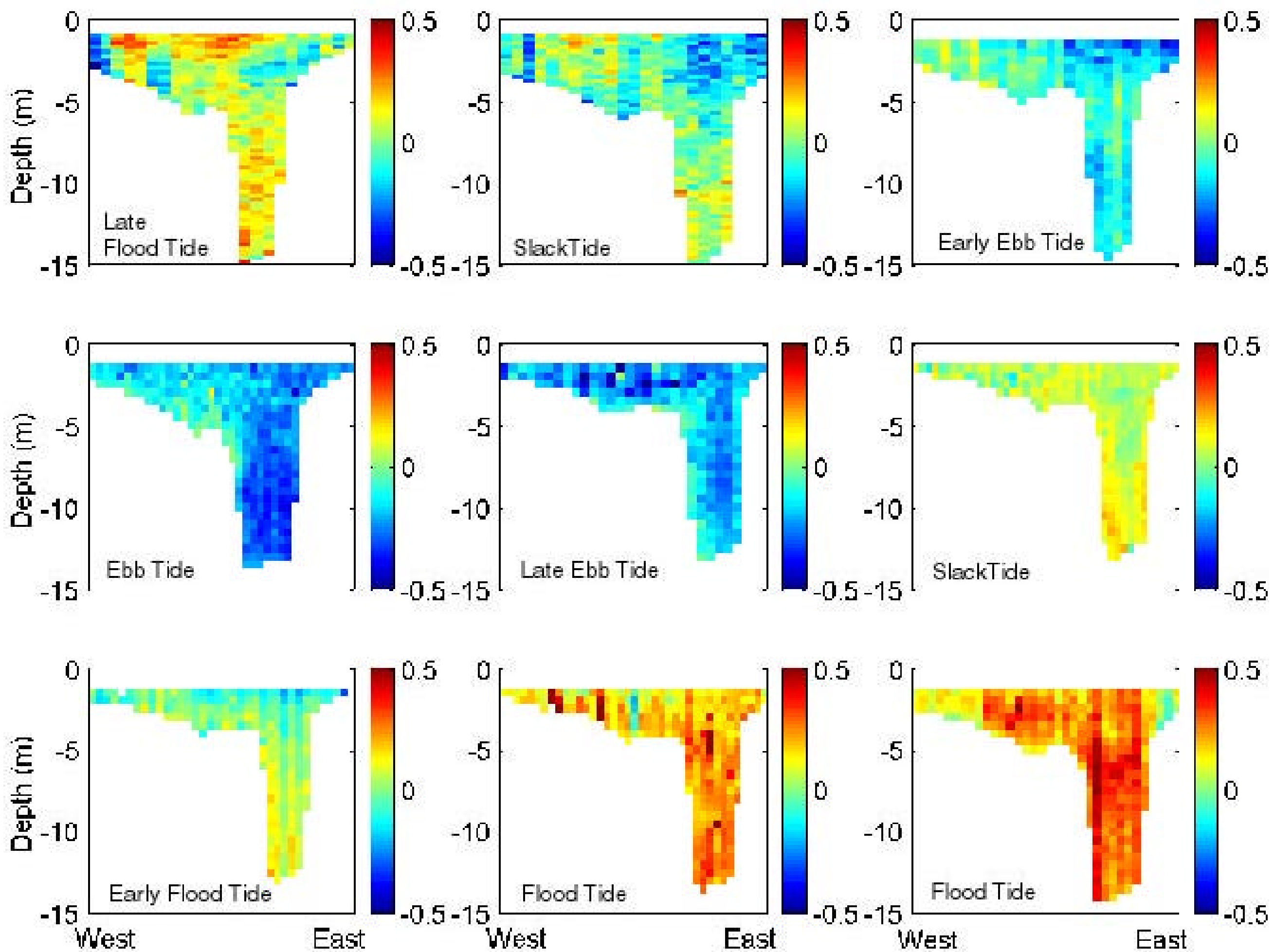


Figure 6. North velocities (m/s) along line 3 modified – Sabin Point during July 21, 2005 the tidal survey. Northward flows are positive (red) and southward flows are negative (blue).

