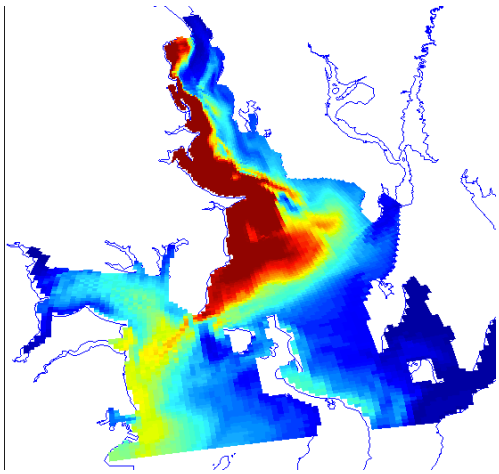
The Development and Application of the Full Bay ROMS Hydrodynamic Model for Simulations of Chemical Transport with Multiple Freshwater Sources



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1.0 Introduction

The Narragansett Bay ecosystem represents an essential resource for the State of Rhode Island that is increasingly subject to anthropogenic and natural impacts. The two most impacted areas of the estuary for hypoxic water conditions are the Providence River and Greenwich Bay (Brush, 2002; Deacutis et al., 2006; Saarman et al, 2008; Deacutis 2008). Chronic areas of low oxygen within the upper bay reflect poor water quality conditions and periodic environmental crises such as the August 2003 fish kill in Greenwich Bay (RI), which killed over a million marine organisms, underscore the need for updated coastal planning and regulation. However, successful and cost effective management of the Narragansett Bay ecosystem requires a deeper understanding of how the system functions, particularly given the looming influences of regional climate change. Policy decisions therefore must be based upon a coupled systems approach that itself is anchored in detailed scientific data sets and with state of the art modeling tools.

In response to the 2003 fish kill a total maximum daily load (TMDL) report for Greenwich Bay speculated that a combination of nutrient loading from point and non-point sources and a range of physical factors (e.g., temperature, circulation and stratification) contributed to the severity of quality problems within Greenwich Bay (Greenwich Bay Special Area Management Plan, 2005). For details and related information see (http://seagrant.gso.uri.edu/G_Bay/Management/). The primary management action was to lower the nutrient release levels in WWTFs. The goal of this project is to scientifically explore both sides of the TMDL equation; nutrient level improvements from WWTF reduction strategies and the role of circulation in water quality issues. This work also aims to improve our base level understanding for Bay-wide circulation processes and the transport/mixing of chemical fields (e.g., nutrients) within the water column introduced from point (WWTFs) and non-point sources (levels in rivers from distributed runoff/groundwater discharge). A combination of targeted, spatially-temporally detailed hydrodynamic data and improved modeling tools are employed, where data-model calibration steps lead to more effective management tools for Narragansett Bay.

Here we report the results of hydrodynamic model simulations for the Providence River and upper Narragansett Bay carried out under the auspices of the Narragansett Bay Commission that build from observational efforts reported elsewhere. The computational simulations utilize the public domain Regional Ocean Modeling System (ROMS) three-dimensional hydrodynamic –transport model for coastal systems. Our work builds from prior efforts to develop a first generation ROMS model of uppermost Narragansett Bay and the physical data sets needed to both understand circulation patterns and provide a quantitative calibration resource for the ROMS models. This recent work includes building a high grid resolution version of ROMS for the upper Bay (Figure 1) and incorporating distinct chemical dyes into the model to represent , and tag, all major rivers and waste water treatment facilities discharging water into the estuary (Figure 2). In this report we summarize the results of a series of numerical model runs which are used to gauge the transport, dispersion and retention characteristics of the different fresh water sources to the estuary.

Two distinct types of model simulations have been developed and completed for this report. One set of model runs defines chemical transport patterns for idealized environmental forcing conditions. These allow for developing general relationships between flushing/retention patterns and various modes of both imposed wind and runoff. A second set of model runs characterizes transport pathways for distinct dye sources as they move and mix through all regions of the Bay given actual 2010 environmental forcing conditions. The 2010 time period incorporates both the Edgewood Shoals TCM experiment (Figure 3) and the occurrence of what has come to be known as the Great Rhode Island Flood of 2010 (Figure 4). Results show that dye transport patterns are far more complex in time and space than simple box model estimates, which assume complete mixing and up/down Bay gradients in chemical influence from disparate freshwater sources. Results show that characteristic residual (non-tidal) flow patterns observed in a number of mid to lower Bay data sets and with a range of data methods within impacted sub-regions like Greenwich Bay and the Providence River control both short and long term patterns in chemical flushing versus retention. Idealized runs show that specific runoff and wind conditions control how long dyes (proxies for nutrients) stay in the Providence River and how the overall chemical signal of this river is felt within the East versus West Passage. Models are used to define which conditions lead to nutrient loads within Greenwich Bay primarily from local sources or from remote sources via the influx and retention of simulated dye fields. Results from the 2010 simulations are used to a) define the short and long term impacts of major flood events on nutrient distributions throughout the Bay and in developing understanding for which nutrient sources most heavily influence key areas of the Bay throughout the different seasons. All cases are used to develop quantitative measures of which dye sources specifically contribute the most to the total nutrient load in the two regions (Edgewood Shoals region of the Providence River and Greenwich Bay) and to quantitatively assess the impact of various management strategies for reducing nutrient levels in these systems.

2.0 Prior Work

A combination of current meter observations and ROMS modeling has lead to an improved understanding of Narragansett Bay circulation (Rosenberger, 2001; Kincaid, 2001a;b;c; Kincaid et al., 2003; Bergondo, 2004; Bergondo and Kincaid, 2007; Kincaid and Bergondo, 2005; Kincaid et al, 2008; Rogers, 2008; Kremer et al., 2010; Pfeiffer-Herbert, 2012; Kincaid 2012). The Bay has been shown to circulate predominantly in a counterclockwise sense, with residual (or net non-tidal) flow up the East Passage and down, or out, the West Passage of the estuary (Figure 2). This large scale gyre stalls and spins up with northward and southward blowing winds, respectively. There are also counterclockwise sub-gyres within each passage (Kincaid et al., 2003). These persistent residual circulation patterns tend to carry water entering at any point (latitude) along the eastern side of the East Passage well northward into the system, as far as the Mt Hope Bay, the Providence River or around the north end of Prudence Island and into the upper West Passage. It is important to note that this background style of flow in the Bay can be upset and altered by prevailing winds and runoff patterns.

The focus of this report is on work within the upper Bay, specifically looking at the transport of water (and nutrients) through the Providence River into upper Narragansett

Bay and potential interactions between northern water/nutrient sources and the impacted region of Greenwich Bay (RI) under a range of wind and discharge conditions. The project builds off of a number of previous studies in which spatially and temporally detailed circulation measurements were collected. A series of underway ADCP measurements by the NBC in 2001 (Kincaid, 2001a-c) show the Providence River is characterized by a strong residual outflow along the western edge of the shipping channel and a strong residual inflow of deeper water along the eastern side of the shipping channel (Figure 5). These data show the weaker, often reversed flow of water in the shallow regions adjacent to the shipping channel. The most notable of these counter-rotating gyres, or eddies, occupies the shallow region of the Edgewood Shoals, west and south of Fields Point and west of the local trend of the shipping channel. NBC funded bottom mounted ADCPs in the shipping channel and within the Port Edgewood channel through the mid to western section of the Edgewood shoals support this basic picture of flow in this region of the estuary and reveal time characteristics of these flows (Kincaid and Bergondo, 2005) (Figure 6). Two layer flow in the shipping channel (surface out and deep in) is seen to be a very stable feature. Moreover, data show a very persistent layered flow structure on the shoals, where the mid to lower portion of the water column moves as part of a northward moving limb of a clockwise gyre on the shoal. The upper water column is strongly influenced by winds, moving in phase, and aligned with, prevailing winds.

Most recently, a joint NBC and Rhode Island Sea Grant effort used a new technology to map Edgewood Shoal circulation in unprecedented spatial and temporal detail. A distributed network of low cost current meters, called tilt current meters (or TCMs), were deployed in 2010 in the Providence River (Figure 3). TCMs utilize buoyant cylinders, tethered to a weight on the bottom by a flexible membrane (Figure 7). In the presence of water currents the cylinders tilt from a vertical position, where tilt angles are calibrated to current magnitudes. These data reveal flow characteristics on the Edgewood Shoals in great detail (Figures 8-10). The TCMs show that water in the Edgewood Shoals gyre moves in a clockwise sense, with residual flow rates of 1-2 cm/s. These data also show how this feature changes with changing environmental forcing conditions, specifically spinning up and down with changes in wind (Kincaid, 2012). For example, runoff has less of an impact on the gyre, as evidenced by a near constant northward flow of water up the western side of the shoals (Figure 9) during the flood of 2010 (Figure 8).

While data provide an essential constraint on local circulation, it is the combination of these data with modeling results that enable us to build toward accurate predictive tools for managing the estuary. When modeled and observed hydrodynamic behavior compare well it improves the models ability to predict higher order chemical and biological transport processes. A number of studies have considered how well ROMS simulations do in matching both flow and hydrographic data collected in the Bay (Rogers, 2008; Kremer et al., 2010; Balt et al., unpublished manuscript). A well accepted parameter for assessing model accuracy is the Willmott skill (Warner et al, 2005; Willmott, 1981), or

$$\text{Skill} = 1 - \sum | X_{model} - X_{data} |^2 \;/\; \sum (|X_{model} - X_{data}| + |X_{data} - \text{mean}(X_{data})|)^2 \qquad (1)$$

, where X represents a time series of either data or ROMS generated values for water velocity, temperature or salinity. A skill of 1.0 would result from a perfect match between data and model fields. Willmott model skill values for instantaneous data-model records (e.g, including tidal responses) are typically >0.9 for surface elevations, water currents and hydrographic parameters (salinity, temperature) (Tables 1, 2). Balt (thesis/manuscript in preparation, 2012) has conducted a detailed study of data-model comparisons for salinity and temperature covering a wide range of ROMS turbulent mixing closure schemes. Results show that for all but one closure scheme (LMD turbulent closure) used in ROMS, the skill parameter for ROMS output versus observed water salinity and temperature at Rumstick Neck (RN) and Bullocks Reach (BR) buoys range from 0.85-0.88 and 0.9-0.92, respectively. Skills calculated on ROMS derived surface elevation variations versus data at Newport, Quonsett, Conimicut Point and Providence tide gauge stations are 0.98, 0.98, 0.97 and 0.96, respectively (Rogers, 2008). Surface elevation skill values calculated for 2010 models in this study are 0.95-0.96 at each of stations. In all cases, the ROMS skill values for instantaneous fields are extremely strong.

While data-model comparisons using instantaneous or tidal records produce very strong calibration statistics, a challenge in coastal ocean modeling is to match residual or non-tidal data records. Residual flow patterns are so important to represent accurately because they control long-term transport and flushing processes. They are challenging to match well because they are significantly lower energy than instantaneous, or tidal variations. A recent NBC report summarizes statistical comparisons made between residual circulation patterns simulated by the Full Bay ROMS and patterns observed in data recorded on the Edgewood Shoals using distributed TCMs. TCM data present a challenging set of observations for the ROMS models to reproduce. However, results show that the Full Bay ROMS model does well at simulating residual flows recorded by TCMs, even given the extreme discharges from the 2010 sampling period (Figures 11,12). Willmott skills of >0.8 are calculated for periods before, during and after the 2010 flood (Table 3). Remarkably, ROMS matches both the amplitude and time-evolution of the flood-induced flows along the shoal-channel interface and within the interior of Edgewood Shoals. The process of calibrating the ROMS model with data from these TCMs (Table 3) greatly improves the usefulness of the models in quantitatively mapping relationships between flow, flushing and transport in the estuary.

3.0 Methods

To simulate coastal circulation patterns, we use the three-dimensional (3-D) Regional Ocean Modeling System (ROMS) hydrodynamic model (Shchepetkin and McWilliams, 2003; 2005). ROMS is a split-explicit, free-surface, primitive equation model with curvilinear and terrain-following coordinates. Using the curvilinear capabilities of the grid, we developed a computational grid for the full extend of Narragansett Bay which focuses resolution towards the northern end of the estuary (Figure 13). Horizontal spacing of grids varies from 300m in the south, near the Bay mouth, to roughly 30m in the vicinity of Fields Point, RI (Figure). There are 15 vertical (or sigma) layers in the model, which results in a vertical resolution that varies locally with the water depth (e.g.,

water depth divided by 15 vertical levels). The sigma coordinates in ROMS allows for modeling circulation in the presence of varying bathymetry.

The development of this grid followed suggestions from outside reviews (Mendahlson, 2007) and the overriding modeling philosophy of keeping the open ocean boundary the hydrodynamic model removed from the region of interest, or in this case further south. The Bergondo (2004) model (Figure 1) has the ocean boundary situated at the northern end of Prudence Island, which is relatively close to the Providence River. Moreover, this model domain does not allow for studying the interaction between the northern rivers (WWTFs) and Greenwich Bay. The latest version of ROMS, referred to as the Full Bay ROMS model, has the open ocean boundary located at the mouth of Narragansett Bay where information on exchange is in turn supplied by a larger, regional scale model (details described below). Advances made with the Full Bay ROMS model have resulted in more accurate simulations of known upper Bay circulation patterns. For example, the relatively coarse (100 to 150 meter) horizontal grid spacing that was employed in the first generation or Providence River ROMS model (Bergondo, 2004) was not able to re-create the gyre structure on Edgewood Shoals (Figure 14a), whereas the finer Full Bay ROMS matches this flow structure both qualitatively (Figure 14b) and quantitatively (Figures 11, 12; Table 3).

For the cases reported here, the Full Bay ROMS is forced for 2010 conditions using freshwater discharge applied at selected river sites (Figure 2), winds and atmospheric air-sea flux conditions applied at the surface and conditions on water velocity, temperature and salinity applied along the open ocean boundary of the model (e.g., the mouth of Narragansett Bay). A nesting procedure is used to apply conditions at the mouth of the estuary. Values for water velocity, temperature and salinity are applied along this boundary from information supplied from the coarser, but spatially larger RIS ROMS model (Figure 1) (Rogers, 2008; Pfeiffer-Herbert, 2012) that covers all of Rhode Island Sound. The RIS ROMS model is, in turn, forced at its open boundaries by information provided from the ROMS-ESPRESSO model of the Mid-Atlantic Bight (http://www.myroms.org/espresso/). As recommended by Janekovic and Powell (2011), separate applications of tidal forcing were applied around the RIS ROMS boundary using tidal harmonics from the ADCIRC model of the U. S. East Coast (Mukai et al., 2002; http://www.unc.edu/ims/ccats/tides/tides.htm). The inclusion of input from the Expresso model has improved the accuracy of this RIS model in terms of providing boundary conditions that match the tidal and non-tidal characteristics of flows at the mouth of Narragansett Bay (Pfeiffer-Herbert, 2012).

Wind forcing for the RIS ROMS is applied from meteorological data from the Buzzards Bay monitoring station (www.ndbc.noaa.gov/station=buzm3). Wind forcing for the Full Bay ROMS grid covering Narragansett Bay is constructing by taking an average of wind speed and direction at four real-time physical oceanographic real-time system sites (PORTS) (http://tidesandcurrents.noaa.gov/ports.html), including Fall River (MA), Providence (RI), Quonset Point (RI) and Newport (RI). A similar process is used for determining air temperature and pressure values. Radiative surface heat flux and relative humidity data used in forcing ROMS were obtained from the North American Regional

Reanalysis data set (http:/www.emc.ncep.noaa.gov/mmb/rreanl/). Precipitation data were gathered from T.F. Green International Airport (Station ID GHCND:USW00014765, http://www.ncdc.noaa.gov/cdo-web/search).

This report summarizes two modes of using the ROMS model to study circulation and chemical transport processes throughout upper Narragansett Bay. In all cases we use 2010 conditions on everything accept runoff and winds. In one mode, we use idealized conditions on wind forcing and river discharge to characterize how chemical input (representing nutrient sources) from northern rivers and WWTFs: 1. move through, or are retained within, the Providence River, 2. partition down the East versus West Passages of Narragansett Bay and 3. interact with Greenwich Bay. We refer to these as *Idealized Simulations*. In a second mode, we use actual 2010 conditions on wind and river discharge to study the short and long term impacts of the 2010 flood and how chemical (nutrient) sources from all input locations (Figure 2) either flush through the system, or are retained within key impacted regions of the Bay (e.g., the Providence River and Greenwich Bay).

Model runs use information on runoff obtained from the United States Geological Survey records (http://waterdata.usgs.gov/nwis/dv). In the development of ROMS for Narragansett Bay, an analysis has been done to correct river discharge values by determining the extend of un-gauged drainage areas, below the last gauging station and correcting published data values by a scale factor (area x rainfall) (Kremer et al., 2010) An important point is that for the purposes of describing the different parameters used in the idealized cases (e.g., Table 4), we quote the corrected runoff value applied through the Blackstone River (to be referred to throughout as Q_B). All other rivers scale from this value based upon additional scale factors that are determined using ratios of relative runoff means from all other rivers in 2006, 2007 and 2010, to Blackstone values for those same years.

One of the goals of the mode 2 simulations, for actual 2010 forcing conditions, is to assess the short and long term effects of large Spring runoff events throughout the estuarine system, extending into the summer period. In order to gauge the influence of the flood event, we compare these results with an identical run with a reduced, or non-Spring flood discharge record (Table 5). This is achieved by reducing the three primary runoff pulses for 2010 (the first 90 days of 2010) (Figures 15, 16) by 50% and 95% for each river input. The discharge values for the WWTFs are based upon information from the Narragansett Bay Commission for 2010, and are not subject to the large events seen in the river data (Figure 17). During these mode 2 simulations, the actual 2010 values for wind (averaged from PORTS sites as described above) are applied. While these wind data add to what the *"reality"* of the models, they also introduce significant levels of high frequency variability to the wind forcing (e.g., Figure 18) and to the model solutions.

The combination of simplified and complex wind forcing used here is optimal for understanding the relationship between environmental forcing and estuarine system response. There are clear benefits to running simulations with as much of the actual known or estimated forcing included as possible. However, it is beneficial to run

simulations where the forcing is highly simplified, and progressively altered. This latter method provides a means for systematically identifying which forcing modes and magnitudes give rise to which responses in the estuarine system. These idealized simulations are summarized in Table 4. They all begin from initial, or starting conditions that represent the last output of a simulation that ran from January 31, 2010 and ended on decimal day 180, or June 29, 2010. The generation of the starting condition on day 180 utilized actual environmental forcing conditions. All subsequent idealized cases then start from this point (day 180) and proceed using actual 2010 tidal, boundary and atmospheric forcing but with simplified wind and discharge conditions. We investigate both constant and simple time-varying discharges (Table 3), where the values encompass conditions generally seen during summer periods (Figure 19). We also explore the impact of late spring – early summer runoff events (Figure 20a), which are becoming more common, and are predicted to be a trend in the future given anticipated regional climate changes. The question we wish to address with these forcing conditions, is what are the transport/dispersion pathways for chemical plumes from runoff events entering the estuary during summertime stratified conditions, rather than typical early spring conditions.

The second variable in the idealized cases is the wind forcing. The simplest mode is to apply constant winds (speed and direction). A next logical step in adding forcing complexity is to represent some of the oscillatory nature of winds on Narragansett Bay, which includes daily and 2-3 day variations (Figure 18). We build idealized wind forcing functions (Figure 20) which include variations in both wind magnitude and direction that are roughly consistent with conditions observed in local wind records (Figure 21). One of these patterns is the daily seabreeze, or northeastward blowing winds.

An essential piece of these ROMS simulations is the use of distinct chemical fields for representing each of the fresh water sources (Figure 2) as they are transported and flushed (or retained) within the estuary given either actual 2010 forcing conditions and more idealized conditions. In the idealized cases each river and WWTF source is assigned a source concentration of 1.0, representing a dimensionless dye, or nutrient concentration. Ambient water within the estuary has a value of 0.0 for all dye fields initially. ROMS tracks each of these dye fields independently by solving the time varying, advection-diffusion equation. Our dyes are meant to be proxies for nutrient transport. In a real estuary there are many source and sink terms operating on these dye/nutrient fields, which in turn are coupled to equations for other chemical-biological species within the estuary and along the sediment-water interface. As each of these terms and equations carries with them a myriad of parameters that are marginally constrained, or in many cases totally unconstrained, we choose to start with the simplest possible chemical model of advection-(eddy)diffusion. Idealized model runs utilize a simplified representation of dye source concentrations by keeping these levels constant at 1.0 through time.

In addition to tracking where each dye field moves within the system, we also set out to identify which dye (nutrient) sources contribute most heavily to total concentrations within the two most impacted regions of the Bay, the Providence River and Greenwich

Bay. Actual nutrient concentrations are determined differently within the idealized versus actual 2010 flood cases. In the idealized model runs all dye concentrations are tracked as what are called dimensionless fields, meaning they all vary from a minimum of 0 to a maximum (in the source water) of 1.0. To convert these to nutrient concentrations in mg/l, we multiply dimensionless values, which vary with space and time within the model domain, by best estimates for source nutrient concentration (mg/l) using,

$$C_i(x,y,z;t) = C^o_i \times C^*_i(x,y,z;t) \qquad (2)$$

Here C_i is nutrient concentration in mg/l, that varies with space and time within the model domain, C^o_i is a constant source concentration in mg/l, one for each fresh water source, and C^*_i is dimensionless dye concentration, the field that is actually solved for throughout the domain using 3-D advection – eddy diffusion equations within ROMS. Here index i refers to the fresh water source. In the idealized cases these include the Blackstone, Pawtuxet, Palmer and Taunton River. The Moshassuck and Woonasquatucket are a single combined river source. There are 3 WWTFs in the idealized runs, the Fields Point, Bucklin Point and East Providence Plants. In calculating relative nutrient contributions from all sources we start with an estimate that all WWTFs release at 10 mg/l and all rivers contribute at 2.0 mg/l, except for the Pawtuxet River we assign a 2.5 mg/l source concentration. The slightly higher Pawtuxet source concentration is based upon Narragansett Bay Commission data, which shows this river exhibits on average 25% higher total nutrient values than the Blackstone.

The procedure for assigning actual nutrient concentrations to individual dye fields is different in the 2010 Flood Simulations. Nutrient concentrations are known to vary within rivers as total discharge, or volume flux (Figures 22-24) changes in time. For the 2010 flood simulation cases we utilize information from the computer simulation program called "The Hydrologic Simulation Program – FORTRAN or "HSPF" developed by University of Massachusetts Water Resources Research Center (P. Rees, Director, Massachusetts Water Resources Research Center, Univ. of Massachusetts; rees@ecs.umass.edu) with funding from the Upper Blackstone Water Pollution Abatement District (UBWPAD) (Patterson, 2007). The HPSF program forms the basis of the Blackstone River Water Quality Model (BRWQ), which was developed to assess the effectiveness of future pollution control strategies on downstream river quality, in line with the goals of this work. The Blackstone River Water Quality model has been run for all of 2010 and predicts time-varying nutrient concentrations for water entering the Bay through the Blackstone River. The BRWQ model predicts not only the total nutrient concentration, but also the percent contribution from each of three sources, one of which is the Upper Blackstone WWTF. The other two nutrient fields include BRWQ-derived estimates for all other non-point sources versus point sources along the Blackstone River (Figures 22-24).

Because only Blackstone nutrient levels are provided by the BRWQ model, we use an empirical model for the relationship between river flux and nutrient concentration from this model, to produce time series for all other river sources based on time-variable runoff

data for these rivers (Figure 24). For the WWTFs, volume flux, and dimensionless dye concentration, are nearly constant throughout the simulations. Equation 2 is used to scale up to nutrient concentration (in mg/l) for WWTF dyes with different values for source concentration, allowing us to test how different WWTF release levels influence overall nutrient levels throughout the estuary. As a reference to the idealized cases, we start with a value of 10 mg/l for WWTF source concentrations. To provide an assessment of the impact of managed changes to WWTF nutrient discharge, we run additional models for Fields Point source concentrations of 7 mg/l and 5 mg/l.

The BRWQ model provides a full 2010 time series of non-point source input and two point source nutrient inputs (e.g., nutrients from the Upper Blackstone WWTF and what are referred to as all other point sources). To take advantage of the three different types of nutrient inputs to Narragansett Bay from the BRWQ, we modified the ROMS code to track three distinct dyes for the Blackstone River, instead of one dye used in the idealized cases. Moreover, we choose to further develop understanding for what controls the relationship between northern fresh water nutrient sources entering Greenwich Bay, and physical factors controlling circulation. To achieve this, we have added fresh water sources within Greenwich Bay, and near Greenwich Bay. These include internal sources of Harding Brook, Muskerchug River and the Greenwich Cove WWTF. Just to the south of Greenwich Bay we also add the Hunt River. The last addition to these models is fresh water (and nutrient) input through the Bristol Harbor WWTF (information supplied by Save Bristol Harbor). Including Greenwich Bay dye (nutrient) sources also allows us to assess the relative contributions of internal to external nutrient input on the total nutrient load in this system, with respect to environmental forcing conditions from 2010.

4.0 Results:

Factors controlling water quality in estuaries are commonly associated with nutrient loads from fresh water sources, along with physical parameters such as stratification or tidal amplitude (e.g. spring versus neap tides). A focus of this work is to assess the importance of both large and small scale water circulation patterns in the estuary to overall water quality. An advancement in the work reported here is using capabilities in the ROMS hydrodynamic model for tracking the evolution of multiple chemical dye sources throughout the estuary. Using ROMS in a relatively simplified mode of modeling advection and eddy diffusion of chemical fields (e.g., without unconstrained sources and sinks), we track transport pathways for each individual major fresh water source to the estuary, including WWTFs. In this mode of forensic oceanography, it is possible to characterize transport pathways/efficiencies for all nutrient sources and test prevailing box-model estimates for flushing timescales. Results address a series of questions for the role of circulation in influencing water quality including:

1) Do all chemical sources flush equally?
2) Do more southern sources exit the system more efficiently?
3) Which chemical sources contribute most to levels in the regions with chronic water quality problems?

4) What is the longer term effect of runoff pulses, either in Spring or Early Summer?
5) What is the cost/benefit of various nutrient reduction management strategies for lowering levels in these chronic areas.

4.1 Idealized Simulation Runs

Two modes of ROMS modeling are used to address the set of questions on circulation and water quality. In one set of simulations idealized forcing conditions are used to characterize the relationship between flushing and chemical transport in Narragansett Bay as a function of freshwater runoff and wind scenarios. A second set of simulations focuses on chemical transport processes during the large flood event of Spring, 2010, continuing through the summer of 2010. A fundamental result of both sets of simulations is that modeled flow patterns are consistent with observations in the mid/lower Bay (Kincaid at al., 2008) and within the Providence River (Data Figures 5,6, 8-10; Model Figures 11,12, 14), and they produce complex, often unexpected, transport pathways for individual chemical sources. For example, Figures 25-27 show common dispersion styles in the upper Providence River for the three of the dominant northern chemical sources, the Blackstone River (Figure 25), the Fields Point WWTF chemical plume (Figure 26) and the Pawtuxet River (Figure 27). The Blackstone River plume is largely dispersed by the time it reaches the Fields Pt. – Edgewood Shoals area of the estuary, spreading out laterally at onto the Shoal at near-surface (Figure 25a) and near-bottom water (Figure 25b). The Fields Point WWTF follows the dominant residual outflow focused along the western side of the shipping channel (Data: Figure 5, Model: Figure 26a). Even without the complicating effects of winds (here Run 10, table 4 has no applied wind), the shallow plume can follow two modes of dispersion. Figures 26 (b and c) show the chemical WWTF plume recycling in a clockwise fashion within the Edgewood Shoals gyre (day 198; 7/17/10). On the next ebb tide (Figure 26 d,e) the plume sweeps southwestward along the western side of the shipping channel, impacting the western shore at the mouth of the Pawtuxet River. Here the Fields Pt. WWTF plume splits, with a portion dispersing southward, towards the river mouth. Another portion is swept northwards into the Edgewood Shoals gyre, starting another cycle.

An underlying tenet of many water quality strategies for estuaries is that chemical sources located closer to the mouth of the estuary, in this case further south, are more efficiently flushed from the system. Combing the 3-D ROMS circulation patterns with transport of the Pawtuxet River chemical dye source shows this is not always the case. In most scenarios, the Pawtuxet River outflow enters the Providence River and is split, vertically, into a shallow plume moving southward along the western side of the estuary (Figure 27a) and a deeper portion that moves northward (Figure 27 b-c). Within the mid-portion of the water column, the Pawtuxet plume spreads out over the shoal, while a percentage of this plume also blends into the near-bottom, northward flowing residual current in shipping channel (Figure 27d; Data Figures 5,6). While certain combinations of parameters can alter the specifics, a basic pattern of the majority of these runs is that southern (Pawtuxet) dye is efficiently transported well northward, towards the head of the estuary, contributing nutrients to the urban regions of the estuary most commonly effected by poor water quality conditions.

Idealized ROMS simulations are used to show how these basic patterns for the three dominant northern fresh water (chemical) sources are altered within the Providence River and upper Narragansett Bay for different combinations of runoff and wind. Figures 28-30 show dispersion patterns for the Blackstone River plume for cases with no applied wind and increasing runoff magnitudes. The Blackstone River plume transport pathway , surprisingly similar for different runoff magnitudes, shows dispersion down both the West Passage and through the western side of the East Passage. Often, a percentage of this plume also moves southward at near-surface levels in the eastern East Passage. The plots (Figures 28a, 29a, 30a) show the Blackstone saturates the full width of the Providence River at shallow levels. With increasing runoff, more of the Blackstone plume enters Greenwich Bay (Figure 30a).

In cases where only runoff magnitude is changed, the Pawtuxet Fields Pt. plumes show typical dispersion patterns. The Pawtuxet plume tends to maintain a distinct shape, tracking the western half of the Providence River and preferentially flowing southward through the West Passage. These plots show the very common northward motion of the plume onto the Edgewood Shoals (Figures 28b, 29b, 30b). As with the Blackstone, as runoff magnitude increases, more of the Pawtuxet plume enters Greenwich Bay. Interestingly, as runoff magnitude increases more of the Pawtuxet plume wraps northward onto the Shoal (Figure 30b) and concentrations of the Fields Point WWTF plume are reduced (Figure 28c-30c).

Wind forcing drives strong residual circulation in Narragansett Bay (Kincaid et al., 2008). In particular, northward winds tend to stall the prevailing residual pattern of net northward flow up the East Passage and net southward flow through the West Passage. Current meter observations show that southward winds to enhance this counterclockwise residual flow, drawing more water northward through the East Passage. Results from ROMS simulations with idealized wind forcing are consistent with these observations. Figure 31 summarizes the dispersion for the Blackstone River chemical dye under three wind directions (and relatively low wind magnitude). Southwestward blowing 3 m/s wind moves more Blackstone dye through the West Passage (Figure 31a). Northeastward winds hold water in the Providence River, concentrating the Blackstone plume against the eastern shore of Upper Narragansett Bay (Figure 31b). Interestingly, (relatively weak) northwestward winds allow Blackstone dye through the West Passage and efficiently pump this dye into Greenwich Bay (Figure 31c). Similar trends are seen for the effect of wind direction on the Pawtuxet River plume (Figure 32). Northeastward winds also hold the Fields Point WWTF plume against the eastern shore (Figure 33a), although mid-Bay concentrations are significantly lower than those seen in the northern river plumes.

Southwestward winds tend to draw dye from southern East Passage sources northward towards the Providence River. Figure 33b shows the relatively weak dispersion of the Taunton River dye field at a near-bottom depth (60% of the local water depth). Taunton dye moves northward, accumulating on the Ohio Ledge region of the upper Bay, before

moving northward in the deep shipping channel or wrapping in a counterclockwise fashion around the northern end of Prudence Island and into the West Passage.

Simulations covering the same range in wind directions, but with higher wind magnitudes show similar chemical dispersion patterns with a few notable differences. With a stronger southwestward wind (Figure 34a) the Blackstone plume remains more confined to the western shore of the upper Bay (much like the common Pawtuxet River pattern), is focussed into the West Passage but, unlike the weaker wind case, largely bypasses Greenwich Bay. Strong northeastward winds (Figure 34b) completely limit Blackstone plume motion into the West Passage. Higher northwestward winds do not result in higher levels of Blackstone chemical plume inflow to Greenwich Bay (Figure 34c). Simulations predict that Blackstone fluxes to Greenwich Bay are limited (enhanced) by strong (weak) northwestward winds. The strongest flux of Blackstone and Pawtuxet River water into Greenwich Bay in these idealized simulations occurs is moderately strong northeastward wind cases, where the winds vary in a diurnal, seabreeze style cycle (between 0 and 3 m/s) (Figure 35).

Stronger winds influence both Fields Point WWTF and Pawtuxet River plumes in a similar fashion to the Blackstone plume. The stronger northeastward (seabreeze-style) winds confine the Pawtuxet and Fields Point WWTF plumes to Providence River and the eastern shore of Ohio Ledge (upper Narragansett Bay, RI) (Figure 36). The latter field is strongly dispersed down bay relative to both the Blackstone and Pawtuxet Rivers for these conditions. Strong southwestward winds cause the Pawtuxet River plume to become even more tightly confined to the western shore (Figure 37a) and confines the relatively weaker Fields Point WWTF outflow into the shallow regions of the Providence River, at Edgewood Shoals and between this region and the Providence River mouth (Figure 37b). Certain winds enhance the accumulation of Blackstone and Pawtuxet River dye on the Edgewood Shoals. Figure 38 shows dispersion patterns for the Blackstone and Pawtuxet Rivers moving in the near bottom water. Both rivers show strong signals on the Shoals and in the relatively shallow regions along both sides of the Providence River. It is interesting that northwestward winds trigger larger percentages of Pawtuxet River dye in the bottom water to make its way into Greenwich Bay (Figure 38b).

Strong southwestward winds produce flow responses that are in line with current meter observations (Kincaid et al, 2008), and these, in turn, lead to complex chemical transport patterns. Figure 39 shows efficient northward transport of Taunton River dye through the East Passage at both shallow and deep levels in response to strong southwestward winds. Instead of dispersing southward, the Taunton River dye flows northward, supplying significant levels of dye up the deep/eastern side of the Providence River and along the northern shore of Greenwich Bay, essentially contributing nutrients to the two most impacted regions of Narragansett Bay (Figure 40).

4.1.1 Dye Percentages: Runoff.

While color contours show spatial patterns in chemical dispersion for each dye source, a goal of the work is to quantitatively compare the relative concentrations of the major

nutrient sources to the estuary. We use a combination of pie charts and time series plots to show the dominance of the northern rivers and the Fields Point WWTF in the controlling overall nutrient budgets for key sub-regions the Bay, and how these vary with different runoff and wind conditions. These plots also allow us to assess when and where the Taunton River dye source becomes an important player in the nutrient budgets in northern regions. Figure 41 uses pie charts to represent the relative nutrient concentrations measured at the Providence River mouth from nine fresh water sources determined using equation (2) as runoff magnitude changes. A more complete presentation of pie charts showing relative nutrient contributions for the nine sources for a much wider range of idealized ROMS simulations is provided in Appendix A. For runoff of Q_B=10 CMS, the Fields Point WWTF roughly equivalent as a nutrient source with the Blackstone River (~32 % of the total) (Appendix A1-A8). The Pawtuxet River measures ~20% of the total during low flow conditions and Bucklin Point is close to 10% of the total as measured at the Providence River Mouth. As runoff increases to Q_B=20 CMS the Blackstone River becomes the dominant source within the Providence River and the Pawtuxet River and Fields Pt. WWTF are roughly equivalent. At Q_B=40 CMS (Appendix A9-A14), and beyond (Appendix A15-A28), the Blackstone and Pawtuxet Rivers grow in importance, contributing ~50% and ~30% of the total nutrient load recorded in ROMS at the Providence River mouth, while the Fields Pt. WWTF drops to <10% of the total.

The pie charts in Appendix A and the time series plots in Appendix B allow for a detailed comparison of all chemical sources vary with respect to each other above and below the Providence River mouth site (Figure 41). Further up in the estuary, the balance of chemical sources contributing to dye/nutrient levels on the Edgewood Shoals shifts (Appendix A1). At Q_B=10 CMS (Run 20) dye/nutrients from Fields Point WWTF are larger (>40%) than either the Blackstone River (30%) or the Pawtuxet River (8%). Roughly 12% of the dye/nutrients come from the Bucklin Point facility. At Q_B=20 CMS (Run 21) the Blackstone and Fields Point plumes are of equal importance on the shoal, and by 40 CMS runoff (Appendix A8) the percentages of Blackstone supplied dye/nutrients greatly exceeds those of Fields Point (50% versus <25%). At this runoff level the Pawtuxet signal is matching that of Fields Point in this key region of the estuary. For a case with 5-day Q_B=100 CMS runoff (Run 24) (Appendix A15) the Blackstone contributes 50% of the nutrient budget 7-8 days after the runoff pulse, and after 15 days has receded to a equal 36% nutrient share with Fields Point.

One of the fundamental results of these idealized runs is that for all runoff events, where the Blackstone flow equals or exceeds Q_B=100 CMS, the Edgewood Shoals gyre and all shallow side regions of the Providence River are dominated Blackstone nutrients (e.g., the ratio of Blackstone/Fields Pt. nutrient levels is > 2.5), for periods well beyond the time scale of the pulse event. For the case of a Q_B=140 CMS runoff pulse (Run 28, 30), the Blackstone contributes >55% of the dye/nutrients to the shoal at 7-8 days after the pulse, versus 18% and 14% for the Pawtuxet and Fields Point plumes, respectively. It is interesting that 13-15 days after the pulse the Blackstone signal has not receded to non-pulse levels (e.g., Runs 20,21; Appendix A1; Appendix B34), but instead remains at 45% of the total relative to 26%, 15% and 6% for the Fields Point, Pawtuxet and Bucklin

dye/nutrient levels. For the discharge pulse in Run 28 (Appendix A23), the Pawtuxet River (31% to 27%), in addition to the Blackstone (50% to 45%), remain the dominant nutrient sources in the vicinity of the Providence River mouth, exceeding the Fields Point contribution by a factor of 3-5 (Appendix B35, frame B). Without applied winds, the runoff pulse seeds the Providence River with river derived nutrients for time scales on the order of 6 days on the Edgewood Shoal and 10-15 days within the extended river.

East versus West Passage:
These simplified cases, with no applied wind, provide insight into the fundamental down-bay dispersion patterns. The dominant pathways for chemical outflow from the northern fresh water nutrient sources are through the West Passage and eastern, shallow region of the East Passage. Here nutrient levels for each of the northern sources declines linear with depth through the water column. For the highest runoff cases, the pie charts (Appendix A24-A27) show the northern river chemical signal extends into the upper water column of the eastern or East Passage channel. Here 44% of the total 0.36 to 0.3 mg/l nutrient concentration is from the Blackstone (Appendix A25). In the near bottom water of the channel the concentrations are a factor of 10 smaller, or ~0.03 mg/l and roughly an equal mix of Blackstone, Pawtuxet and Taunton River nutrient sources.

The distribution of nutrients along an east to west trend through the Passages (recorded at a latitude of North Prudence Island, RI) follows a pattern consistent with counterclockwise residual flow through the mid-Bay. For low to intermediate runoff, (Runs 20-22), the relative nutrient concentrations on both the eastern extreme, near Colt State Park, and on the East Passage shoal (western side of East Passage) are >40% ~30% <10% and <5% for the Blackstone, Pawtuxet, Fields Point and Bucklin Point sources, respectively (Appendix A10, A12). In the East Passage Channel, where residual northward flows are stronger, there is a larger contribution in dye/nutrient levels from the Taunton and Palmer Rivers (16-28% of the total; Appendix A11). Consistent with the mapview contour images (Figures 29b; 30b), the relative contribution of Pawtuxet nutrients increases on the western, West Passage end of this transect (36% of the total load ; Appendix A13).

Greenwich Bay
A long-standing question with regard to water quality in Greenwich Bay, perhaps the highest profile region of Narragansett Bay with regards anoxia, is how much of the nutrient load comes from outside Greenwich Bay. ROMS idealized simulations provide a foundation for understanding how different runoff and wind conditions contribute, either favorably or unfavorably, to the influx of nutrients from outside sources. For low runoff (Q) cases (Run 20, 22), where Q_B <30 CMS, these simulations show very little flux of nutrients from the northern sources into Greenwich Bay. For Q_B=10 CMS (Run 20, Appendix A7) total nutrient concentrations at day 200 from the nine sources are ~0.01, with approximately a 30% share for each of the Blackstone, Pawtuxet and Fields Point WWTF sources (Appendix A14, A21, A28). For a larger pulse (Q_B=100 CMS; Run 24), concentrations from both the Blackstone and Pawtuxet reach 0.5-0.1 mg/l in Greenwich Bay after a 2-day time lag (Appendix A21; Appendix B20). The largest early summer pulse of Q_B=140 CMS, well within the range of values seen in recent summer

events, and in line with predicted future trends for regional climate change, produces a very large response in Greenwich Bay (Appendix B36). Both the Pawtuxet and Blackstone rivers each contribute 0.2 mg/l and 0.1 mg/l in nutrients within the outer and inner basins of Greenwich Bay, respectively. The relative contributions to nutrient levels in Greenwich Bay (excluding internal sources) after one of these large pulses is 40-45% each for the Blackstone and Pawtuxet Rivers and 3-4% versus 1 % for the Fields Point and Bucklin Point WWTFs. It is noteworthy that the continuing trend in time in Greenwich Bay for nutrient levels from outside (river) sources remains flat, suggesting the system can be seeded with nutrients from the northern Rivers, and then hold on to those nutrients well-beyond the runoff event. This trend also appears later in the full flood simulations, summarized below.

4.1.2 Dye Percentages: Wind Forcing

Results are presented on the relative sizes of all nutrient sources calculated for key regions of the Bay for a range in wind forcing conditions, with particular focus on the Edgewood Shoals, the mouth of the Providence River, the East and West Passages and Greenwich Bay (Figure 42, Appendix A 29-91). While pie charts provide a quantitative comparison of the importance of the nine major nutrient sources in key locations, a complete set of corresponding time series plots for dye concentration provide an additional level of temporal information on the chemical transport patterns (Figure 43, Appendix B). As with the runoff-only cases above, the general results of wind forcing simulations follow trends reported for current meter data (Kincaid et al, 2008), where northward (southward) blowing winds tend to stall (enhance) the residual counterclockwise flow between the Bay's two primary Passages. Figure 42 compares dye/nutrient concentrations in the bottom water of the shipping channel in the upper East Passage (at same latitude as Northern Prudence Island, RI) with a 140 CMS (Blackstone) river pulse and no applied wind. Here the Blackstone and Taunton Rivers are the dominant suppliers of local nutrients, at 35% and 30%, respectively. The Pawtuxet River provides ~20% of the nutrient load and Fields Point WWTF supplies ~2% of the nutrients. With moderate northwestward winds applied (Figure 42b) the Blackstone and Fields Point WWTF signals are unchanged, while the Taunton percentage drops to be equivalent with the Pawtuxet River at ~27%. Figures 42c and 42d show that moderate southwestward and northeastward winds change the Taunton nutrient contribution at this site to 52% and 16%, respectively. The southwestward winds spin up the mid-Bay counterclockwise gyre, carrying significant levels of Taunton River water northward. The northeastward winds stall the mid-Bay counterclockwise gyre, limiting northward Taunton River water flow up the East Passage, resulting in a decrease to 16% of the total. Stronger 8-10 m/s wind along these directions enhance these trends, driving the Taunton contributions at this site to >80% and < 4% for southwestward and northeastward winds, respectively. As with the runoff cases, the strong wind cases, coincident with a late Spring, early Summer runoff pulse to the system, drastically modify nutrient retention/transport patterns.

