

# Assessing the Effect of Effluent Discharge from Proposed Ocean Outfall Sites off of West Falmouth MA

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### **Executive Summary**

The town of Falmouth MA lies on the southwestern, down-gradient side of a sole source aquifer, the Sagamore Lens, which feeds multiple Falmouth watersheds flowing to coastal embayments of Buzzards Bay and Vineyard and Nantucket Sounds. This trend of ground water flow poses a challenge in choosing a site to discharge the town's treated wastewater. Wastewater discharged at a ground-based site within the town limits will, almost certainly, be carried in the down-gradient ground water flow into a coastal embayment. Currently, the primary site at which the Town of Falmouth disposes treated wastewater is at the Town's Waste Water Treatment Facility in West Falmouth, which lies in the watershed of West Falmouth Harbor. It is well established that West Falmouth Harbor has experienced significant degradation due to the influx of nutrients carried in the treated wastewater discharged at the treatment facility. As part of Falmouth's current wastewater planning process, potential upland discharge sites throughout town are being evaluated. Several have been found to be problematic because of the projected impact on coastal estuaries.

An alternative to upland discharge of treated wastewater is an ocean outfall. Historically, this option has been widely used by municipalities in southeastern New England, and is still employed (for example, by New Bedford, Dartmouth, and Boston). An ocean outfall was also used in Woods Hole from 1946 through 1985.

As part of a study of wastewater discharge options, the Town of Falmouth contracted with GHD and its consultants, J. Churchill, G. Cowles and J. Rheuban, to evaluate the potential impact of effluent discharge from an ocean outfall in Buzzards Bay. Two candidate outfall locations were considered. One was 4380 ft from the West Falmouth shoreline and the other was roughly 900 ft further offshore. High-resolution modeling was conducted to track a hypothetical effluent discharged from these two sites. The discharge was set at a rate of 4 million gallons per day and at a total nitrogen concentration of 3 mg/L (by permit, the maximum concentration of total nitrogen currently allowed in effluent discharged by the Town of Falmouth).

The results of the year-long, effluent-tracking simulations reveal that the hypothetical discharge from either candidate outfall would have negligible effects on total nitrogen concentrations in surrounding waters. The projected impact of the discharge on the total nitrogen concentration in either Buzzards Bay or West Falmouth Harbor is considerably less than 1 percent. Furthermore, because the candidate outfalls are situated in an area of vigorous ocean mixing, the simulations show that the discharged effluent is rapidly diluted upon release. This is a

critical finding as national shellfish sanitation regulations generally prohibit shellfish harvest within the area where the effluent dilution from an outfall is less than 1000:1. The simulations indicate that 1000:1 effluent dilution is achieved within 600 ft from either proposed outfall location, and far distant from any shellfish beds. Importantly, the simulations show little difference in the impact of effluent discharge from one outfall vs the other, making the more inshore site, which would be less expensive to install, a viable option for replacing the current ground-based discharge of wastewater at the West Falmouth Treatment Facility and eliminating this large source of nitrogen pollution to West Falmouth Harbor.

## 1. Introduction – Goals and Approach

Currently, the wastewater effluent processed by the Town of Falmouth MA at two Waste Water Treatment Facilities (WWTFs) is discharged into ground-based infiltration basins (open sand beds at the West Falmouth WWTF and leaching trenches at the North Falmouth WWTF). The open sand beds of the West Falmouth WWTF, which services most of the properties connected to the town's sewer lines and processes septage as well, are located less than 1 mile from West Falmouth Harbor (Figure 1). The effluent enters a ground water flow directed towards West Falmouth Harbor and Buzzards Bay, and has degraded the water quality of West Falmouth Harbor. In 2005, Falmouth upgraded the plant to tertiary treatment and reduced the concentration of nitrogen in the effluent to 3 mg/L. Falmouth is now exploring options to remove all future discharge of treated effluent from the ground water and West Falmouth Harbor.

As part of the investigation into alternate methods of wastewater effluent disposal, GHD and subcontractors, J. Churchill, G. Cowles and J. Rheuban, were contracted to explore the possibility of open-water effluent discharge at an ocean outfall within Buzzards Bay. The area considered for siting an outfall was directly offshore of West Falmouth (Figure 1). The GHD team was charged with the principal goals of:

1. Selecting suitable open-water outfall sites based on the potential effect of disposal on coastal and estuarine concentrations of total nitrogen (TN).
2. Undertaking high-resolution modeling to estimate the coastal and estuarine TN concentrations resulting from effluent discharge of 3 mg/L at the chosen sites.

In working towards Goal 1, the team utilized high resolution bathymetry of the area of Buzzards Bay off of West Falmouth with the aim of selecting candidate outfall sites in an area of deep water (to maximize initial dilution) and sufficiently distant from the coast so that the effluent discharged from the sites would have a negligible effect on nutrient concentrations in sensitive areas (e.g., West Falmouth Harbor). As detailed below, two locations were selected as potential open-water outfall sites.

A high-resolution water quality model was employed to achieve Goal 2. The model utilized velocity fields generated by a high-resolution hydrodynamic model to track the movement and mixing of TN in effluent (hereafter 'effluent TN') set out from the candidate outfall sites. To assess the possible effect of discharge from the candidate sites on existing TN concentrations, the effluent TN concentrations estimated by the model were compared with recent measurements of TN concentrations acquired in Buzzards Bay and West Falmouth Harbor.

This report details the data and methodology employed by the GHD team (Section 2 and Appendix 1), offers a detailed description of the findings focusing on the effects of the proposed open-water discharge on TN concentrations in Buzzards Bay and West Falmouth Harbor (Section 3), and concludes with a summary of the findings (Section 4).

## 2. Methods

### 2.1 Measured Total Nitrogen Concentrations

The measurements of TN concentrations used in this study came from two principal sources: Massachusetts Estuary Project (MEP; see Howes et al., 2006 and <http://www.smast.umassd.edu/Coastal/research/estuaries/estuaries.html>) and the Buzzards Bay Coalition online Bay Health data directory (<http://www.savebuzzardsbay.org/bay-health/>)

As part of data acquisition for both sources, water samples were collected over the summer months (primarily in July-September) and principally during the last three hours of an outgoing tide. The samples were either filtered on site or after immediate transport to a laboratory. The typical sample analysis procedure was carried out as follows. Inorganic nutrients, nitrate and nitrite, ( $\text{NO}_3^-$  and  $\text{NO}_2^-$ ) were analyzed spectrophotometrically by automated Cd reduction (Johnson and Petty, 1983). Ammonium ( $\text{NH}_4^+$ ) was measured using the phenol hypochlorite method (Strickland and Parsons, 1972). Total dissolved nitrogen (TDN; the sum of  $\text{NO}_3^- + \text{NO}_2^- + \text{NH}_4^+$ ) was measured as nitrate following persulfate digestion (D'Elia and Steudler, 1977). Particulate organic nitrogen (PON) was measured by elemental analysis (Sharp, 1974). The methodology is outlined in a Quality Assurance Project Plan that has been approved by the Massachusetts Department of Environmental Protection and the U.S. Environmental Protection Agency (Williams and Neill, 2014).