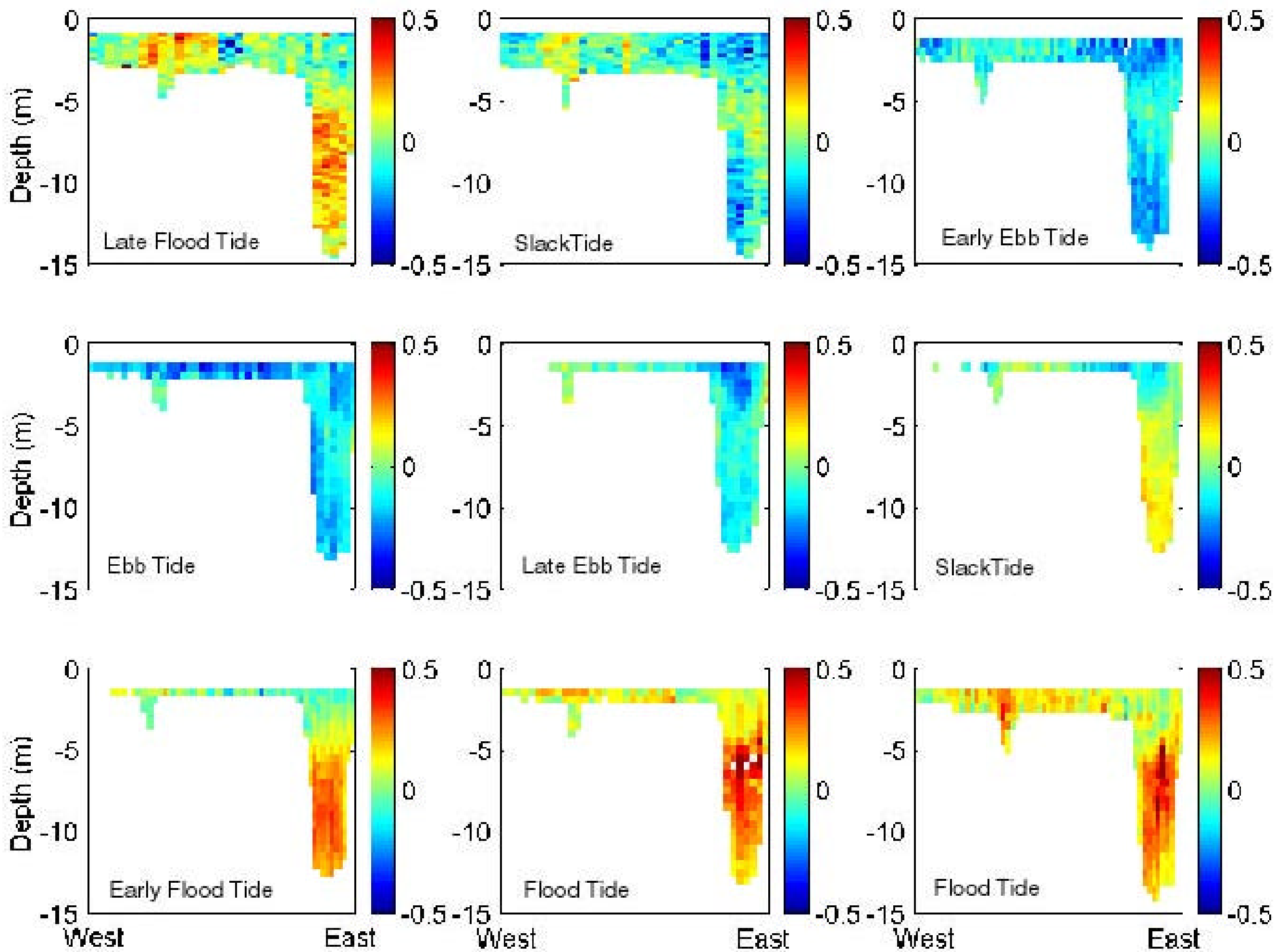


Figure 7. North velocities (m/s) along line 2.5 - Edgewood Yacht Club during July 21, 2005 the tidal survey. Northward flows are positive (red) and southward flows are negative (blue).