ROMS simulations show how wind forcing influences flow and chemical transport, both on the scale of the Providence River sub-estuary and the larger scale of Narragansett Bay. In general, northward winds hold water (nutrients) in Providence River and limit

northward flow of southern chemical sources, like the Taunton River (A43-49; A50-56, A78-84; A85-91). Subtle changes in wind appear to have the ability to strongly influence transport/retention processes within the Providence River. For example, northeastward wind (Appendix A50-56) tends to flush the Edgewood Shoal while northwestward wind tends to drive up concentrations of Pawtuxet River water on the shoal, and to retain that water on in the Edgewood gyre. For example, Pawtuxet concentration levels on the Edgewood Shoal are 0.22 mg/l and 0.47 mg/l in Runs 32 and 35 (Table 4), for moderate (3 m/s) northwestward winds. Northeastward winds of similar magnitude (Runs 31, 29) produce Pawtuxet concentrations of 0.12 and 0.18 mg/l, or roughly equivalent to the 0.13 mg/l value for the no-wind reference case (Run 28).

Whereas strong northward winds tend to limit dye/nutrients from northern rivers entering the mouth region of Greenwich Bay (Figure 43), weaker northward winds, particularly northwestward winds, produce optimal conditions for allowing northern river nutrients to be advected into the upper West Passage and then diverted into Greenwich Bay. Run 32, with a moderate northwestward blowing 0 to 3 m/s seabreeze, produces the largest influx of Blackstone and Pawtuxet River water to Greenwich Bay (e.g., both reach concentrations of ~0.2 mg/l within inner Greenwich Bay; Appendix B48). Alternatively, prevailing southwestward winds (A36-42; A57-63; A64-70; A71-77) work to flush the Providence River, where the outflow blends with northward flowing in the East Passage channel carrying nutrients from the Taunton River (Figures 39,40; Appendix A39, A59). The confluence of Providence River water and East Passage water combine as an enhanced outflow through the upper West Passage at Warwick Neck. An important outcome of these simulations is that regardless of wind conditions, when discharge through the Blackstone River reaches or exceeds Q_B=40 CMS, this source appears to be the dominant supplier of nutrients in most parts of the Providence River, the Ohio Ledge region of upper Narragansett Bay and within the upper reaches of the West Passage.

4.2 2010 Flood Simulation (Comparison with Limited Flood Case)

A second set of ROMS circulation and chemical transport simulations has been conducted. This work builds upon model runs that have already been completed as part of calibrating the Narragansett Bay ROMS model using spatially detailed tilt current meter data collected in the Providence River during the period March-April, 2010 (Design: Figures 3,7; Data: 8-10; Data-Model Comparisons: Figures 11,12, Table 3). The new model runs extend from the March-April period through the summer months in order to characterize chemical transport associated with the great flood of March 2010 and the longer term evolution of the flood signal throughout the estuary. As with the idealized cases, the 2010 Flood Simulation considers the relative accumulation of nutrients from all majors sources a) within the Providence River, b) through the mid-Bay (East versus West Passage) and c) within Greenwich Bay. As outlined in the methods section, added features of the 2010 Flood Simulation are a) modeling three distinct nutrient sources for the Blackstone River (two point source nutrient fields and a non-point source nutrient field) and b) the inclusion of internal nutrient sources to Greenwich Bay for assessing the importance of internal versus external contributions.

Figures 44-54 use color contours of different chemical dyes, representing distinct river nutrient fields, to highlight transport patterns. As with the idealized cases, these contours showing dye dispersion for each major source are consistent with evolving knowledge about both small- and large-scale circulation patterns. While contour maps provide a qualitative feel for dispersion, pie charts are used to allow for a more quantitative description of the relative importance of each source within key regions of Narragansett Bay, at different times relative to the large flood event (day 88, 3/28/10). In Appendix C, pie charts are presented for surface versus deep nutrient concentrations (percentages) prior to the flood (Day 80 (3/21/10)) and for 10 and 30 days after the flood (days 98 (4/8/10) and 118 (4/28/10)). These figures also show how surface/bottom patterns in nutrient concentration at each site change through the summer (days 145 (5/25/10), 175 (6/24/10) and 230 (8/8/10)). The progression in sampling sites presented in Appendix C is from north to south, and east to west. The northern sequence of depth/time pie charts includes the Providence River channel (near Fields Point), the western side of the Edgewood Shoals and the Providence River mouth (Appendix C1-C6). A mid-Bay sequence of pie charts runs east to west at a latitude roughly equivalent to the northern end of Prudence Island, RI and includes sites in the East Passage channel, the East Passage Shoal (western side of East Passage) and along the eastern and western sides of the constriction marking the entrance to the upper West Passage (at Warwick Neck, RI). A important focus of this work is the role of circulation in influencing nutrient loading in key sub-systems of the Bay, including Greenwich Bay (Appendix C14-C17) and Mt. Hope Bay (Appendix C18,19). A second, more southern mid-Bay section for monitoring nutrient distributions with pie charts runs from East to West passage at a latitude of southern Prudence Island, RI. This includes values in the East Passage (Appendix C20, 21), on the eastern and western ends of the line connecting Prudence and Jamestown Islands (Appendix C22-24) and finally, on the eastern and western sides of a line across the West Passage, connecting Jamestown to Quonset Point, RI. (Appendix C25-28).

4.2.1 Providence River Chemical Transport

During the 2010 Flood on Day 88 (3/28/10) the discharge through the Blackstone and Pawtuxet reached 600 CMS and 450 CMS. However, preceding this event there where two other high amplitude runoff events, one on day 74 of Q_B=250 CMS and another on day Q_B=84 of 175 CMS. The first of these was sufficient to make the Blackstone by far the leading source of nutrients throughout the Providence River (Appendix C1, C3, C5), accounting for 74% of the 0.91 mg/l nutrient load in the surface water of the channel near Fields Point (RI) (Appendix C1.a). By comparison, the Fields Point WWTF plume at this time (day 80) accounted for 9% of the load. Within the problematic Edgewood Shoals region (Appendix C2.a), the Blackstone accounts for 63% of the 0.9 mg/l nutrient load versus an 18% contribution from Fields Point WWTF. At the mouth of the Providence River on day 80 the 0.8 mg/l surface nutrient load is due mostly to the Blackstone (53%) and Pawtuxet (24%), followed by the Fields Point WWTF (12%), Bucklin Point WWTF (6%) and Moshassuck (3%) (Appendix C5.a). The deep water at the mouth has a lower concentration (0.37 mg/l) but a roughly similar distribution of

sources. The exception is an intriguingly larger contribution from the Taunton River (9%).

The increase in Taunton signal in the day 80 records is completely consistent with current meter records (Kincaid et al., 2008; Rogers, 2008; Pfeiffer-Herbert, 2012) showing persistent northward flow, particularly of bottom water, through the East Passage. The result is consistent with NBC supported studies of currents in the Providence River, showing this deep northward flow extends all the way to Fields Point (Figures 5,6). Lastly, it is consistent with ROMS model simulations showing how efficiently Taunton River water can be advected northward (Figure 45), particularly in response to southwestward winds (Figures 39, 40). In following this signal back northward, we see consistently large Taunton River nutrient contributions in the deep water of the channel near Fields Point before (14%) and just after the flood (21%; Appendix C1.d-f). Indeed, a full 30 days beyond the flood, once the Taunton pulse has had time to reach well into the Providence River, the relative contribution of Taunton River nutrients to the total load reaches 23%. Remarkably, this remote southern source is roughly equivalent to the Fields Point WWTF contribution (Appendix C1.f). The other major contributor during this time is the Pawtuxet River (36% to 41% of the total load), highlighting the deep bifurcation of the Pawtuxet plume into the northward flow in the shipping channel. These results show how important it is to consider the southern sources even in the nutrient balance for northern regions experiencing poor water quality. These results suggest that management strategies based upon assumptions that nutrient sources closer to the mouth of the system are less important are neglecting crucial information.

We continue to discuss results of the 2010 flood simulation in terms of near-term Providence River dispersion patterns, first in the near term relative to the flood and then in the long term. This is followed with a discussion of results on down-Bay chemical transport patterns. Progressing from day 98 to day 118 (10 and 30 days post-flood), the surface nutrient loads in the shipping channel south of Fields Point rise to 1.04 mg/l and then drop off to 0.63 mg/l. Over this time, the Blackstone percentage falls from 63% of the total to 50% of the total. The Fields Point contribution rises from 15% to 19% of the total (Appendix C1b-c). At the mouth, total concentrations in the surface water also rise (0.9 mg/l) and fall (0.6 mg/l) over the 30 day post-flood period, but with slightly different contribution profiles (Blackstone 47-43%, Pawtuxet 27-21%, Fields Point 11-17%, Bucklin Point 6-8% and Taunton 3-6%). The Edgewood Shoals is not isolated from this chemical transport event, reaching a total of 1.25 mg/l at day 98 before receding to 0.93 mg/l 30 days after the flood (Appendix C3.b-c). During this period the Blackstone is the major contributor (56%-50% of the total load), followed by Fields Point (20-24%) and both Bucklin Point and the Pawtuxet River (each contributing ~10% of the total). As shown in Figure 45b, the Taunton River intrudes up the Port Edgewood channel that cuts through the Edgewood Shoals. This style of intrusion is reflected here in the progressive rise of the Taunton signal in the bottom water of the shoal (7% on day 118, Appendix C3.f).

ROMS simulations allow for assessing the longer term impacts of major spring runoff events, like the 2010 flood, on chemical/nutrient patterns through the late Spring and

Summer months (Appendix C2, C4, C6). Over the period of days 145 to 230, extending from late May to early August, 2010, there are consistent trends in the results for Providence River. Over this period the total concentrations in the Fields Point channel region, Edgewood Shoals and the Providence River mouth rise by roughly 10%. On average nutrient concentrations are highest on Edgewood Shoals (1.02-1.135 mg/l at the surface and 0.8 to 1.02 mg/l at the bottom) (Appendix C4) and lowest at the Providence River mouth (0.54-0.67 mg/l at the surface and 0.22-0.24 mg/l at the bottom) (Appendix C6). The roughly linear decrease in concentration with depth is consistent with trends seen in Narragansett Bay Commission data (T. Uva, personal communication, 2012). For days 145 and 175, the Blackstone is by far the largest contributor of nutrients to the surface waters (43-51% of the total). On day 230, in August 2010, the Blackstone and Fields Point sources are nearly equal (at roughly 35% each) and the Pawtuxet and Buckling Point sources are nearly equal (at roughly 15% each).

The near-bottom distribution patterns are remarkably different between the three sites over this time period. In the deep shipping channel near Fields Point there is a cycling in which source is the dominant contributor (at >30% of the total) that occurs between the Pawtuxet and Blackstone Rivers and Fields Point WWTF (Appendix C2.d-f). At the mouth the Blackstone is consistently the dominant contributor of nutrients at 33-42% of the total (Appendix C6.d-f). In both of these deep channel locations, there are periods where the Taunton River contributes 10-15% of the total nutrient load. The late stage evolution of nutrient levels on the Edgewood Shoals is roughly the same, surface versus bottom (Appendix C4.d-f). At the start of the summer, the Blackstone is the dominant contributor at 47% of the total. By August, the Blackstone and Fields Point WWTF have become the dominant contributors to the nutrients on the shoal, at 35% each (Appendix C4.f).

4.2.2 Mid-Bay Chemical Transport

The combination of the two pre-flood discharge events and the strong flood pulse on day 88 maintain a saturation in the Providence River with nutrients from the Blackstone River and the Pawtuxet River (Figure 44a,b). In general, these river sources overwhelm nutrient levels from the WWTFs like Fields Point and Bucklin Point (Figure 44c; Appendix C1, C3, C5). The down bay dispersion of the northern nutrient sources produce patterns that are consistent with idealize results, showing the Pawtuxet tends to track the western shore of the Providence River and Ohio Ledge, the Blackstone plume splits between the West and East Passages and the northward flow up the East Passage tends to carry the Taunton signal onto Ohio Ledge, where it splits between the deep water of the Providence River and the whole water column entering the West Passage (Figures 40, 45, 49). An example of differences in down-bay dispersion of the Blackstone versus Pawtuxet plume is shown in Figure 44 where on day 100, 12 days after the flood, the Blackstone-supplied nutrients move preferentially through the East Passage, as opposed to the Pawtuxet plume, which has a much larger concentration within the West Passage and Greenwich Bay. Interestingly, the intrusion of Pawtuxet River water into Greenwich Bay at this point occurs in the bottom water of Greenwich Bay (Figure 47b). By comparison, the Fields Point WWTF plume is significantly weaker within the Providence

River and the East Passage than either of these river signals, and remains relatively localized to the Edgewood Shoals (Figure 44c).

It is important to note that down-bay chemical dispersion through the shoals of the East Passage and through the West Passage is largely the result of Blackstone and Pawtuxet near-surface fields (Figure 44a,b versus 44c) and that deeper portions of both these northern river plumes, and the Fields Point plume, track differently through the system (Figures 46-48). The deeper chemical signals for each of these northern sources are shown in ROMS to spread out within the Edgewood Shoals and within the shallower regions lining both sides of Providence River. While it is difficult to calculate flushing rates for nutrients occupying these regions with the continuous sources of dye entering through rivers that employed in these simulations, the nearly flat or increasing trends in dye concentration versus time for Edgewood Shoals under no-wind (Appendix B30, B34) and northward wind cases ((b) frames in Appendix B38, B54, B62, B66, B70, B74, B86) shows that for what are very common conditions on in summer in Narragansett Bay, long term retention and relatively high total nutrient levels in these shallow Providence River areas is to be expected.

While the idealized cases showed how different wind styles could fundamentally alter the transport pathways for the different sources, the 2012 Flood Simulation shows a fairly consistent pattern in mid- to lower-bay transport from early to late stages (Figures 46-48 versus Figures 50-53). On day 196 the Blackstone plume is widely dispersed in the Providence River at shallow levels, occupies the shallow edges of the Providence River and is diminished within the deep channel (Figure 50). At both shallow and deep levels, the Blackstone plume flows into the West Passage (largely by-passing Greenwich Bay) and down the East Passage shoals (on the western side of the East Passage). The Pawtuxet River plume on day 196 (Figure 51) has some distinct features. For one, the plume is strongly delineated in the surface waters along the western half of the Providence River, with some dye appearing north of the Pawtuxet mouth, on the Edgewood Shoals. The nutrient saturation level of Pawtuxet plume is far less on Edgewood Shoals and slightly less down-bay (Figure 51) than the Blackstone plume (Figure 50). More of the Pawtuxet plume appears to pass into the West Passage than down the western side of the East Passage. As with the Blackstone plume, most of the shallow feature by passes Greenwich Bay, while some intrusion of nutrients into Greenwich Bay is seen through the lower water column (Figure 51b). A bigger change is seen in the Taunton River chemical signal between days 150 and 196 (Figure 53). The persistent northward chemical flux of Taunton River nutrients in the counterclockwise flow through Narragansett Bay diminishes significantly over this time period, reflecting the decrease in Taunton River discharge.

The total nutrient concentration values and the relative sizes of different sources at mid-Bay locations also follow trends that are consistent with high concentration northern nutrient sources exiting the Providence River into an overall residual Bay circulation consisting of strong, deep northward flow in the East Passage and net, residual outflow through the West Passage. During the period just before and after the flood, the total nutrient concentration in the East Passage channel (along the northern mid-Bay transect)

is 0.4-0.5 mg/l in the surface water and 0.08-0.07 in the deep water (Appendix C7). Before the flood, the near-surface total is made up of 43% from Blackstone sources, 18% from Pawtuxet and 18% from Taunton sources and 10% from Fields Point WWTF. The average distributions from 10 to 30 days after the flood are 43%, 24%, 11 % and 12% from the Blackstone, Pawtuxet, Taunton and Fields Point WWTF discharges, respectively. In the summer (days 145 to 230), the total at this East Passage site falls to an average of 0.3 mg/l, made up of 43 to 32% Blackstone nutrients, 21 to 16 % Pawtuxet nutrients and 20 to 26 % Fields Point nutrients. During this time period, Taunton River contributions fall from 17% in early summer to 4% in late summer, consistent with reduction in transport seen in Figure 53. The deep water at this site remains uniformly low in total nutrients, at least from the sources included in this model (0.08 – 0.07 mg/l). Contributions to this very low concentration from the two big northern sources do not change significantly (Blackstone 38 – 31%; Pawtuxet 14-18%). As expected, the Taunton changes from 38% of the total nutrients at this site in spring and early summer to 10% in late summer. The Fields Point WWTF does the opposite change, from <10% in spring-early summer to 15-23% in mid-late summer (Appendix C8).

Concentrations on the East Passage shoals reflect the splitting of the chemical plumes coming out of the Providence River down the eastern side of Prudence Island. These values vary between 0.6 mg/l and 0.5 mg/l in the surface water, at 10 days before, and 10-30 days after, the flood (Appendix C9). The near-bottom nutrient load is also higher, at ~0.25 mg/l. The totals in the surface water are dominated by the Blackstone (51-44%) and Pawtuxet (22-25%) Rivers. The same is true for the deep water here, except that Taunton River sources reach 20% of the total). By late summer (Appendix C10) the concentration at this site has fallen to 0.31 mg/l and 0.19 mg/l in the surface and bottom water. The Fields Point WWTF also contributes ~18% of the nutrients to this region as of day 230 (8/8/10).

Results for nutrient levels in the upper West Passage are summarized in pie chart figures in Appendix C11-C13. As expected from the mapview images of dye/nutrient dispersion from the northern fresh water sources, the western side of the West Passage (at North Prudence Is.) show the highest nutrient concentrations for this east-west transect across the mid-Bay. Near-surface values range between 0.67-0.5 mg/l around the time of the flood. The highest near-bottom nutrient loads are also seen at this point along the transect (0.38-0.35 mg/l). The nutrients throughout the water column at this site are between 40-50% supplied by the Blackstone and 24-26% from the Pawtuxet River. Interestingly, the levels of Taunton River and Fields Point derived nutrients are roughly equivalent, reflecting the mixing of these smaller sources on Ohio Ledge (Taunton from the south, Fields Point from the north) and subsequent southward advection towards the entrance to Greenwich Bay. Concentrations at this site, essentially the head of the West Passage, are fairly consistent throughout the summer period (~0.3 mg/l) (Appendix C13), as are the distribution patterns (32-42% Blackstone; 16-22% Pawtuxet; 16-26% Fields Point WWTF; 7-11% Bucklin Point; 7-9% Taunton). In late summer the relative concentrations of Fields Point and the Taunton River rise and fall by roughly the same amount. The presence of the Greenwich Bay plume (all sources summed together) is seen to grow to the 3-5% level in summer.

4.2.3 The Flood & Greenwich Bay

In moving from north to south, and east to west in our presentation of results, the next location to discuss is the system with chronically poor water quality (hypoxic) conditions, or Greenwich Bay (RI). Figure 54 shows just two frames of the mapview distribution of Greenwich Bay nutrient sources. The details, and very rich detail, of how water circulates and flushes from within Greenwich Bay is the focus of a URI PhD Thesis by C. Balt. Here we summarize the basic patterns for nutrient loading between internal and external sources for both the outer basin (Appendix C14-C15) and inner basin (Appendix C16-C17) of Greenwich Bay (RI). The ROMS simulations show that internal Greenwich Bay nutrient sources and the two dominant northern rivers (Blackstone, Pawtuxet) dominate the nitrogen story in this impacted sub-system to Narragansett Bay. During the period before and after the spring flood 2010, the average total concentration in the outer basin is ~0.5 mg/l, of which 33-40% is due to the Blackstone River and 20-26% is the from the Pawtuxet River. The Greenwich Bay contribution clearly drops off in the outer basin during the period from 10 to 30 days after the flood, or 9-10% of the total load (Appendic C14.b-c and d-f). During most striking result from these simulations is the dramatic increase in percent load to Greenwich Bay from internal sources as the summer progress (reaching 50% by day 230; Appendix C15.c).

ROMS simulations show the inner basin of Greenwich Bay, clearly one of the regions of the Bay suffering most from the hypoxia, is dominated by internal nutrient sources (Appendix C16, C17). Before the flood ~50% of the 0.6 mg/l nutrient concentration in surface and bottom water is supplied by internal sources, with the rest coming from the Blackstone and Pawtuxet Rivers. During the period of 10-30 days after the flood total concentrations rise to 0.7 mg/l and then drop to ~0.4 mg/l in the inner basin, with the supply of these from internal sources dropping to 11% and 25% of the total in the bottom and surface water, respectively. This change reflects an infusion of nutrients with the northern rivers that arrive through the upper West Passage. However, during the summer period, when Greenwich Bay is most susceptible to hypoxic conditions, models predict that total concentration levels remain nearly constant at 0.4-0.5 mg/l, and that the supply of nutrients is primarily from internal sources (55-65% by late summer) (Appendix C17.d,f).

4.2.4 Mt. Hope Bay and Lower Bay Chemical Transport

Results on circulation and nutrient levels are also presented for Mt. Hope Bay, on the opposite side of the Bay from Greenwich Bay, as well as a transect across the southern part of the mid-Bay region (e.g., latitude of North Jamestown Is.). During spring 2010, the mouth of Mt Hope Bay is controlled by the Taunton River in the outflowing surface waters (0.3 mg/l before the flood, 0.4 mg/l after the flood and 0.22 mg/l 30 days beyond the flood) (Appendix C18). The deep water along the mouth of Mt. Hope Bay has far more influence from the Blackstone and Pawtuxet Rivers (33-37 % and 19-23%), although the total nutrient concentrations are very low (0.08 mg/l before and a month after the flood, 0.1 mg/l 10 days after the flood). Moving into summer the surface concentrations drop from 0.2 to 0.1 mg/l, with a wide mix of source distributions

(Appendix C19) and near bottom concentrations drop to ~0.05 mg/l in summer, reflecting inflow of water from southern East Passage, rather than the northern East Passage.

Patterns in nutrient levels for what we are referring to as the southern mid-Bay region (North Jamestown Is.) are summarized in Appendix C20-C26. The changes in total concentration and the distribution of sources in this region of the Bay are, again, consistent with our basic picture of residual flow through Narragansett Bay. For the period before the March 28, 2010 flood, the total nutrient concentration in near –surface waters varies from 0.2 mg/l in the East Passage (near T-wharf), to 0.27 mg/l and 0.26 mg/l at the eastern and western sides of the line connecting South Prudence Island to Northern Jamestown Island and finally to 0.35 mg/l on the western side of the West Passage (at Quonset Point). Near bottom water concentrations vary from the extreme of 0.01 mg/l in in the East Passage to 0.14 mg/l in the western West Passage. On day 80, the East Passage water is supplied by the Taunton River and Blackstone River nutrients (56%, 21%) whereas the western West Passage site is supplied by Blackstone and Pawtuxet River water (45%, 27%). The intermediate region, between Prudence and Jamestown Islands represents an interesting connection point between the two Passages. Water at these sites is supplied on Day 80 from the Taunton (43%), Blackstone (28%) and Pawtuxet (16%) Rivers. In late summer, as in many aras of the Bay, the Taunton River contribution falls off as the Fields Point contribution to these southern sites grows (reaching 18-24% of the total nutrient supply). It is interesting that lateral variations in total nutrient levels also falls off in late summer, ranging from 0.1 mg/l in the East Passage surface water to between 0.18 and 0.11 mg/l in the western West Passage surface water.

5.0 Discussion

Two additional goals of this work are to assess how manmade changes and natural changes might change the overall results on circulation and the transport of varous chemical sources throughout the estuary. To address the first of these additional goals, nutrient distributions were recalculate for certain areas given models where Fields Point WWTF release levels were reduced from 10 mg/l to 7 mg/l and then 5 mg/l. These results are summarized in Appendix C27-C37 and Figures 55-62. We do not present results from the spring to early summer period, because nutrient concentrations throughout the Bay are so strongly controlled by river input that these WWTF changes would have minimal impact. Instead we focus on the lower flow, summer period. Figure 55 highlights the role of changing Fields Point WWTF output from 10 mg/l to 5 mg/l on the Edgewood Shoals. In early summer this drops the total concentration from 0.9 mg/l to 0.8 mg/l, or roughly 10%. The Fields Pt. contribution to the total load changes from 22% to 15%. In late summer, the largest impact of this change in the Bay is seen in the Edgewood records. Total nutrient load drops from 1.0 mg/l to .84 mg/l and the percent contribution from Fields Pt. changes from 35% to 21% of the total. A similar impact assessment is presented in Figure 56, for the Providence River mouth. Here the strategy of changing from 10 mg/l to 5 mg/l in the source water from Fields Point changes the total concentration at the Providence River mouth from 0.22 mg/l to 0.2 mg/l. The effect is more noticeable in late summer at this site, where total concentrations drop from 0.34 to 0.29 mg/l due to this management strategy.

Further south the influence of the change in Fields Point change is not discernable in the near-bottom water of the East or West Passage (Figures 57, 58). For surface water, the change from 10 mg/l to 5 mg/l release level results in changes of 0.29 mg/l to 0.27 mg/l in the East Passage channel for early summer and 0.26 mg/l to 0.22 mg/l for late summer. Similarly, the source changes appear in the surface water of the West Passage at Warwick Neck as reductions in total nutrient load from 0.31 mg/l to 0.29 mg/l in early summer and 0.33 mg/l to 0.32 mg/l in late summer. Within Greenwich Bay, the distant change in Fields Point release levels is also muted (Figure 59). Here the total nutrient load is calculated to change from 0.37 to 0.35 mg/l in early summer and 0.42 mg/l to 0.4 mg/l in late summer. Results for changes in the water column versus various Fields Point WWTF source water nutrient reductions are also plotted as a function north-south distance in Figures 60-62.

The final application of the ROMS hydrodynamic – chemical transport model was to test the outcome of a long term 2010 model simulation where a major natural effect, the Great Flood of 2010, was removed from the simulation, allowing us to asses the role of this event in determining nutrient levels thoughout the system. Figures 15 and 16 show how the three primarly fresh water pulses of Spring 2010 were removed from the river forcing file for the Blackstone River. These pulses were also removed from all other river files. As with the Full Flood model, the simulation was run from January 31, 2010 through Septenber 7, 2010 (day 250). The comparison of the two simulations is shown in a set of time series plots of total nutrient concentration at three Providence River sites and within Greenwich Bay for full flood versus reduced flood forcing (Figures 63-68). On the Edgewood Shoals, the tow solutions converge after roughly 20 days after the first runoff event of 2010. A similar timescale for returning to background conditions is seen at the mouth the Providence River. Interestingly, the longest influence of the flood is seen in Greenwich Bay (Figures 67-68) where the effect of the large runoff pulses are seen to last for 40 days.

6.0 Conclusions

Results have been presented on ROMS hydrodynamic simulations which are able to recreate the both small and large scale features of circulation observed to exist within Narragansett Bay. The simulations provide a powerful management tool by tracking the transport and fate of 16 chemical dyes representing nutrient input from all major fresh water sources to Narragansett Bay. Results from two modes of ROMS modeling are presented. A series of idealized model simulations is used to characterize chemical transport within the Providence River, between the East and West Passages and within Greenwich Bay using simplified runoff and wind forcing conditions. Results show that chemical transport follows basic residual flow styles seen in both current meter observations, and ROMS model simulations. Dispersion of the Blackstone and Fields Point WWTF plumes produces repeatable patterns, with near-surface material spreading out within the Providence River and partitioning between East and West Passages. Deeper material saturates the Edgewood Shoals and shallow regions along the edges of the Providence River. The Pawtuxet River plume tends to follow a different dispersion path, splitting between a surface portion that exits down the western side of the

Providence River and a deeper portion which moves northward onto the Edgewood Shoals and within the shipping channel. Southwestward winds effectively drain the Providence River, focusing outflow through the West Passage, and enhancing northward flow of Taunton River water onto Ohio Ledge (RI). Northward blowing winds hold water in the Providence River, driving up nutrient concentrations on the Edgewood Shoals, and deflect down-bay dispersion into the East Passage. In terms of nutrient loads, simulations show the Blackstone and Pawtuxet Rivers tend to dominate the nutrient levels throughout the estuary, except in cases where Blackstone runoff is 10 CMS (and other rivers are proportionally less than this value, see Table 4). A second set of simulations recreates the 2010 season, tracking both short and long term impacts of the late winter – early spring high runoff events throughout the estuary. These cases also show dispersion matches basic residual flow patterns reported previously, where chemical transport (e.g., Taunton River) moves northward within the eastern East Passage and southward through the West Passage and the East Passage shoals. The Blackstone and Pawtuxet chemical signals tend to dominate the system within the Providence River, the West Passage and much of the East Passage. An important model prediction is that from winter through mid-summer, the Taunton River is also an important nutrient source, not only within the East Passage but throughout the Providence River, West Passage and even Greenwich Bay. Interestingly, persistent deep residual flows transport what are often considered "southern" nutrient sources, like the Taunton and Pawtuxet River plumes, into impacted regions well northward of their entry points. Management strategies should not assume southern nutrient sources are always more efficiently dispersed towards the ocean than northern sources. Finally, results suggest that lowering nutrient levels in Fields Point WWTF source water from 10 mg/l to 5 mg/l will have limited impact on total nutrient levels in most regions of the Bay.

7.0 References

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Table 1: Model skill parameters and statistical root-mean-square (RMS) values for station locations within the Providence River and at Conimicut Pt. (Rogers, 2008) (using NOAA tide gauges). Model and data values are instantaneous (tidal time scale) records for 2006. Comparisons based on a 9 month ROMS simulation (Rogers, 2008). Skills of 0.8 and higher are considered very strong. A skill of 1 is a perfect match.

	Skill	RMS Diff (cm)
Newport	0.98	9.8
Quonset	0.98	11.3
Conimicut	0.97	14.7
Providence	0.96	17.7
CN-NP Slope	0.82	1.2

Table 2: Temperature skill values and statistical root-mean-square (RMS) differences between ROMS output and data for buoy locations at Conimicut Pt., Mount View and Poppasquash Pt. Values are comparing instantaneous or unfiltered records. Because records are unfiltered they are referred to as tidal.

Buoy	Skill	RMS (°C)
Conimicut Top	0.98	0.78
Bottom	0.95	0.86
Mount View Top	0.97	1.11
Bottom	0.96	1.13
Poppasquash Top	0.98	0.88
Bottom	0.81	2.19

Table 3. Statistical data-model comparison for sub-tidal or residual flow fields for NBC - supported TCM stations.

ROMS Station	**TCM Station**	Willmott Skill (eqn. 1)	RMS (cm/s))
18	**3**	0.78	4.2
16	**5**	0.88	3.7
14	**7**	0.82	5.2
12	**10**	0.89	2.3
8	**14**	0.82	1.3
3	**19**	0.8	3.6

Table 4: Summary of parameter values for idealized Providence River Dye Dispersion ROMS scenarios All idealized cases use Summer 2010 tidal conditions and background density conditions. Simulations begin on decimal day 180 (June 29) and run for 20 days. The use of ">" symbol indicates a time-variation in forcing read from left to right (e.g., the notation 10>100>10 in the runoff column indicates a runoff event, day 180-183 at 10 CMS day 183 to 188 at 100 CMS and returning to a 10 CMS background for the remainder of the simulation. For winds, the notation 0>6 indicates a daily wind speed cycle between 0 and 6 m/s, repeating for the duration of the simulation.

Note: All runoff values are given for the Blackstone River. Other rivers are calculated from this based on average reduction factor calculated from 2006, 2007 and 2010 data.
Moshassuck/Woonasquatucket=15% of Blackstone.
Hunt & Palmer=10% of Blackstone.
Pawtuxet=50% of Blackstone
Taunton=82% of Blackstone

Idealized Summer 2010 Simulations

Run #	Blackstone Runoff (CMS)	Wind Speed (m/s)	Wind Direction (blowing towards)
7	10	0	
8	10	2 > 5	northeastward
9	10	0 > 6	northeastward
10	40	0	
20	10	0	
21	20	0	
22	40	0	
23	10 > 40 > 10	0	
24	10 > 100 > 10	0	
25	10 > 20 > 10	0	
26	20	3	northeastward
27	20	5	northeastward
28	20 > 140 > 20	0	
29	20 > 140 > 20	0 > 6	northeastward
30	20 > 140 > 20	0	
31	20 > 140 > 20	0 > 3	northeastward
32	20 > 140 > 20	0 > 3	northwestward
33	20 > 140 > 20	3	westward
34	20 > 140 > 20	3	southwestward
35	20 > 140 > 20	3	northwestward
36	20 > 140 > 20	3	northeastward
37	20 > 140 > 20	5	northeastward
38	20 > 140 > 20	0 > 9	northeastward
39	20 > 140 > 20	8 > 10	northeastward
40	20 > 140 > 20	8 > 10	southwestward
41	20 > 140 > 20	8 > 10	southeastward
42	20 > 140 > 20	8 > 10	northwestward

Table 5. Summary of parameters used in dye simulations of the 2010 flood season (January – September, 2010), using actual 2010 forcing data (tide, wind, runoff and atmospheric forcing). Ocean boundary information is supplied by RIS-ROMS for 2010, in turn forced on boundaries by Espresso Model for Atlantic (described in methods). For comparison, a set of runs is done where the three runoff pulses in Spring 2010 are reduced in magnitude by 98%. These provide a reference to gauge the chemical transport with the flood versus a spring with no flood.

Run #	Start(dec. day)	End(dec. day)	Comments
Jan31d forcing	30	60	Simulations with 2010
FF1	60	87	
FF4	84	95	
FF5	92	101	
FF5b	100	120	
FF6a	120	130	
FF6b	130	133	
FF6e	132	150	
FF7	150	180	
FF8	180	210	
FF9	210	220	
FF10	220	250	
Fp2_30	60	120	Flood pulses reduced by 98%
Fp2_30a	120	152	
Fp2_30b	151	177	
Fp2_30c	176	197	

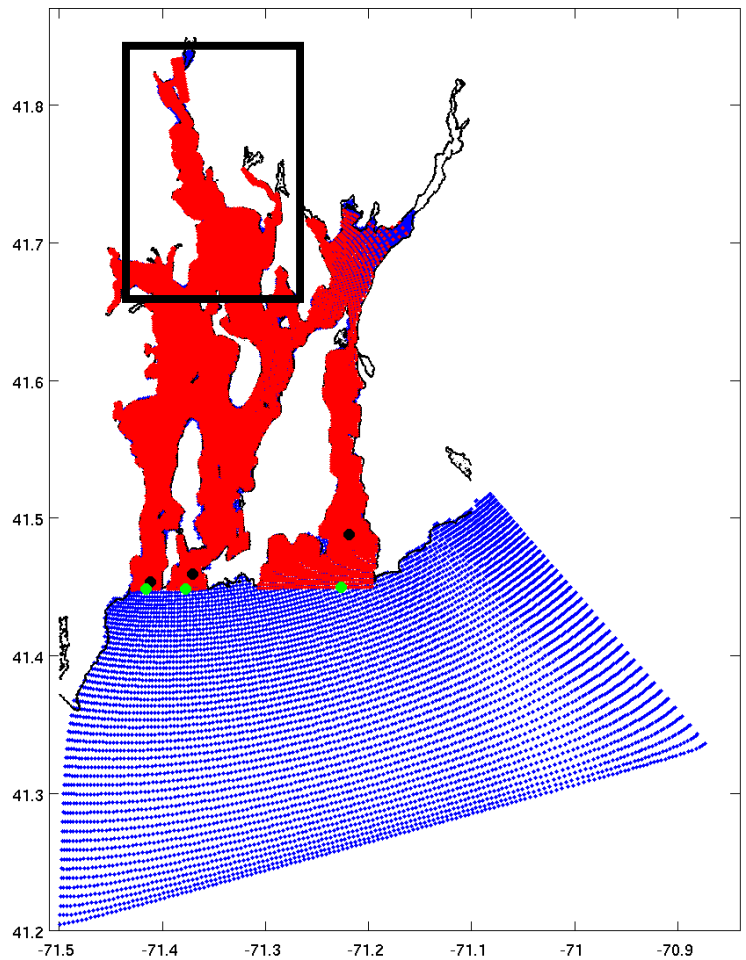


Figure 1. The Narragansett Bay Regional Ocean Modeling System (or ROMS) hydrodynamic-transport model has been developed for the Narragansett Bay and Rhode Island Sound (RIS) (Bergondo, 2004, Rogers, 2008). Bergondo (2004) used a relatively coarse grid version to focus on upper Bay processes (black box) (referred to as the PR-ROMS model). Rogers (2008) developed a wider extend ROMS extending from RIS up through the Seekonk River (blue grid), referred to here as the RIS-NB ROMS model. Both of these model grids have relatively coarsely spaced grid boxes in the Providence River (>150 m horizontal spacing). A Full-Bay ROMS model (red region) has been developed with finer grid box spacing in the Providence River (<50 m).

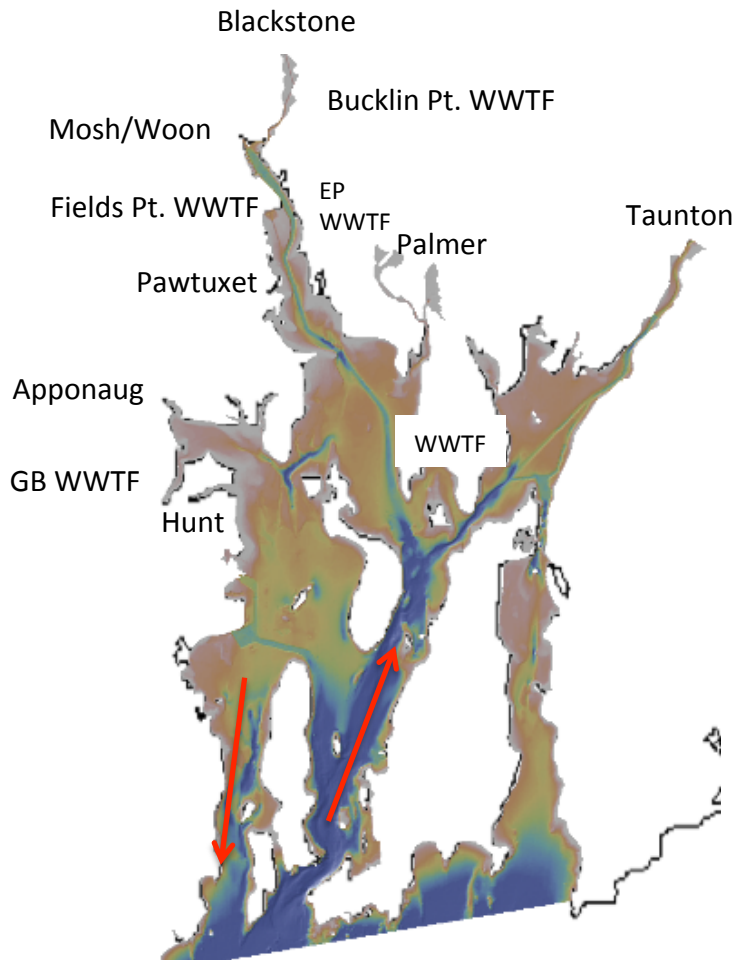


Figure 2. Map of Narragansett Bay showing the freshwater sources to the estuary that are included in the ROMS modeling covered in this report. Freshwater sources include a combined Moshasuck and Woonasquatucket River, in addition to the Blackstone, Palmer, Taunton and Pawtuxet Rivers. The Hunt River is included outside of Greenwich Bay as inputs through Apponaug and Greenwich Coves inside Greenwich Bay. There are also five waste water treatment facilities (WWTFs) included: Fields Point, Bucklin Point, East Providence and the facilities within Greenwich Cove and Bristol Harbor. At each freshwater location the model applies a temperature and salinity to the incoming water, and introduces a unique chemical tracer to the water to enable long term tracking of each source. Arrows highlight mid-Bay residual flows (Rogers, 2008; Kincaid et al., 2008, Pfeiffer-Herbert, 2012).

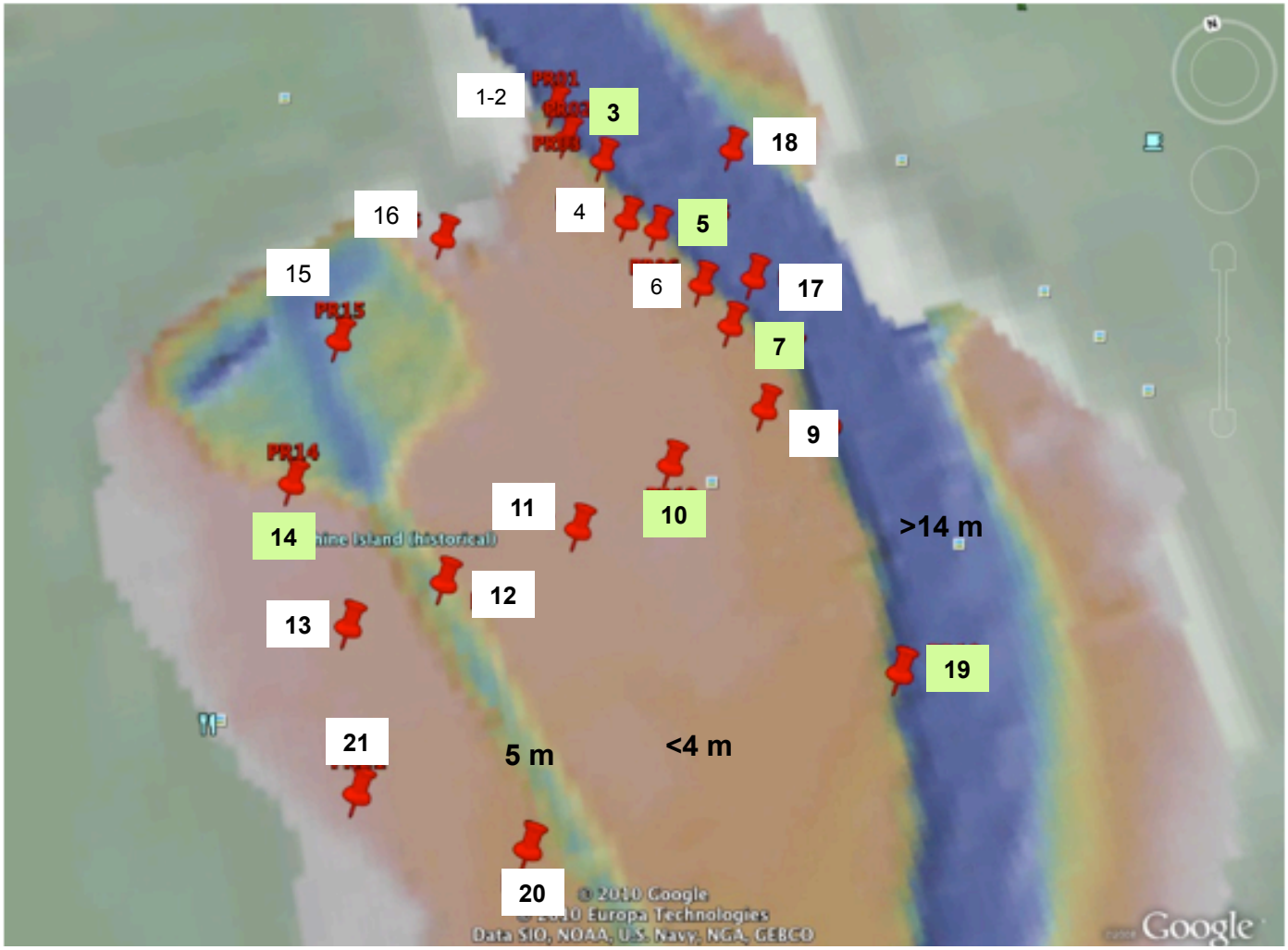


Figure 3. Map showing close up of the Edgewood Shoals region of the Providence River, just south of Fields Point. Dark blue color shows the deep shipping channel. Brown colors show the shallow Edgewood Shoals. Also shown are locations of the tilt current meters (TCMs) deployed in the Providence River during March 8 -May 1, 2010. As et of NBC-supported TCMs, shaded in green, were used to fill in the array in key locations along the channel edge and on the Edgewood Shoals.