Detection limits for nitrogen measurements in coastal waters vary depending on the methods and instruments used for analysis. In West Falmouth Harbor, TN has commonly been determined from measurements of various nitrogen species including some combination of nitrate+nitrite (detection limit 0.0014 mg/L), ammonium (detection limit 0.0014 mg/L), total dissolved nitrogen (detection limit 0.007 mg/L), and particulate organic nitrogen (detection limit 0.007 mg/L) (Gunn et al. 1994). The best estimate of the overall detection limit for TN from West Falmouth Harbor is then in the range of 0.0014-0.007 mg/L, with the limit of a particular sample depending on the relative contribution of each nitrogen species.

TN concentrations in the interior of Buzzards Bay were characterized using the data from the Buzzards Bay Coalition mid-bay buoy (BBC in Figure 1). TN concentrations from samples taken at the buoy are available online (<http://www.savebuzzardsbay.org/subembayments/center-bay-buoy/>) in the form of yearly averages spanning the period 2007-2017.

Characterization of recent (2016-2018) TN concentrations within West Falmouth Harbor was carried out using data from MEP sampling at seven sites within the harbor (Table 1, Figure 2).

Longer-term (1992-2017) data of TN concentration within West Falmouth Harbor were obtained from the Buzzards Bay Coalition website (see above), which lists yearly averages of TN concentration at the seven MEP sampling sites (Figure 2).

## **2.2 Bathymetry Data**

The choice of candidate open-water outfall locations was guided by high resolution bathymetry data compiled by the US Geological Survey (USGS). The data represent the bottom depth at a horizontal resolution of 10 m (32.8 ft), and are produced using public domain depth measurements as well as measurements from LiDaR (Light Detection and Ranging) surveys (Andrews et al., 2018). In coastal waters, the fine resolution of the USGS bathymetry is principally a product of the LiDaR depth data, which are typically acquired from aircraft and have an accuracy of  $\pm 15$  cm (6 inches) and maximum vertical extent of roughly 130 ft.

The USGS data show complex bathymetry in the area considered for open-water outfall (Figure 3). Prominent features are Gifford Ledge, extending offshore of West Falmouth, and an unnamed deep (>50 ft) basin to the north. As detailed below (Section 3.1), the basin was chosen as the area to be considered for siting an open-water outfall. It is situated offshore of a coastal escarpment that extends roughly 3500 ft from shore (Figure 4).

## **2.3 Hydrodynamic Model**

As noted in the Introduction, the modeling component of this project was carried out in two parts. In the first, flows in the region of interest (Buzzards Bay and the estuaries near the proposed open-water outfalls) were simulated with a high-resolution hydrodynamic model. The second part entailed using the modeled flow fields to simulate the transport and mixing of effluent discharged at the proposed outfalls. This section presents an overview of the hydrodynamic model (with further details presented in Appendix 1). Details of the plume tracking model are presented in Section 2.4.

### **2.3.1 Model Description**

The hydrodynamic modeling was carried out using the Finite-Volume Community Ocean Model (FVCOM: Chen et al., 2003, 2006; Cowles, 2008), an open source model system with over 4000 registered users that has been applied in a wide array of coastal and open ocean studies. FVCOM operates by solving the equations of motion on an unstructured grid, with triangular elements that can be aligned with coastline and bathymetric irregularities. To produce a 3-dimensional solution, FVCOM employs a sigma-coordinate system, in which the vertical component of the model domain is divided into a fixed number of layers that follow changes in model terrain. Layer thickness is thus proportional to water depth.

The modeling of this project was carried out using a regional FVCOM-based model known as the Southeastern Massachusetts-FVCOM (SEMASS-FVCOM), which includes the Massachusetts and Rhode Island coastal zones as well as Long Island Sound (Figure 5). SEMASS-FVCOM has been employed, and its output velocity fields extensively evaluated, by co-PIs Cowles and Churchill for recent studies of tidal energy in the Massachusetts coastal zone (Hakim et al., 2013; Cowles et al., 2017) and the dispersal of bay scallop larvae in Buzzards Bay (Liu et al., 2015). Churchill and Cowles are currently using SEMASS-FVCOM in two NOAA-funded studies. One is aimed at assessing the impact of climate change on the delivery of lobster larvae to

suitable juvenile habitat off of southern New England. The other is directed at quantifying the impact of municipal sewage discharge on coastal acidification, focusing on effluent released by the towns of New Bedford, Fairhaven and Wareham MA.

In the regions of interest, the SEMASS-FVCOM grid scales are small (Figure 5), giving highly resolved modeled velocity fields. In the area considered for the proposed outfalls, for example, the horizontal grid spacing is of order 350 ft (giving modeled velocities of the same spacing). Grid spacing is smaller close to shore and in the estuaries, equaling 100-200 ft in West Falmouth Harbor. In the vertical, SEMASS-FVCOM is divided into 20 equally spaced layers, giving a fine vertical resolution of velocity in coastal water (i.e., of 0.5 ft in 10 ft of water).

As demonstrated by the modeled surface velocity fields of maximum flood and ebb tides on 14-15 July 2015 (Figure 6), the model captures the complexities of the flows over West Falmouth Harbor and the near-shore waters to the west.

### 2.3.2 Model Forcing and Execution

As detailed in Appendix 1, the hydrodynamic model simulations were generated with a full suite of natural forcings, including tides, surface wind stress, surface heat flux and fresh water runoff. For this project, the model was executed to produce velocity fields, saved at hourly intervals, throughout 2015. These fields were then used by the water quality model to simulate the movement and mixing of effluent discharged from the proposed ocean outfall, as described in the section below.

Further details of the operation of the hydrodynamic model and examples of model verification using field data are given in Appendix 1.

## **2.4 Water Quality Model**

The water quality model is formulated to operate on a grid linked with the hydrodynamic model grid (Figure 5). In the horizontal plane, the grid is formed by a series of polygon-shaped cells, which give the grid something of a honeycomb appearance (Figure 7). In the vertical plane, each cell is divided into 20 evenly spaced layers (corresponding to the sigma-layers of the hydrodynamic model). This arrangement gives a concentration field with a fine vertical resolution. For example, a cell with a water depth of 10 ft would consist of layers with a thickness of 0.5 ft. The effluent concentration is considered to be uniform within each layer of each cell.

The advective transport (carried by water velocities) of effluent across the grid cell boundaries and between the grid cell layers is determined using the velocities from the hydrodynamic model. Diffusive transport across the cell and layer boundaries is also incorporated into the model.

In mathematical terms, the effluent-tracking simulations operate by solving the diffusion-advection equation in three dimensions with a source term (applied at the outfall). Denoting the effluent TN concentration as  $C_E$ , the equation is expressed as:

$$\frac{\partial C_E}{\partial t} = - \left[ \underset{A}{u \frac{\partial C_E}{\partial x}} + \underset{B}{v \frac{\partial C_E}{\partial y}} + w \frac{\partial C_E}{\partial z} \right] + \underset{C}{K_H \left[ \frac{\partial^2 C_E}{\partial x^2} + \frac{\partial^2 C_E}{\partial y^2} \right]} + \underset{D}{K_V \frac{\partial^2 C_E}{\partial z^2}} + \underset{E}{SS}$$

where:  $x$ ,  $y$  and  $z$  are the east, north and vertical coordinates, respectively;  $t$  is time;  $u$ ,  $v$  and  $w$  are the east, north and vertical velocity components;  $K_H$  and  $K_V$  are the horizontal and vertical diffusivities; and  $SS$  is the source of TN introduced at the outfall.