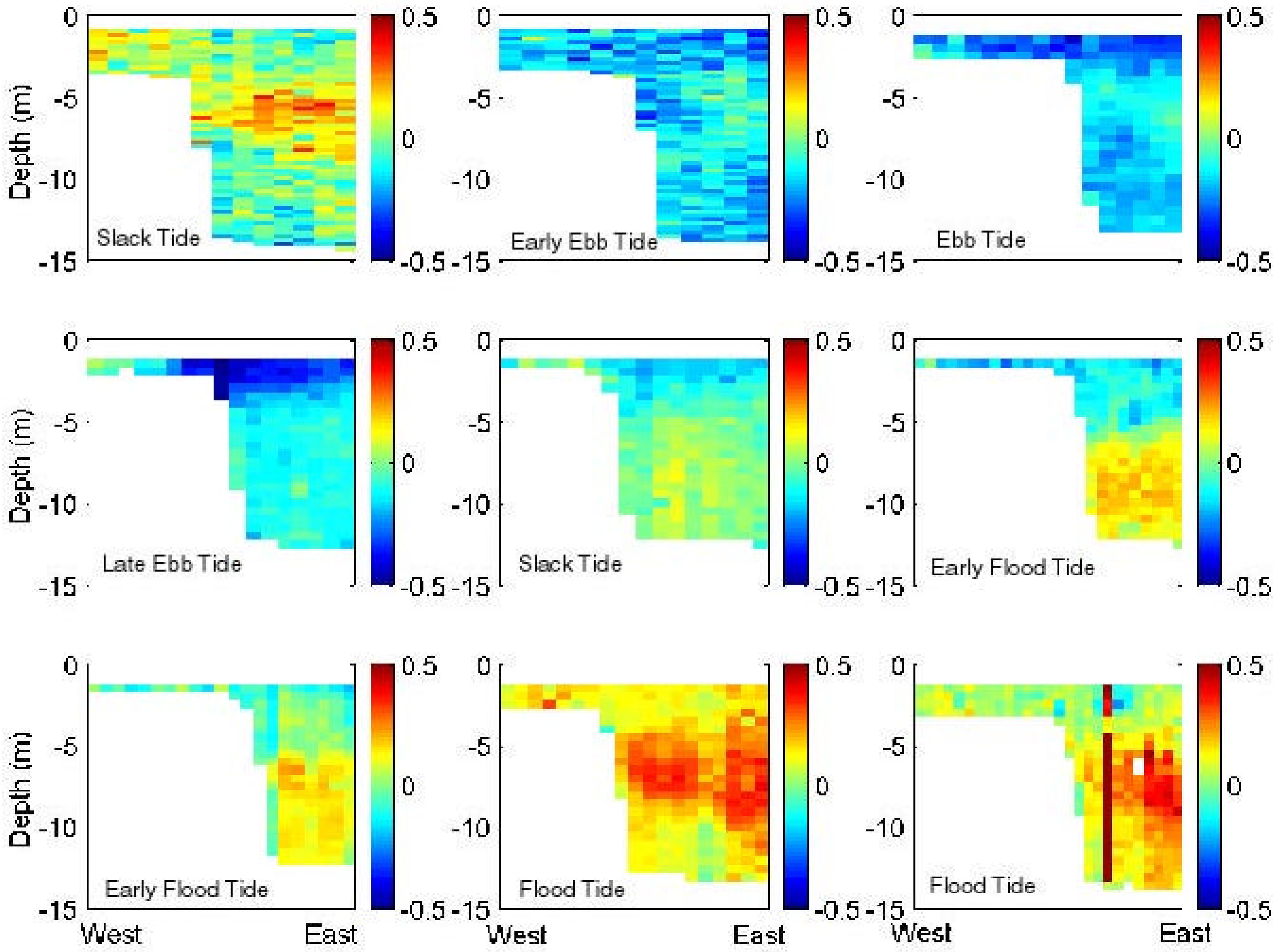
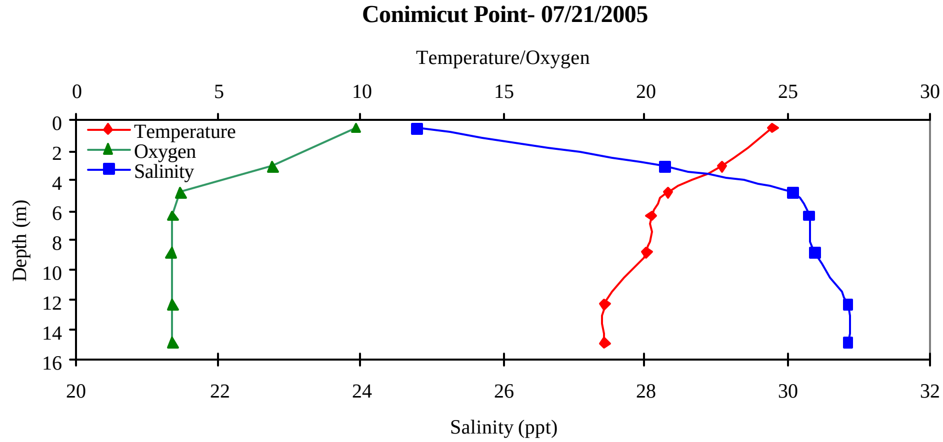
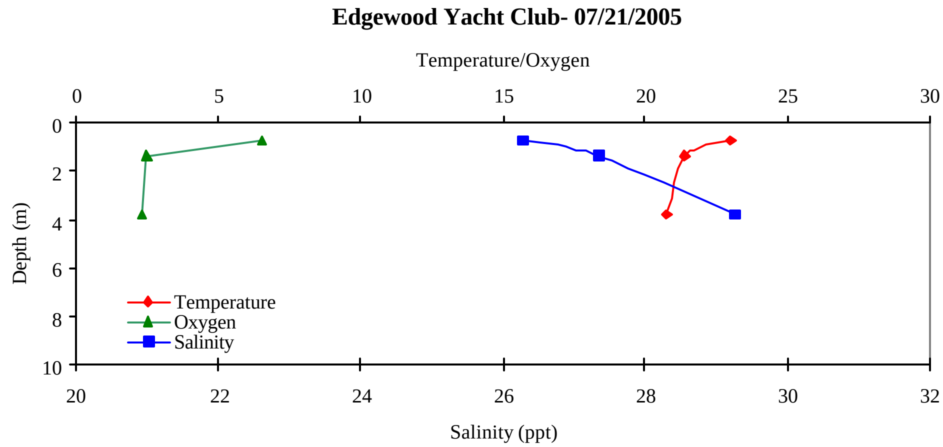