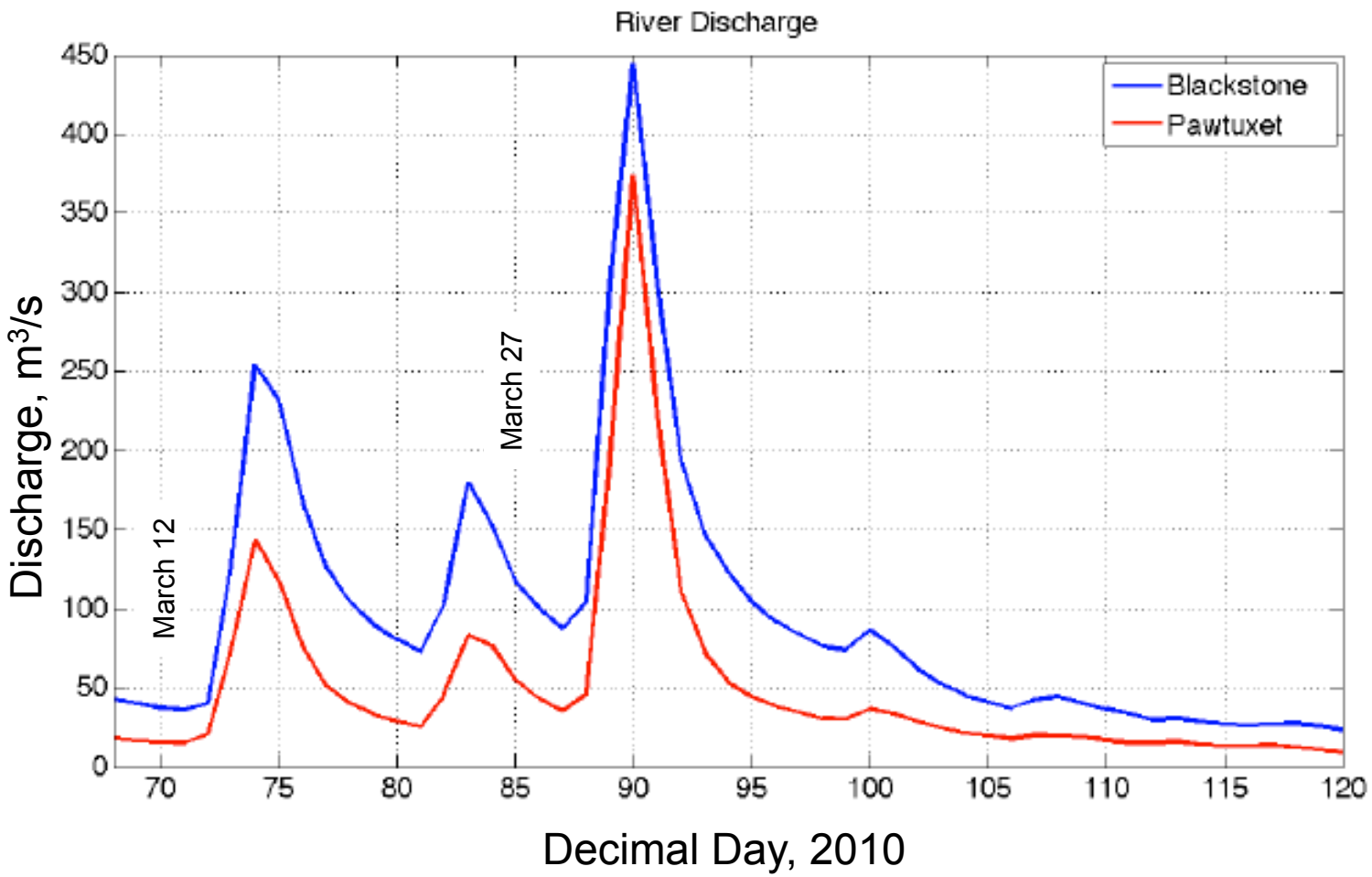


Figure 4. Plot of river discharge for the Blackstone and Pawtuxet Rivers for the TCM deployment period in 2010. Plots show the large flood event that occurred at the end of March, 2010. Two smaller runoff eventswere recorded in mid-March, 2010, prior to the flood event. Discharge was low during the end of the deployment period .

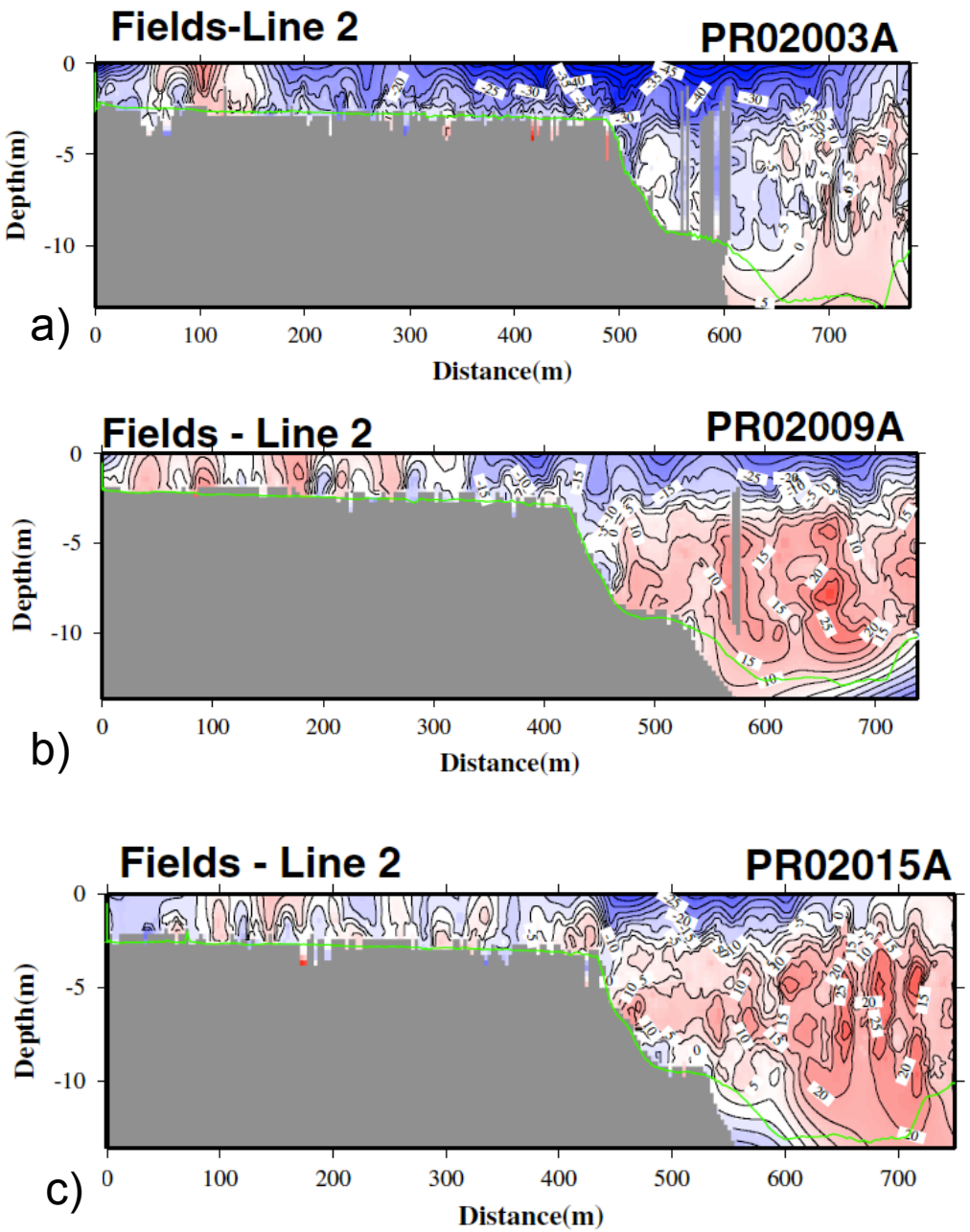


Figure 5. Cross sections through the Providence River just south of Fields Point showing northward velocity measured from NBC-sponsored underway ADCP surveys on 10/28/01 (Kincaid, 2000b). Orientation is viewed looking northward. Data are from Line 2, just south of Field Pt.. View is northward. (Red=inflow, Blue=outflow). Data are from three stages of the tide: a. Ebb, b. Early Flood, c. Flood. Data show clear differences in flow direction between western shoal, eastern shoal and channel. Flows on the western shoal tend to be weak and northward moving over most stages of the tide indicating a clockwise gyre.

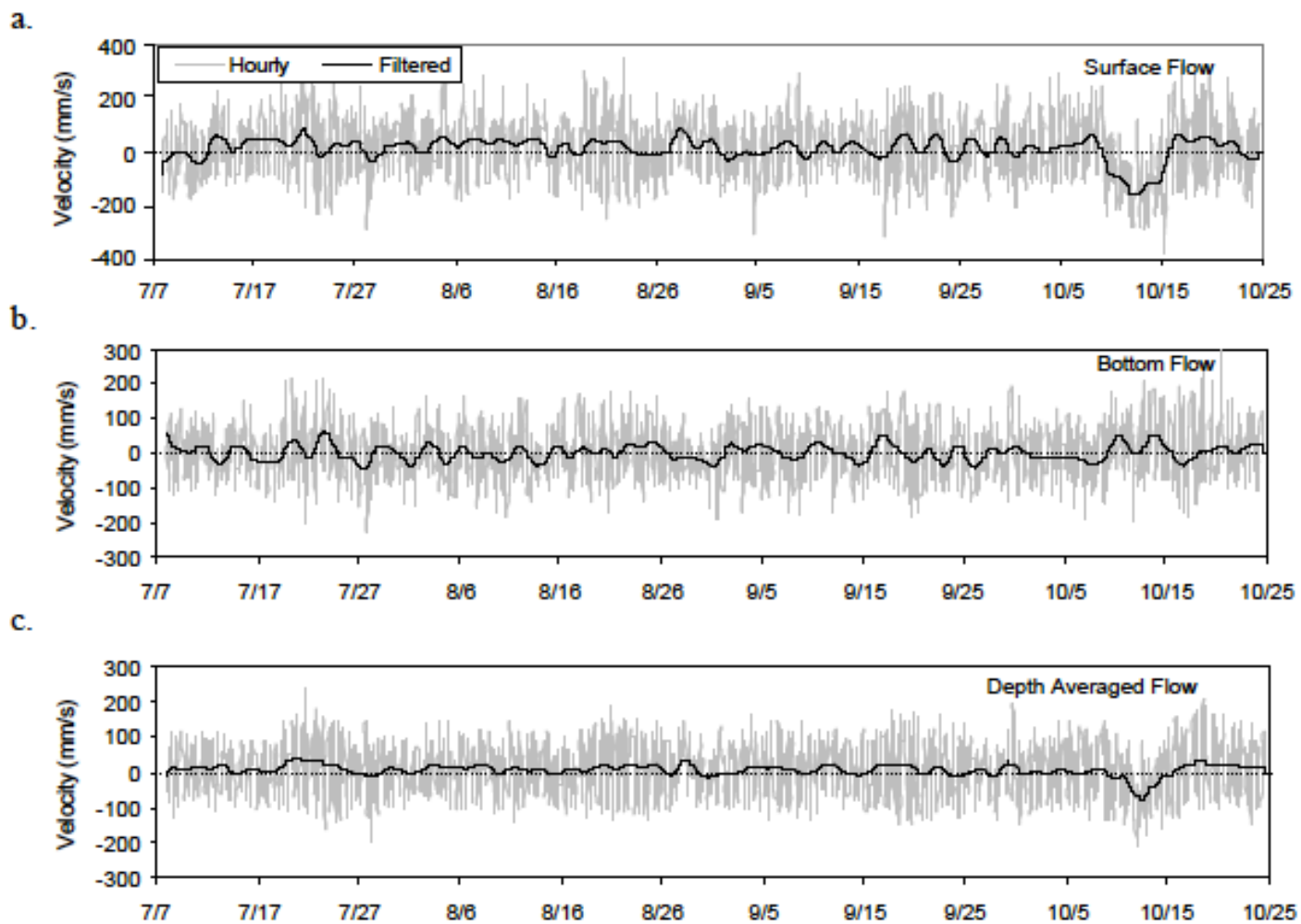


Figure 6. Time series plots of bottom mounted ADCP (acoustic Doppler current profiler) data deployed in the Port Edgewood channel on the Edgewood Shoals (RI) during 2005 (from Kincaid and Bergondo, [2005] NBC report). Grey lines show the actual data, including tidal variations. The dark lines show the residual (de-tided) flow. Residual flow on the shoals oscillates between weakly northward and stagnant, particularly in the bottom water (frame b).

Figure 7. Images of the tilt current meter (TCM) model used in this study. These are designed and built by URI Marine Scientist V. Sheremet. The TCM is a 1m high buoyant cylinder that floats upright in the water column. Water currents cause the TCM to tilt in the direction of flow. The tilt angle is calibrated to flow speed. A total of 21 TCMs were deployed on Edgewood Shoals on March 8, 2010 and recorded usable data at 5 minute intervals through April 30, 2010 or for ~52 days. Data from TCM are omitted due to low signal to noise ratio.

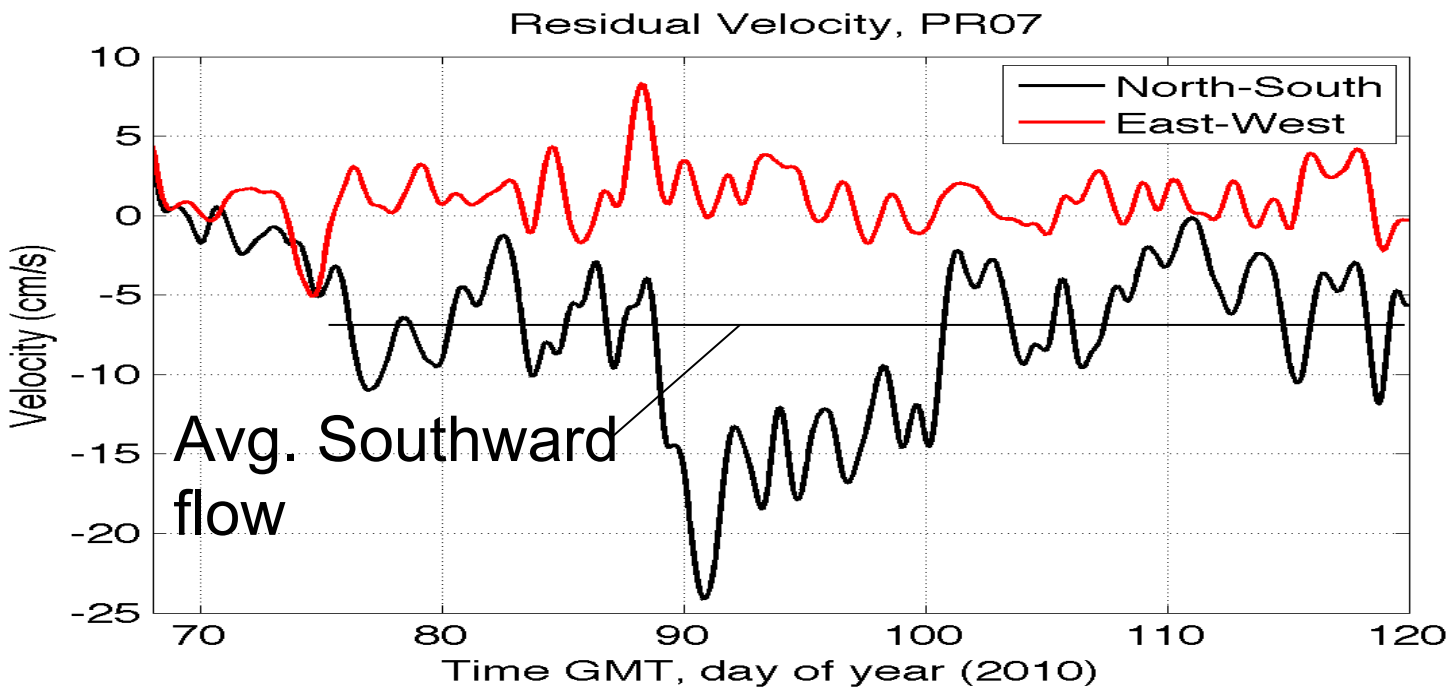


Figure 8. Plot of north-south (black) and east-west velocity values recorded at NBC-sponsored TCM (TCM station 7) during spring, 2010 (see Figure 3). The station is located at the southern end of the cluster of TCMs situated on the eastern side of Edgewood Shoals. The record has been filtered to remove tidal oscillations and the residual record shows average non-tidal outflow (southward) in this region of ~5 to -10 cm/s before (<day 88) the spring 2010 flood and from 0 to -10 cm/s after (>day 104) the flood. During the flood event (days 89-100) the average southward flow is -15 to -25 cm/s. (data from Balt, 2012 manuscript in preparation).

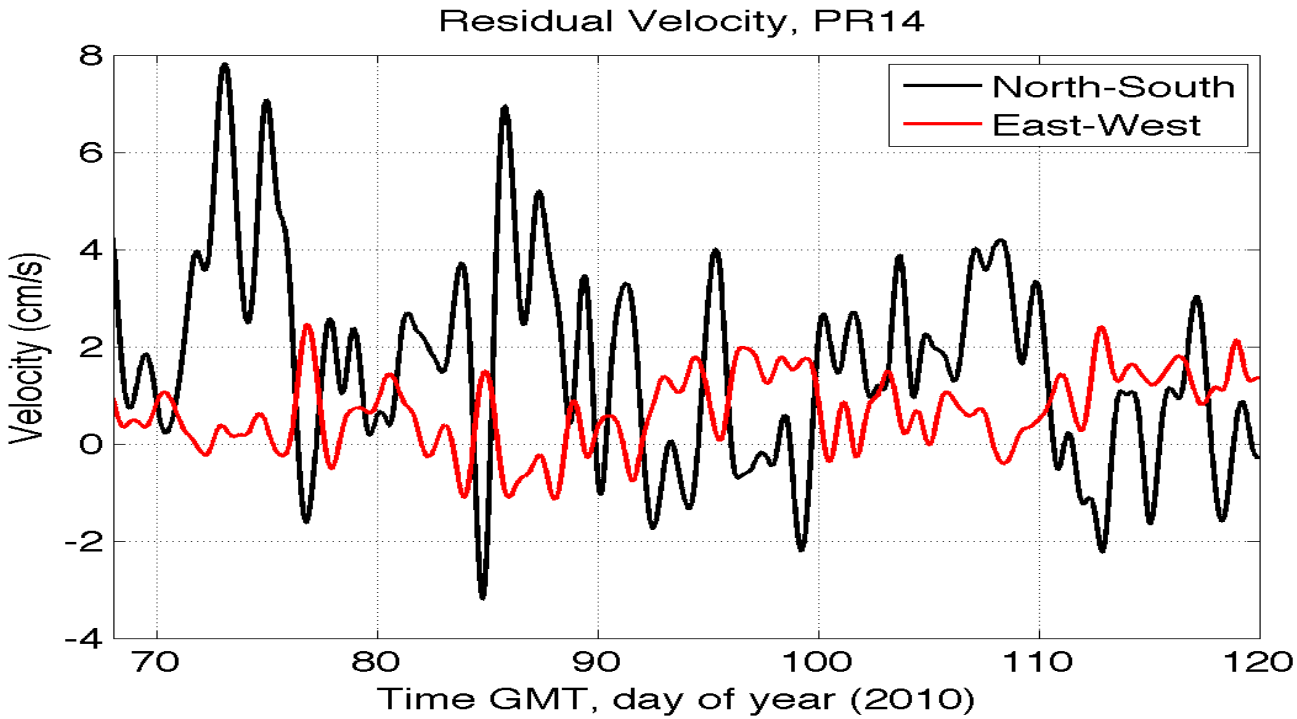


Figure 9. Plot of residual north-south (black) and east-west velocity values recorded at NBC-sponsored TCM shoal locations at TCM station 14. (see Figure 3). Station 14 is on the western shoal. Non-tidal flows in this region are on average northward, which is consistent with a clockwise gyre seen in prior ADCP data (Figure s 5,6). This record does not record a noticeable signal in response to the flood event. A very weak pulse of eastward flow is seen during the this flood period. (data from Balt (2012), manuscript in prep.)

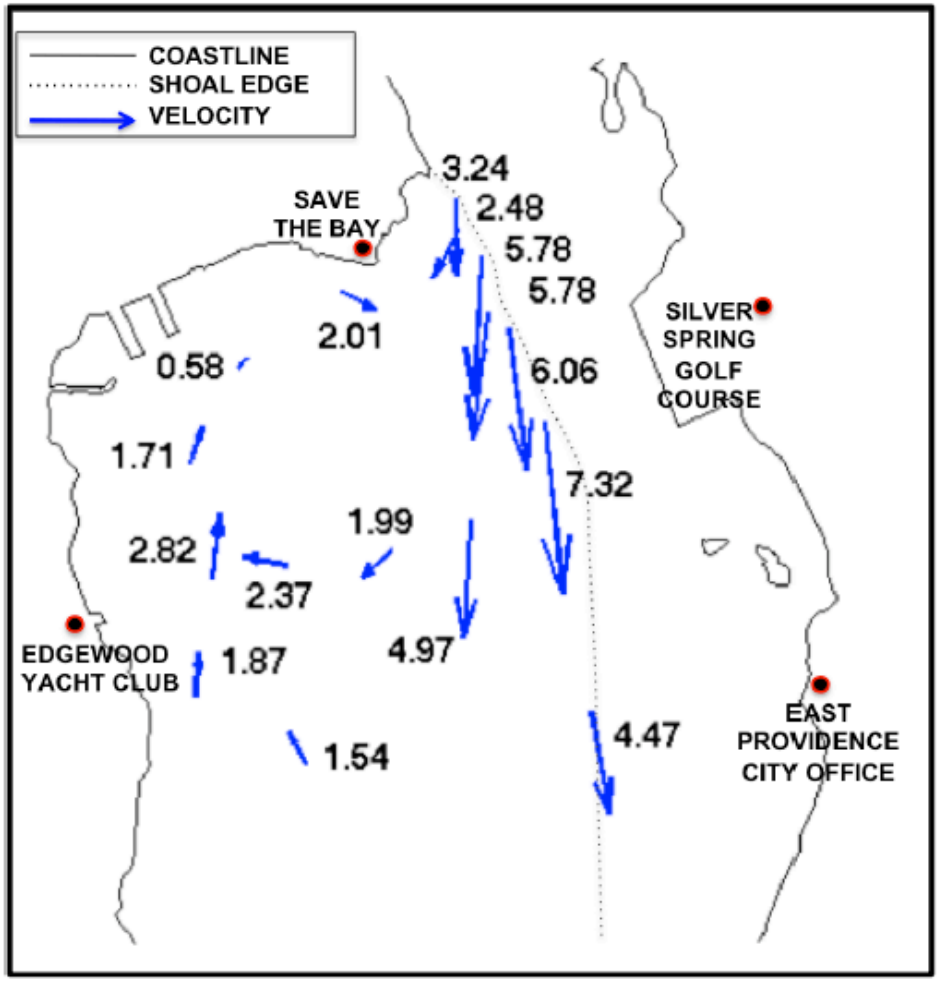


Figure 10. Map showing plots of velocity vectors at each TCM station. The arrows represent flow vectors for data that is averaged over the entire TCM deployment (locations of the tilt current meters (TCMs) deployed in the Providence River during Spring, 2010. Arrows show average directions. Flow speeds (cm/s) are listed by each arrow. On average, a very stable clockwise flow gyre exists on the Edgewood Shoals (figure from Balt (2012), manuscript in prep.).

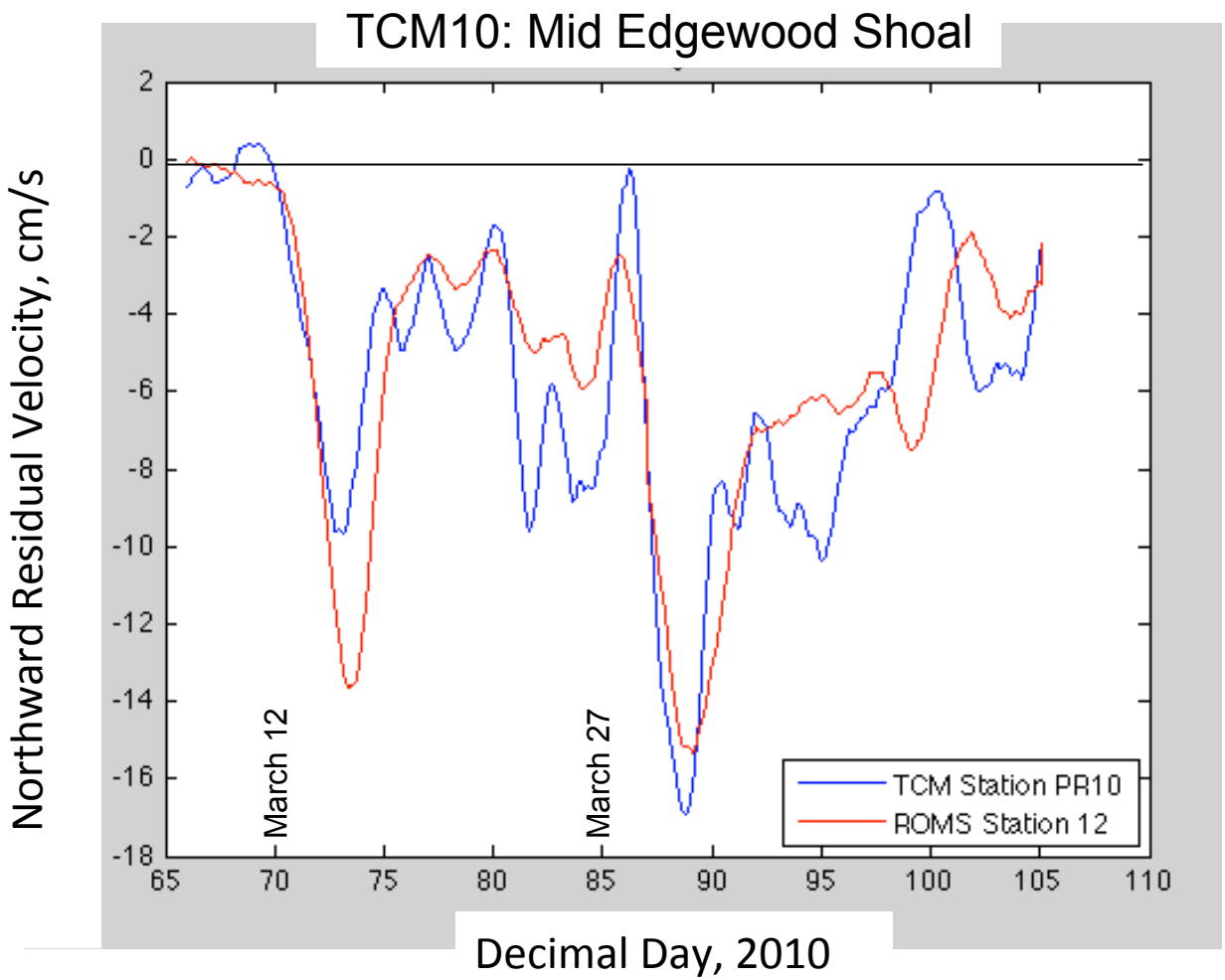


Figure 11. Many hydrodynamic models can readily recreate the instantaneous, or tidal, data records for estuaries. The residual, or non-tidal records are often very challenging to recreate. The Narragansett Bay ROMS does an excellent job of simulating non-tidal flow patterns. This is particularly apparent in the data-model comparison for TCM 10, where ROMS captures both the flood event and the decay of the flood in amplitude and timing. TCM 10 is west of the shoal-channel boundary, midway across the shoal (Figure 3).

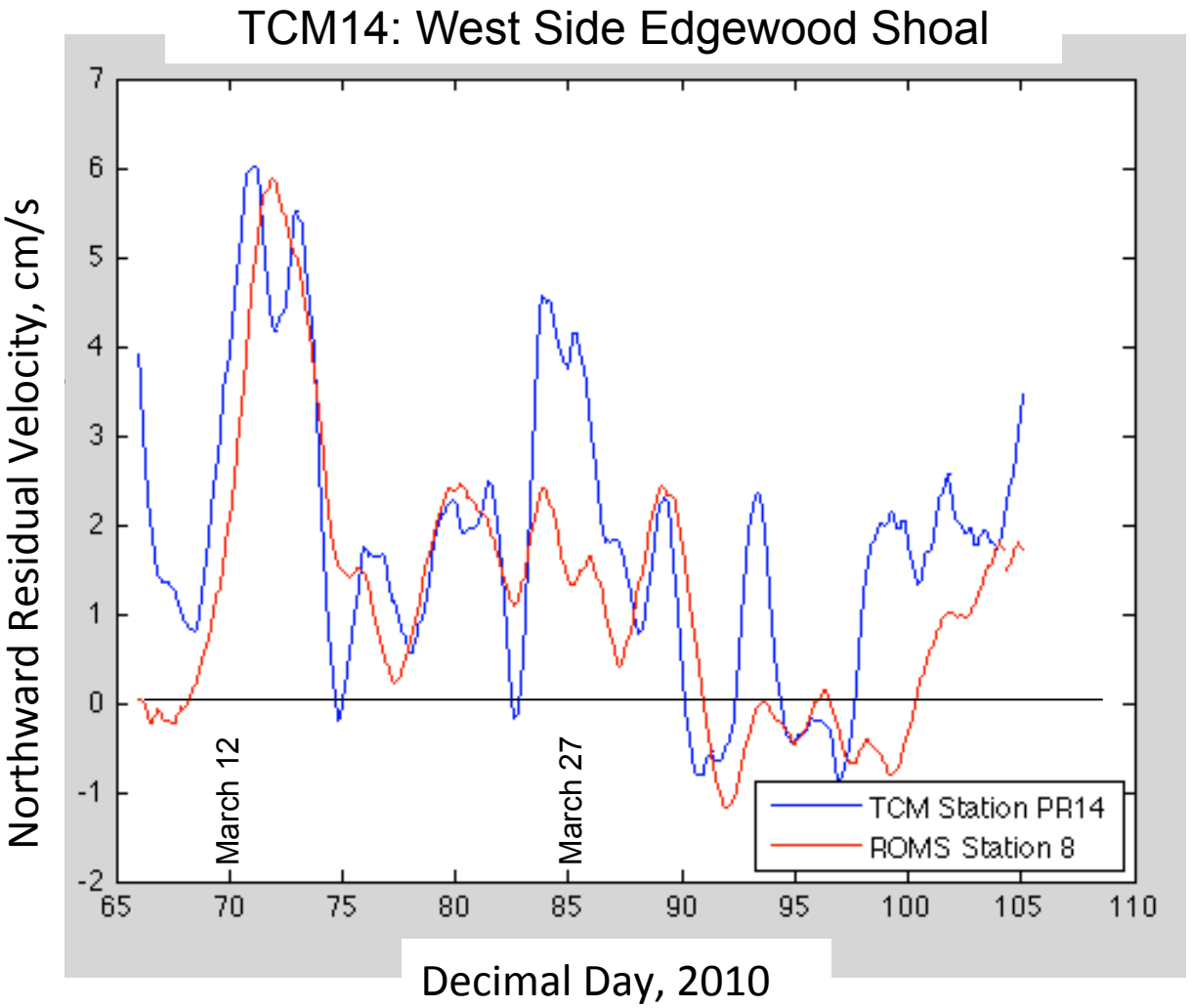


Figure 12. Plot showing the remarkable match between ROMS simulations and the TCM record at station 14 (see Figure 3) located along the western side of the shoals. ROMS captures the magnitude and timing of most of the oscillations recorded in the TCM data.

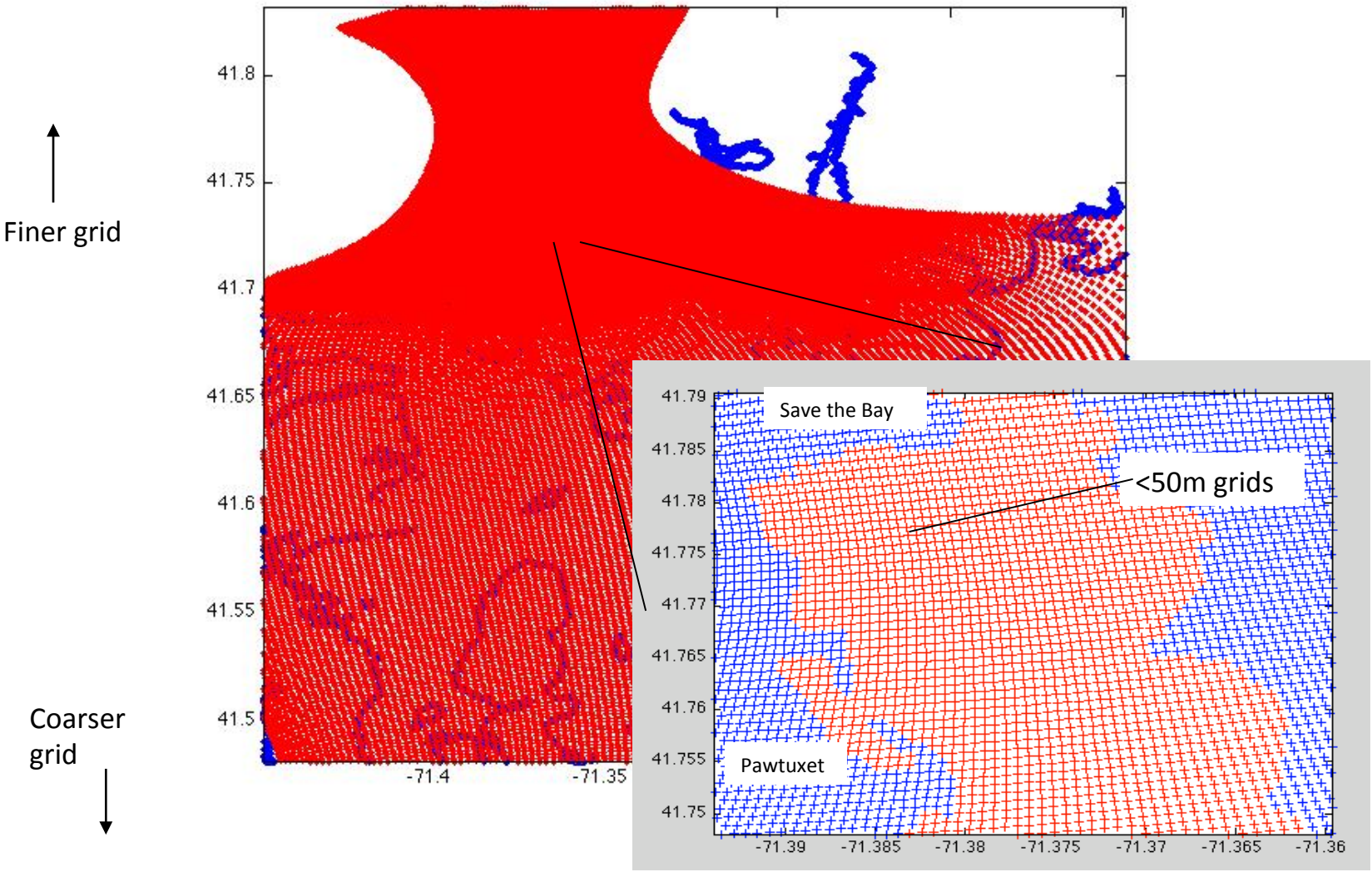
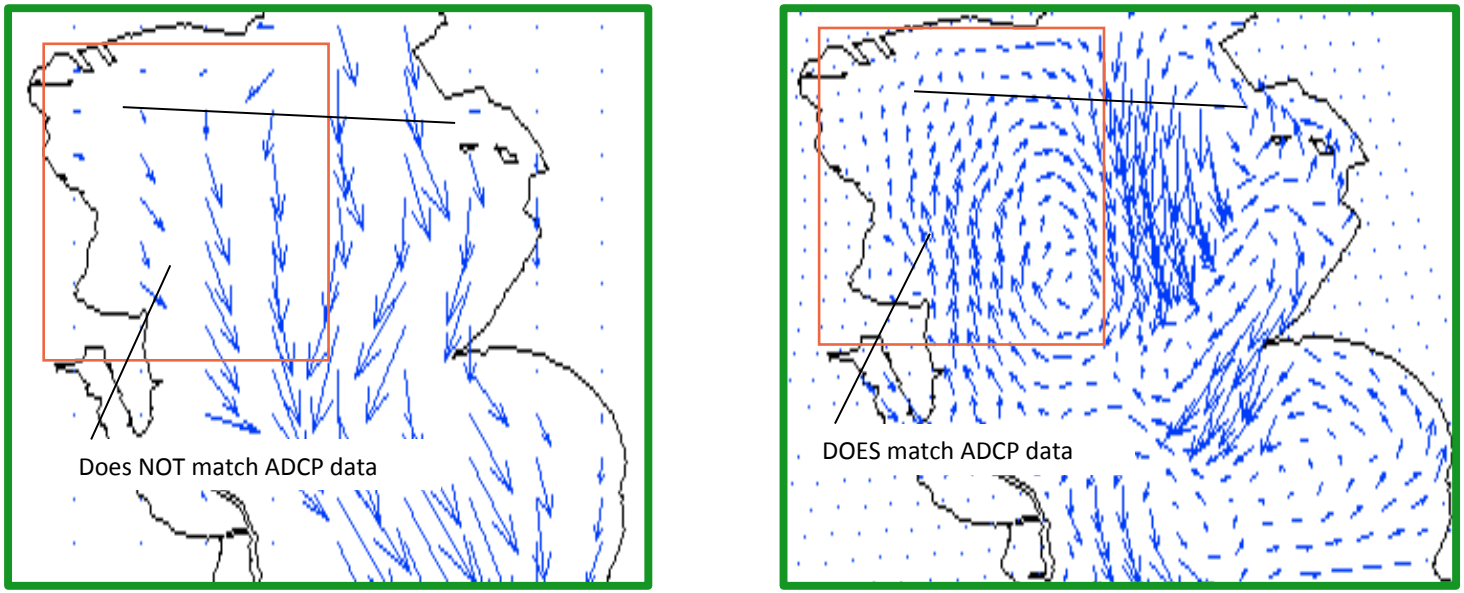


Figure 13. Map showing the computational grid boxes (red squares) for the Full Bay ROMS model. The curvilinear grid allows for finer grid resolution in the northern areas and less resolution nearer the mouth. The inset shows the number of grid boxes that are concentrated on near the Edgewood Shoals (RI). This strategy with the grid development allows for fine resolution in the impacted areas, but without the need for so many boxes in the south, thereby allowing for reasonably sized computational loads.



A ROMS: 150 m grid spacing

B ROMS: 35 m grid spacing

Figure 14. Mapview plots showing vertically averaged flow vectors for the Edgeswood Shoals region (red box) of the Providence River highlight the importance of grid spacing on computational accuracy. The blue arrows indicate the direction and flow speed (length of arrow) for data at each grid node location within the ROMS model domain for similar 2006 forcing conditions, at similar ebb stages of the tide cycle. The plots are shown to compare how different the flow fields are for ROMS runs with coarse grid spacing (A) and fine grid spacing (B). In A, there is no flow field on the western shoals that matches data (e.g., Figure 10). But in the fine grid model run (B), a very stable clockwise flow gyre produces a flow field that matches very closely with trends seen in ADCP data (summarized above). The dark line shows location of ADCP data transect shown in Figure 5.

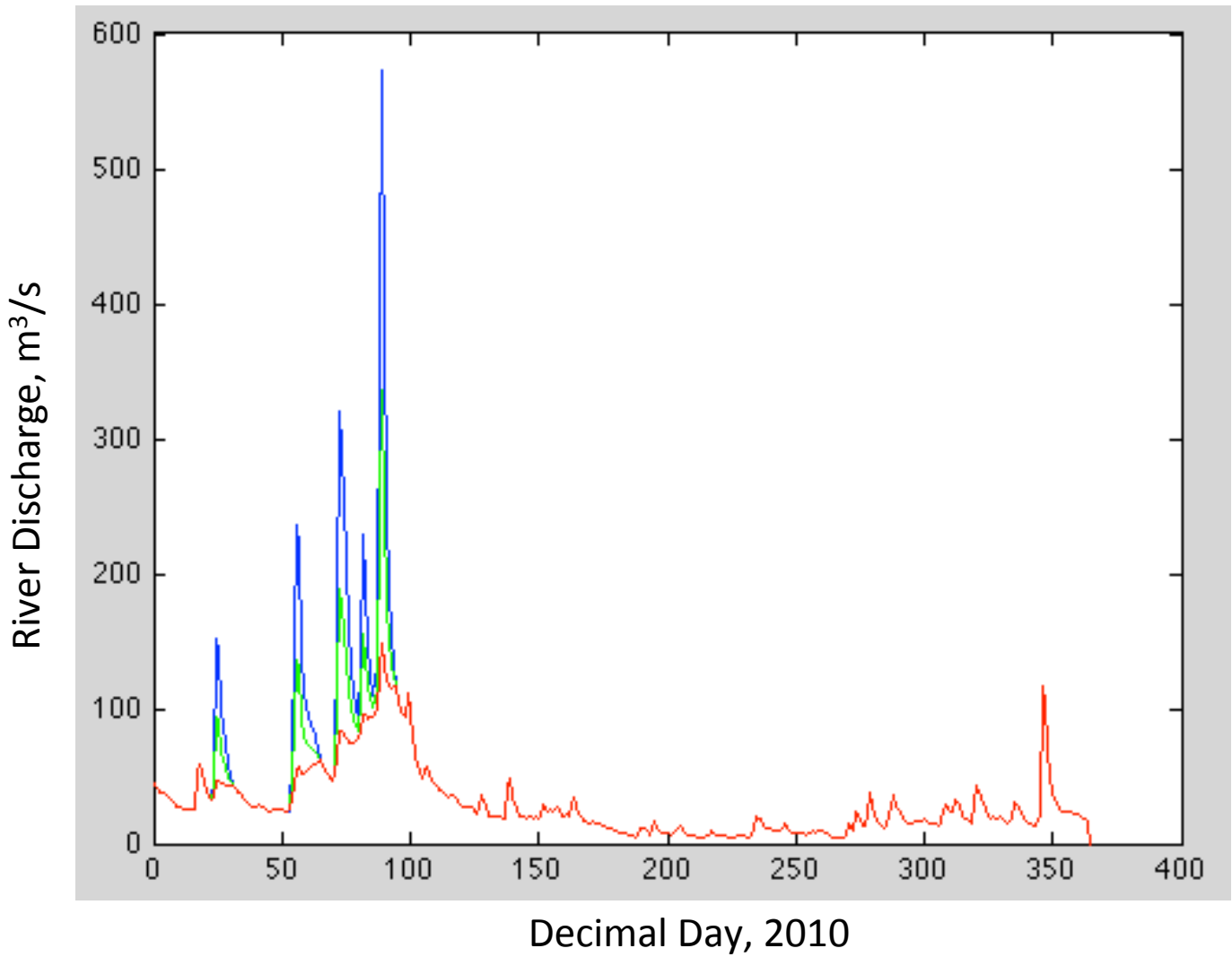


Figure 15. Plot of total Blackstone River discharge during 2010, including the 2010 flood event on decimal day 88. The different color lines represent the discharge records which are either the full flood (blue) or have been reduced by 50% (green) or 95% (red) during the period of precipitation event period (days 30 to 100). After day 90 all discharge lines are the same, and overlay each other. These flood reductions are also applied to all other freshwater river sources.