Solving for the change in effluent TN concentration (term  $A$  above) in each layer of each cell is done by determining the advective fluxes (term  $B$ ) of TN through the horizontal and vertical boundaries of each layer of each cell. Also included are the diffusive TN fluxes through the layer's horizontal (term  $C$ ) and vertical (term  $D$ ) boundaries. The advective fluxes are determined with the velocities output from the hydrodynamic model. In determining the horizontal diffusive fluxes,  $K_H$  is set to a uniform value of  $0.2 \text{ m}^2 \text{ s}^{-1}$ . Values for  $K_V$  are taken from the output of the hydrodynamic model ( $K_V$  depends on the vertical shear of the horizontal velocity) with a minimum value of  $0.3 \times 10^{-2} \text{ m}^2 \text{ s}^{-1}$  imposed.

The input of effluent TN (term  $E$ ) occurs in the control volume encompassing the outfall (Figure 7) at a rate (mass per unit time) of  $V * C_{discharge}$ , where  $C_{discharge}$  is the concentration of TN emerging from the outfall and  $V$  is the volume rate of discharge. It is assumed that the discharged TN is initially mixed vertically and horizontally in the model cell containing the outfall. It is also assumed that all effluent TN passing through the model's oceanic (open) boundary (Figure 5) is lost to the system (i.e., does not return to the model domain). As the model boundaries are far from the areas of interest (i.e. eastern Buzzards Bay and the estuaries of West Falmouth), this boundary condition has no appreciable effect on the modeled TN concentrations in these areas.

The model was executed in monthly increments for all of 2015. The final concentration field of each month was used as the initial concentration field for the subsequent month. The model time step was set at 20 s. In solving the equation for each time step, the velocities and  $K_V$  values output by the hydrodynamic model (at hourly intervals) were interpolated to center of each time step.

The model code was formulated (in MATLAB) by project team members Churchill, Cowles and Rheuban for use in a MIT Sea Grant-funded project aimed at quantifying the impact of municipal effluent discharge on the carbonate system of coastal waters. As part of this project, the code has been subject to considerable testing (i.e., by comparison of modeled and observed effluent concentration patterns). In the simulations for this project, testing was done for mass conservation (that the accumulated effluent TN in the model domain equaled the amount discharged minus the amount lost at the open oceanic boundary) and to ensure the spatially

averaged TN concentrations in each region matched the TN mass in the region divided by the region's volume.

It's important to note that the effluent TN was considered to be conservative, and not subject to natural processes that would tend to extract TN from the water column (i.e., transfer through the air-water interface or biological uptake and transfer to the sediments). The modeled concentrations of effluent TN thus represent an upper limits for TN released from the open-water outfall.

### **2.5 Selection of Proposed Outfall Sites**

In addressing Goal 1 (Section 1), the region deemed most suitable for siting an outfall was confined to the basin immediately north of Gifford Ledge (Figure 3). The basin was deemed to be an ideal area for a near-bottom outfall for two principal reasons. One is its proximity to shore, an important factor when considering outfall construction costs. The second is its depth of greater than 50 ft (Figures 3 and 4), which will allow for considerable initial dilution of discharge effluent through vertical mixing.

Two locations within the basin, both at roughly 52 ft depth, were chosen as candidate outfall sites. Designated as D1 and D2, the sites are roughly 4380 and 5250 ft, respectively, from shore (Figure 3 and 4).

### **2.6 Discharge Parameters**

As noted above (Section 2.4) the rate at which effluent TN is discharged at each outfall site (i.e. the mass rate of discharge in units of mass/time) is a product of two parameters: the volume rate of discharge ( $V$ ) and the TN concentration contained in the discharge ( $C_{discharge}$ ). In executing the effluent transport simulations,  $C_{discharge}$  was set to 3 mg/L, the effluent nitrogen concentration set by permit for the Falmouth WWTF. In accordance with the scope of the project as specified by the Town of Falmouth,  $V$  was 4 million gallons per day (MGD), which is roughly twice the current rate of effluent discharge by the town.

It should be noted that because the model system is linear, the simulated effluent TN concentrations are proportional to the mass rate of discharge. For example, with  $C_{discharge}$  unchanged, the simulated TN concentrations for a volume rate of discharge of 2 MGD would be half of the concentrations shown here (determined with a 4 MGD discharge rate).

In assessing the viability of the outfall options proposed here, it's useful to compare their site and discharge characteristics with those of existing outfalls situated in Buzzards Bay. At present there are two such outfalls. One, operated by the City of New Bedford MA, is sited off of Clarks Point, New Bedford, while the other is operated by the Town of Dartmouth MA and situated off of Mishaum Point in Dartmouth. Both facilities discharge a wastewater effluent that has received secondary treatment. By contrast, the Falmouth WWTF is a tertiary treatment facility, designed to produce a lower TN effluent concentration than that of a secondary treatment facility. Compared with the projected 4 MGD flow rate through the proposed Falmouth WWTF ocean outfall, the volume rate of release is slightly greater for the Town of Dartmouth

discharge (at 4.2 MGD), and is significantly greater for the New Bedford discharge (at 30 MGD). With regard to location, both the New Bedford and Dartmouth outfalls are situated closer to shore and in significantly shallower water (<25 ft depth) than the proposed D1 and D2 sites (which are at >50 ft depth). Because of the difference in release depth, initial dilution through vertical mixing should be less effective at the existing outfalls than at D1 and D2. A detailed comparison of the existing outfalls with D1 and D2 is given in Appendix 2.

### **3. Results**

#### ***3.1 Existing Total Nitrogen Concentrations in Buzzards Bay and West Falmouth Harbor***

The means of recent TN concentrations compiled in this study show something of a steady rise going from Buzzards Bay into the interior of West Falmouth Harbor (Table 1, Figure 2). The mean TN concentration (in mg/L) increases from 0.26 at the BBC mid-bay buoy to 0.37 at the outer West Falmouth Harbor stations, and further rises to values of 0.42-0.51 and 0.48-0.86 at stations in Chapoquoit Basin and Snug Harbor, respectively. As demonstrated by Howes et al. (2006), a principal cause of this trend is the influx of groundwater-borne nutrients into West Falmouth Harbor from residential septic systems and from the Town of Falmouth's effluent discharge from the WWTF in West Falmouth (Figure 1).

In addition to this spatial trend, long-term (1992-2017) data reveal complex temporal changes in the TN concentrations within West Falmouth Harbor. These are exemplified by the yearly averaged concentrations at the MEP Snug Harbor station (WF5 in Figure 2), often referred to as the 'Sentinel Station' for the inner portion of West Falmouth Harbor. In addition to significant year-to-year variations, of up to 0.24 mg/L, these yearly averages show what appears to be a long-term rise to a maximum TN concentration of 0.79 mg/L in 2010 followed by a decline to concentrations of between 0.48 and 0.61 over the last four years (Figure 8). Yearly averaged TN concentrations at other MEP sites in West Falmouth Harbor show a similar pattern, with maximum values appearing in the 2010-2012 range.

In the sections to follow, the projected concentrations of effluent TN determined by the model simulations are compared with 2016-2018 averages of the measured TN concentrations in West Falmouth Harbor (Tables 1-2, Figure 2), as these averages best represent the existing TN concentrations, unbiased by the 2010-2012 maxima.