Figure 8. North velocities (m/s) along line 2- Fields Point during July 21, 2005 the tidal survey. Northward flows are positive (red) and southward flows are negative (blue).





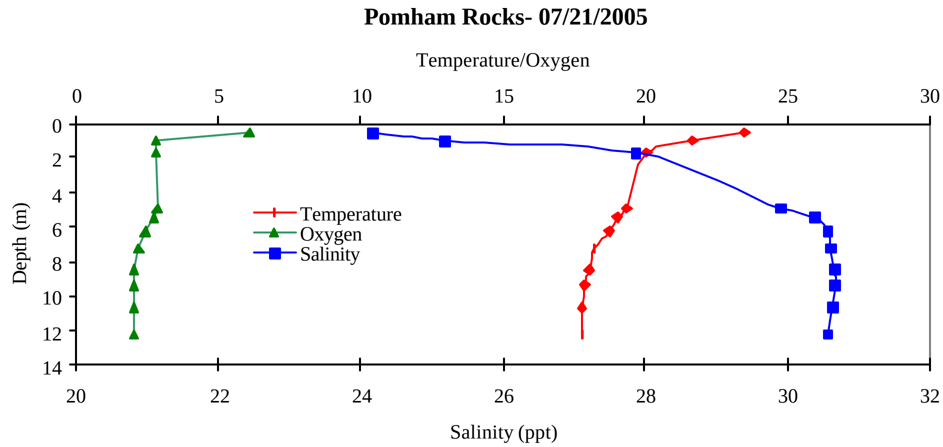


Figure 9. YSI data obtained at the three bottom mounted ADCP locations the day of the tidal survey (a) Conimicut Point, (b) Edgewood Yacht Club Shallows and (c) Edgewood Yacht Club Deep Channel. Red diamonds – temperature, blue squares – salinity and green diamonds – oxygen.