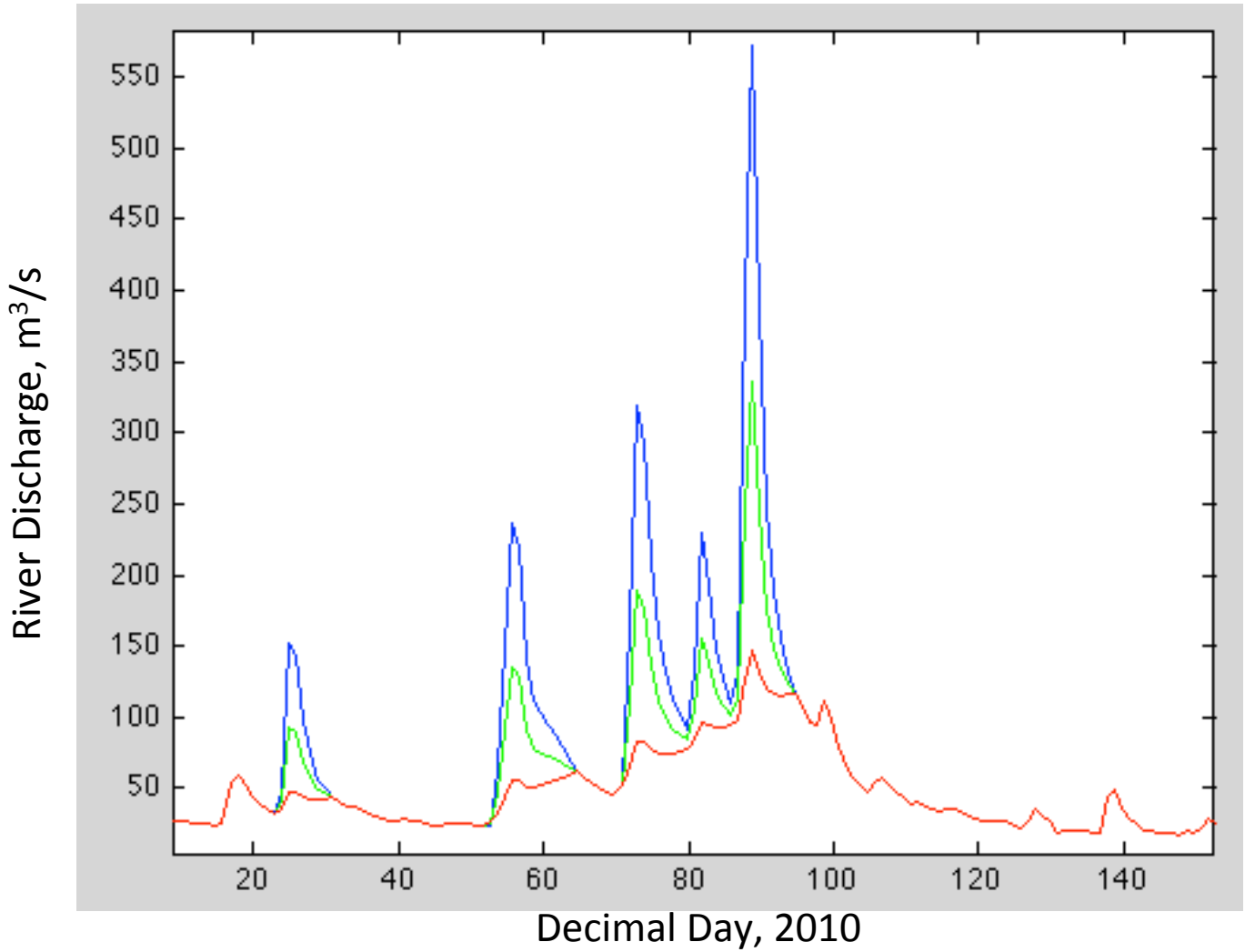


Figure 16. Similar Blackstone River discharge versus day plot to Figure 15, but focused on the spring period.

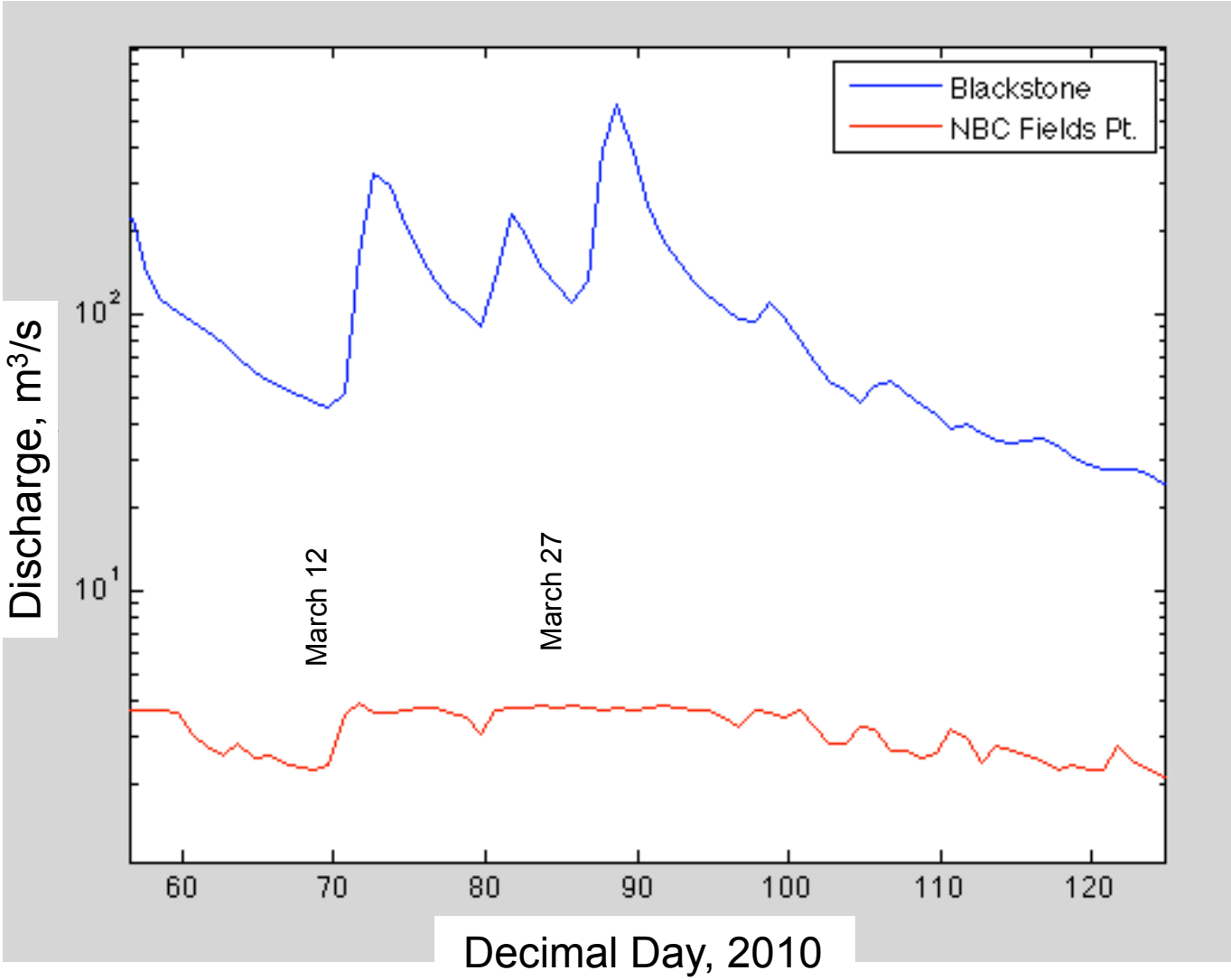


Figure 17. Plot of river discharge for the Blackstone River and the Fields Pt. WWTF for the TCM deployment period in 2010. The plot highlights the fact that the large runoff events in the rivers are not seen in the Fields Pt. discharge record. Discharge from the treatment facilities varies between ~2-3 CMS during both 2010 Flood simulations and idealized model simulations.

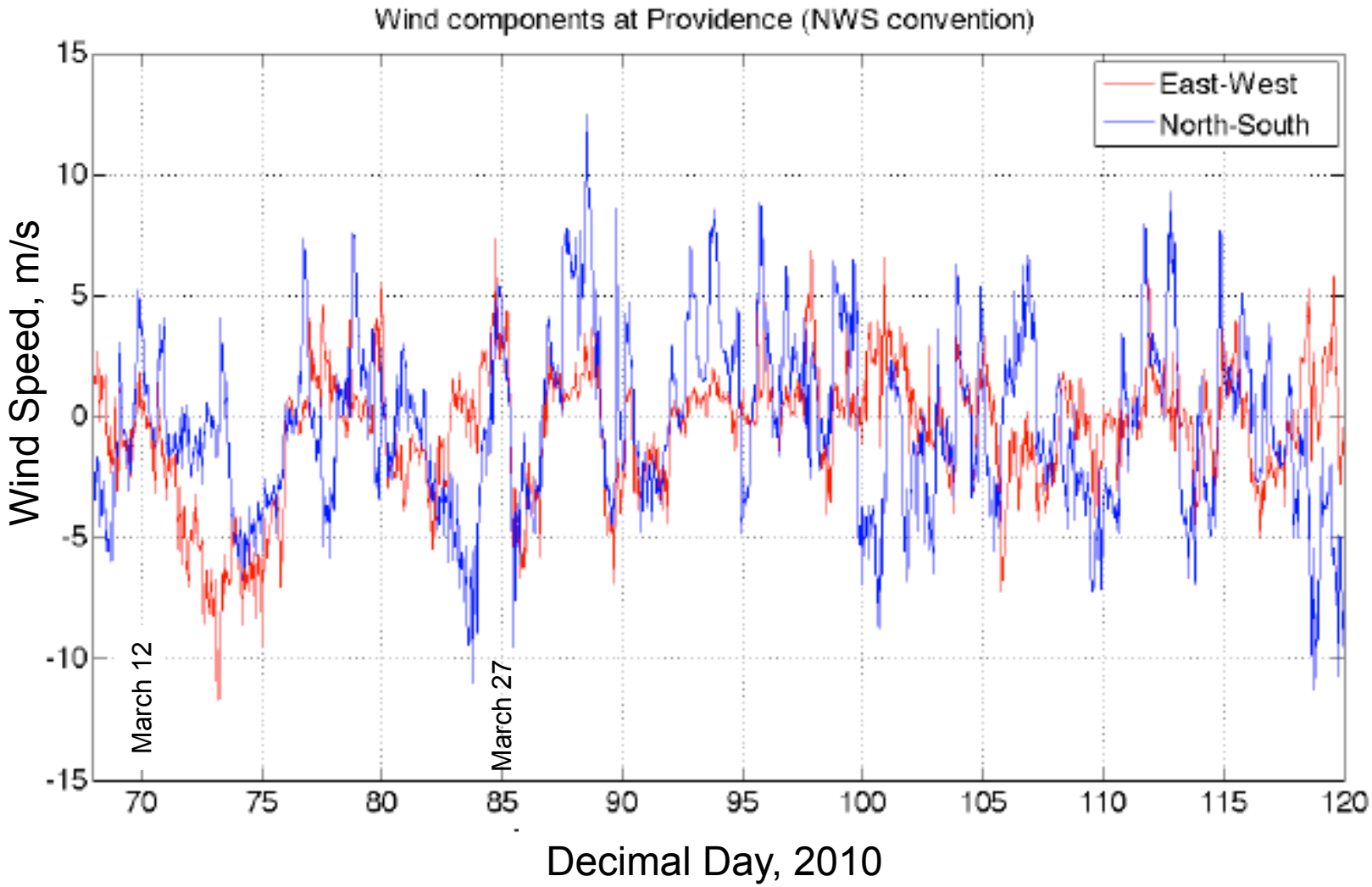


Figure 18. Plot of northward blowing (positive)(blue) and eastward blowing (positive) components of the wind vector measured in Providence for the spring period in 2010, showing the range in wind forcing applied to the 2010 (non-idealized) ROMS model simulation.

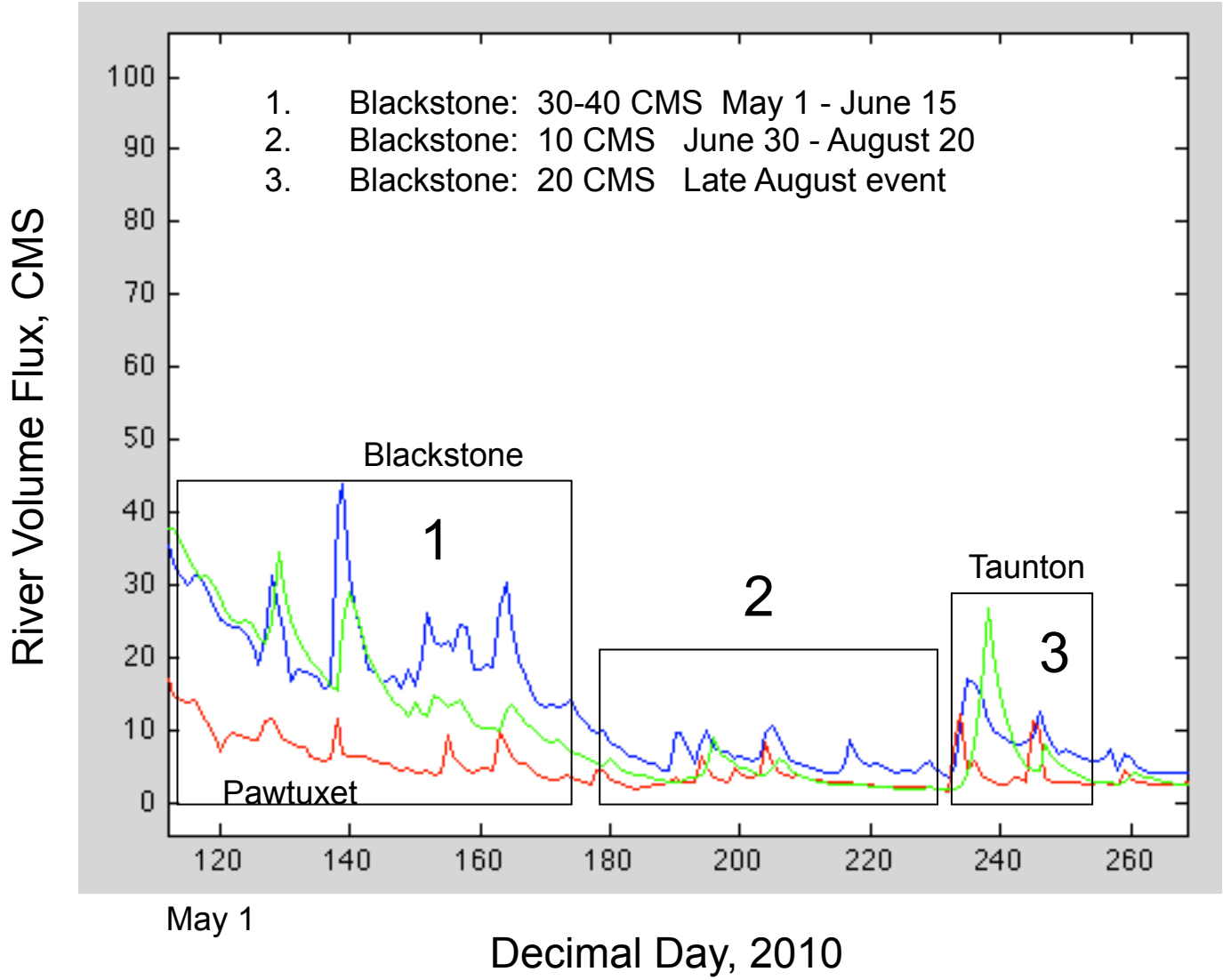
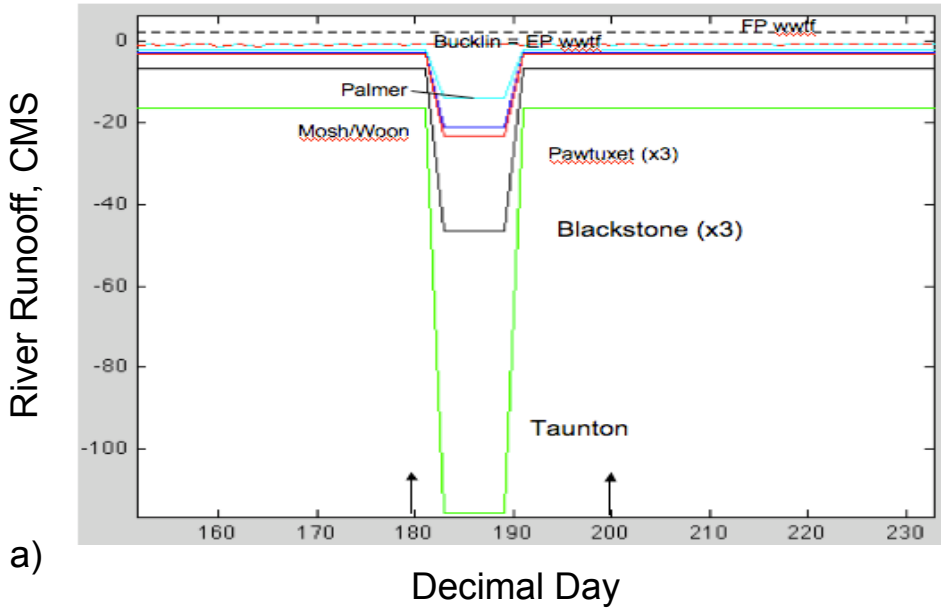
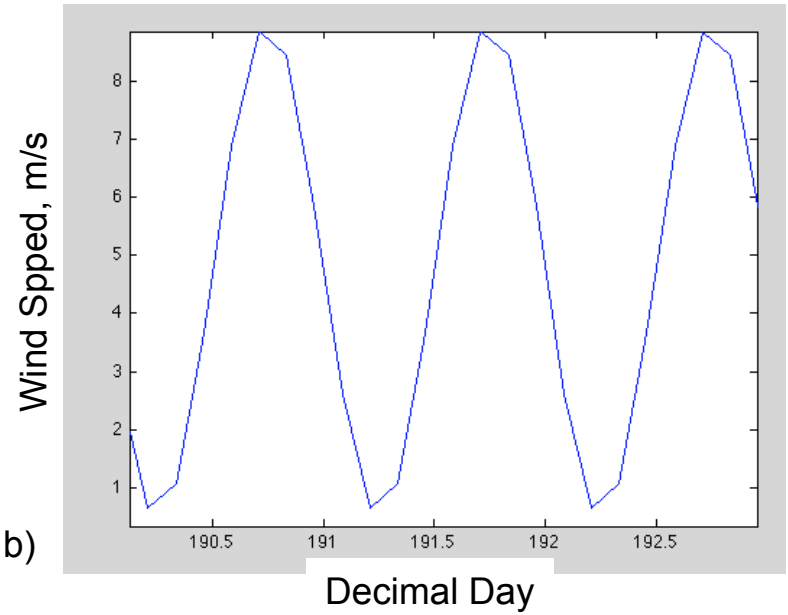


Figure 19. A series of idealized chemical transport ROMS simulations has been completed to show how various characteristic environmental conditions influence the long term dispersion of each major nutrient source to Narragansett Bay. Summer conditions for runoff for major rivers are shown in this plot. Three regimes for summer runoff in the Blackstone are outlined. A goal of this set of runs is to test how chemical plumes from all freshwater sources during these runoff magnitudes, and higher magnitude events, or what would be called late spring or early summer high discharge events, disperse through the summer period.





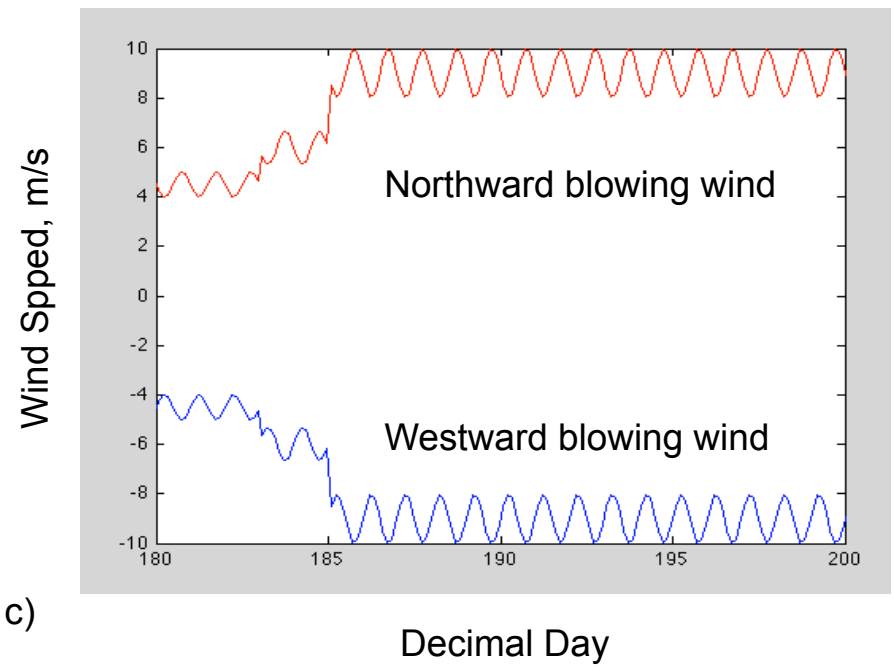
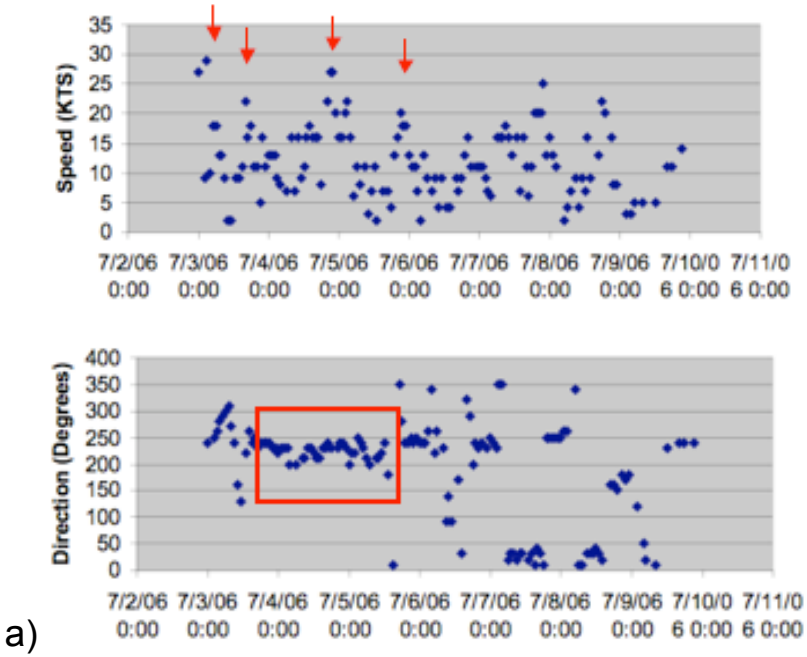
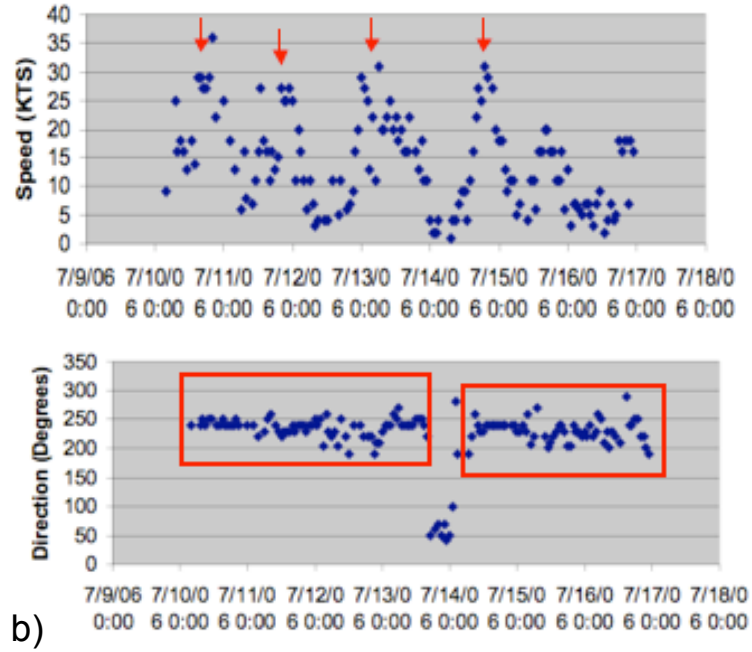


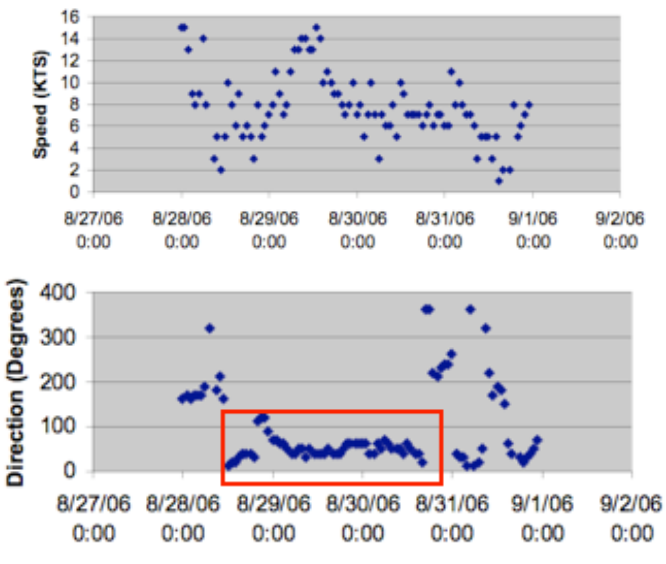
Figure 20. ROMS runs simulated Bay flow and hydrography processes using 2010 environmental conditions from Jan. 31 2010 through early summer, 2010. This end point was subsequently used to run a series of 20 day long idealized ROMS simulations using a range of representative forcing conditions. A) Average runoff values are entered for all major rivers based on ranges in Figure 19. Simulations also consider the response of the system to high amplitude runoff pulses such as shown in (A), where a background value changes to a 5 day pulse of higher runoff before returning to the background flow. Values are chose for the Blackstone and this runoff is scaled to other rivers based on USGS average runoff rations between RI rivers. Various simplified wind conditions are utilized including (B) a diurnal oscillation (e.g., seabreeze style wind) and (C) wind events that come on like the runoff pulse at day 185, with diurnal oscillations in magnitude and direction.



a)



b)



c)

Figure 21. Idealized wind conditions are developed that cover the styles of wind forcing seen for Narragansett Bay. (wind direction expressed here as direction blowing from). a) Records shows summers exhibit a typical seabreeze with prevailing northeastward blowing winds that cycle in magnitude (1 kt = 0.514 m/s) between 5 and 15 m/s. This is shown here in July records from 2006 PORTS data. This record shows a common southward component to the wind. b) A very persistent north to northeastward blowing seabreeze varys from 1 to 15 m/s July 2006. c) Another common Bay pattern is westward blowing wind.

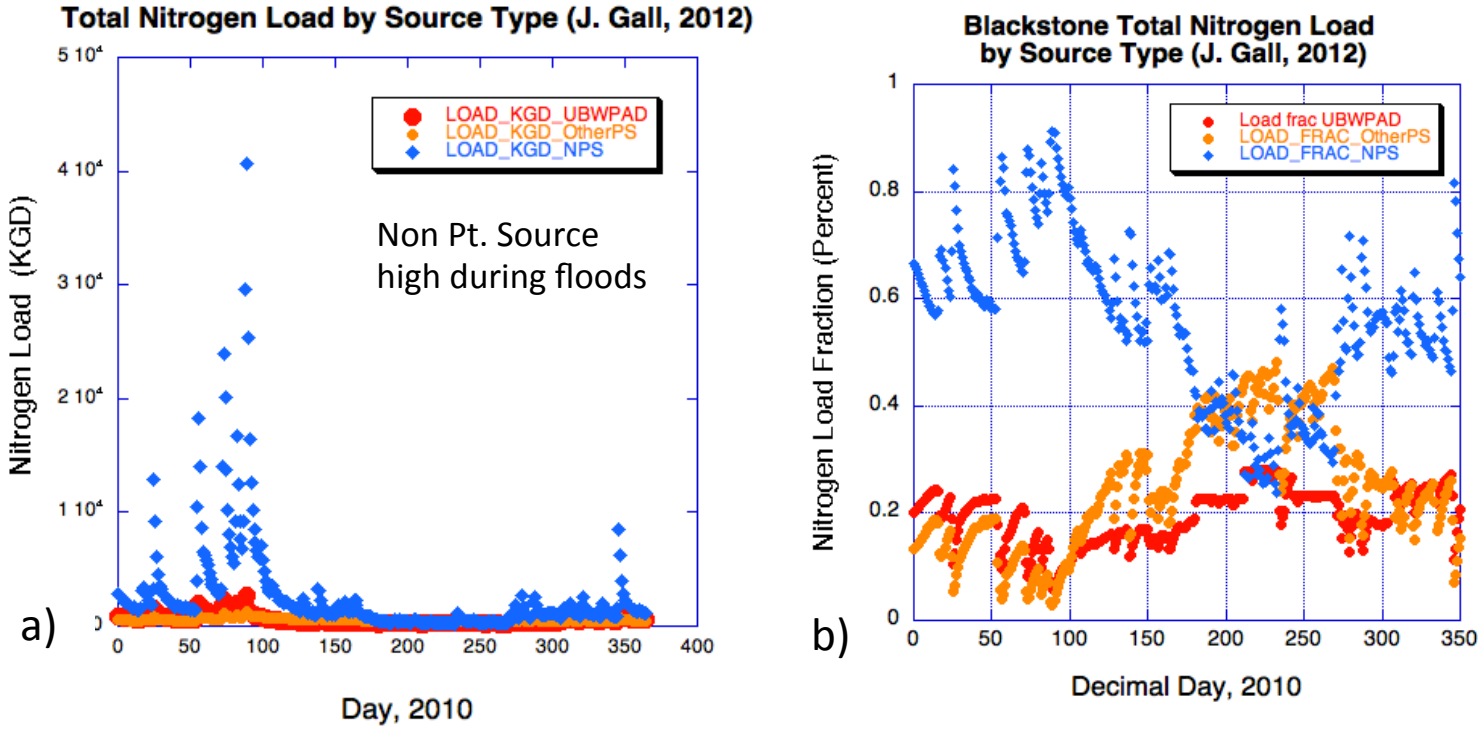


Figure 22. a) Plot of nitrogen loading to the Bay from the Blackstone River on a daily basis in 2010. Nitrogen input to the Bay varies with discharge magnitude, as do the percent contributions to the total nitrogen load from point sources versus non-point sources. Researchers at University of Massachusetts (Prof. P. Reese) have developed a TMDL model for the Blackstone River which outputs the magnitude of nutrient levels entering Narragansett Bay from point sources (given as the Upper Blackstone WWTF (red) and other point sources (orange)) and from all other non-point sources (blue). b) Plot of the percent fraction of each nutrient source entering the Bay through the Blackstone River as a function of day in 2010, predicted from UMass. Blackstone TMDL Model (data provided by P. Reese, Univ. Mass.). During high runoff periods non-point sources (blue) contribute higher levels as a percent of total. During low flow, summer periods, the percent contribution from other point sources increases.

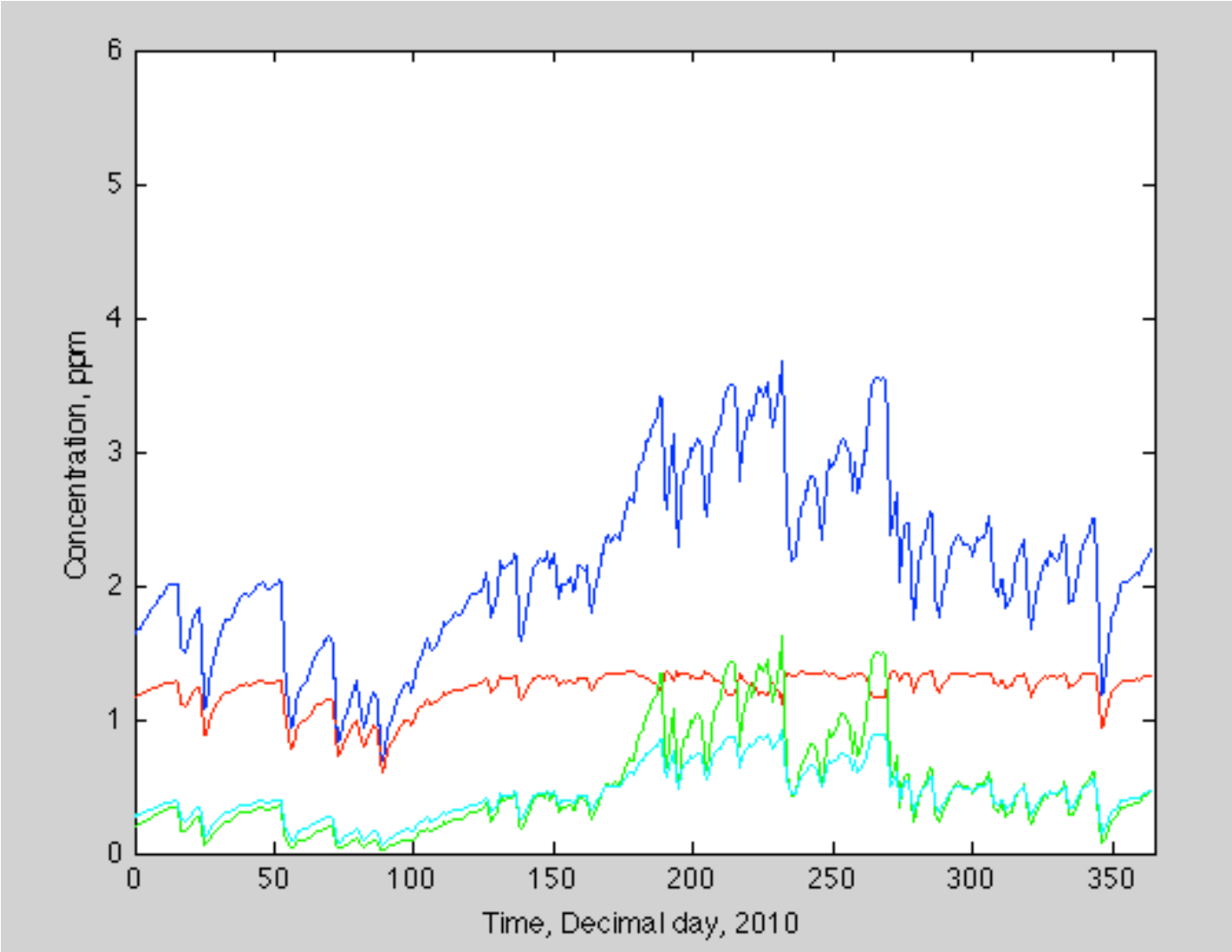


Figure 23. Plot of total nutrient concentrations (blue) in source waters for Blackstone River for the 2010 Flood simulation cases, as supplied from non-point sources (red), other point sources (green) and the Upper Blackstone WWTF (cyan).

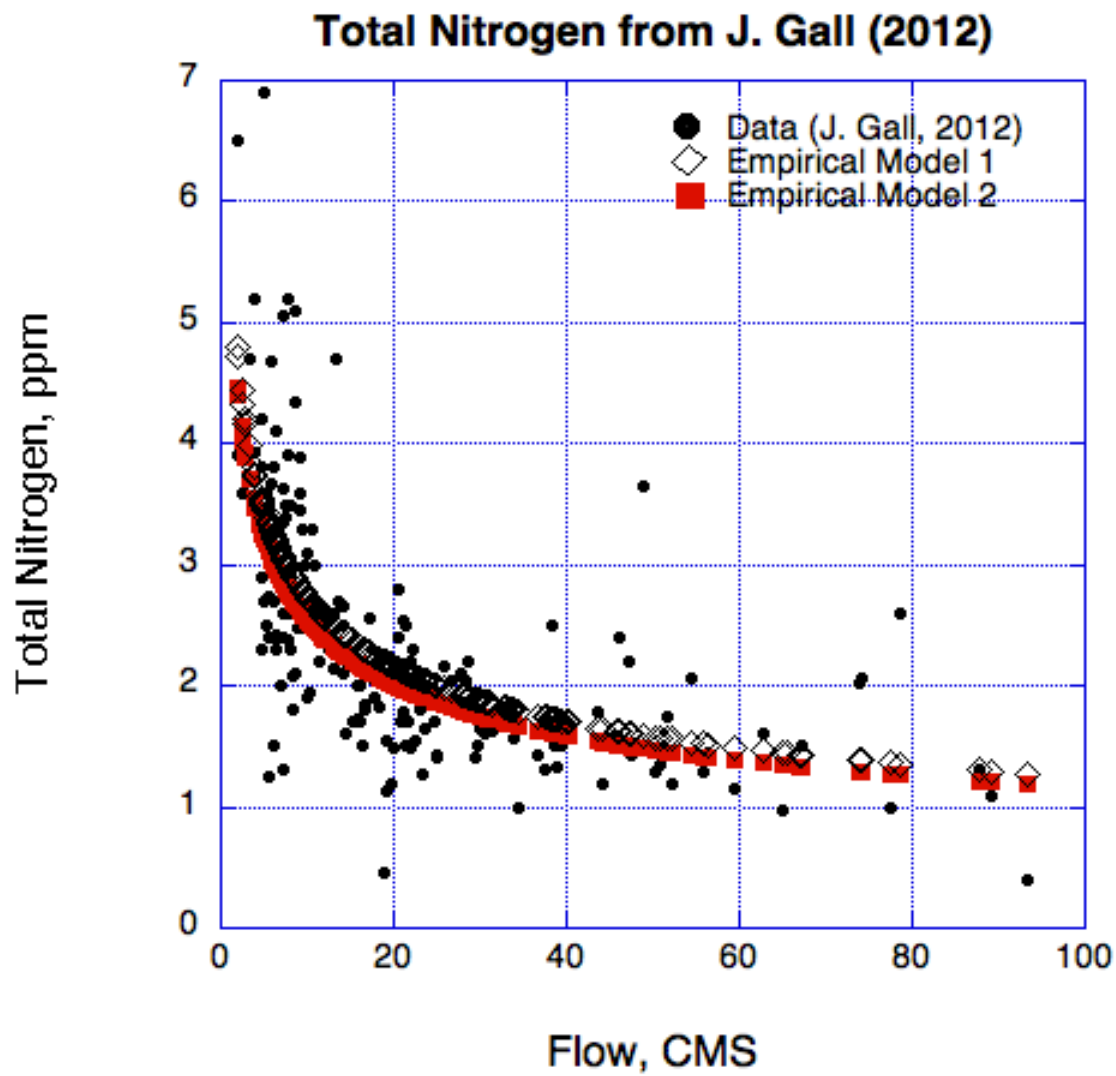
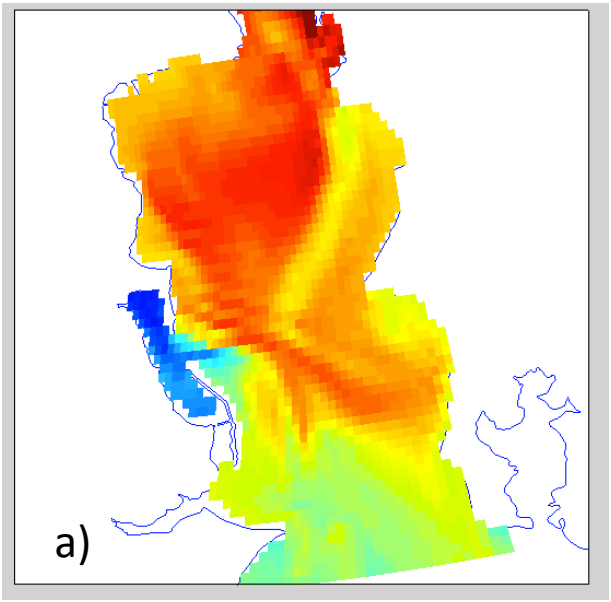


Figure 24. For the 2010 Flood simulation cases, we use information supplied by the U. Mass. Blackstone River TMDL Model. For other rivers we estimate varying concentrations by developing an empirical model for nutrient concentration in the supply water versus discharge level. The empirical model utilizes information for 2010 from the U. Mass Group, and and is used then to calculate each rivers nutrient concentration in 2010 based on that rivers runoff time series.



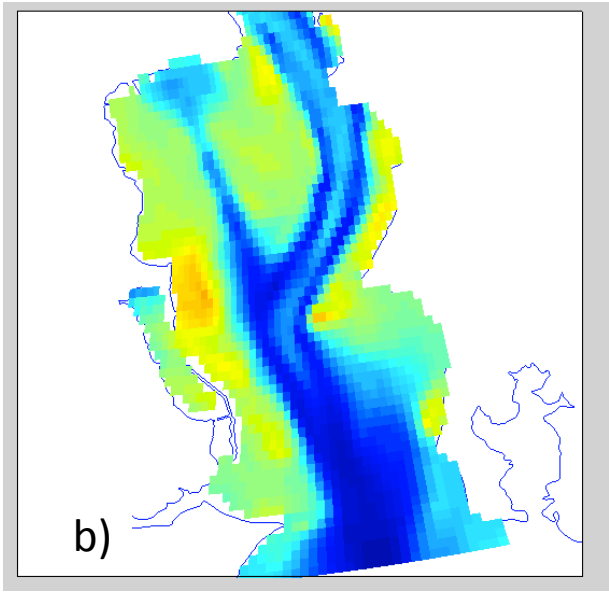


Figure 25 . Close-up images of dye dispersion in the Providence River, near Fields Pt and Edgewood Shoals for run 10 (constant 40 CMS runoff through the **Blackstone River**, other rivers scale to this value; no applied wind) a) Blackstone River dye in the near surface water is strongly dispersed when entering this region of the river. Red=0.5 concentration. b) Blackstone River dye moving in the bottom water accumulates on Edgewood Shoals.