#### ***3.2 Effluent Transport Simulations***

The presentation of the simulation results in this section begins with a description of the projected effluent TN fields resulting from discharge at the two candidate outfalls (Section 3.2.1). This is followed by a description of the manner in which effluent discharged at the two sites is projected to influence TN concentrations in Buzzards Bay (Section 3.2.2) and in West Falmouth Harbor (Section 3.2.3). Attention is given to quantifying the relative effect of discharge at the one site vs the other, i.e., addressing the question of whether or not the discharge at the more offshore site (D2) results in significant lower effluent TN concentrations in West Falmouth Harbor than projected for discharge at the more onshore site (D1). Also

considered is the time required to flush effluent TN from the harbor, should it be exposed to relatively high concentrations of effluent TN (Section 3.2.4).

In discussing the model results, the **concentration of effluent TN** (i.e., the TN emanating from the outfall, which is **separate** from the **'background' concentration of TN in the receiving waters**) is denoted at  $C_E$  (see the above section). The **vertical average of  $C_E$**  is represented by  $\langle C_E \rangle$ , whereas the **near-surface effluent TN concentration** is denoted at  $C_{E(S)}$ . **Time averages of effluent TN concentration** are represented by the operator  $[\ ]_T$  (i.e.  $\langle C_E \rangle_{July}$  is the vertically averaged effluent TN concentration that is also averaged over the month of July).

### 3.2.1 Modeled Fields of Effluent Total Nitrogen Concentration

Monthly averaged fields of both  $\langle C_E \rangle$  and  $C_{E(S)}$  reveal a seasonal variation in the distribution of effluent TN that is linked to the seasonal variation in the wind field over the eastern portion of Buzzards Bay (discussed further in Appendix 1). For example, the fields of  $\langle C_E \rangle_{July}$  and  $C_{E(S)}_{July}$  (averaged over July) (Figures 9a, 10a, 11a and 12a) are noticeably skewed with higher concentrations tending to appear to the NNE of the outfall. This pattern is a result of circulation forced by the summer-time winds in eastern Buzzards Bay, which are dominated by the daily sea-breeze and are predominately from the SSW (Figure 13). The wind forcing characteristic of autumn (Figure 13) results in an effluent TN distribution noticeably different from that of the summer. For example, the  $\langle C_E \rangle_{Nov.}$  and  $C_{E(S)}_{Nov.}$  fields have lower values than their July counterparts due to the stronger autumn winds, which result in more vigorous wind-driven flow and more rapid transport of effluent away from the outfall (Figures 9-12). Furthermore, the November-averaged effluent TN fields tend to be skewed with higher concentrations appearing to the south of the outfall, a result of the tendency for winds of November to be directed from the WNW (Figure 13).

Notable in all monthly averaged  $\langle C_E \rangle$  and  $C_{E(S)}$  fields is a rapid decline in the concentration of effluent TN moving away from the outfall (Figures 9-12). For example, the November-averaged TN concentrations of effluent discharged from outfall D1 (i.e.,  $\langle C_E \rangle_{November}$ ) (Figure 9b) decline from 0.0046 mg/L at the cell containing the outfall to no greater than 0.0017 mg/L at cells roughly 800 ft from the outfall. All monthly averaged fields of  $\langle C_E \rangle$  and  $C_{E(S)}$  show a similar pattern of decline (by a factor of more than 2.5 going 800 ft from the outfall).

The rapid decline in  $\langle C_E \rangle$  moving away from the outfall is reflected in the fields of dilution ratio, defined here as the ratio of the  $\langle C_E \rangle$  to the TN concentration released at the outfall ( $C_{discharge} = 3$  mg/L for the simulations here). Mathematically, the dilution ratio averaged over some time period,  $T$ , is defined as

$$F_T = \frac{C_{discharge}}{[\langle C_E \rangle]_T},$$

It should be noted that because a change in  $C_{discharge}$  will produce a corresponding change in  $[\langle C_E \rangle]_T$ ,  $F_T$  is independent of the discharged TN concentration.

National shellfish sanitation regulations generally prohibit shellfish harvest within the area of less than 1000:1 dilution from a WWTF outfall. All monthly  $F_T$  fields exhibit a rapid increase in magnitude moving away from the outfall and contain a small area over which  $F_T$  is less than the 1000:1 threshold. In all but the summer months of July-September, the region over which  $F_T < 1000:1$  is confined to the outfall cell (e.g., the  $F_{November}$  field for discharge from D1 shown in Figure 14b). In the  $F_T$  fields of the summer months, the area with dilution of less than 1000:1 is contained within two cells and extends no more than 600 ft from the outfall (e.g., the  $F_{July}$  field in Figure 14a).

Of particular importance are the low values of all the monthly averaged  $\langle C_E \rangle$  and  $C_{E(S)}$  fields. Even with the outfall cell included, monthly averaged  $\langle C_E \rangle$  fields determined with effluent discharge at D1 never exceed 0.0056 mg/L, while the monthly averaged  $\langle C_E \rangle$  fields determined with the outfall at D2 have a slightly smaller maximum of 0.0049 mg/L. These maximum values are dwarfed by the TN concentrations measured at the BBC buoy in the central region of Buzzards Bay (Table 1).

### 3.2.2 Effect on Total Nitrogen in Buzzards Bay

In all modeled  $C_E$  fields, the decline in magnitude is particularly steep going westward from the outfall into the interior of Buzzards Bay (Figures 9-12). For example, in the fields computed with the outfall at D1, the yearly averaged  $\langle C_E \rangle$  at a site roughly ½ mile due west of the outfall is 0.001 mg/L, more than a factor of 5 lower than the yearly averaged  $\langle C_E \rangle$  at the outfall.  $C_E$  is further reduced going westward to the central region of Buzzards Bay. The yearly averaged  $\langle C_E \rangle$  (for discharge at D1) in the cell containing the BBC mid-bay buoy (Figure 1) is 0.00016 mg/L, more than three orders of magnitude lower than the mean TN concentration derived from samples taken at the buoy (Table 1). However, as these samples were taken near the surface and predominately during summer, a more appropriate comparison of their mean TN concentration is with the summertime average of the  $C_{E(S)}$  within the model cell containing the buoy. For the discharge at D1 and D2, this concentration ( $[C_{E(S)}]_{June-Aug.}$ ) is, respectively, 0.00024 and 0.00025 mg/L, both still three orders of magnitude less than the mean TN concentration measured at the buoy (Table 2, Figures 15 and 16). Clearly, the model simulations indicate that open-water discharge at sites D1 and D2 should have negligible effect on the TN concentrations within the central portion of Buzzards Bay.

Furthermore, the monthly averaged model results described in the section above indicate that the impact of discharge at D1 and D2 is negligible on TN concentrations throughout Buzzards Bay, even in the area near the discharge sites. In particular, the largest monthly averaged  $\langle C_E \rangle$  of 0.0056 mg/L (for an outfall at D1) is 2 % of the mean TN measured at the BBC buoy (Table 1). It's noteworthy that even if the discharge TN concentration were, for some reason, temporally increased to 10 times the permitted value of 3 mg/L, the maximum  $\langle C_E \rangle$  determined by the model would still be a relatively small fraction, order 20 %, of the existing TN concentration in Buzzards Bay. As demonstrated below (Section 3.2.5), the flushing near the selected outfalls is vigorous and would quickly reduce any increase in  $\langle C_E \rangle$  resulting from discharge at an elevated concentration of TN.