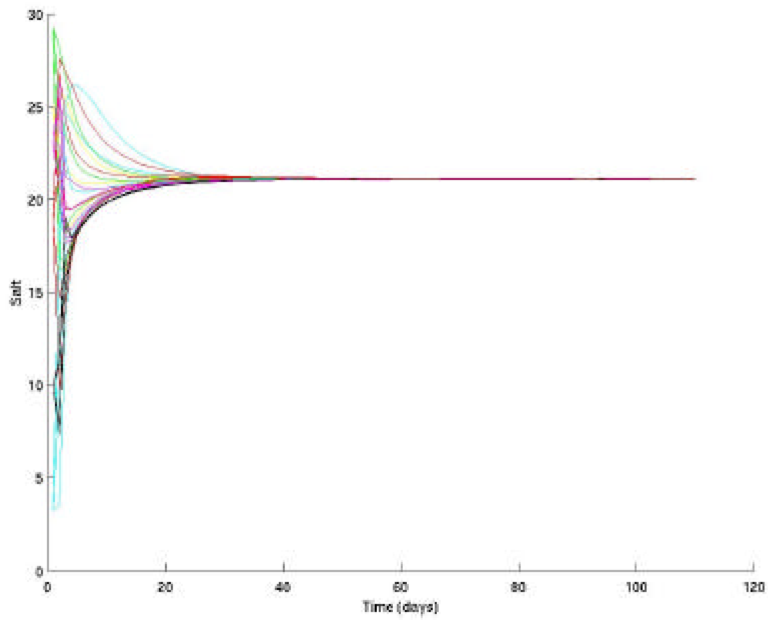


Figure 10. Concentration of salt over time at various grid points throughout the Providence River grid.

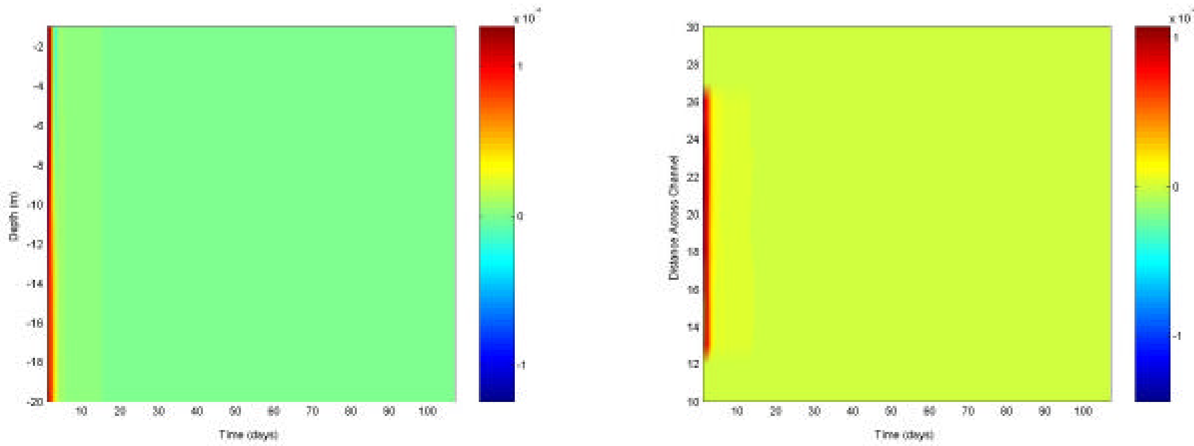


Figure 11. Time rate of change of salt for ROMS Providence River grid salt (a) single point in the Providence River over time at all depth levels (b) east-west cross-section across the Providence River over time.