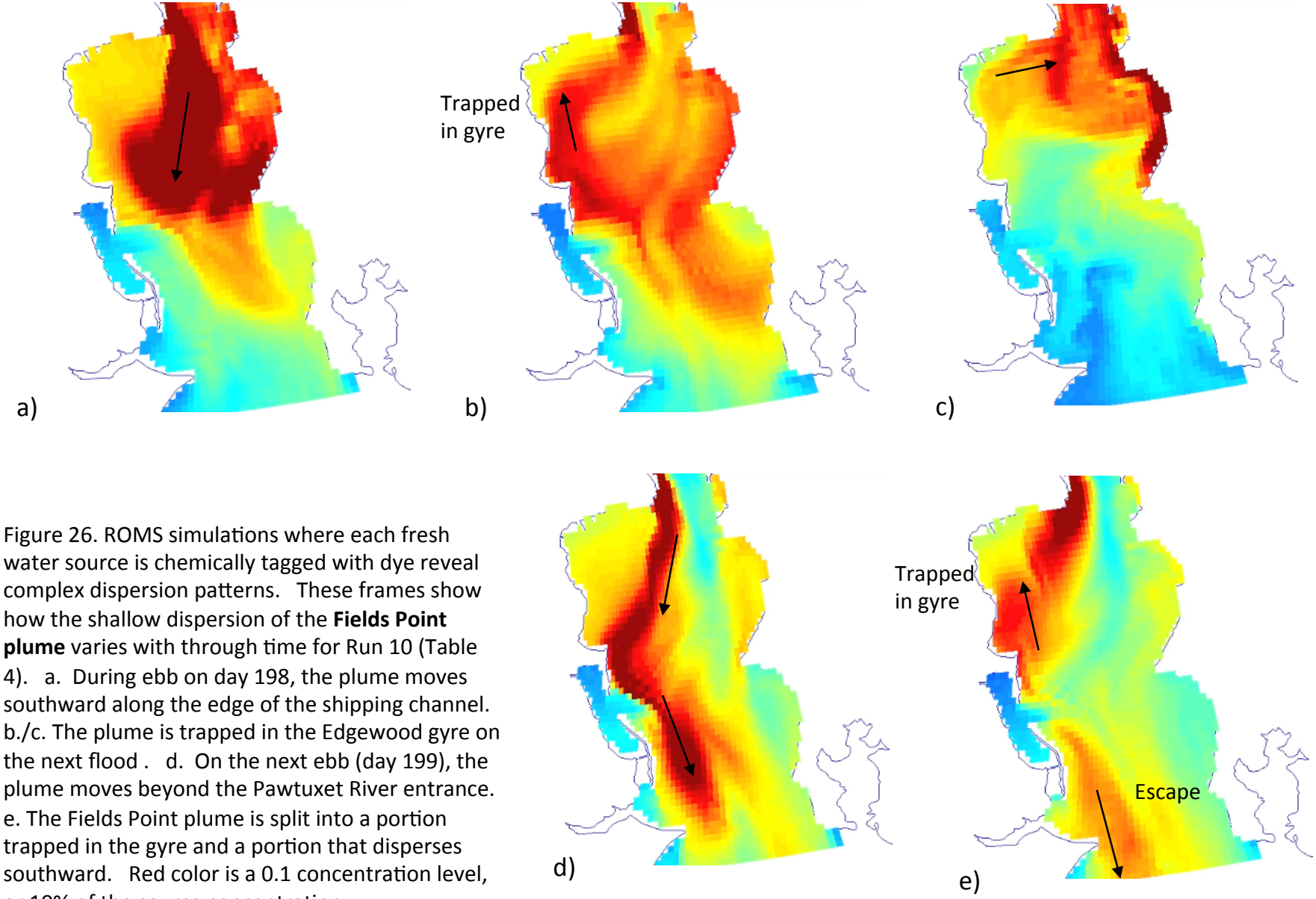


Figure 26. ROMS simulations where each fresh water source is chemically tagged with dye reveal complex dispersion patterns. These frames show how the shallow dispersion of the **Fields Point plume** varies with through time for Run 10 (Table 4). a. During ebb on day 198, the plume moves southward along the edge of the shipping channel. b./c. The plume is trapped in the Edgewood gyre on the next flood . d. On the next ebb (day 199), the plume moves beyond the Pawtuxet River entrance. e. The Fields Point plume is split into a portion trapped in the gyre and a portion that disperses southward. Red color is a 0.1 concentration level, or 10% of the source concentration.

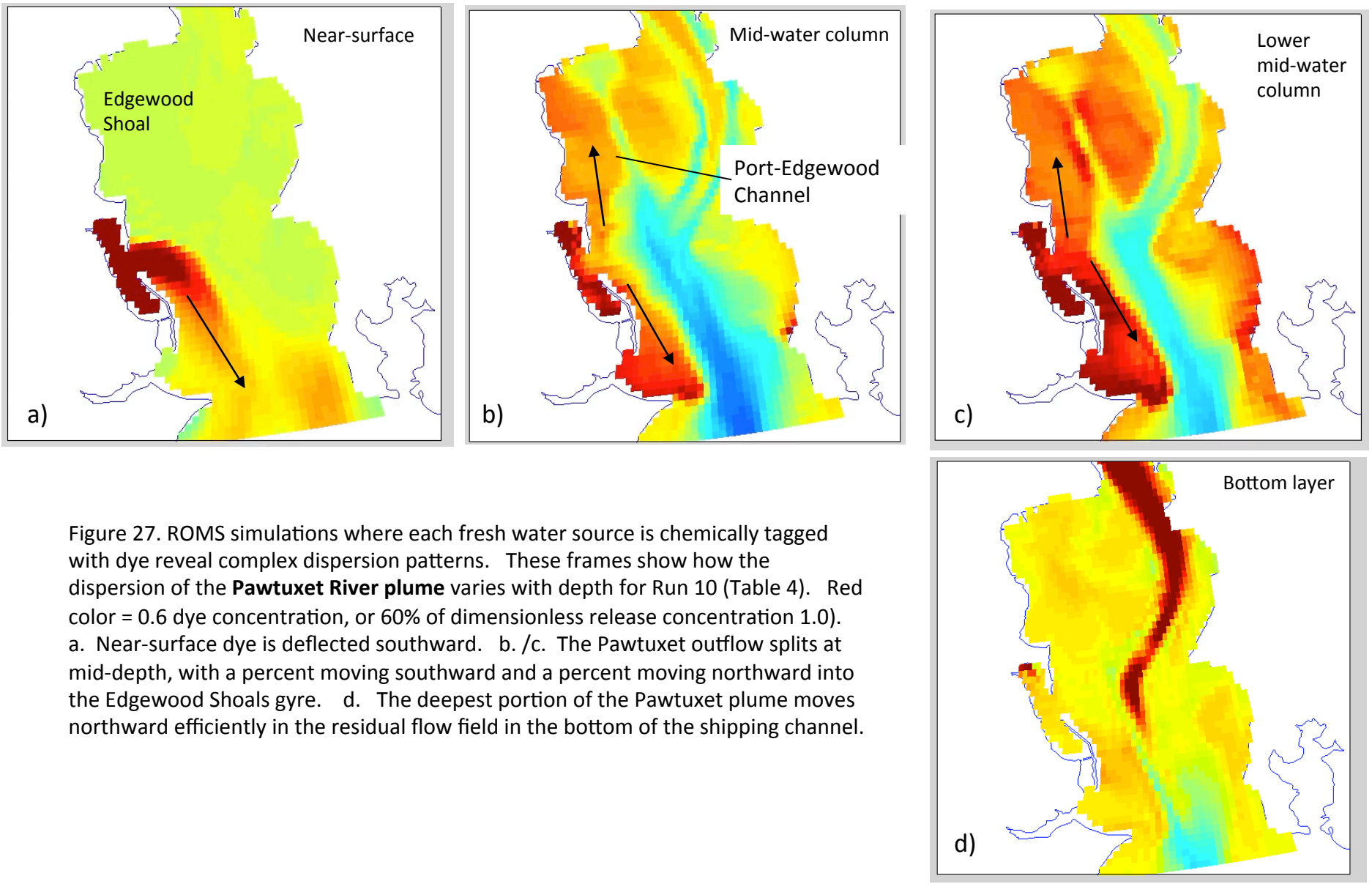


Figure 27. ROMS simulations where each fresh water source is chemically tagged with dye reveal complex dispersion patterns. These frames show how the dispersion of the **Pawtuxet River plume** varies with depth for Run 10 (Table 4). Red color = 0.6 dye concentration, or 60% of dimensionless release concentration 1.0). a. Near-surface dye is deflected southward. b. /c. The Pawtuxet outflow splits at mid-depth, with a percent moving southward and a percent moving northward into the Edgewood Shoals gyre. d. The deepest portion of the Pawtuxet plume moves northward efficiently in the residual flow field in the bottom of the shipping channel.

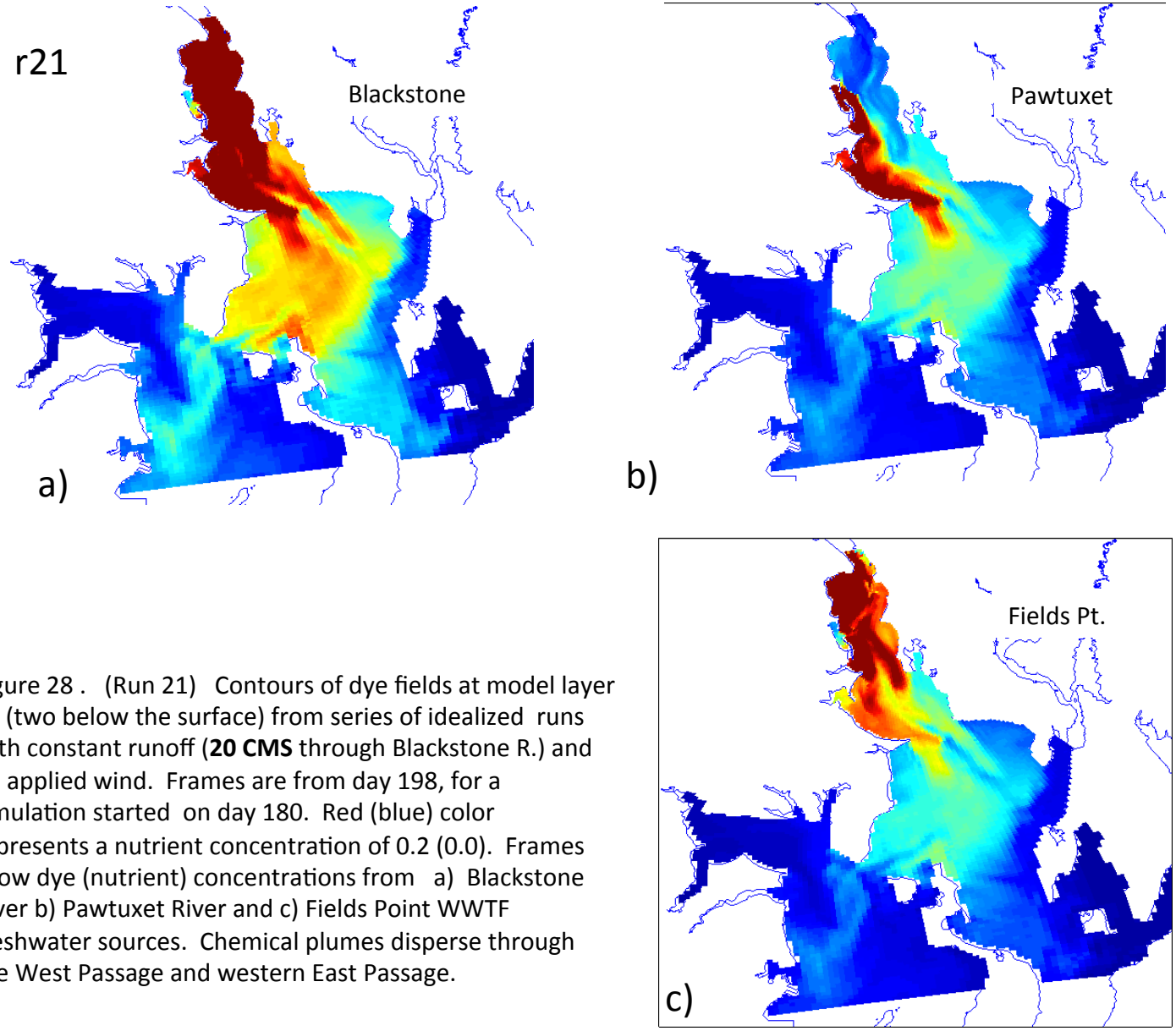


Figure 28 . (Run 21) Contours of dye fields at model layer 13 (two below the surface) from series of idealized runs with constant runoff (**20 CMS** through Blackstone R.) and no applied wind. Frames are from day 198, for a simulation started on day 180. Red (blue) color represents a nutrient concentration of 0.2 (0.0). Frames show dye (nutrient) concentrations from a) Blackstone River b) Pawtuxet River and c) Fields Point WWTF freshwater sources. Chemical plumes disperse through the West Passage and western East Passage.

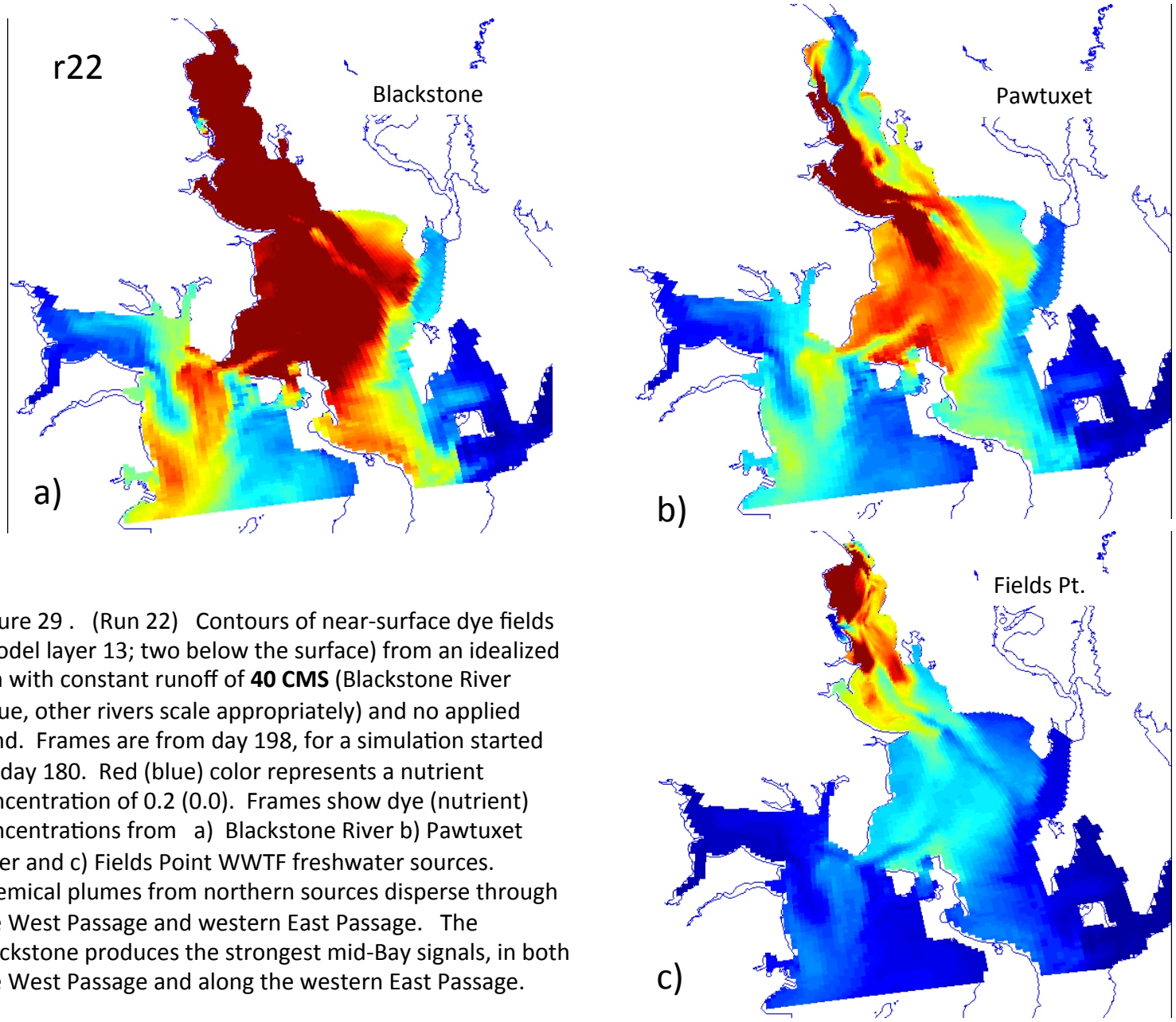
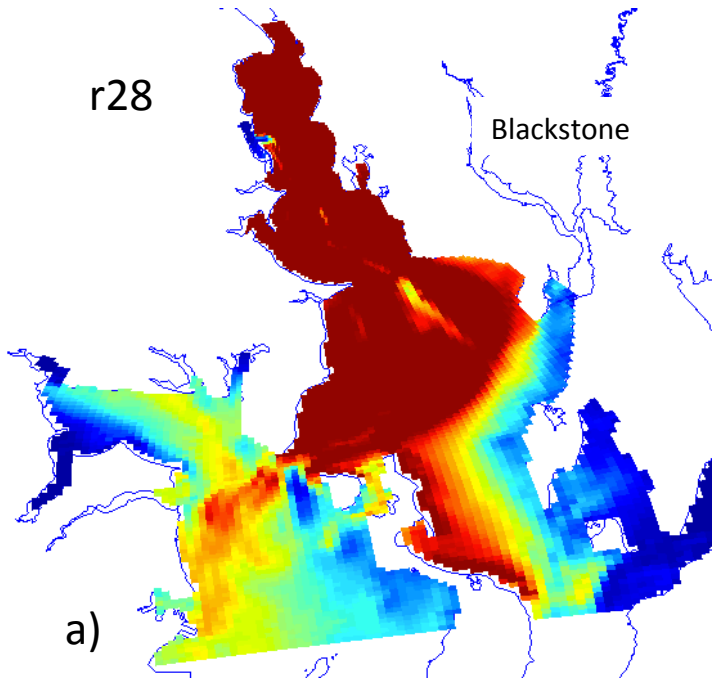
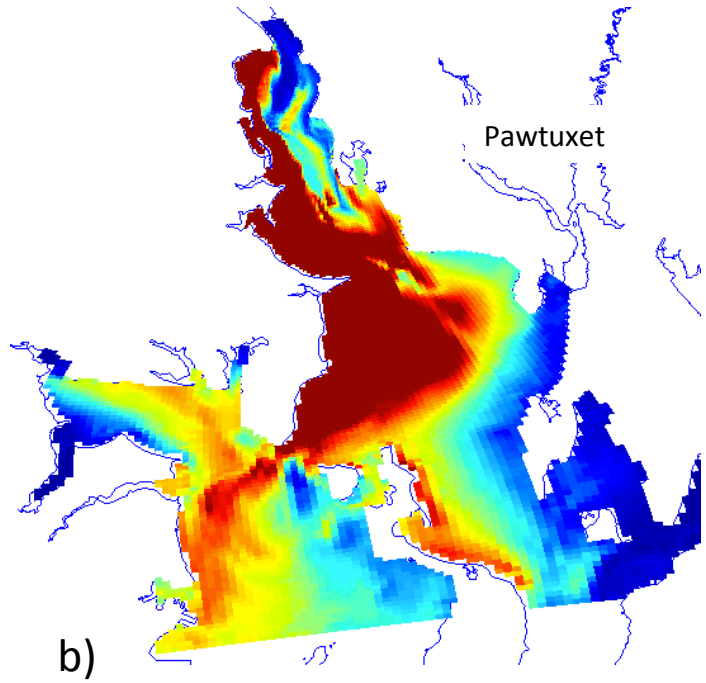


Figure 29 . (Run 22) Contours of near-surface dye fields (model layer 13; two below the surface) from an idealized run with constant runoff of **40 CMS** (Blackstone River value, other rivers scale appropriately) and no applied wind. Frames are from day 198, for a simulation started on day 180. Red (blue) color represents a nutrient concentration of 0.2 (0.0). Frames show dye (nutrient) concentrations from a) Blackstone River b) Pawtuxet River and c) Fields Point WWTF freshwater sources. Chemical plumes from northern sources disperse through the West Passage and western East Passage. The Blackstone produces the strongest mid-Bay signals, in both the West Passage and along the western East Passage.





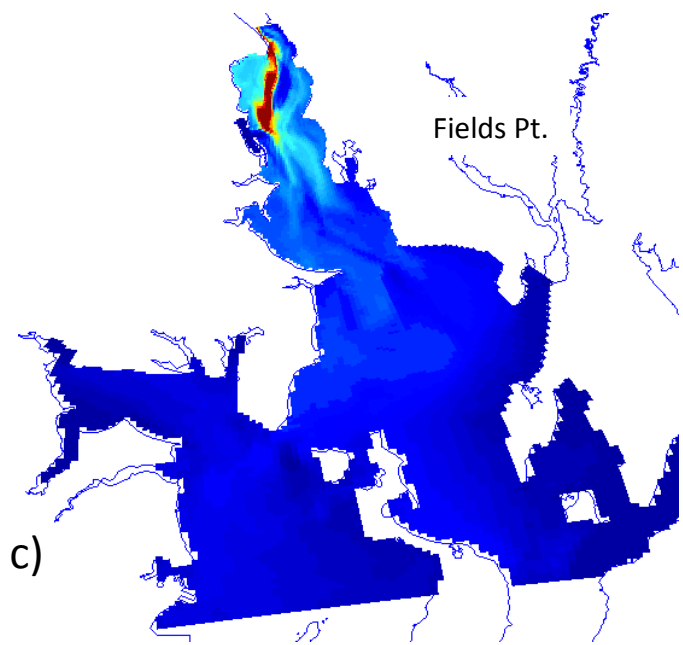
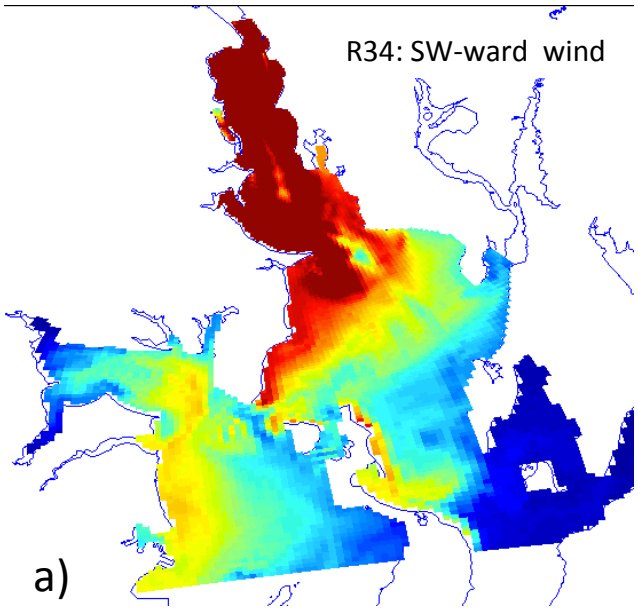
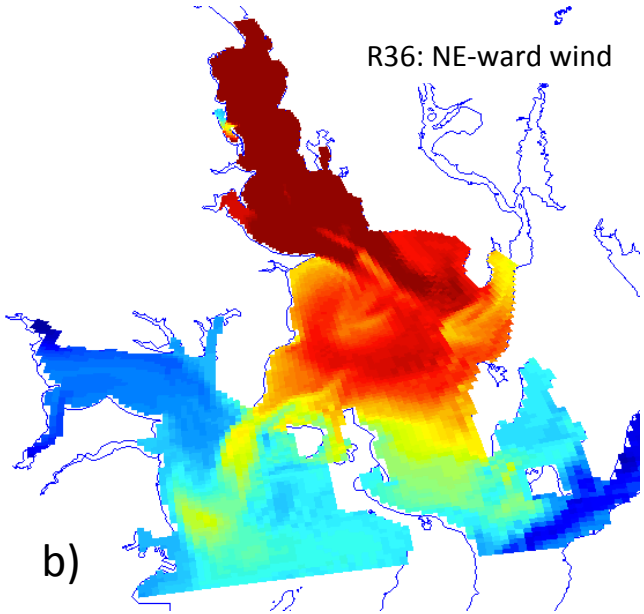


Figure 30 . (Run 28) Contours of near-surface dye fields (model layer 13; two below the surface) from an idealized run with no applied wind and a 5 day runoff pulse, starting from a background of 20 CMS, going to a peak of 1**40 CMS.** Frames are from day 188, for a for a flood event starting on day 183. a) Blackstone River dye where red color represents a concentration of 0.4. b) Pawtuxet River dye, where red color is a concentration of 0.3. c) Fields Point WWTF dye where red color is a concentration of 0.2. The Blackstone plume splits down the West and East Passages. The Pawtuxet favors the West Passage, and is seen to wrap up in the Edgewood Shoals. The Fields Pt WWTF plume is dwarfed by the runoff event, showing the sliver of dispersal along the western side of the shipping channel.





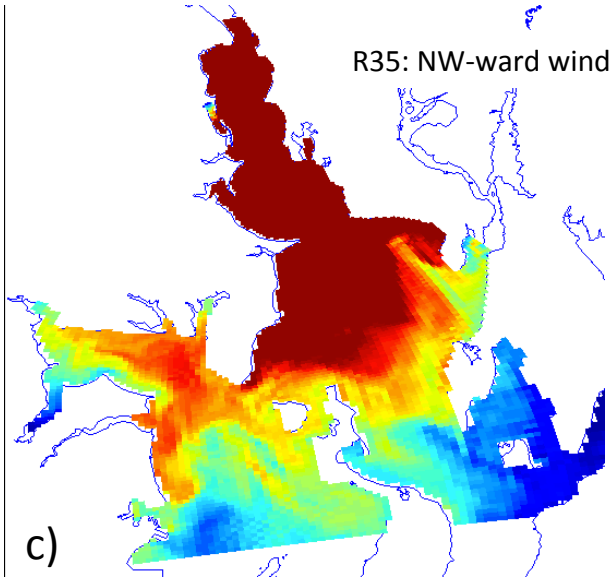
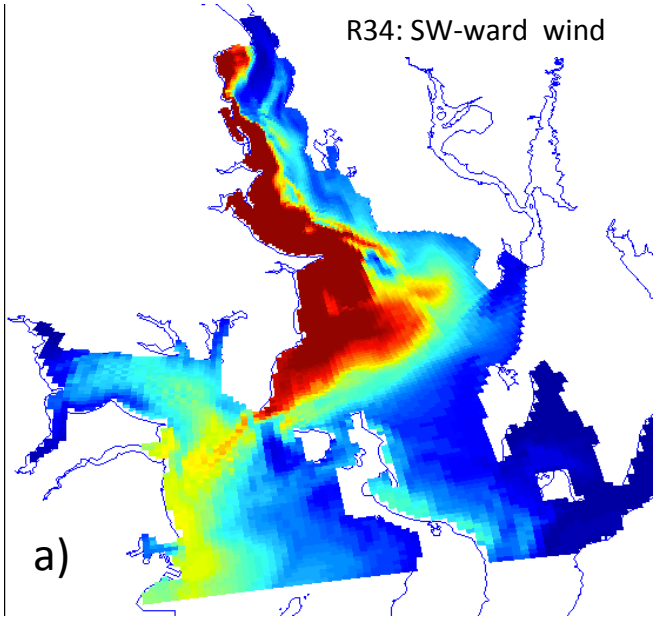


Figure 31 . (Runs 34, 36, 35) Comparison of near-surface dye (nutrient) transport patterns for water entering through the **Blackstone River** for cases with a runoff pulse (background of 20 CMS with a 5 day pulse of 140 CMS starting day 183) and variable wind conditions. a) Run 34 with constant 3 m/s southwestward wind. b) Run 36 with a constant 3 m/s northeastward wind. c) Run 35 with a constant 3 m/s northwestward wind. Frames are for day 198, or 10 days after the pulse. With a southwestward wind (a) more northern dye enters the West Passage, largely by-passing Greenwich Bay. With a northeastward wind (b), northern dyes tend down the East Passage. Northwestward winds (c) produce the largest intrusions of northern dyes into Greenwich Bay.



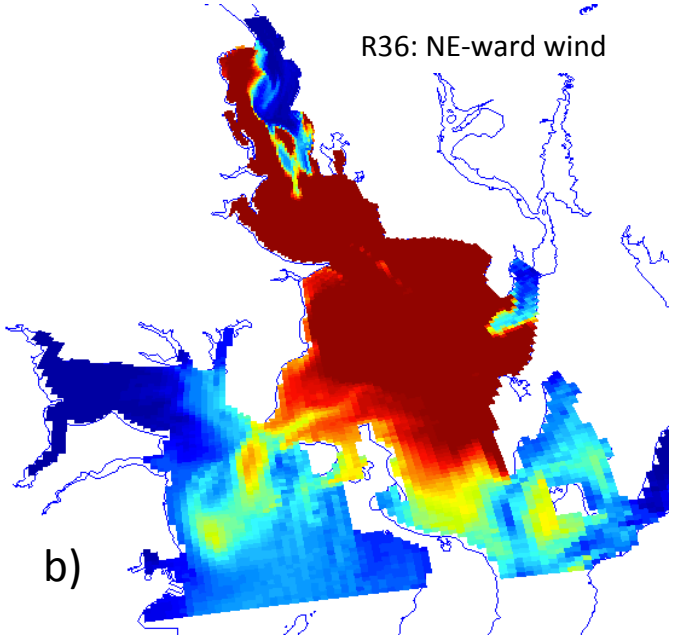
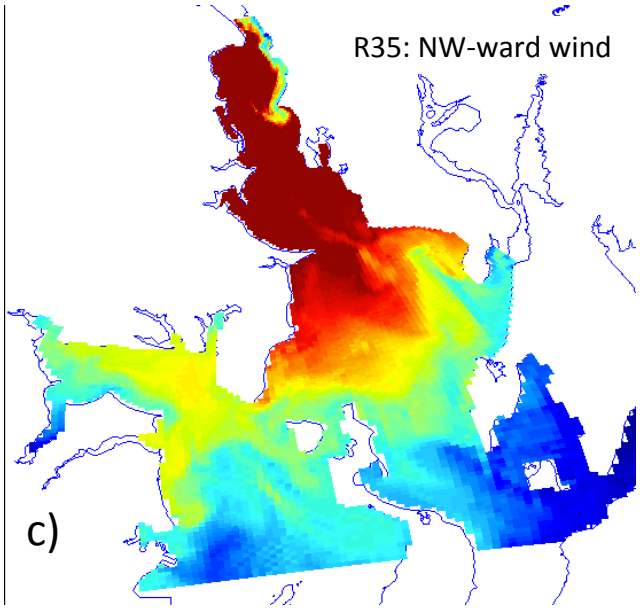


Figure 32 . (Runs 34, 36, 35) Comparison of near-surface dye (nutrient) transport patterns for water entering through the **Pawtuxet River** for cases with a runoff pulse (background of 20 CMS with a 5 day pulse of 140 CMS starting day 183) and variable wind conditions. A) Run 34 with constant 3 m/s southwestward wind. B) Run 36 with a constant 3 m/s northeastward wind. C) Run 35 with a constant 3 m/s northwestward wind. Frames are for day 198, or 10 days after the pulse. Results are similar to Figure (31) for the Blackstone under these varying wind conditions, although the Pawtuxet shows consistently more West Passage and Greenwich Bay intrusion. Frames (a) and (b) show the northward wrapping of Pawtuxet dye into the Edgewood Shoals gyre.



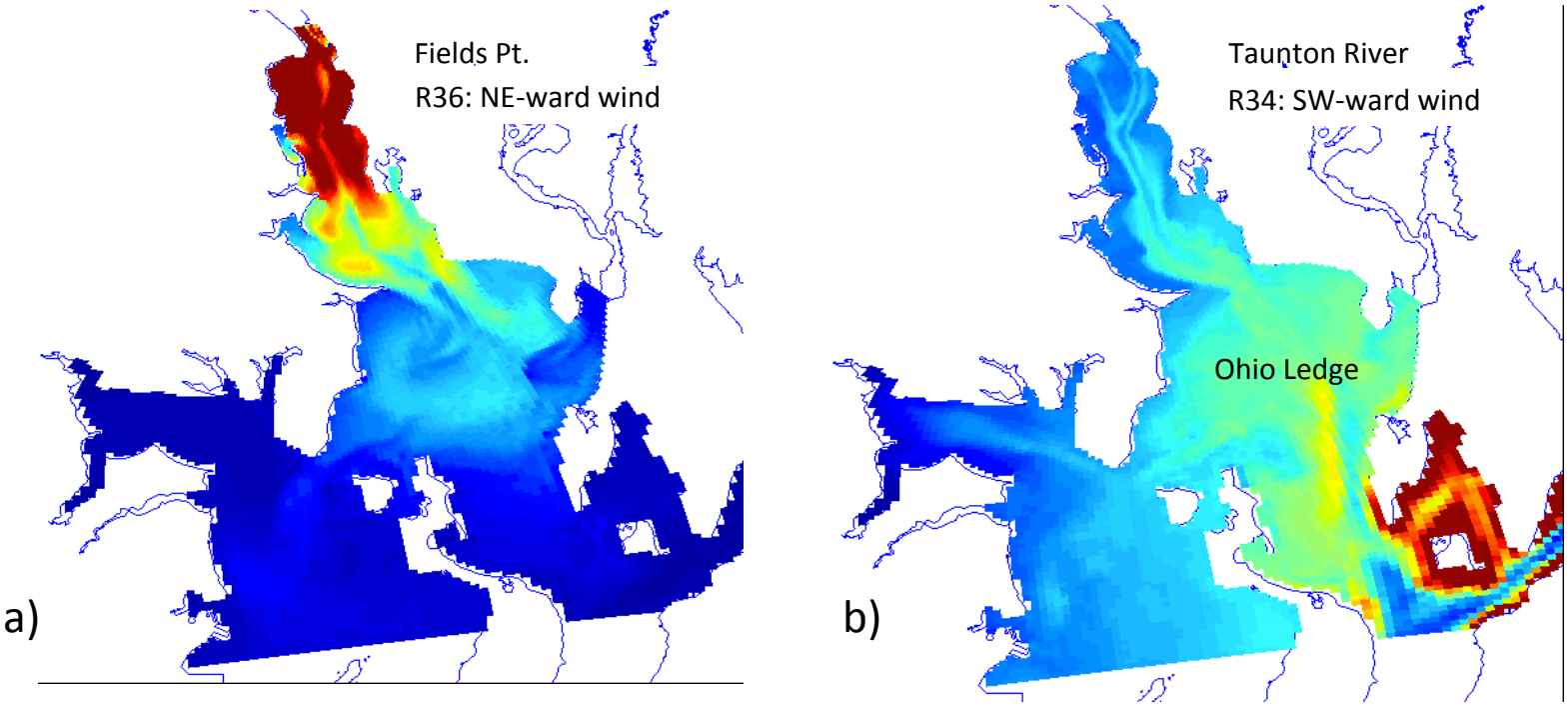
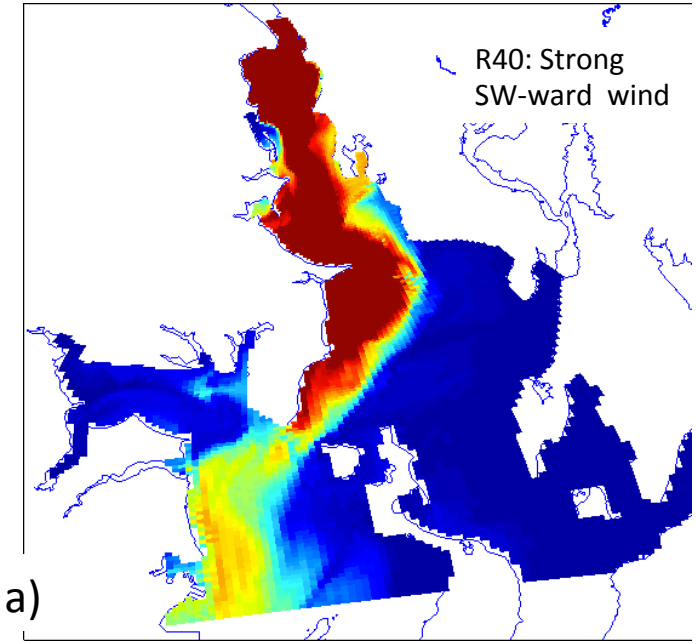
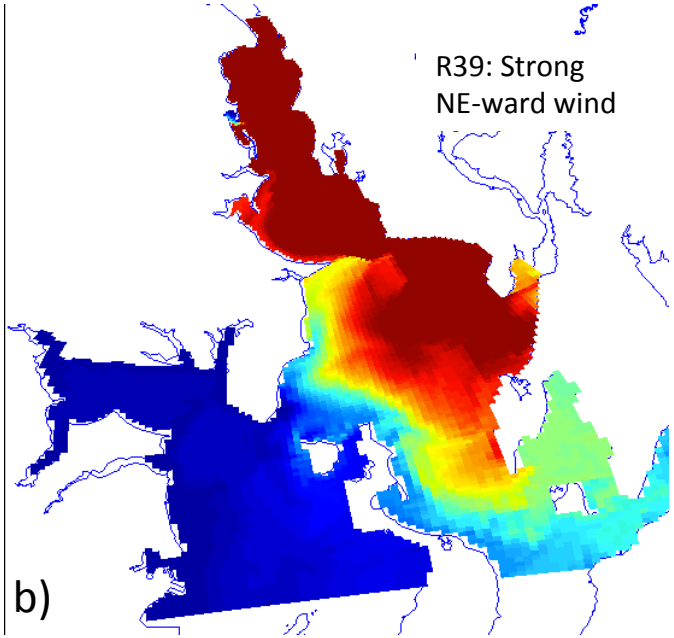


Figure 33 . (Runs 36) (a) Near-surface dye (nutrient) transport pattern for water entering through the **Fields Pt. WWTF** with a runoff pulse (20 CMS-140CMS-20CMS) constant 3 m/s northeastward wind. The Fields Pt. signal is dispersed by mid-Bay locations. Red color = 0.2 concentration. (b) (Run 34) Dye dispersion patterns for depth layer 5 (lower 3rd of water column) for water entering through the **Taunton River** with the same runoff pulse as (a) but with a constant 3 m/s southwestward wind. Red color = 0.05 concentration. Deep Taunton dye moves northward into the Providence River Channel and also counterclockwise around North Prudence into the West Passage.





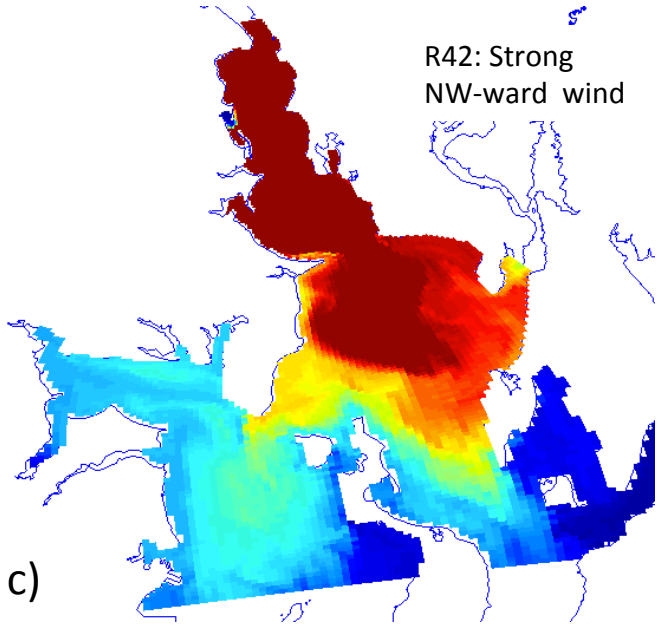


Figure 34 . (Runs 40, 39, 42) Comparison of near-surface dye (nutrient) transport patterns for water entering through the **Blackstone River** for cases with a runoff pulse (background of 20 CMS; 5 day pulse of 140 CMS starting day 183) and with stronger wind speeds, but variable wind directions. Here the winds vary on a diurnal cycle between 8 and 10 m/s. a) Run 40 with an applied 8 to 10 m/s southwestward wind (day 188). b) Run 39 with a 8 to 10 m/s northeastward wind (day 197). c) Run 42 with a strong 8 to 10 m/s northwestward wind (day 198). As with 3 m/s winds, the strong southwestward winds (a) confine northern dyes to the West Passage and a mode of by-passing the Greenwich Bay. Strong northeastward winds (b) confine the northern dyes to the East Passage. Stronger northwestward wind (c) limits inflow of northern dye to the West Passage and, subsequently, to Greenwich Bay.

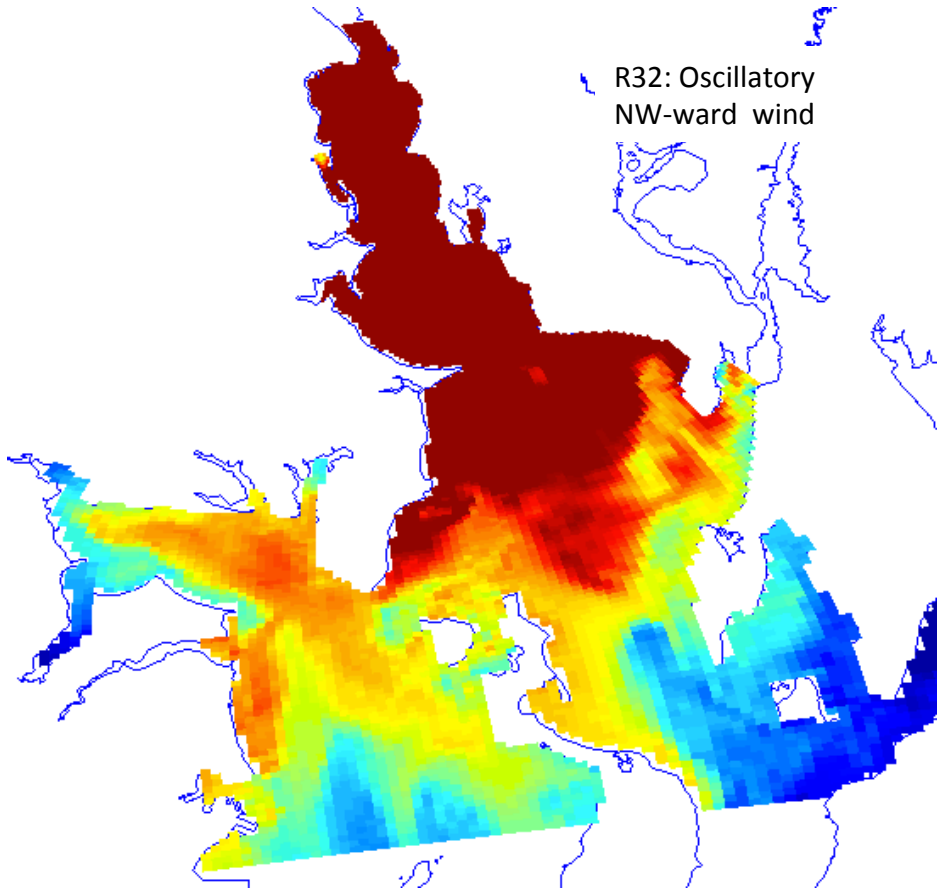


Figure 35 . (Run 32) The maximum transport of northern river dyes (nutrients) into Greenwich Bay is recorded in the idealized simulations for a case with a relatively weak seabreeze style oscillation in wind. Here a daily oscillation in northwestward wind (0 to 3 m/s) is weak enough to allow the runoff pulse (a 5 day 140 CMS on top of a background constant 20 CMS flow) of Blackstone River dye to enter the West Passage, but strong enough to push this water into Greenwich Bay. Red = a 0.4 nutrient concentration.