### 3.2.3 Effect on Total Nitrogen in West Falmouth Harbor

A number of metrics are employed to assess the effect of effluent discharge from each of the candidate outfall locations on the mass and concentration of TN within West Falmouth Harbor. One such metric is the spatially averaged value of  $C_E$  within the harbor. This is taken as the ratio of the total mass of effluent TN within the model cells contained within the harbor (the colored cells in Figure 17) to the overall volume of these cells, which changes with the rising and falling tide.

The time series of the mean  $C_E$  in West Falmouth Harbor (Figure 18) have prominent temporal variations spanning 0.003 mg/L. These include a weak seasonal modulation (tending to be higher during the warmer months) as well as changes occurring on a roughly weekly time scale. These variations are presumably the result of varying wind conditions and the attendant changes in the delivery of effluent TN to West Falmouth Harbor.

Despite these variations, the magnitude of the mean  $C_E$  in West Falmouth Harbor is always minute compared with the recent measurements of TN concentration in the harbor. With the exception of a brief period of <1.5 days in early September, the mean  $C_E$  in the harbor is less than 0.003 mg/L. By contrast, the measured TN concentrations in the harbor are typically well in excess of 0.3 mg/L (Table 1, Figure 2).

Of particular note is the similarity of mean  $C_E$  in West Falmouth Harbor derived from simulations with the outfall at D1 and D2 (the blue and magenta lines in Figure 18). The mean  $C_E$  of effluent discharged from D2 is typically lower than the mean  $C_E$  of effluent from D1, but never by more than 0.001 mg/L and by less than 0.0004 mg/L over 98 % of the year-long series.

Another metric used in assessing the effect of effluent discharge on TN within West Falmouth Harbor is the projected time series of  $\langle C_E \rangle$  at the Snug Harbor sentinel station (Figure 2). For discharge at either outfall location, the sentinel station  $\langle C_E \rangle$  never exceeds 0.003 mg/L (Figure 19a) and is always less than 0.5 % of the mean measured concentration (averaged over 2016-2018) of TN at the sentinel stations (Figure 19b). As seen in time series of mean  $C_E$  in West Falmouth Harbor, the time series of sentinel station  $\langle C_E \rangle$  derived from simulations with the outfall at D1 and D2 are closely aligned, differing by less than 0.0004 mg/L over 98 % of the series.

A final metric considered here is a comparison of the measured existing TN concentration with the projected mean  $\langle C_E \rangle$  in three regions of West Falmouth Harbor: the Outer Harbor, Snug Harbor and Chapoquoit Basin (Figure 17). The mean existing TN concentration in each region is taken as the average of all Pond Watcher measurements taken within the region's border over 2016-2018 (Table 1, Figure 2). The mean existing TN concentration is greatest in Snug Harbor and smallest in the Outer Harbor (Figure 15). By contrast, the mean 'regional'  $\langle C_E \rangle$  (averaged over the full year of 2015) is greatest in the Outer Harbor, owing to closer proximity to the outfall than the other two regions. For all regions, the mean  $\langle C_E \rangle$  is less than 0.4 % of the mean existing TN concentration (Figure 16).

From all the metrics presented above, it is clear that the model simulations indicate that the effect of discharged effluent on TN concentrations in West Falmouth Harbor should be negligible for effluent released from either site D1 or D2.

### 3.2.4 Flushing Rate of West Falmouth Harbor

To explore a worst-case discharge scenario, simulations were carried out to examine the flushing of West Falmouth Harbor after being subject to outfall discharge with elevated concentrations of TN. The model setup consisted of a month-long period over which effluent with an elevated TN concentration was discharged at D1 followed by a month-long period of no effluent discharge. For the month of discharge,  $C_{discharge}$  was set to 35 mg/L and the volume rate of discharge was set to 4 MGD. The simulations tracked the rise and subsequent decline (after discharge shutoff) of effluent TN contained in the harbor (in the colored cells of Figure 17). The simulations were carried out over two periods with discharge in July and November and followed by model execution without discharge in August and December.

The results show that following the discharge shutoff, the mean concentration of effluent TN within the harbor undergoes a steady decline modulated by relatively small tidal variations (Figure 20a). For both periods modeled, the total mass of effluent TN contained in the harbor is reduced by a factor of 10 roughly 3 weeks after shutoff (Figure 20b). At this 3-week after shutoff mark, the mean  $C_E$  within the harbor is roughly 0.001 mg/L in the December simulation and slightly higher, roughly 0.0016 mg/L, in the August simulation. Based on these results, it appears that TN is effectively flushed from West Falmouth (to 10 % of the original mass) over a period of 3 weeks.

### 3.2.5 Flushing Rate of Buzzards Bay at Site D1

In considering the worst-case discharge scenario outlined above, another concern is the rate at which effluent TN resulting from a temporary discharge at an elevated TN concentration is flushed from the area near the discharge site. It may be expected that the flushing of TN from the open water near the outfall locations would proceed relatively quickly. This expectation is borne out by the simulations described above. Following the cessation of the discharge with  $C_{discharge}$  set to 35 mg/L, the time series of  $\langle C_E \rangle$  at the discharge site (D1) shows a dramatic drop over the first hour (Figure 21), by a factor of roughly 2 and 4, respectively, in the August and December simulations. Following this drop,  $\langle C_E \rangle$  at the discharge site continues to decline, and is reduced to 10% of its value at discharge cessation in roughly 8 and 2 days, respectively, in the August and December simulations. Based on these results, it appears that in the 'worst-case scenario' specified here, any temporary increase in effluent TN near the outfall would be quickly flushed away, in the course of a few days.

## **4. Summary**

The outfall option considered here, relocating the Town of Falmouth effluent discharge from the West Falmouth facility to Buzzards Bay, would completely remove the discharge of treated effluent into the groundwater upstream of West Falmouth Harbor, and thus eliminate a

significant source of TN to the Harbor. This study addressed the question of whether or not implementation of this option might have a significant impact on TN concentrations in areas of Buzzards Bay or its tributaries.

The results of the year-long simulations of effluent transport from two candidate outfall sites in Buzzards Bay leads to the overarching conclusion that this effluent will have negligible effects on TN concentrations in Buzzards Bay and West Falmouth Harbor. Among the notable findings supporting this conclusion are:

- Except at the candidate outfall sites, the monthly averaged concentration of effluent TN derived from the simulations never exceeds 0.004 mg/L.
- In the central portion of Buzzards Bay, the projected mean concentration of effluent TN is of order 0.00024 mg/L and less than 0.1 % of the mean existing TN concentration measured by the Buzzards Bay Coalition at a mid-bay location.
- The dilution factor of effluent TN (computed from monthly averaged TN fields generated by the model) exceeds 1000:1 at all locations except for a small area near each candidate outfall site.
- For the year-long simulation, the projected mean concentration of effluent TN carried into West Falmouth Harbor is less than 0.003 mg/L for all but a brief period, 1.5 days, when the mean concentration rises to 0.0036 mg/L.
- The concentration of effluent TN at the Snug Harbor sentinel station within West Falmouth Harbor, derived from the year-long simulation, never exceeds 0.003 mg/L and is always less than 0.5 % of the mean TN concentration measured at the station.

The overarching conclusion is reinforced by noting that because the effluent TN was considered to be conservative, and not subject to natural processes that would extract nitrogen from the water column, the modeled effluent TN concentrations should be viewed as upper limits.