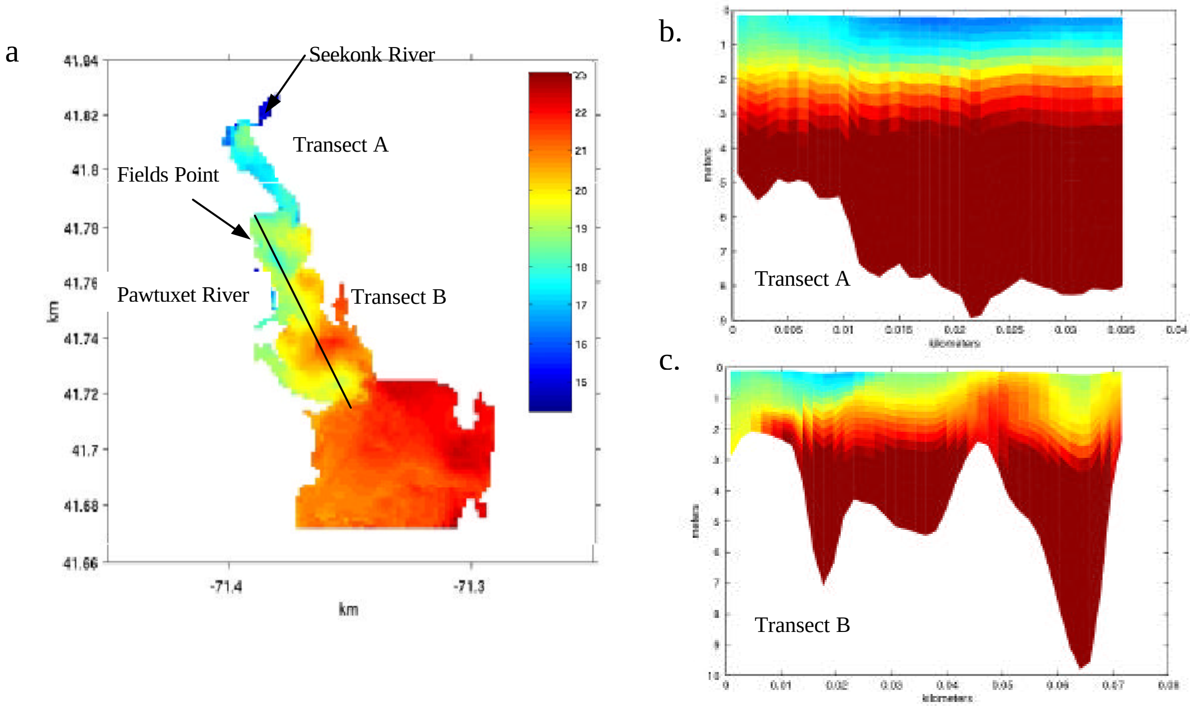


Figure 12. (a) Horizontal distribution of model output for salt after 30 days with three freshwater sources. (b) Vertical distribution of model output for salt along transect A after 30 days with three freshwater sources (c) Vertical distribution of model output for salt along transect B after 30 days with three freshwater sources.