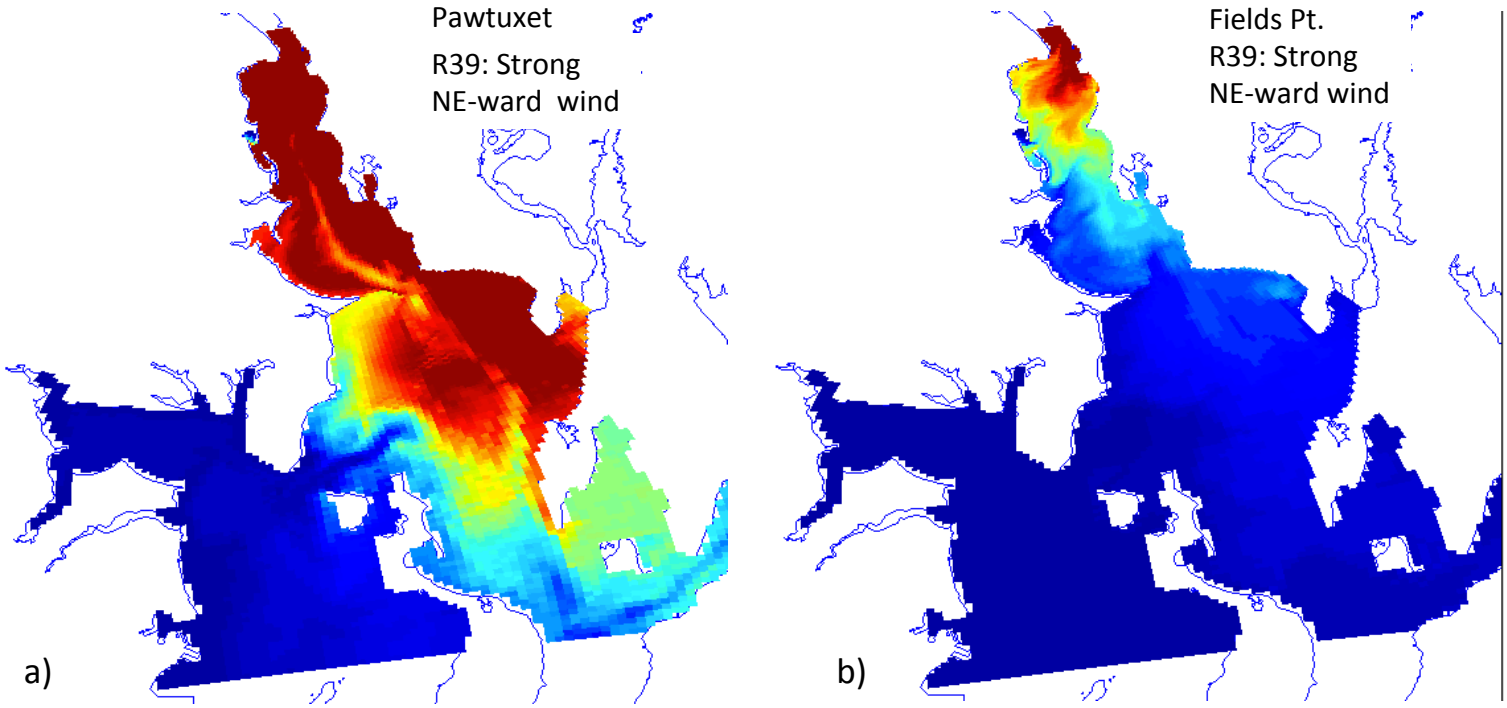


Figure 36 . (Run 39) Comparison of near-surface dye (nutrient) transport patterns for water entering through the **Pawtuxet River and Fields Pt.** WWTF (runoff pulse 20-140-20 CMS) with varying **northeastward** wind (8 to 10 m/s). a) The stronger wind confines the Pawtuxet dye(Red=0.4 concentration) to the East Passage. b) The Fields Point dye (Red=0.3 concentration) is retained in the Providence River and very dispersed within the mid-Bay.

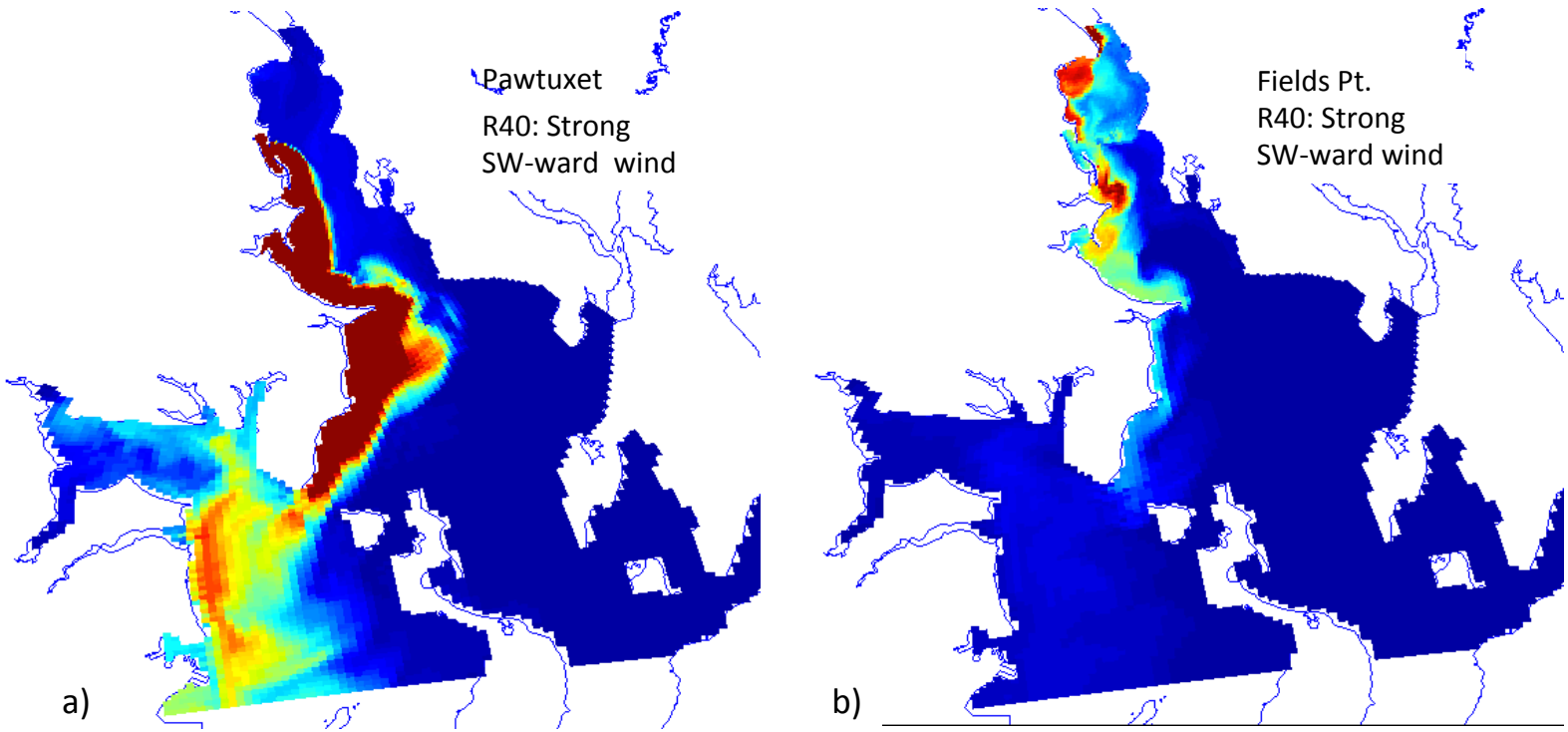


Figure 37 . (Run 40) Comparison of near-surface dye (nutrient) transport patterns for water entering through the Pawtuxet River and Fields Pt. WWTF (runoff pulse 20-140-20 CMS) with varying **southwestward** wind (8 to 10 m/s). In both cases Red color = 0.2 concentration. a) The stronger southwestward wind confines the Pawtuxet dye to the western shore of the West Passage, with intrusion into Greenwich Bay. b) The Fields Point dye is dispersed southward along the western shore of the Providence River and is highly dispersed along the western shore of the mid-Bay.

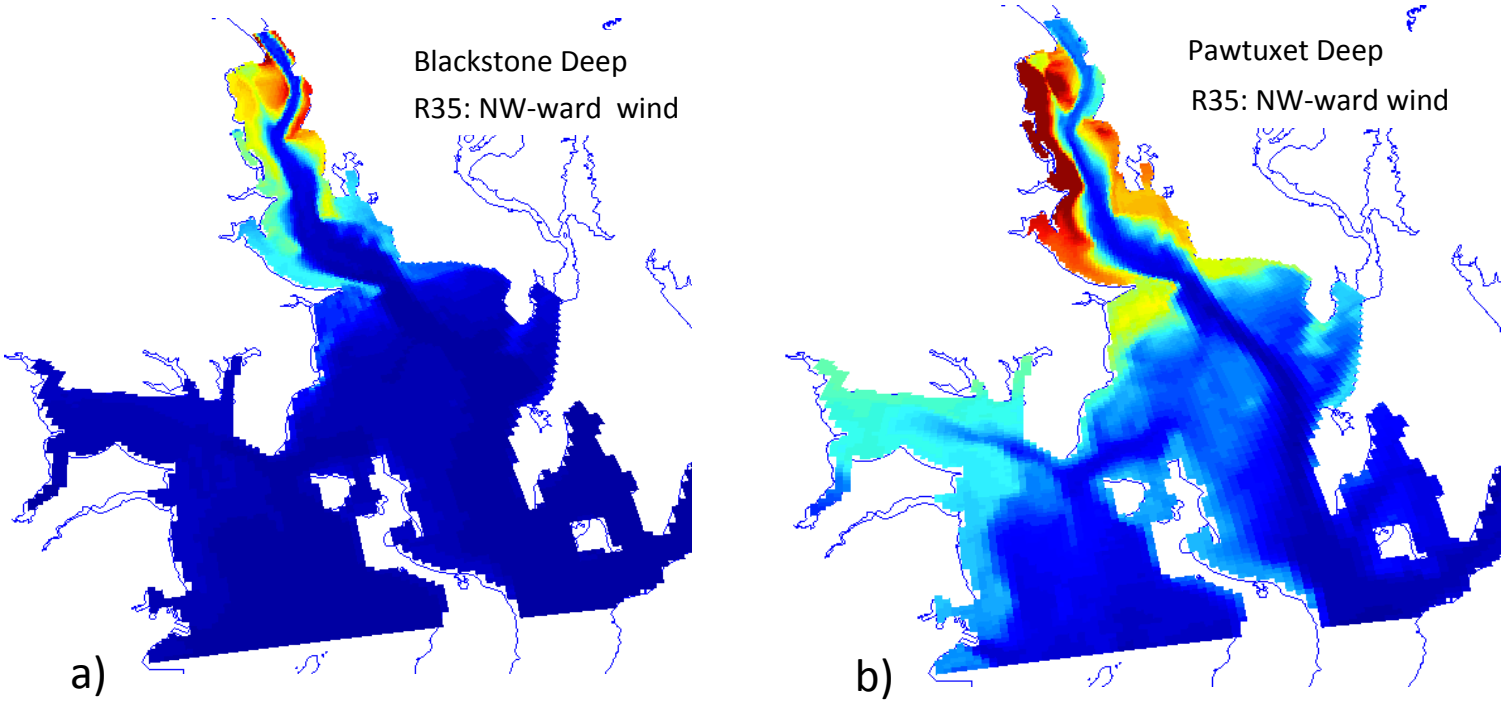


Figure 38. (Run 35) Patterns in deep bottom transport (sigma layer 3, or 80 % of the local water depth) of Blackstone (a) and Pawtuxet (b) River water for Run 35 (runoff pulse; 3 m/s northwestward wind) on day 197. Red = 0.4 concentration. Plots show that nutrients from northern rivers can be retained within the Edgewood Shoals and shallow edge regions of the Providence River. Also, Pawtuxet River dye is dispersed in the bottom water of the mid-Bay down the West Passage and into Greenwich Bay.

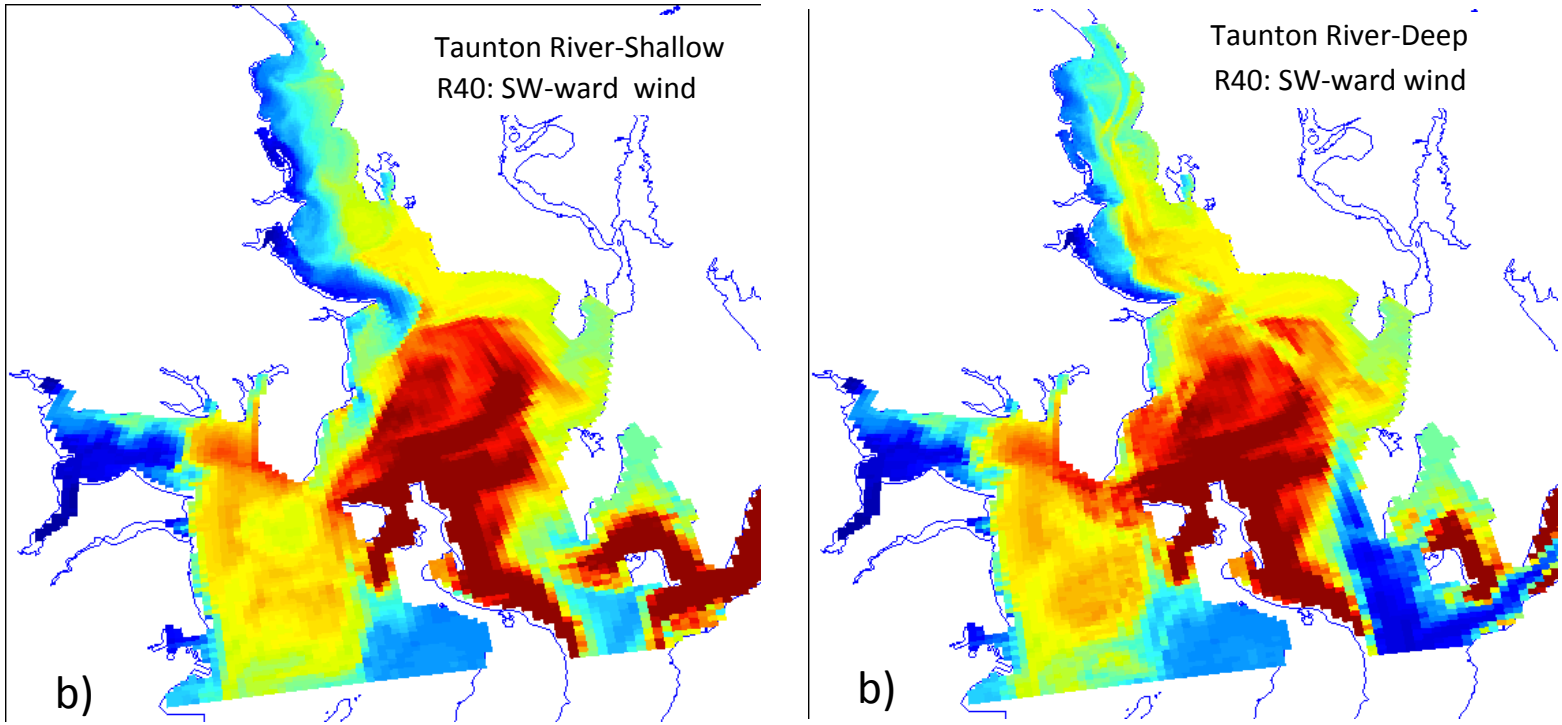


Figure 39 . (Run 40) Comparison of (a) near-surface (z13) and (b) near-bottom (z5) dye (nutrient) transport patterns for water entering through the Taunton River (runoff pulse 20-140-20 CMS) with varying **southwestward** wind (8 to 10 m/s) (day 190). In both cases Red color = 0.1 concentration and Taunton River water is shown to be carried northward up the East Passage, partitioning between counterclockwise flow around Northern Prudence Island into the West Passage and intrusion up the shipping channel of the Providence River. This result is consistent with observational records showing southwestward winds spin up the large scale counter-clockwise gyre in the Bay (Kincaid et al., 2008).

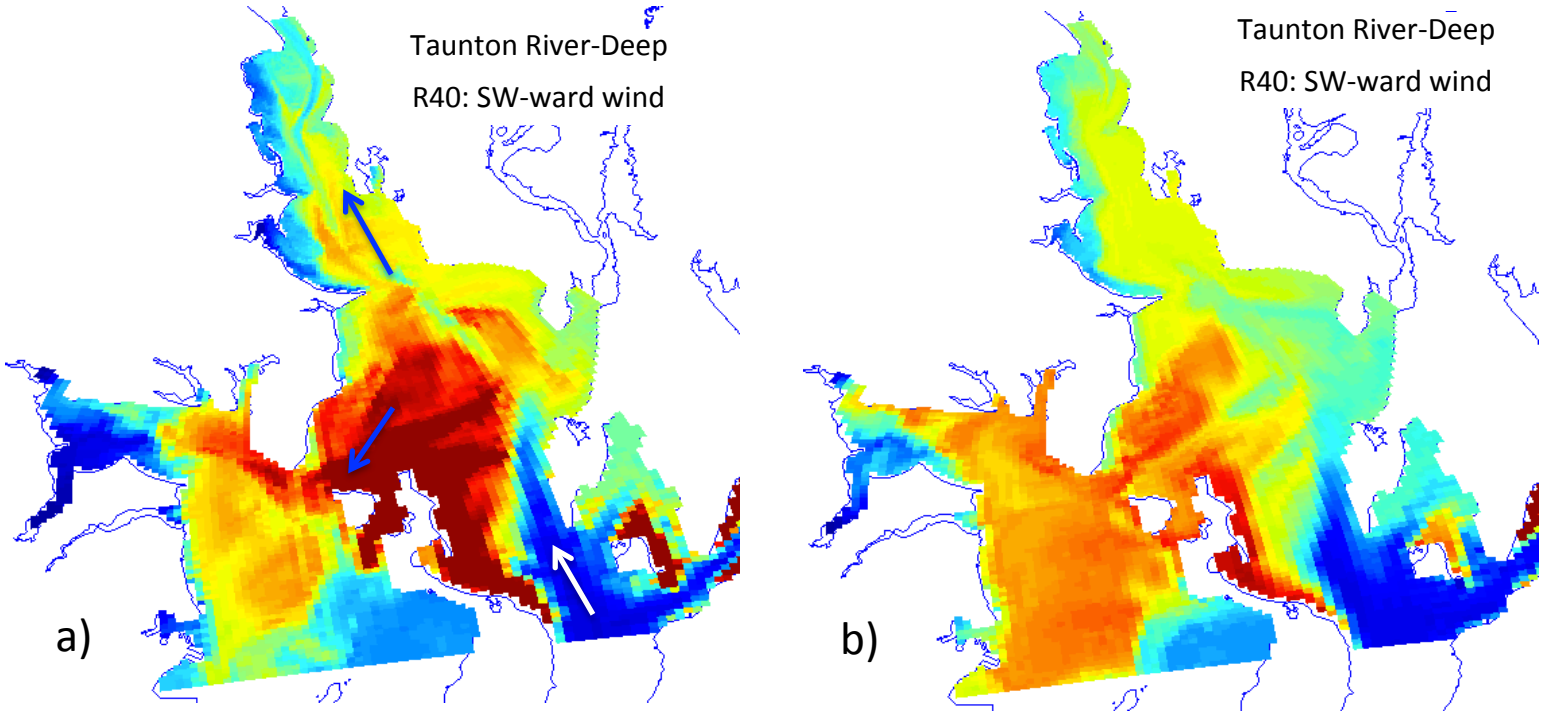


Figure 40 . (Run 40) Time progression of deep bottom (z3) transport (sigma layer 3) of Taunton River water for Run 40 (runoff pulse; southwestward 8 to 10 m/s wind) on (a) day 190 and (b) day 192. Red = 0.1 concentration. Southwestward wind enhances counterclockwise residual flow in the mid-Bay, transporting Taunton River dye/ nutrients efficiently into the deep water of the Providence River and Greenwich Bay.

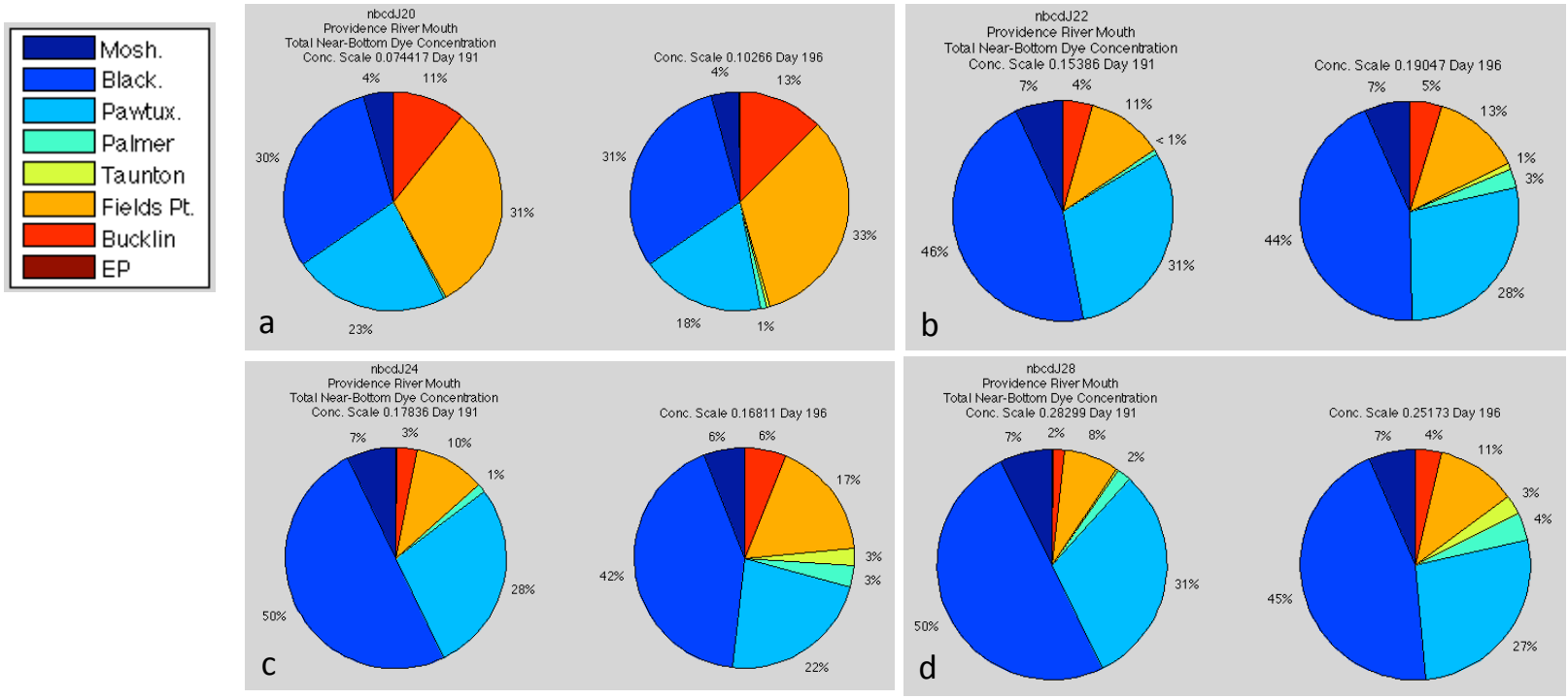


Figure 41. A benefit of modeling all fresh water sources with distinct dyes is that it is possible to look in key regions and determine the percentages of nutrients contributed by each source. We use pie diagrams to represent relative contributions of 8 dye sources. These frames show dye/nutrient levels in the bottom third of the water column at the mouth of the Providence River for idealized cases with no applied wind and constant runoff of a) 10 CMS (Run 20) and b) 40 CMS (Run 22) and 5-day runoff pulses c) 100 CMS and d) 140 CMS. As runoff increase the system becomes dominated by the Blackstone and Pawtuxet Rivers and other sources shrink as a percentage of the total. A more complete compilation of pie plots for idealized runs is given in Appendix A.

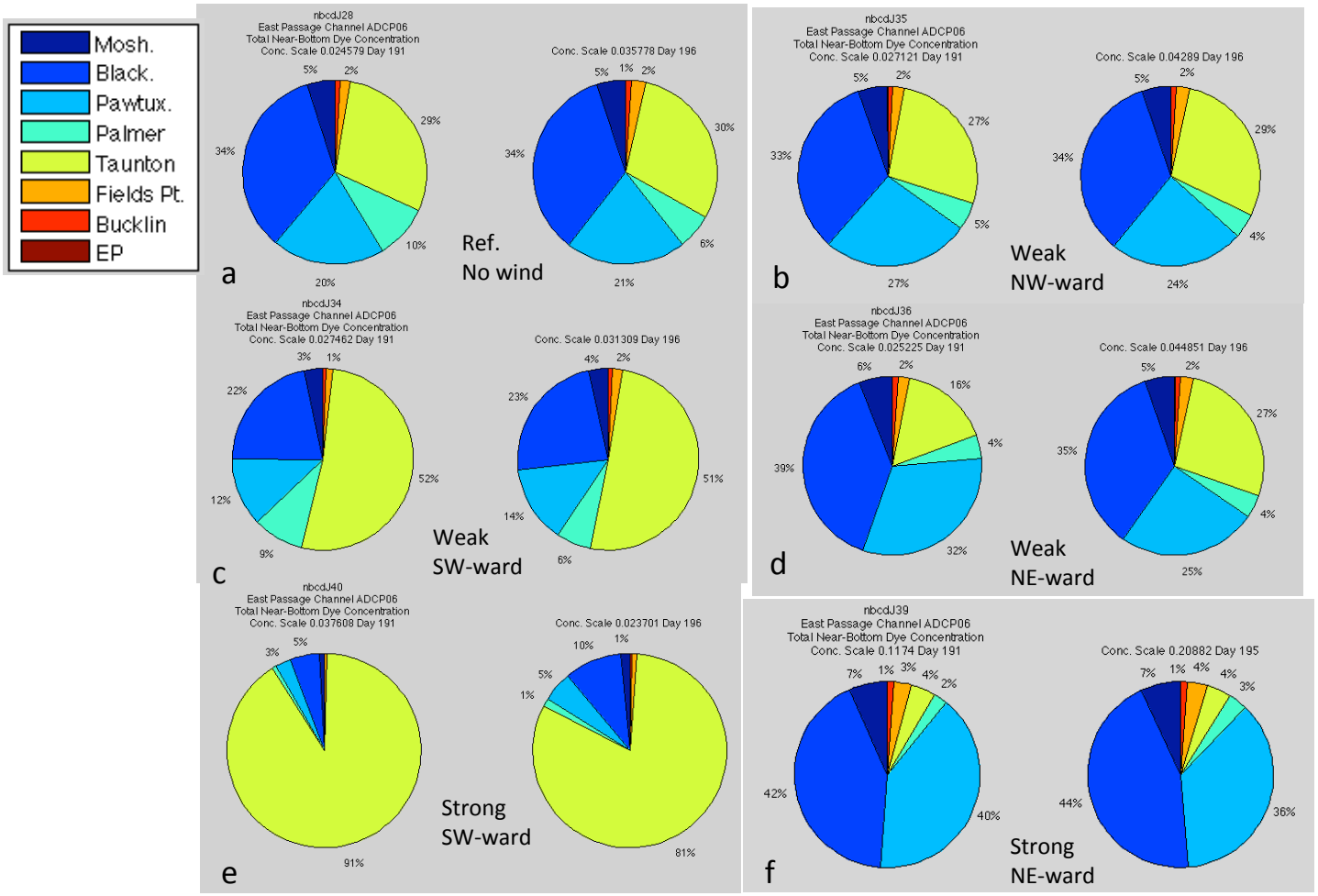


Figure 42. The idealized ROMS simulations are also used to characterize how chemical transport and accumulation patterns vary with changing environmental conditions. These frames show dye percentages in the bottom water of the East Passage channel (near North Prudence Is.) for cases with a 140 CMS runoff pulse and a) no applied wind, b) a 3 m/s northwestward wind, c) a 3 m/s southwestward wind, d) a 3 m/s northeastward wind, e) a varying 8 to 10 m/s southwestward wind and f) an 8 to 10 m/s northeastward wind. Southwestward winds spin up the counterclockwise flow in the Bay, drawing more Taunton River water northward. Northeastward winds stall this flow, bringing more of the northern river dyes into the East Passage Channel. Additional pie plots are included in Appendix A.

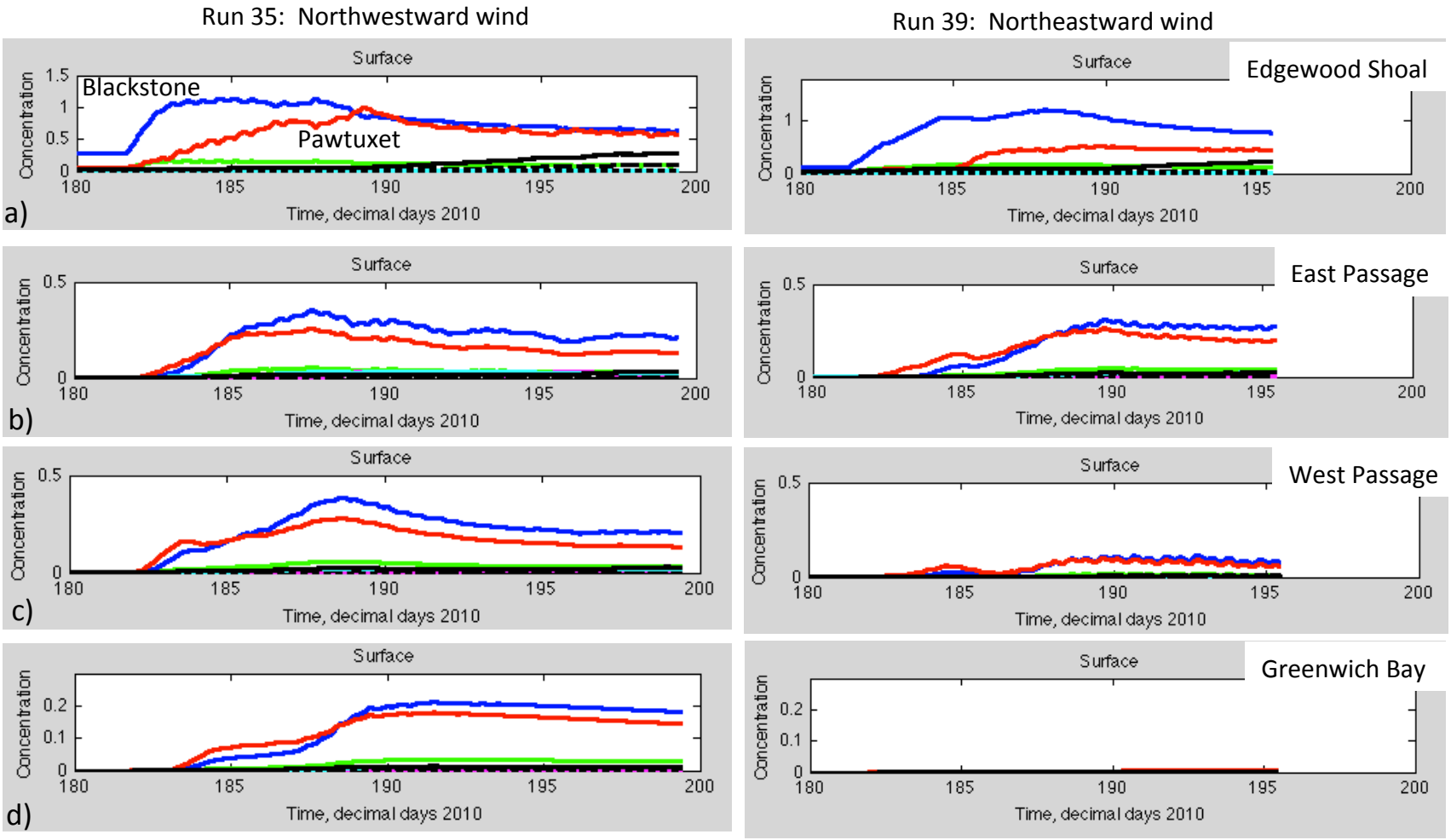


Figure 43 . Time series plots of dye concentrations from idealized runs 35 (left column) and 39 (right column) measured in ROMS simulations (a) on Edgewood Shoal, (b) in the East Passage Channel (North Prudence Is.), (c) in the West Passage (at Warwick Neck) and (d) in the inner basin of Greenwich Bay. A more complete set of figures for time series plots from all idealized cases is presented in Appendix B. These plots highlight the difference in transport pathways for northern river dyes (Blackstone and Pawtuxet Rivers) after a 140 CMS runoff pulse, and given northwestward blowing (Run 35) versus northeastward blowing (Run 39) wind. In Run 35 river dyes move through the West Passage and into Greenwich Bay. In Run 39, winds cause reduced flow through the West Passage and very limited interaction with Greenwich Bay.

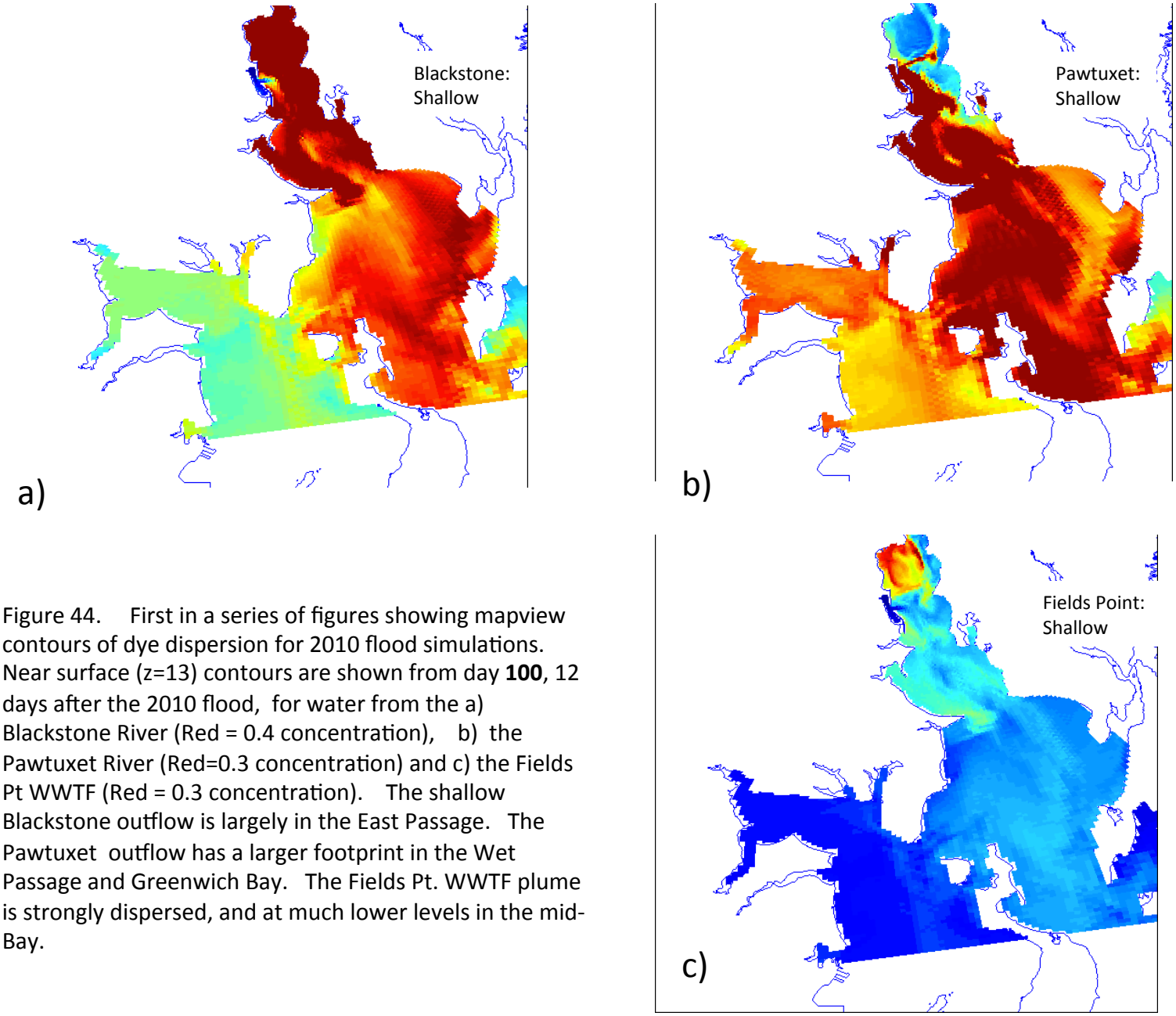


Figure 44. First in a series of figures showing mapview contours of dye dispersion for 2010 flood simulations. Near surface (z=13) contours are shown from day **100**, 12 days after the 2010 flood, for water from the a) Blackstone River (Red = 0.4 concentration), b) the Pawtuxet River (Red=0.3 concentration) and c) the Fields Pt WWTF (Red = 0.3 concentration). The shallow Blackstone outflow is largely in the East Passage. The Pawtuxet outflow has a larger footprint in the Wet Passage and Greenwich Bay. The Fields Pt. WWTF plume is strongly dispersed, and at much lower levels in the mid-Bay.

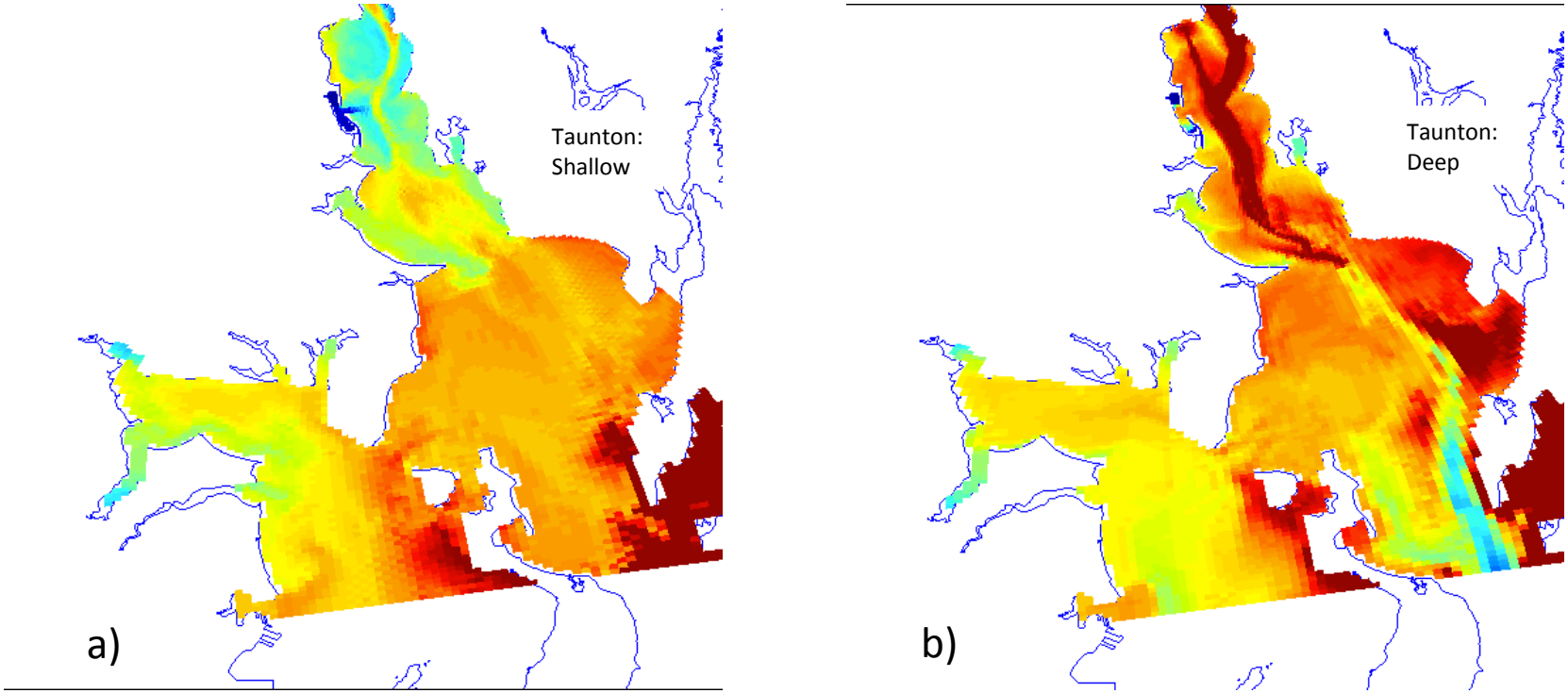


Figure 45 . Nutrient fields which entered the estuary through the **Taunton River** are shown for (a) near surface (z=13) and (b) near bottom (z=3) water on day **100**, 12 days after the 2010 flood (Red = 0.1 concentration). At shallow levels the Taunton River nutrients are advected towards and into the Providence River. The chemical signal from this eastern fresh water source also moves efficiently northward and westward around the north end of Prudence River into the West Passage. The near-bottom water moves more efficiently northward than near-surface water, carrying higher nutrient levels well into the shipping channel of the Providence River. Taunton River nutrient fields also move up the smaller Port Edgewood channel, dispersing onto the Edgewood Shoals.

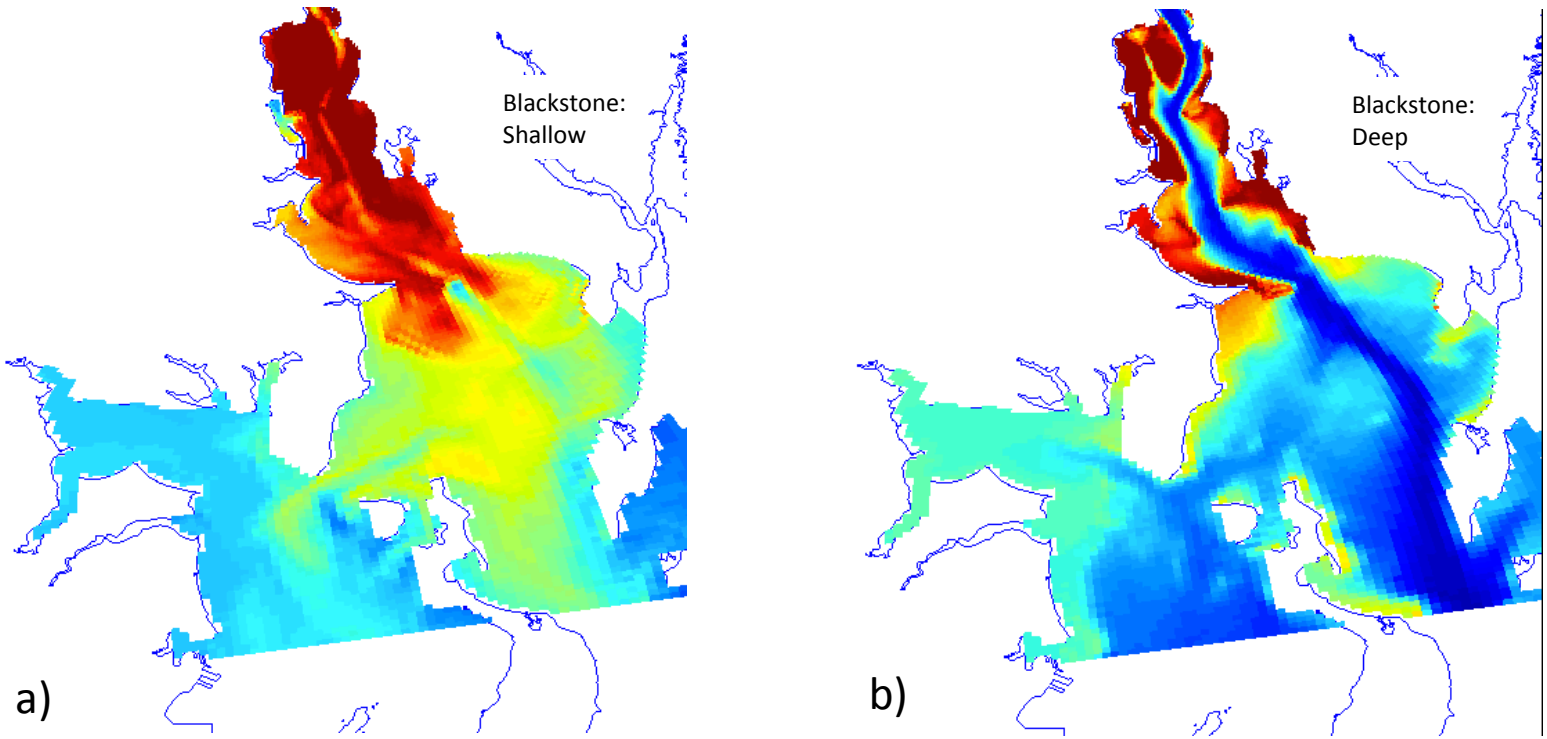


Figure 46 . Near surface (z=13) (a) and near bottom (z=3) contours of nutrient fields from day **127** of the 2010 flood simulation for water from the **Blackstone River** (Red = 0.4 concentration). At shallow levels there remain high nutrient concentrations through the Providence River and most of the Blackstone plume dispersion occurs down the western East Passage. In the near-bottom water there are high Blackstone-derived concentrations in the shallow regions on both sides of the Providence River (including Edgewood Shoals) and within Greenwich Bay bottom water.