## **Appendix 1 – Details and Testing of the Hydrodynamic Model**

As noted in Section 2.3, the hydrographic modeling of this project was carried out with a model encompassing all of Buzzards Bay as well as the Massachusetts and Rhode Island coastal zones and Long Island Sound (Figure 5). The purposes of this Appendix are to describe this model, known as SEMASS-FVCOM, in much greater detail than done in the main body of the report and to present information on model assessment in the areas of interest.

### **A.1 Grid Setup**

As part of a recent project directed at the potential effect of effluent discharge into the western portion of Cape Cod Canal, the computational mesh of SEMASS-FVCOM has been refined in Buzzards Bay and Cape Cod Canal. The refined model grid contains 284,305 elements in the horizontal and 20 evenly spaced sigma-layers in the vertical.

The model bathymetry is interpolated from a composite dataset. The majority of the model domain is encompassed by the 3-arcsecond Gulf of Maine bathymetry product (Twomey and Signell, 2013) and the 1/3-arcsecond Nantucket Inundation Digital Elevation Model (NOAA: Eakins et al., 2009). Data from a directed sounding survey are used to specify the bathymetry of the Cape Cod Canal (USACE, 2011). The coastal boundary is derived from a high-resolution (1/2 arc-second) product developed and distributed by the Massachusetts Office of Coastal Zone Management.

### **A.2 Boundary Forcing**

The model is driven at the open boundary by sea surface elevation constructed from the six primary tidal constituents ( $M_2$ ,  $S_2$ ,  $N_2$ ,  $K_1$ ,  $O_1$  and  $M_4$ ). The phase and amplitude of these constituents and the associated regional barotropic response have been extensively evaluated in prior work (Cowles et al., 2017). Values of the salinity and temperature of water flowing into the domain are also set at the open boundary from a hindcast of a large-scale Gulf of Maine/Southern New England FVCOM-GOM model developed by Dr. Changsheng Chen of U. Mass. Dartmouth (NECOFS, 2017).

### **A.3 Surface Forcing**

At the surface, SEMASS-FVCOM is driven by net heat flux and surface wind stress, which are also derived from the regional 30-year FVCOM-GOM hindcast (NECOFS, 2017). The wind field in Buzzards Bay during 2015 (the year of the model runs for this project) displays a strong seasonality (Figure A1-1). The southwest sea breeze dominates the Buzzards Bay wind field from late spring to early fall. By contrast, winds from late fall to early spring are characterized by synoptic events with the strongest wind magnitudes directed from NW and NE. These characteristics of the 2015 wind field are typical of the seasonal wind field in Buzzards Bay (Liu et al., 2015).

In addition to utilizing wind and heat flux data to force the model at the surface, the model simulations also employ satellite-derived sea surface temperature (SST) derived from the NOAA

4 km-resolution product. SST is assimilated into the model using a Newtonian relaxation (nudging) approach, which adjusts the modeled SST to best match the observed SST.

#### **A.4 Freshwater Input**

Freshwater is input into the model domain at discrete points along the coastal boundary. The locations of the freshwater entry points into Buzzards Bay are based on the watershed delineations of the Buzzards Bay National Estuary Project, which established 32 watersheds draining into the bay. Currently, the only long-term record of freshwater influx into the bay is from a gauge in the Paskamansett River in Dartmouth (USGS 01105933). The freshwater flow from the other watersheds is estimated by multiplying the gauged flow of Paskamansett River by the ratio of a given watershed's area to the area of the Paskamansett River watershed. Using this method, it is estimated that the average freshwater discharge into the Bay in 2015 is  $21.3 \text{ m}^3 \text{ s}^{-1}$ , which is 14% below the 20-year annual mean discharge of  $25.0 \text{ m}^3 \text{ s}^{-1}$ . Inputs of freshwater from the major rivers outside the Bay (Connecticut, Blackstone, Pawtuxet, Taunton, Neponset, and Charles) are included in the model and are specified from hourly flow data recorded by USGS gauges (available from <https://waterdata.usgs.gov/nwis>).

#### **A.5 Execution and Data Archiving**

The model was executed for the period Jan 1, 2015 to Jan 1, 2016 using a time step of two seconds. The execution required 110,000 core-hours of wall time on 2.6 GHz Intel Haswell Xeons. The two-dimensional fields of sea surface height and depth-averaged velocity, and the three-dimensional fields of velocity, temperature, salinity, and the vertical turbulent eddy diffusivity and viscosity were archived at hourly intervals into NetCDF format files. The total dataset (1.5 TB in size) is accessible through the SMAST Thredds server at: [http://www.smast.umassd.edu:8080/thredds/catalog/buzzards/BBC\\_WW/catalog.html](http://www.smast.umassd.edu:8080/thredds/catalog/buzzards/BBC_WW/catalog.html).

#### **A.6 Model Testing and Verification**

SEMASS-FVCOM has been subject to extensive testing, principally through comparison of the model results with water levels and velocities measured at various locations within the model domain. Notable comparison studies have been carried out by Lui et al. (2015) as part of a study of the dispersal of bay scallop larvae in Buzzards Bay, by Cowles et al. (2017) as part of a study of tidal energy in the Massachusetts coastal zone, and most recently by project members Churchill, Cowles and Rheuban as part of a study of the possible impact of effluent discharge into Cape Cod Canal (Churchill et al., 2017). All studies found that the velocities and water levels produced by the model to be in close agreement with observations.

To assess the performance of the model in the areas of interest (West Falmouth Harbor and the waters of Buzzards Bay west of Falmouth MA), the model-derived velocities are compared with velocities measured by the USGS at two sites: one in the open waters of Buzzards Bay roughly 3 nautical miles SSW of the entrance to West Falmouth Harbor (hereafter, the southern Buzzards Bay site) and the second in the entrance to the Harbor (hereafter, the harbor entrance). The measurements at these sites did not overlap with our 2015 simulation period, so the

comparison is directed at the velocity statistics (i.e., does the model produce velocities with statistical properties similar to those of the measured velocities?). The focus is on the mean velocity and the tidal and subtidal signals.

The model velocity statistics were derived from model time series taken from the model cell with the center closest to the location of the observed currents and from the same time period (i.e., same year days) as the observed current time series. The tidal signal of the observed and model currents was determined by decomposing the depth-averaged velocity time series into the principal tidal constituents (M2, S2, N2, K1, O1 and M4) using the MATLAB routine T-Tide (Pawlowicz et al., 2002). The harmonic constituents were then used to reconstruct the full tidal signal of the model and measured currents for the measured current time period. Properties of the subtidal velocity signal were determined from the low-pass-filtered (40-hr half-power period) vertically-averaged modeled and observed velocity time series at each measurement site.

The modeled and observed depth-averaged velocities at the southern Buzzards Bay site both have a tidal signal roughly twice as strong as the subtidal signal and very weak (order 1.5 cm/s) means (Figure A1-2). The reconstructed observed and modeled tidal velocity signals are highly correlated ( $R=0.88$ ) with tidal ellipses that are nearly identical in orientation and magnitude (Figure A1-2a).

The modeled and observed depth-averaged velocities at the harbor entrance are both dominated by the tidal signal, with a subtidal signal and mean that are very small in comparison (Figure A1-3). As at the southern Buzzards Bay site, the measured and modeled tidal signal at the harbor entrance are highly correlated ( $R=0.90$ ) with tidal ellipses of similar orientation and magnitude (Figure A1-3a).