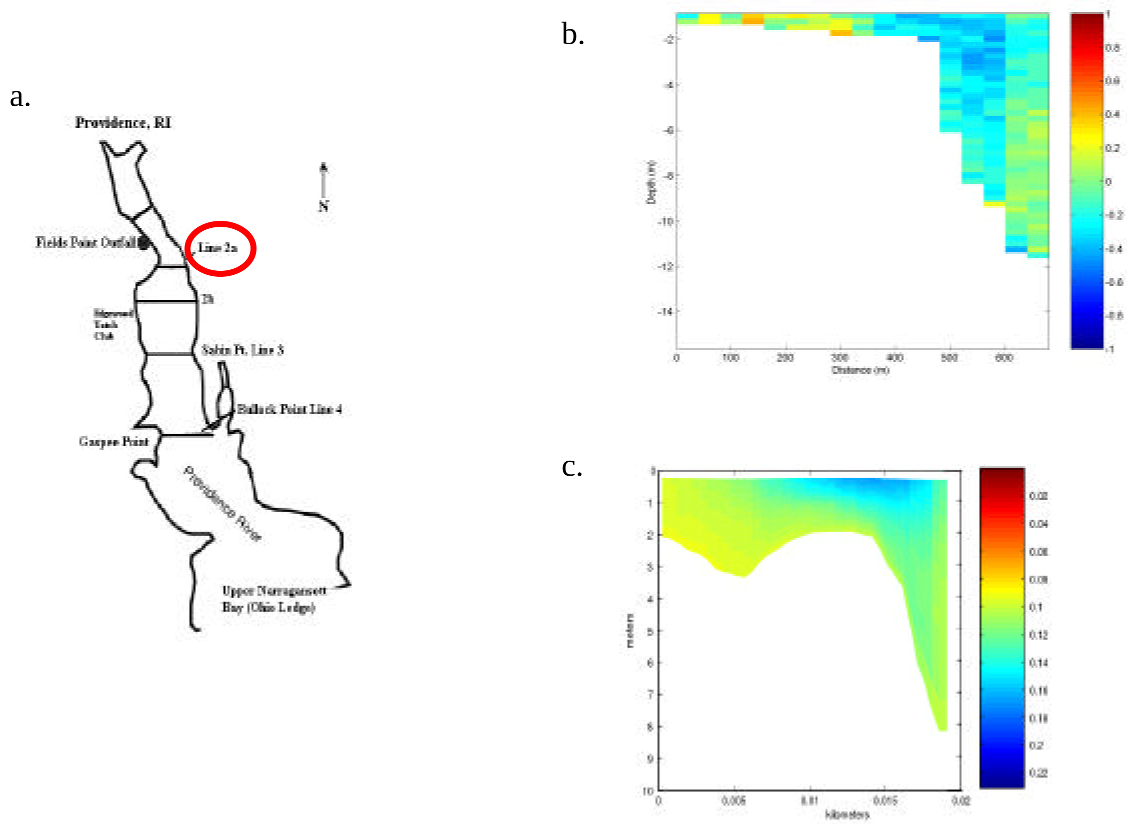


Figure 13. (a) Map of Providence River ADCP survey conducted in July 2001. (b) ADCP north-south velocity across transect line 2a near the Fields Point outfall under late ebb conditions. (c) ROMS model north-south velocity across a transect near the Fields Point outfall under ebb conditions. Velocities are shown in m/s- blue is flow towards the north and red towards the south.

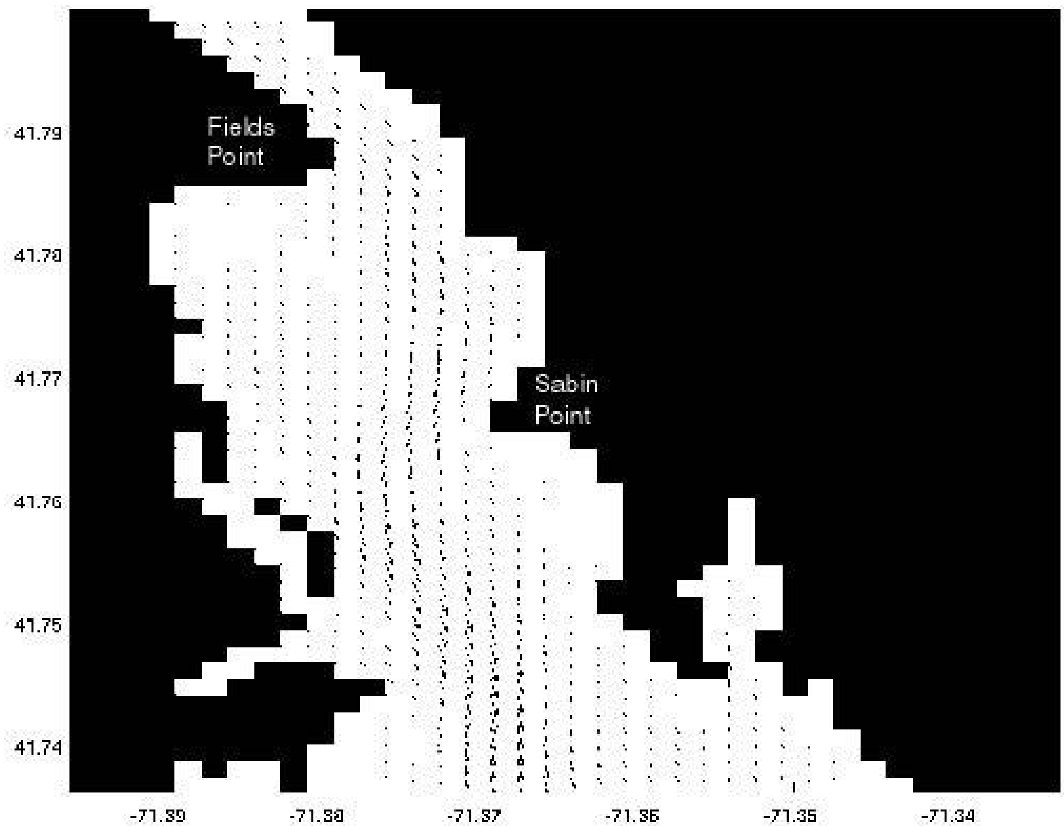


Figure 14. Modeled surface velocity during the ebb tide in the region between Fields Point and Sabin Point.