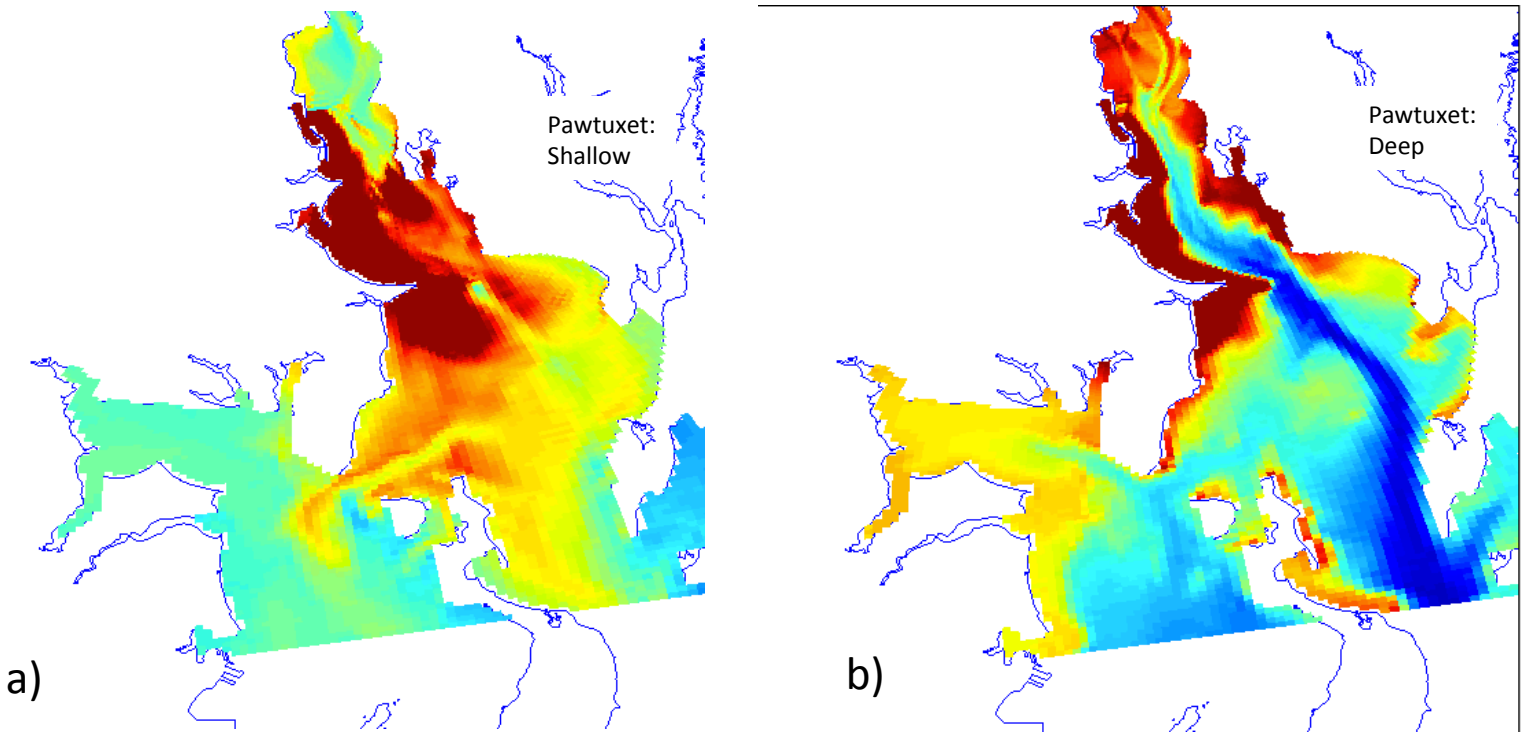


Figure 47 . Near surface (z=13) (a) and near bottom (z=3) contours from day **127** of the 2010 flood simulation for water from the **Pawtuxet River** (Red = 0.3 concentration). At shallow levels (a) the Pawtuxet plume follows a classic evolution, bending southward along the western side of the Providence River, feeding high nutrient levels in the mid to lower Providence River. In the mid-Bay the shallow Pawtuxet nutrient field disperses through both the West Passage and the western East Passage. At deeper levels, the Pawtuxet plume is seen to also follow a classic pattern, moving both southward and northward onto the Edgewood Shoals, and into the uppermost Providence River channel. Nutrients from the Pawtuxet plume remain at high levels in the bottom water of Greenwich Bay, almost 40 days after the flood.

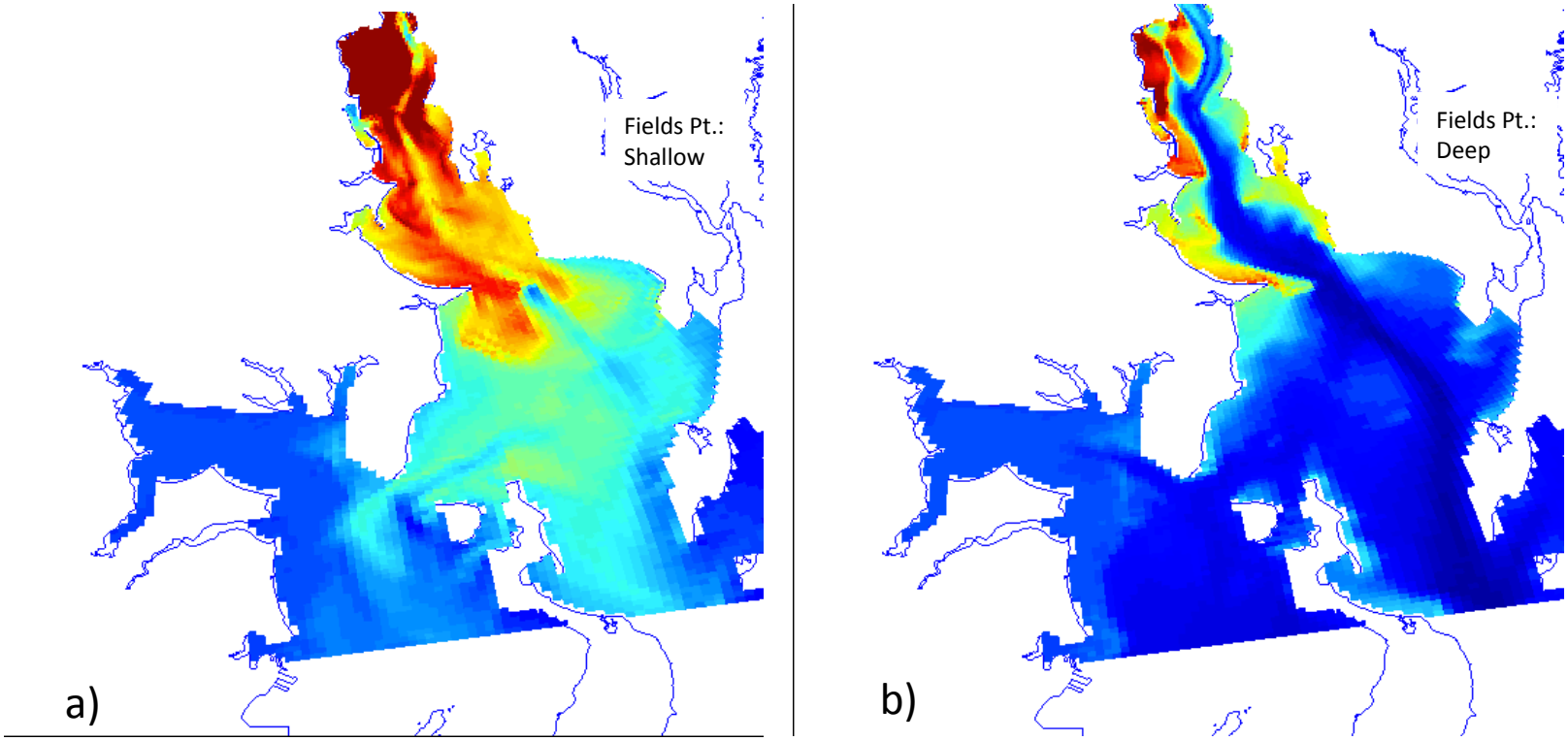


Figure 48 . Near surface (z=13) (a) and near bottom (z=3) contours from day **127** of the 2010 flood simulation for water from the **Fields Pt. WWTF** (Red = 0.2 concentration). At shallow levels (a) the Fields Pt. plume nutrient concentrations disperses to low levels down both sides of Prudence Island, with limited intrusion into Greenwich Bay. Following the pattern of the northern rivers, the Fields Pt. nutrient plume is entrained into the bottom water (b) of the Edgewood Shoals.

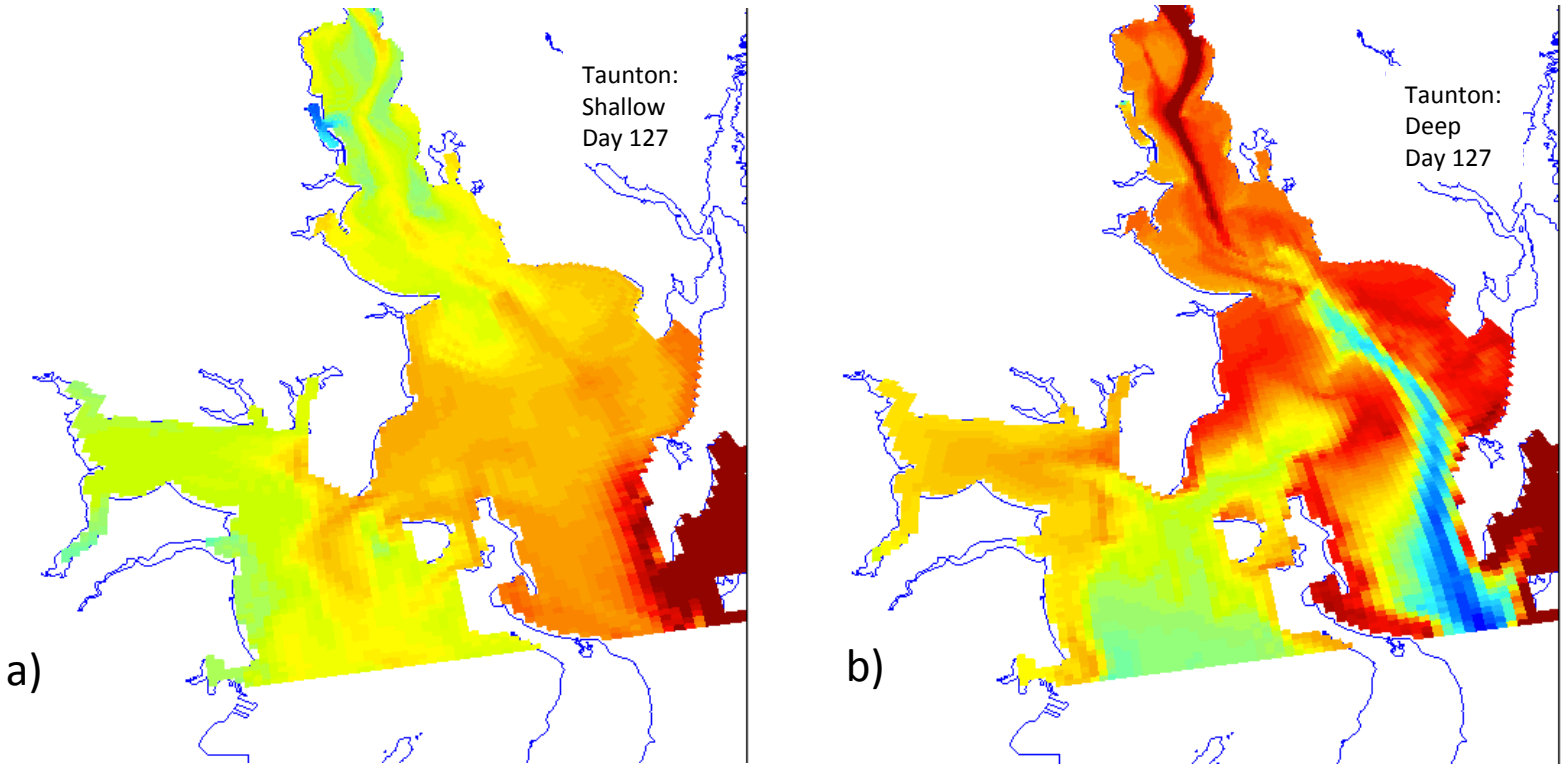


Figure 49 . Near surface (z=13) (a) and near bottom (z=3) contours from day **127**, 39 days after the 2010 flood, for water from the **Taunton River** (Red = 0.1 concentration). A shallow levels the Taunton water moves towards the Providence River and around into the West Passage (a). The near-bottom water moves efficiently northward in the shipping channel of the Providence River.

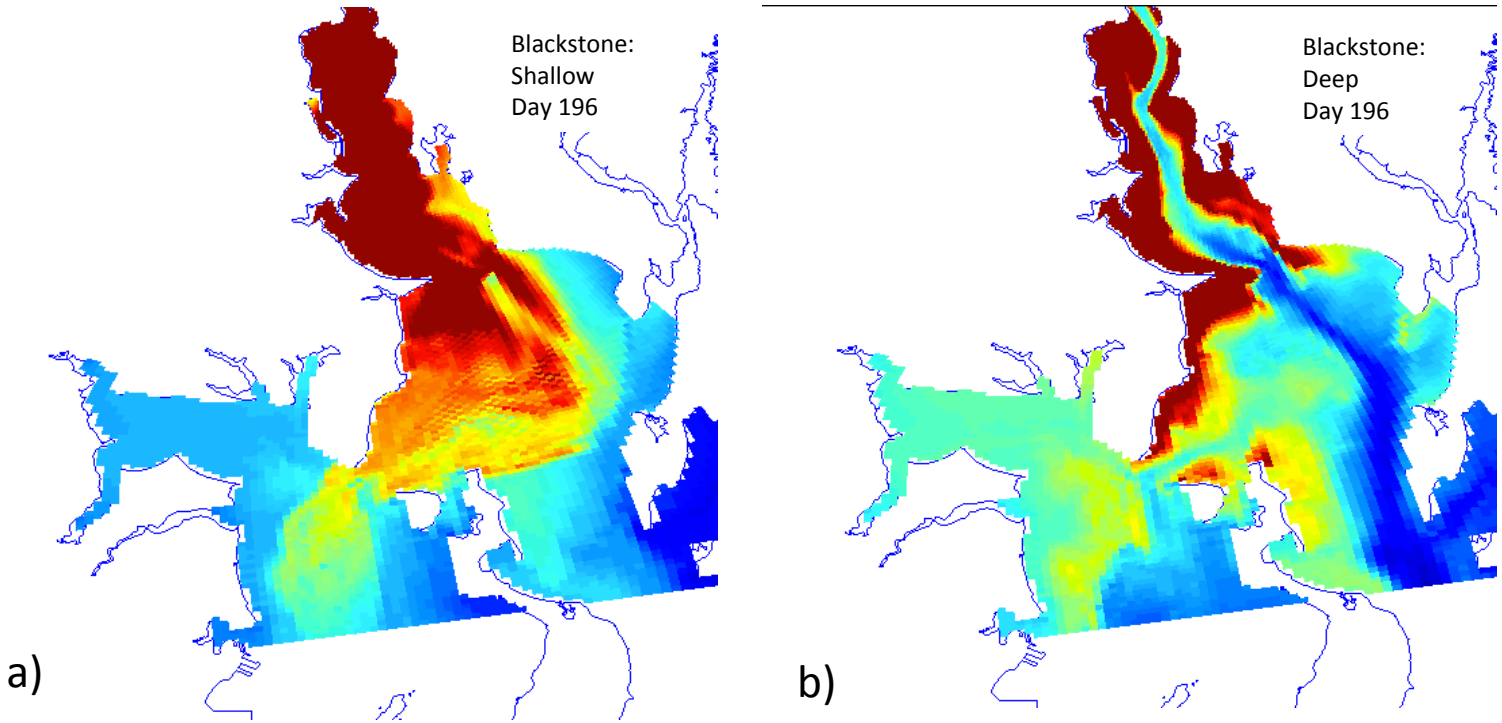


Figure 50. Near surface (a) (z=13) and near bottom (b) (z=3) nutrient concentrations for **Blackstone River** water dispersing through Narragansett Bay from day **196**. In (a) Red = 0.3 dye concentration. In (b) Red = 0.2 dye concentration. Dispersal patterns from earlier in the summer are repeated here, where the near-surface Blackstone plume (a) moves preferentially through the West Passage, by-passing Greenwich Bay. Within near-bottom water, the Blackstone plume high nutrient concentrations occur within Edgewood shoals, the shallow edges of the Providence River and along the western shore, south of the Providence River. The plume extends southward into the West Passage and along the western East Passage. Interestingly, there is a larger Blackstone signal in Greenwich Bay within the bottom water.

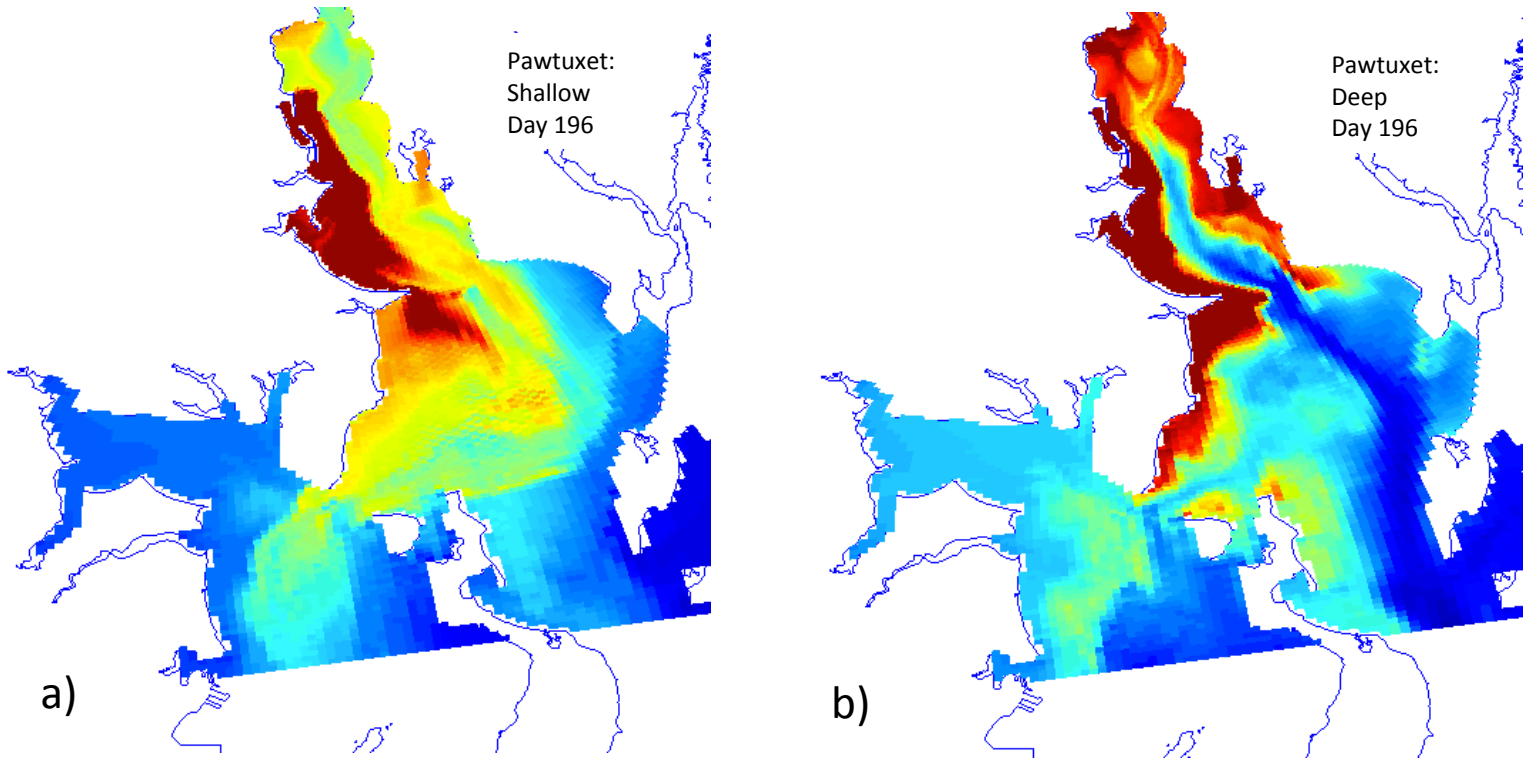


Figure 51. Near surface (a) (z=13) and near bottom (b) (z=3) nutrient concentrations for **Pawtuxet River** water dispersing through Narragansett Bay from day **196**. In (a) Red = 0.3 dye concentration. In (b) Red = 0.2 dye concentration. Near-surface Pawtuxet plume water (a) moves preferentially down the western side of the Providence River, into the West Passage and by-passes Greenwich Bay. A patch of this water also appears in the Port Edgewood basin, in the northwest corner of the Edgewood Shoals. Pawtuxet River nutrients are concentrated in the bottom water within Edgewood shoals, the shallow edges of the Providence River and along the western shore, south of the Providence River. The plume extends southward into the West Passage, seeding the bottom water outside the entrance to Greenwich Bay.

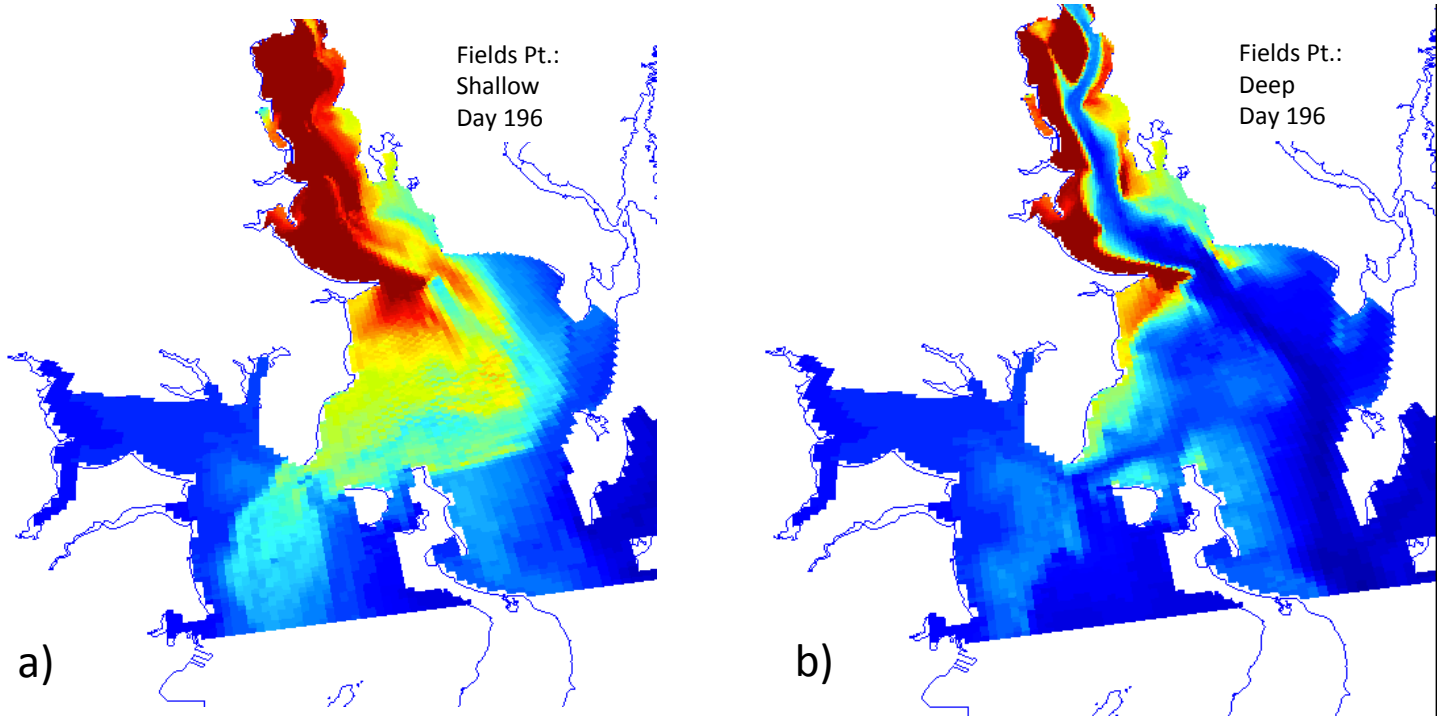


Figure 52. Near surface (a) (z=13) and near bottom (b) (z=3) nutrient concentrations for **Fields Pt WWTF** water dispersing through Narragansett Bay from day **196**. In (a) Red = 0.3 dye concentration. In (b) Red = 0.3 dye concentration. Near-surface Fields Pt. plume water (a) is broadly dispersed within the Providence River and follows the shallow northern rivers by trending into the West Passage, by-passing Greenwich Bay. In near bottom water (b), the Fields Pt. plume also has a similar distribution pattern in the shallow edges of the Providence River. The concentration of the Fields Pt. plume is much reduced outside the entrance to Greenwich Bay, relative to the Blackstone and Pawtuxet concentration levels

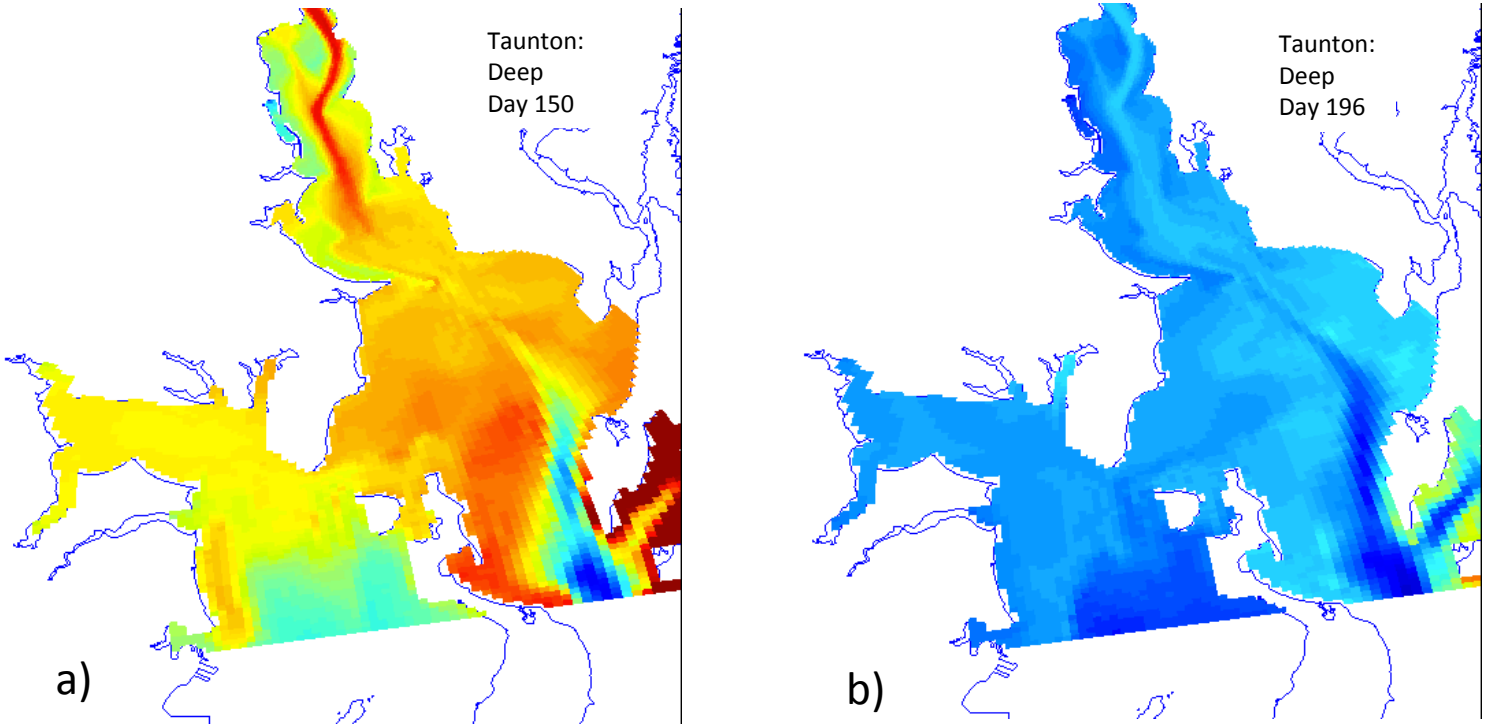


Figure 53 . Near bottom (z=3) nutrient concentrations for Taunton River water from 2010 simulation days (a) **150 and** (b) **196.** Red = 0.1 dye concentration. On day 150 (b) Taunton River water is still contributing significantly to the nutrient budget within the Providence River shipping channel and Greenwich Bay, roughly 60 days after the flood event. b) By day 196, the Taunton-derived nutrient levels have dispersed.

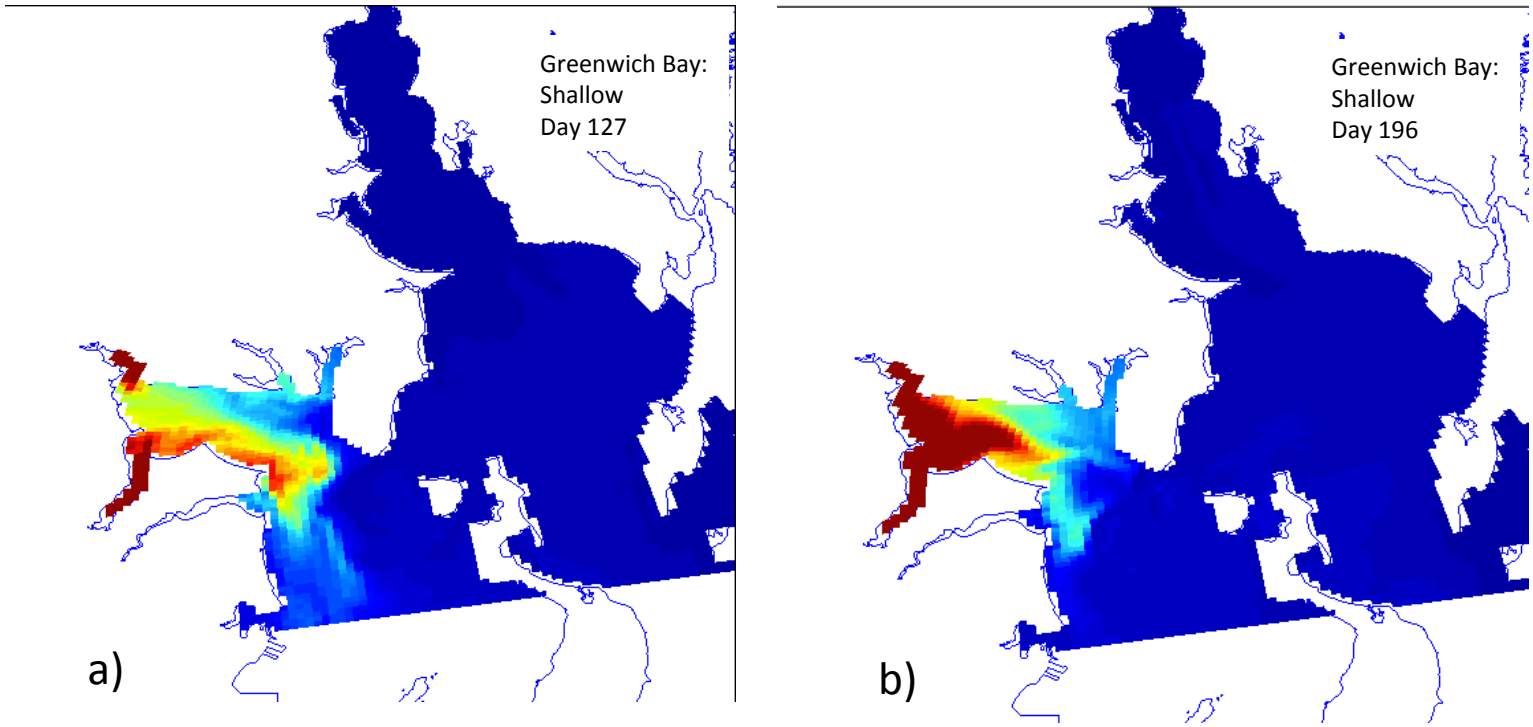


Figure 54. Near surface (z=13) nutrient concentration contours for water released by sources internal to Greenwich Bay from 2010 simulation days (a) **127 and** (b) **196.** A common pattern is shown in both frames, where a plug of Greenwich Bay dye is retained within inner Greenwich Bay, and periodically split apart and flushed by prevailing circulation patterns. Red= 0.2 nutrient (dye) concentration.

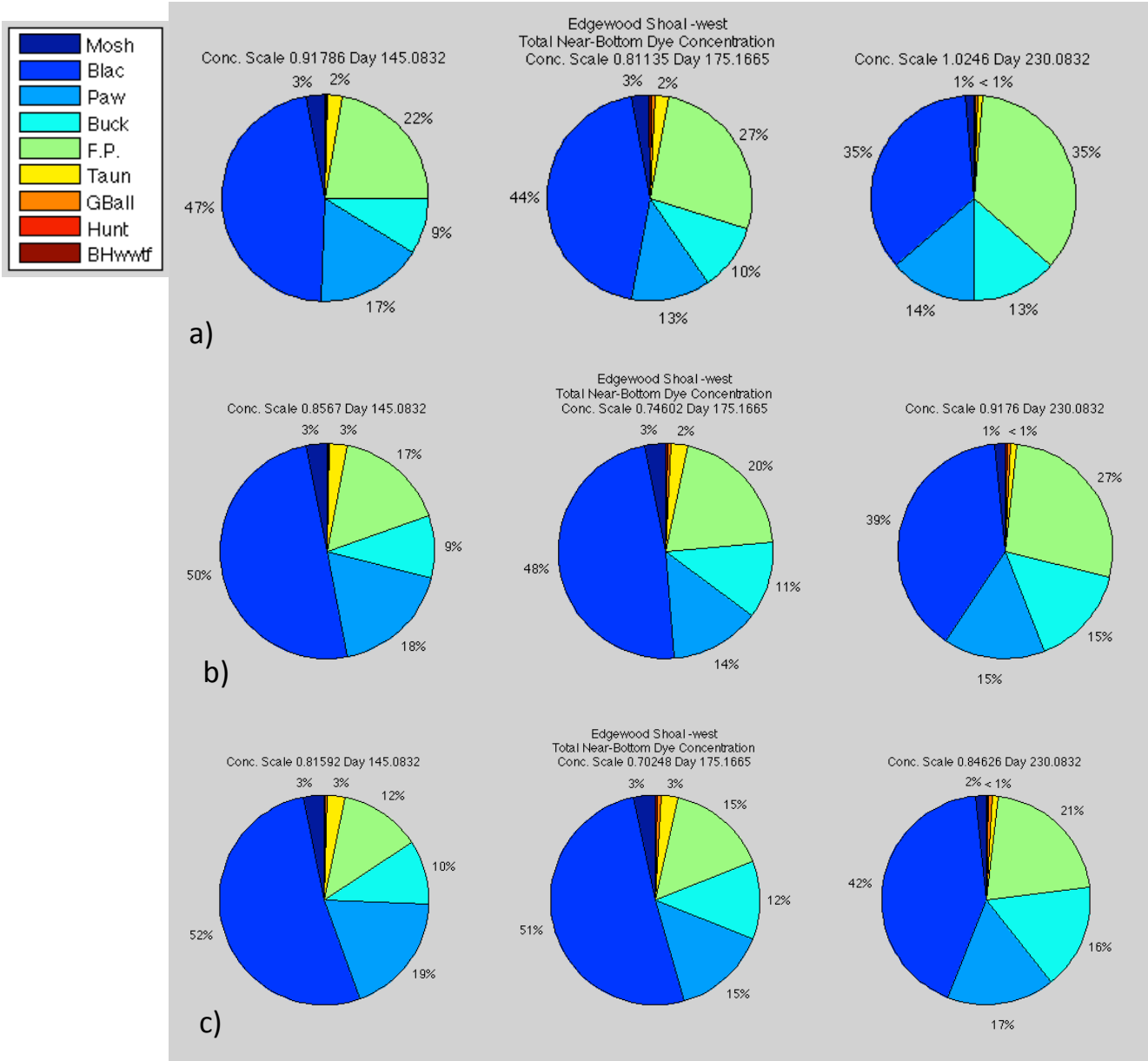


Figure 55. Models are used to test various nutrient reduction scenarios for the Fields Point WWTF. Here nutrient distributions for all 9 sources are determined for **Edgewood Shoal bottom water** for late summer 2010 conditions (days 145, 175 and 230). The percentages are expressed as pie slices (and total concentrations are listed on each plot) for Fields Point WWTF source output of a) 10 mg/l, b) 7 mg/l and c) 5 mg/l.

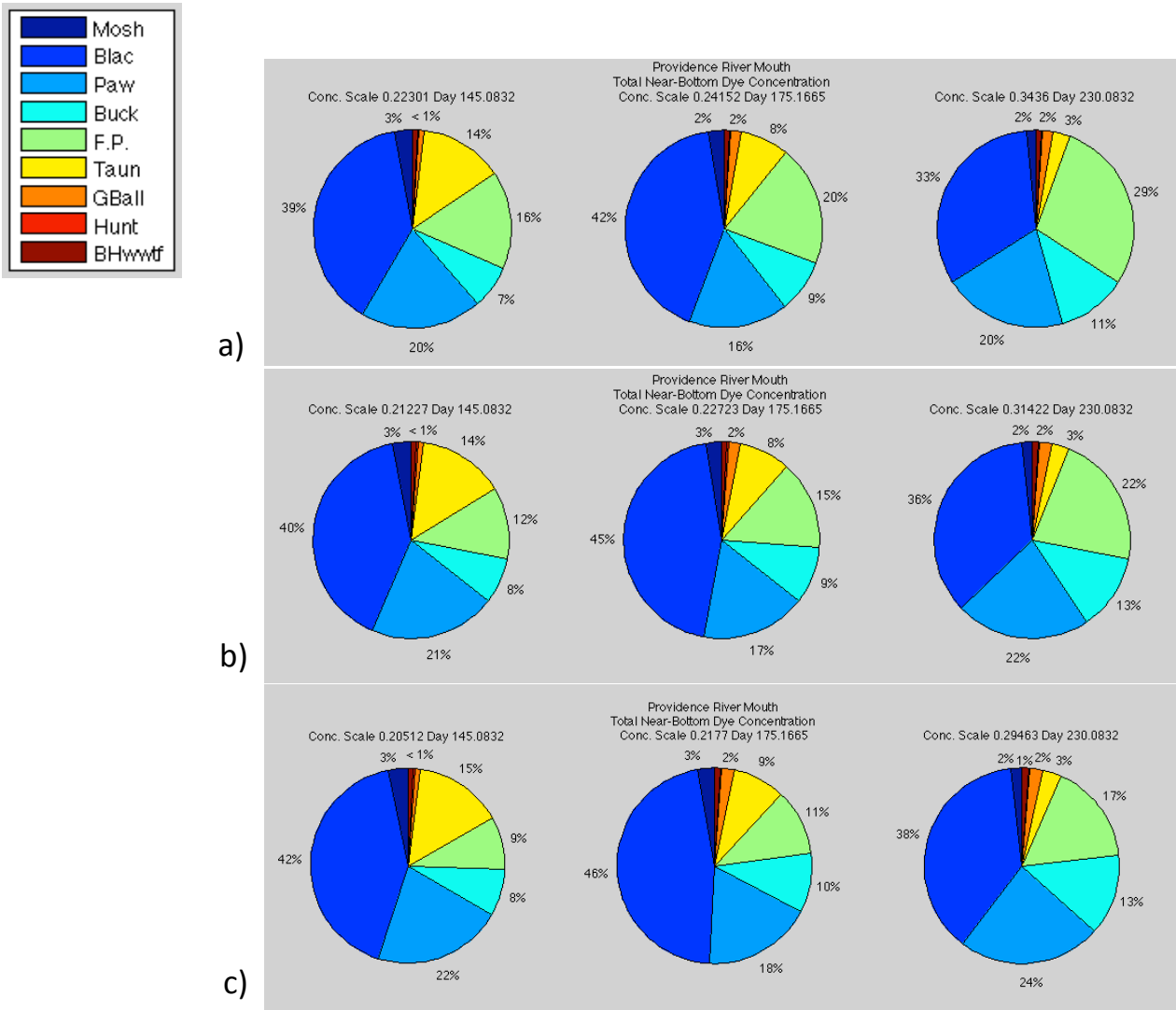


Figure 56. Models are used to test various nutrient reduction scenarios for the Fields Point WWTF. Here nutrient distributions for all 9 sources are determined for **Providence River mouth bottom water** for late summer 2010 conditions (days 145, 175 and 230). The percentages are expressed as pie slices (and total concentrations are listed on each plot) for Fields Point WWTF source output of a) 10 mg/l, b) 7 mg/l and c) 5 mg/l.

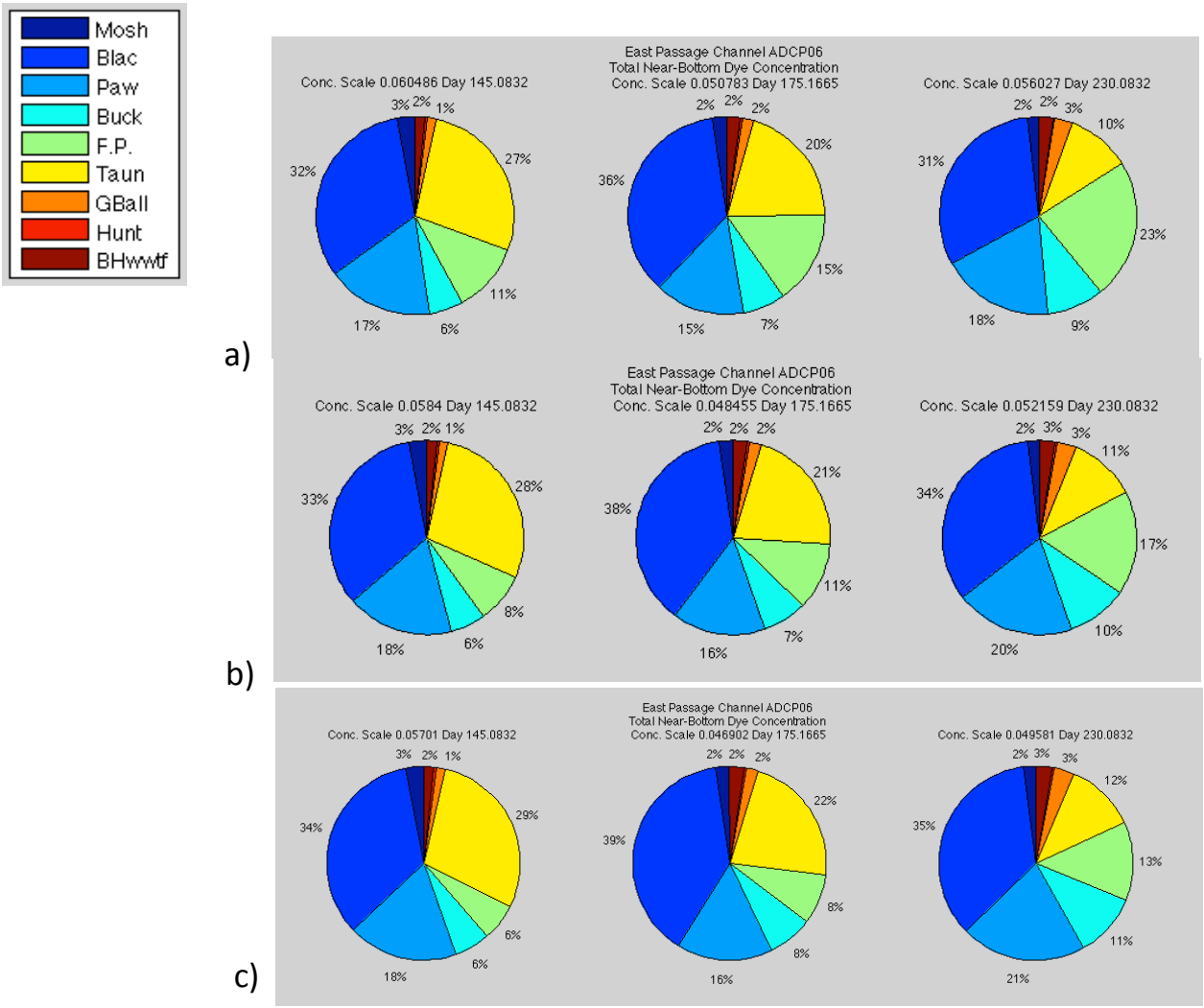


Figure 57. Models are used to test various nutrient reduction scenarios for the Fields Point WWTF. Here nutrient distributions for all 9 sources are determined for **East Passage channel bottom water** (near North Prudence Is.) for late summer 2010 conditions (days 145, 175 and 230). The percentages are expressed as pie slices (and total concentrations are listed on each plot) for Fields Point WWTF source output of a) 10 mg/l, b) 7 mg/l and c) 5 mg/l.