Based on this comparison, and the more extensive validation work cited above, the model is deemed capable of closely reproducing the flows of Buzzard Bay, including the area of the proposed outfall sites.

## **Appendix 2 – Comparison of Proposed to Existing Effluent Outfalls in Buzzards Bay**

As noted in Section 2.6, there are currently two municipal outfalls discharging effluent directly in Buzzards Bay. One, operated by the City of New Bedford MA, is situated off Clarks Point, New Bedford (Figure A2-1a). The other is operated by the Town of Dartmouth, MA and is sited east of Mishaum Point in Dartmouth (Figure A2-1b). Given here is a tabulated comparison of the characteristics of these outfalls with the characteristics of the candidate outfalls proposed for the Town of Falmouth (Table A2-1). In brief, both candidate outfall locations are further from shore, in deeper water, have lower flow rate and likely much lower effluent TN concentration (because of tertiary vs secondary waste water treatment) than either of the existing outfalls in Buzzards Bay.

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**Table 1.** Statistics of total nitrogen (TN) concentrations measured in Buzzards Bay and West Falmouth Harbor. Values for the Snug Harbor Sentinel Station are in bold.

Location	Identifier ( Figs 1 and 2)	Period of Meas.	Mean TN Conc. mg/L	Stand. Dev. mg/L
BBC Mid-Bay Buoy	BBC	2007-2017	0.266	0.049
Nashawena Road	WF1	2016-2018	0.856	0.166
Harbor Head	WF2	2016-2018	0.507	0.091
Chapoquoit Basin	WF3	2016-2018	0.425	0.077
Inner W. Fal. Harbor	WF4	2016-2018	0.477	0.104
<b>Snug Harbor Sentinel Sta.</b>	<b>WF5</b>	<b>2016-2018</b>	<b>0.553</b>	<b>0.126</b>
Outer W. Fal Harbor	WF6	2016-2018	0.374	0.069
Outer W. Fal. Harbor	WF7	2016-2018	0.370	0.076

**Table 2.** Comparison of measured concentrations of total nitrogen (TN) with projected effluent TN concentrations discharged at outfall sites D1 and D2 (Figure 3).

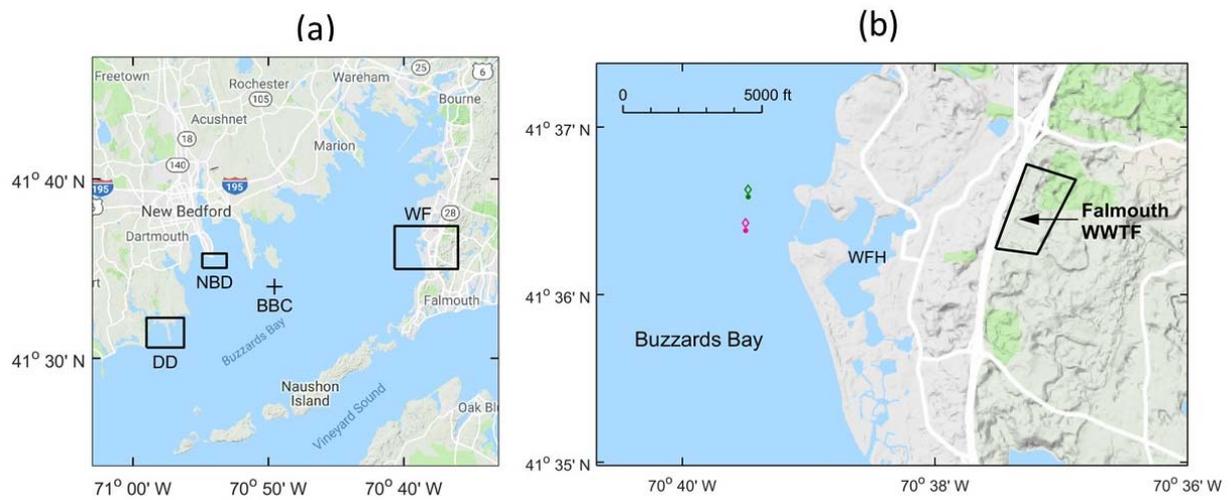
Site or Region	Measured TN Conc. mg/L	Modeled TN Conc. – D1 mg/L	Modeled TN Conc. – D2 mg/L
BBC Mid-Bay Buoy (Fig 1)	0.266	0.00024	0.00025
Outer Harbor (Fig. 16)	0.372	0.0013	0.0011
Chapoquoit Basin (Fig. 16)	0.466	0.0010	0.0009
Snug Harbor (Fig. 16)	0.629	0.0012	0.0011

**Table A2-1.** Comparison of Proposed to Existing Effluent Outfalls in Buzzards Bay.

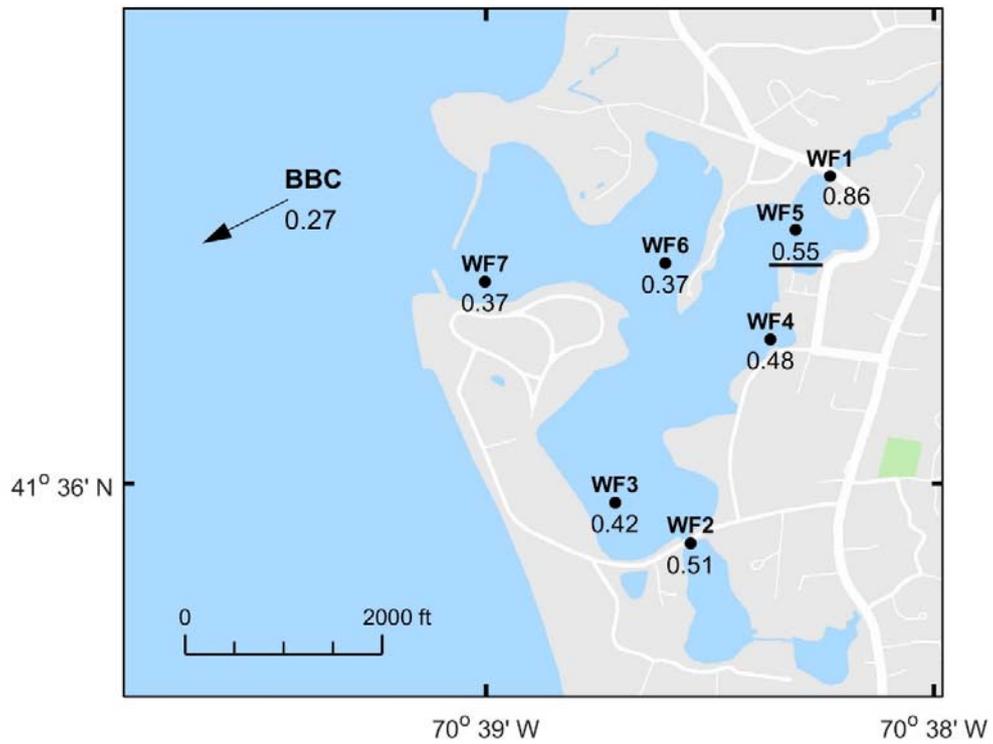
	Proposed Outfalls (Figure 3)		Existing Outfalls (Figure A2-1)	
	D1	D2	New Bedford <sup>1</sup>	Dartmouth <sup>2</sup>
<b>Treatment type</b>	Tertiary	Tertiary	Advanced secondary	Secondary
<b>TN limit</b>	3 mg/L	3 mg/L	None, report only	None, report only
<b>Proposed/permitted flow rate</b>	4 MGD	4 MGD	30 MGD	4.2 MGD
<b>Distance from shore</b>	4380 ft	5250 ft	3050 ft from Clark pt (4600 ft from beaches)	2550 ft (to Mishaum Pt.)
<b>Bottom depth</b>	52 ft	52 ft	~22 ft	~ 10 ft
<b>Industrial Input</b>	No	No	Allowed	No
<b>Storm water Input</b>	No	No	Allowed	No