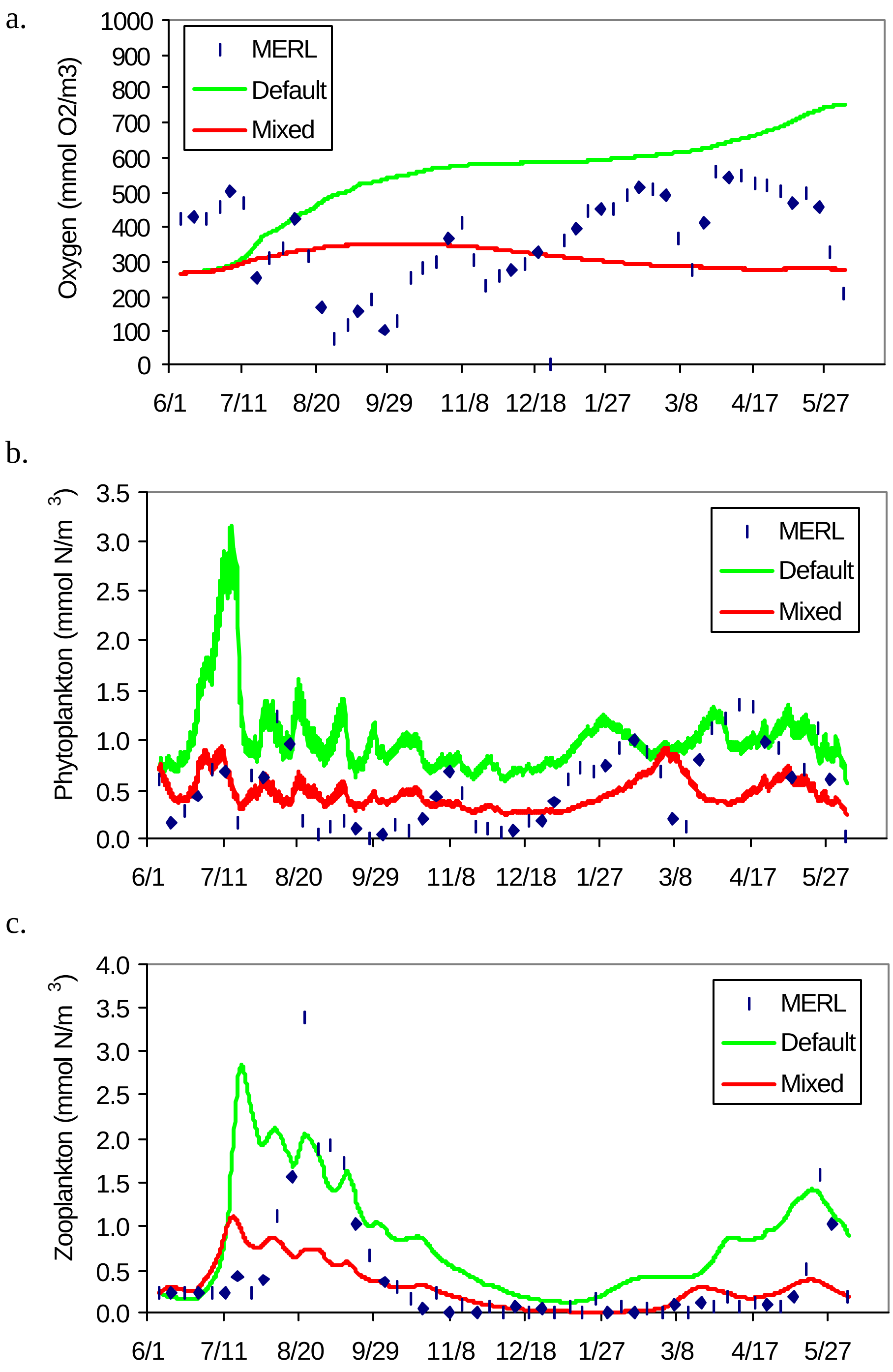


Figure 15. Comparison of a mixed parameter model run (red line), the default model run (green line), and MERL data (diamonds) for (a.) oxygen, (b.) phytoplankton, and (c.) zooplankton.