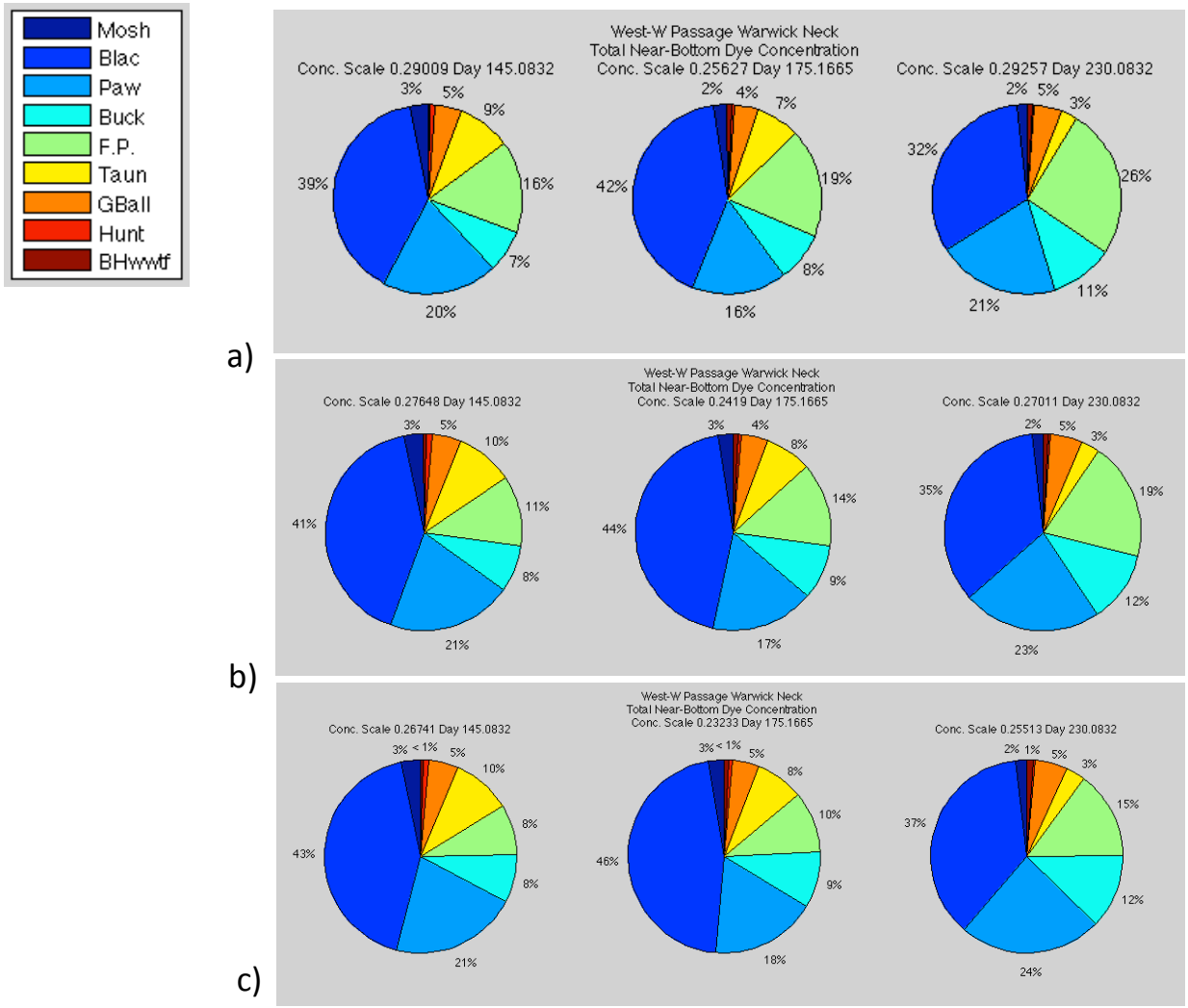


Figure 58. Models are used to test various nutrient reduction scenarios for the Fields Point WWTF. Here nutrient distributions for all 9 sources are determined for **West Passage bottom water** (near North Prudence Is.) for late summer 2010 conditions (days 145, 175 and 230). The percentages are expressed as pie slices (and total concentrations are listed on each plot) for Fields Point WWTF source output of a) 10 mg/l, b) 7 mg/l and c) 5 mg/l.

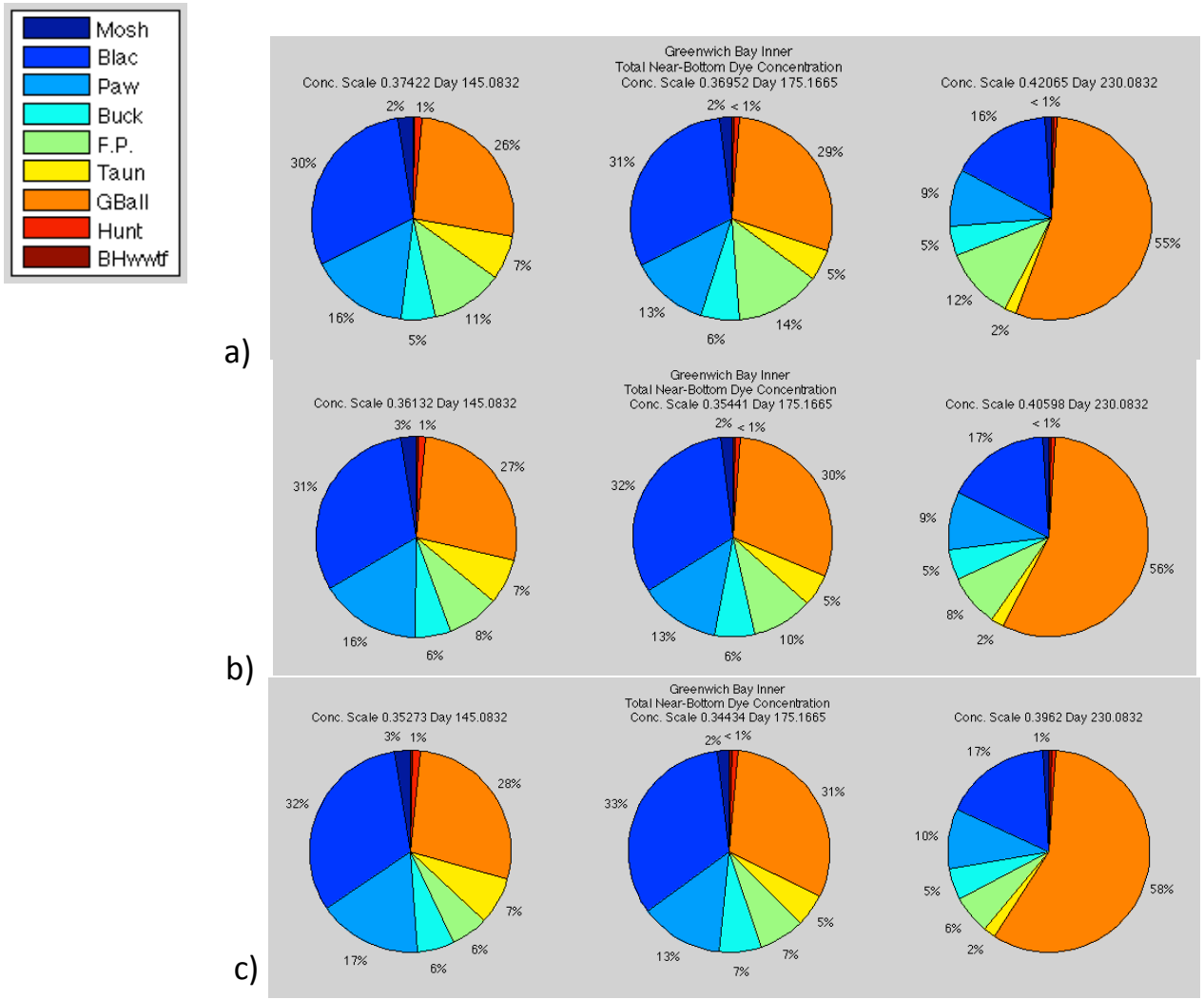


Figure 59. Models are used to test various nutrient reduction scenarios for the Fields Point WWTF. Here nutrient distributions for all 9 sources are determined for **the inner basin of Greenwich Bay bottom water** (near North Prudence Is.) for late summer 2010 conditions (days 145, 175 and 230). The percentages are expressed as pie slices (and total concentrations are listed on each plot) for Fields Point WWTF source output of a) 10 mg/l, b) 7 mg/l and c) 5 mg/l.

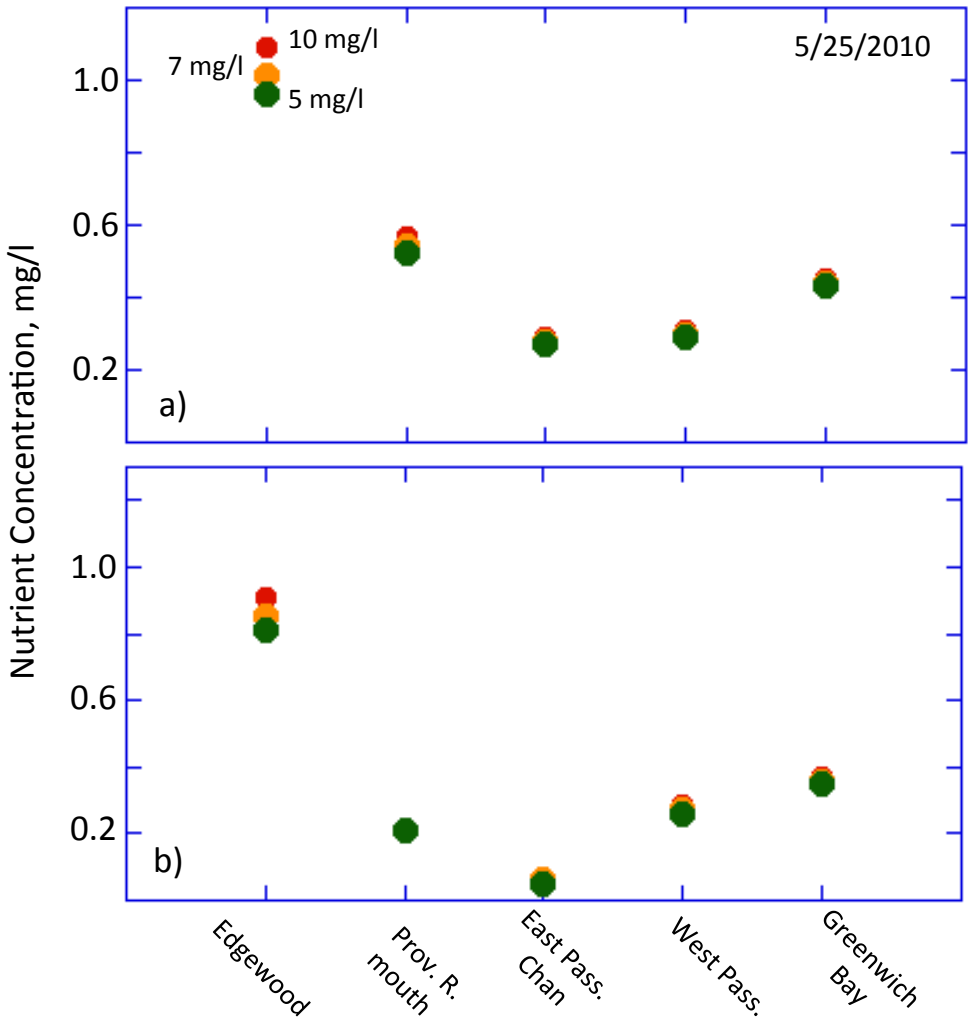


Figure 60. Plots of total nutrient concentration calculated at key locations throughout the estuary showing the role of different management strategies for near surface water (a) and near bottom water (b) on day 145 (5/25/2010). Colored circles represent Fields Point WWTF source water nutrient concentration of (red) 10 mg/l, (orange) 7 mg/l and (green) 5 mg/l.

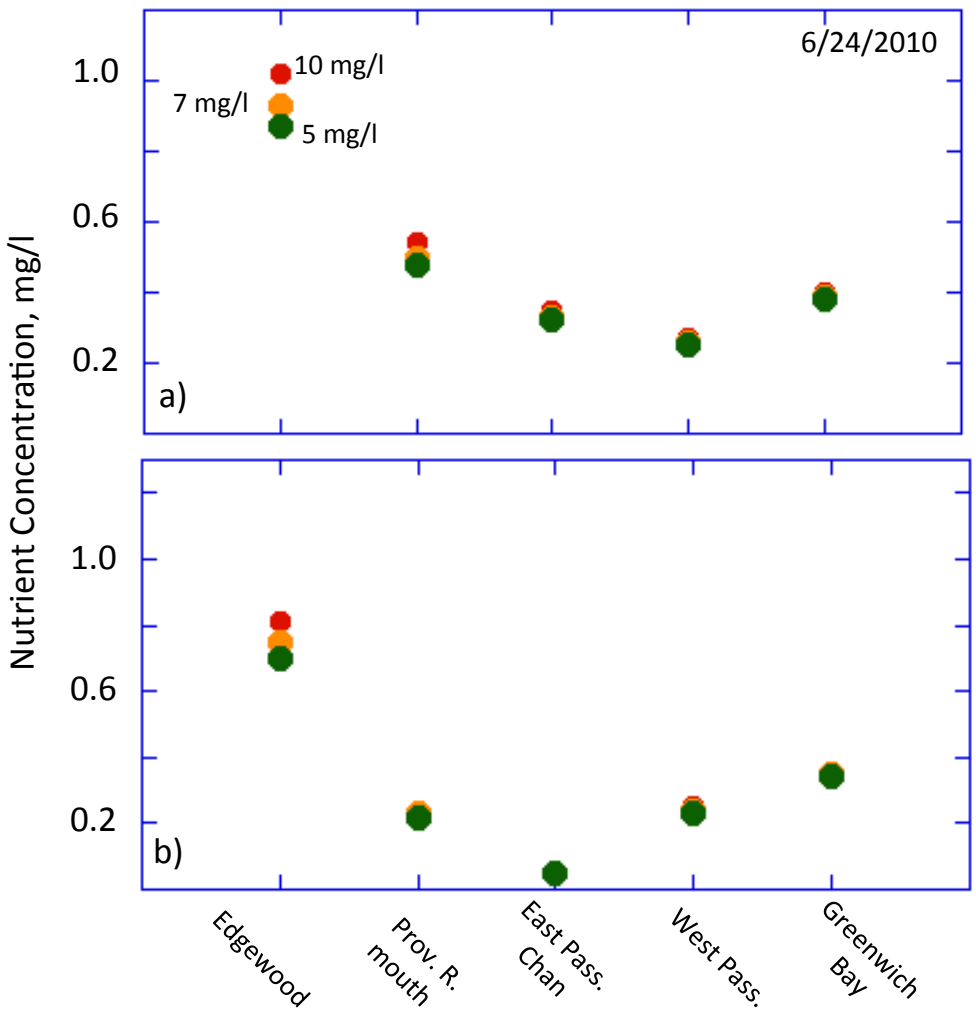


Figure 61. Plots of total nutrient concentration calculated at key locations throughout the estuary showing the role of different management strategies for near surface water (a) and near bottom water (b) on day 175 (6/24/2010). Colored circles represent Fields Point WWTF source water nutrient concentration of (red) 10 mg/l, (orange) 7 mg/l and (green) 5 mg/l.

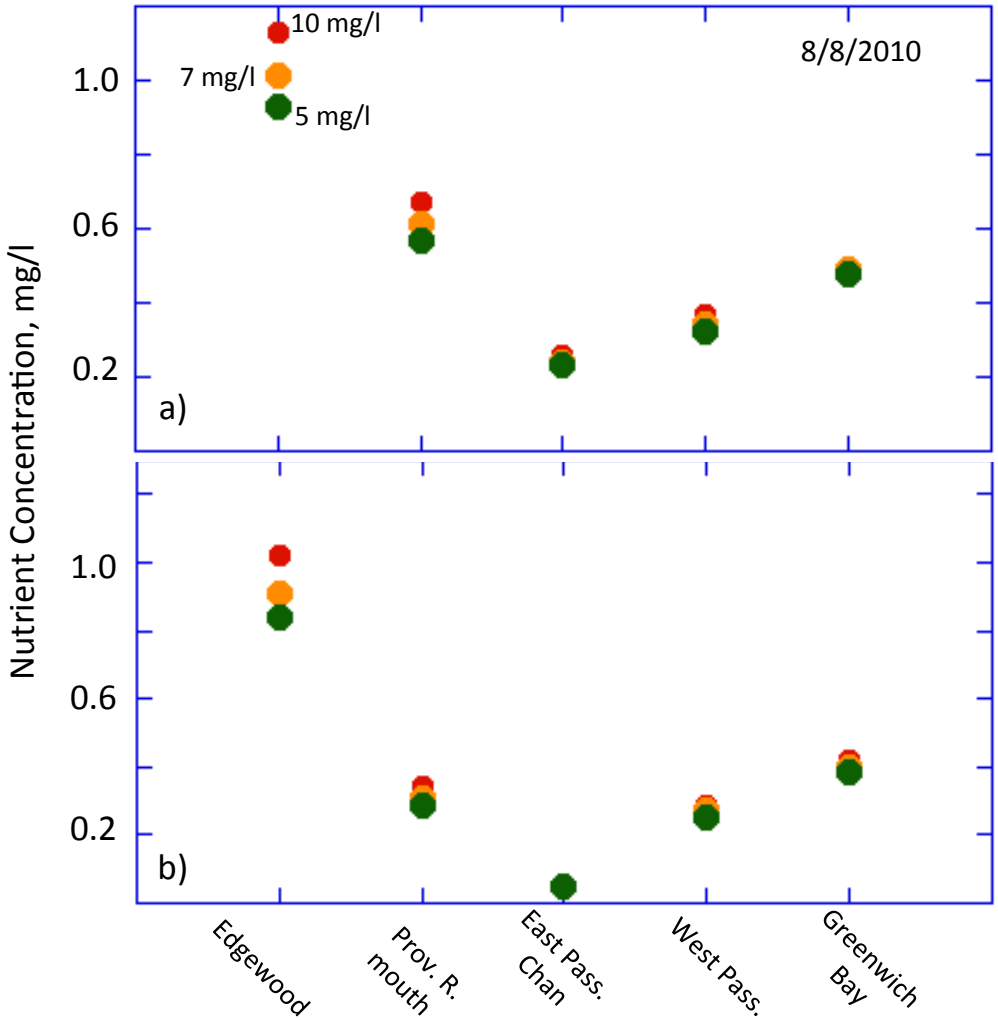


Figure 62. Plots of total nutrient concentration calculated at key locations throughout the estuary showing the role of different management strategies for near surface water (a) and near bottom water (b) on day 230 (8/8/2010). Colored circles represent Fields Point WWTF source water nutrient concentration of (red) 10 mg/l, (orange) 7 mg/l and (green) 5 mg/l.

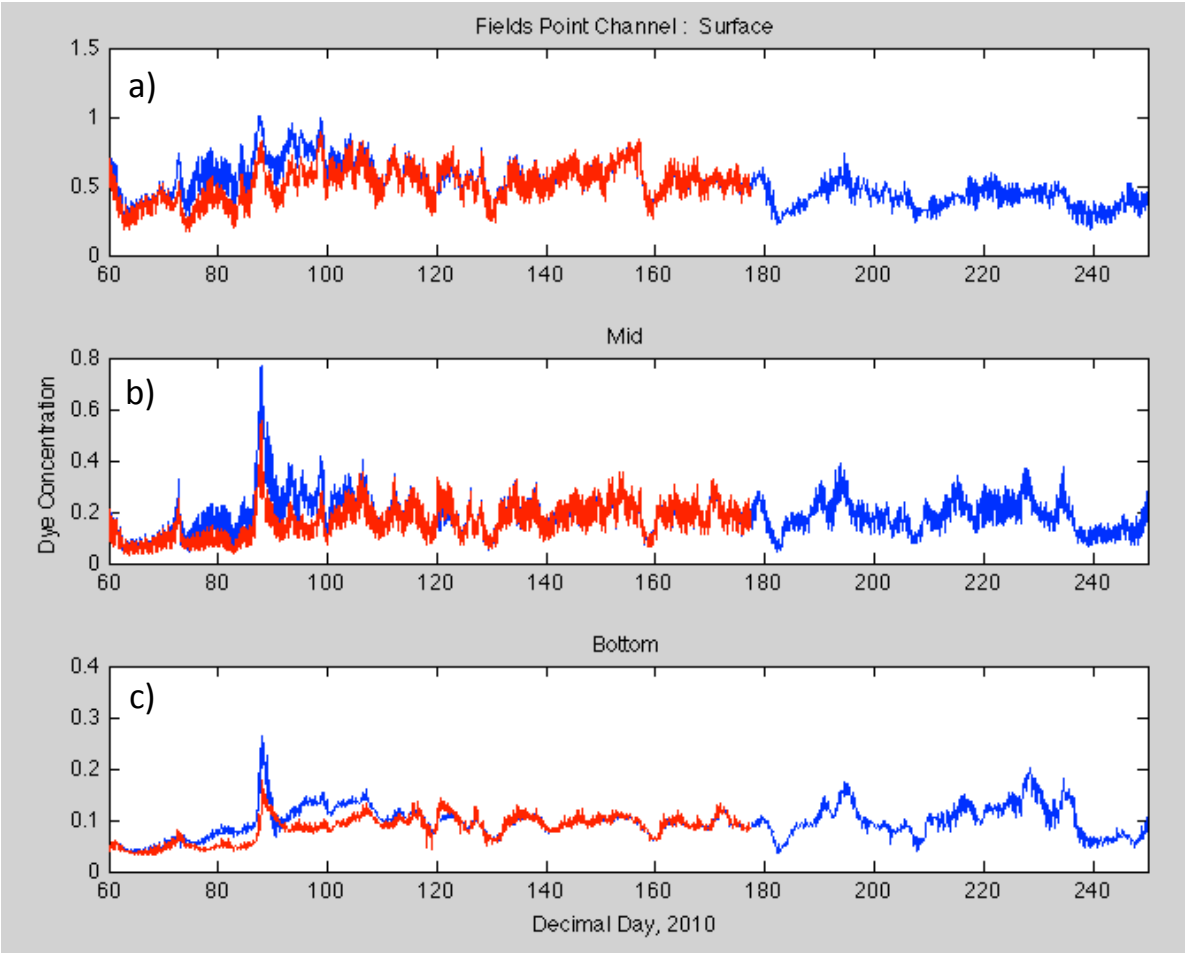


Figure 63. Time series plots of total nutrient concentration from all modeled fresh water sources, for 2010 conditions, averaged at three locations within the shipping channel near Fields Pt. Here flood nutrient concentrations return quickly to those of the non-flood reference case, or shortly after day 110.

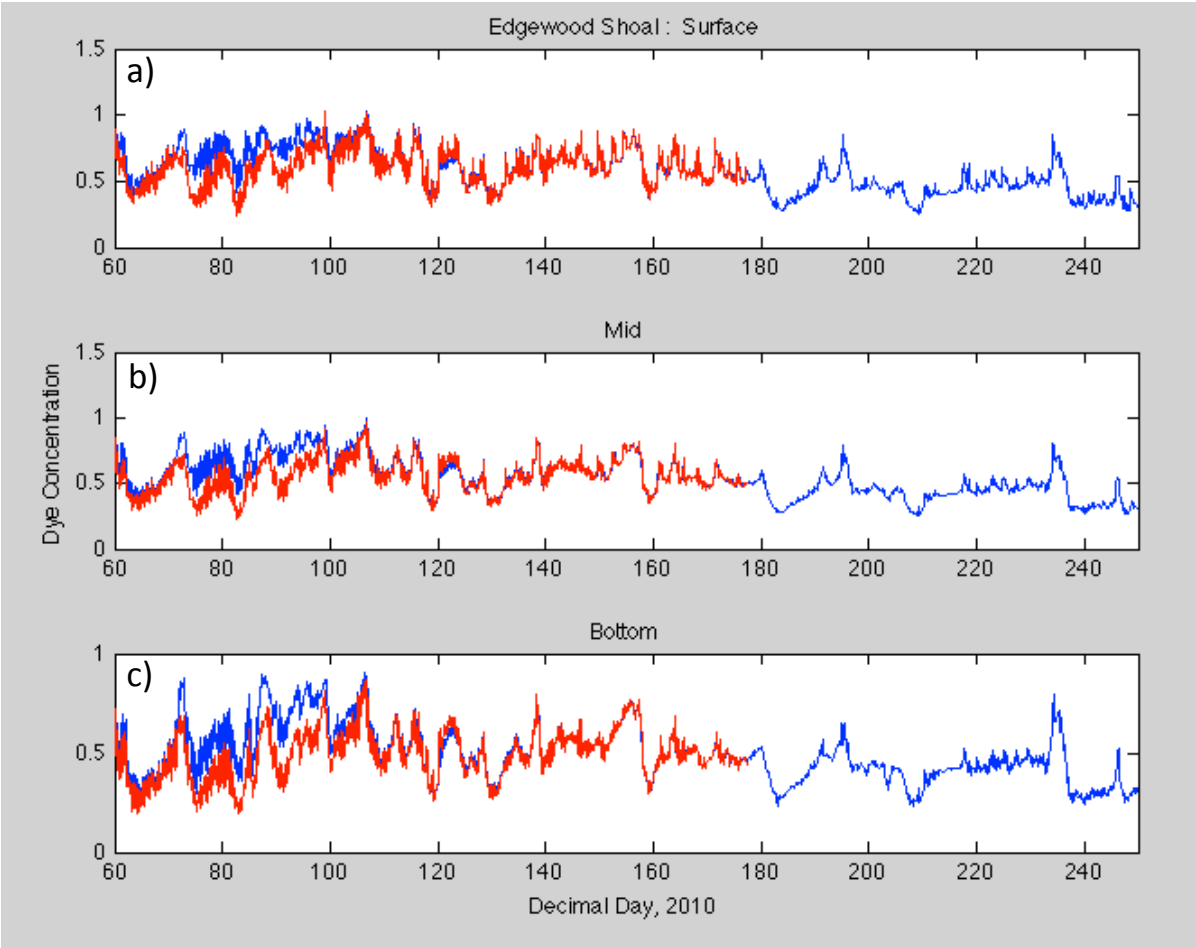


Figure 64. Time series plots of total nutrient concentration from all modeled fresh water sources, for 2010 conditions, averaged at four locations within the Edgewood Shoal region of the Providence River. The plots show the rise and fall of nutrient levels around the flood (~ day 90), however the amplitude of the flood effect is muted on the shoals compared to elsewhere in the estuary.

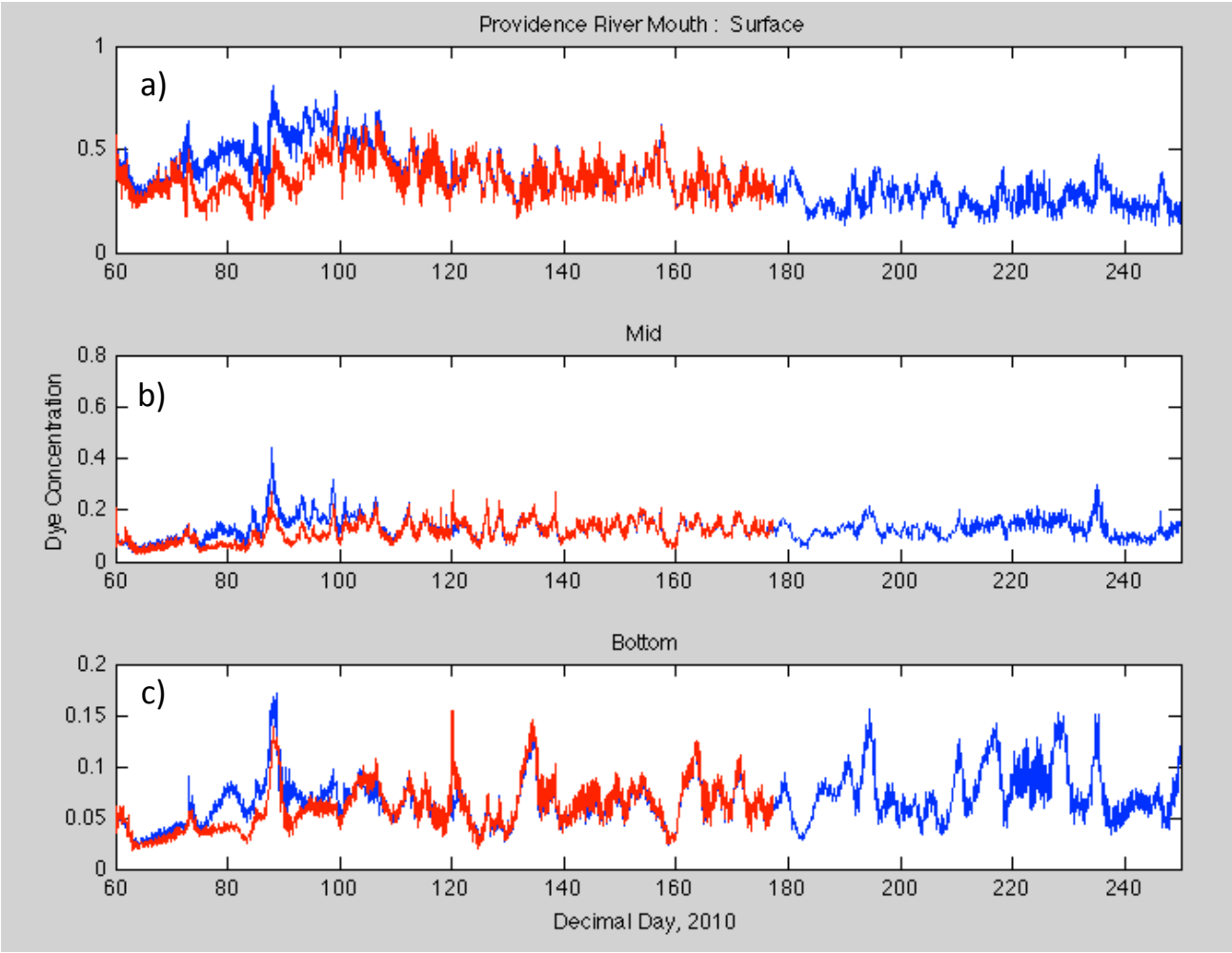


Figure 65. Time series plots of total nutrient concentration from all modeled fresh water sources, for 2010 conditions, averaged at three locations near the mouth of the Providence River. Flood-induced elevation of nutrient levels in this area returns within 20 days to the reference, non-flood simulation values.

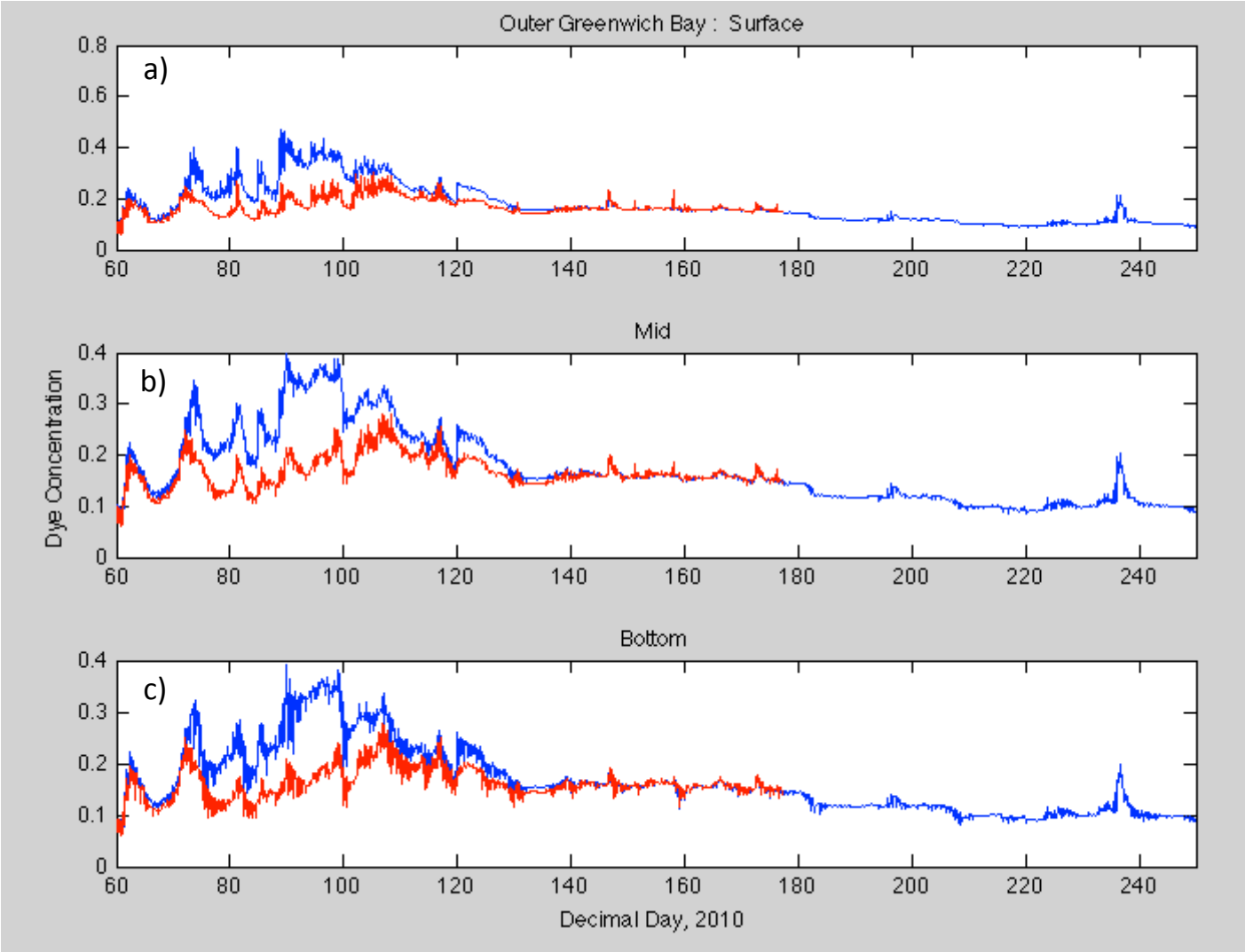


Figure 66. Time series plots of total nutrient concentration from all modeled fresh water sources, for 2010 conditions, averaged at four locations within **outer Greenwich Bay**. As in the inner basin, the biggest and longest lasting effects of the flood on nutrient concentrations are felt in the bottom water of the outer basin.

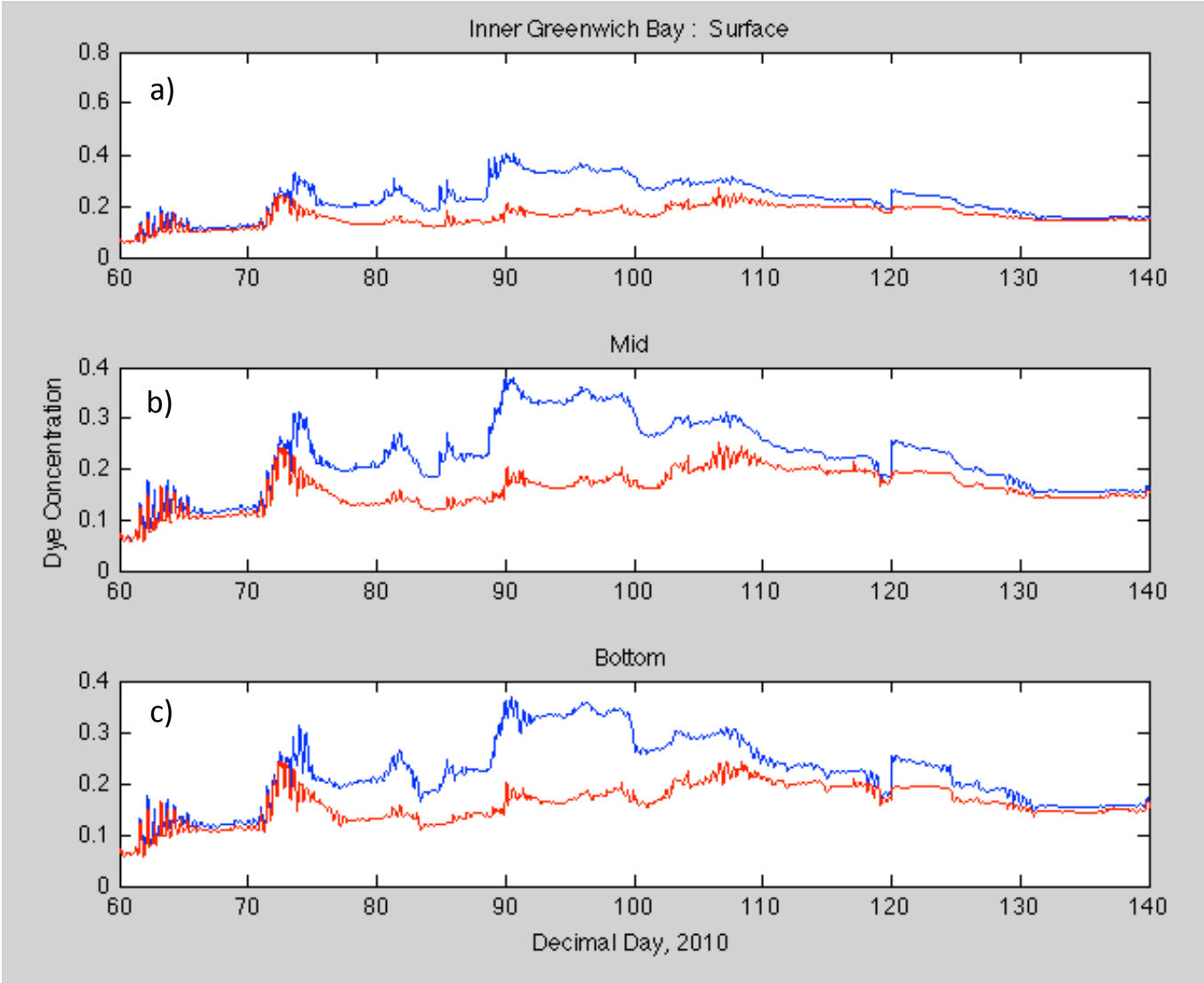


Figure 67. Time series plots of total nutrient concentration from all modeled fresh water sources, for 2010 conditions, averaged at four locations within **inner Greenwich Bay**. The plots show the rise and fall of nutrient levels around the flood (~ day 90). The plots compare concentrations for a run with runoff information from the actual flood of 2010 (blue line). A second line marks the concentration levels for a similar run, but when the flood runoff amplitudes are reduced by 95%. Here the influence of the flood is felt within the mid- to bottom water columns of Greenwich Bay through day 130, or 42 days after the flood.

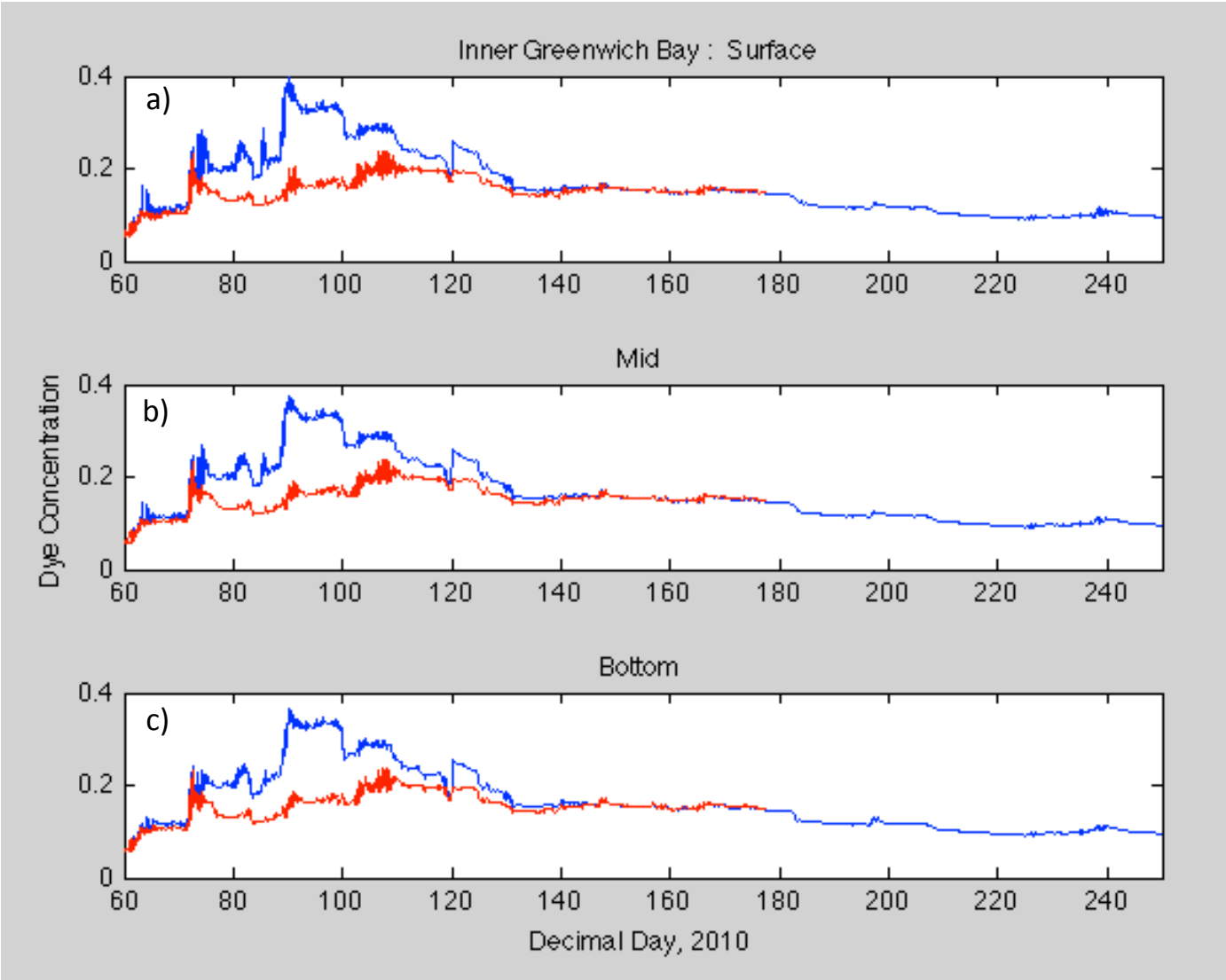


Figure 68. Same plot as the previous Figure, except showing a longer time period. By the time of decimal day 130, the system has reached a background, and the nutrient values for flood versus non-flood solutions converge.