1

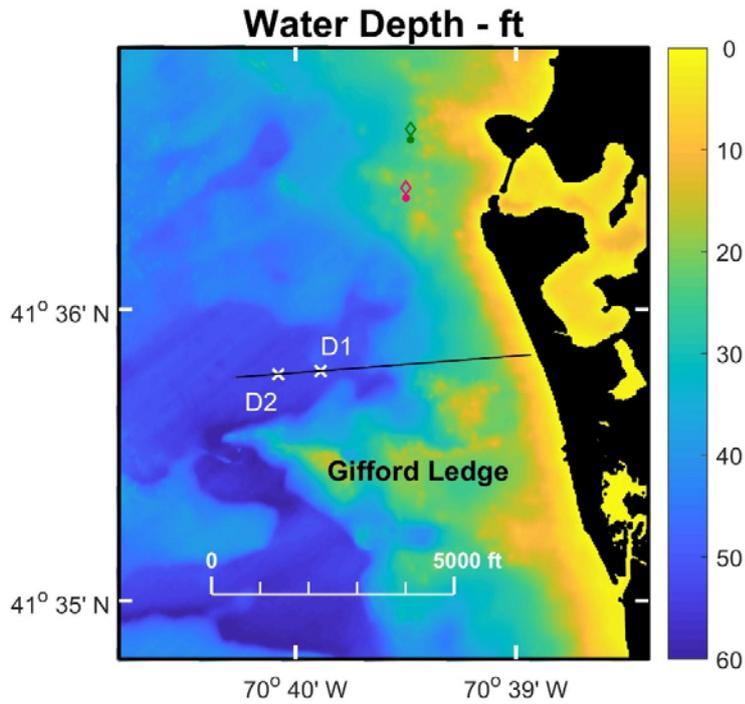
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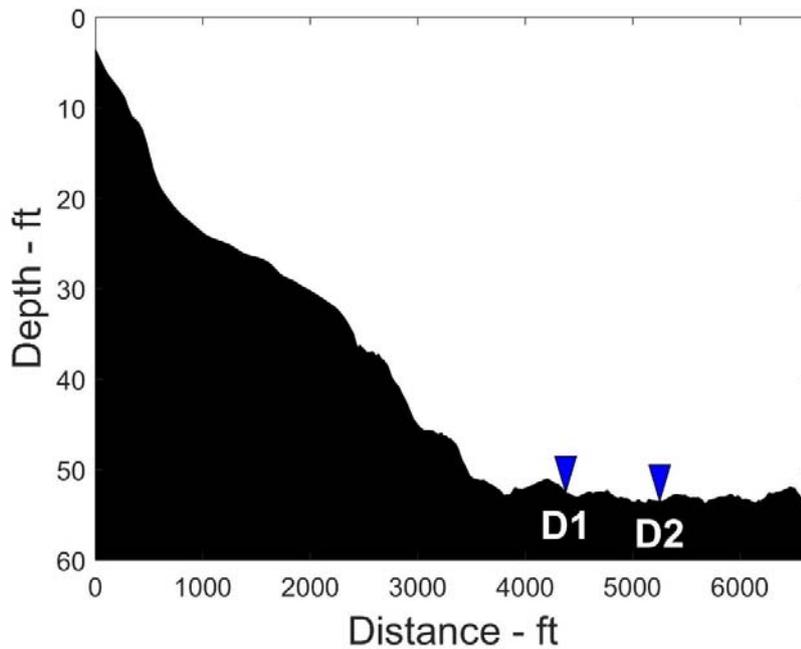
**Figure 1.** (a) A large-scale view of Buzzards Bay, MA showing the location of the Buzzards Bay Coalition mid-bay buoy (BBC). The box labeled NBD encloses the city of New Bedford MA waste water discharge off of Clark Point, New Bedford, whereas the box labeled DD encompasses the waste water outfall of the Town of Dartmouth MA. The box labeled WF encloses this study's area of interest. As shown in (b), this area includes the waste water treatment facility (WWTF) currently used by the town of Falmouth MA for in-ground discharge of treated effluent as well as West Falmouth Harbor (WFH) and the region of Buzzards Bay considered for open water effluent discharge (south of the entrance to WFH).



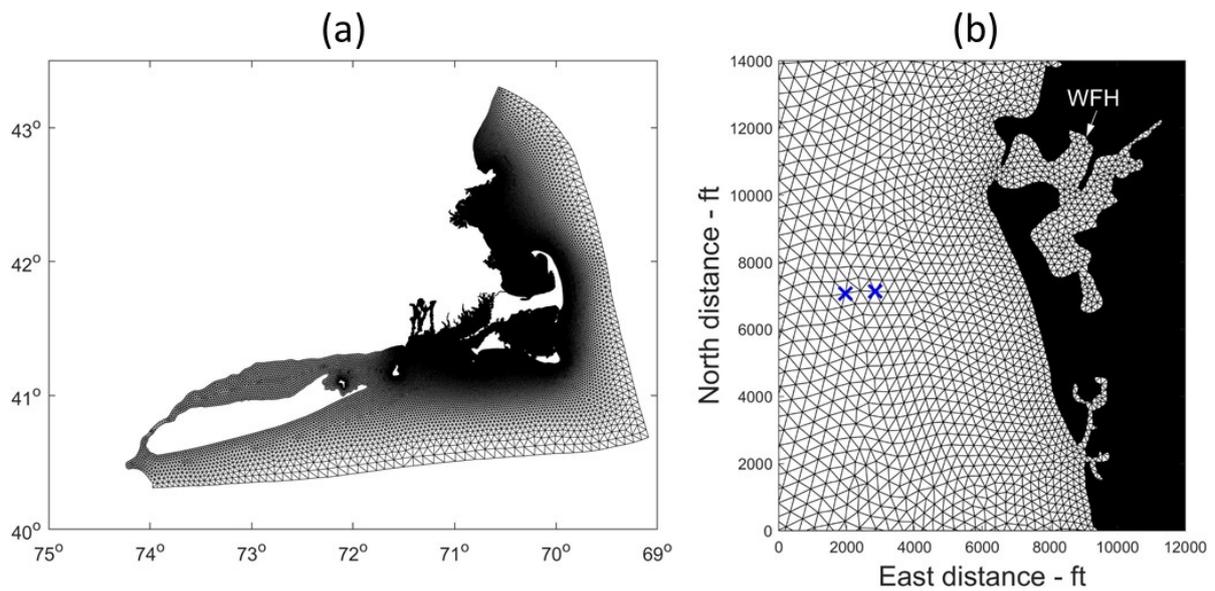
**Figure 2.** Averaged (over 2016-2018) concentrations of TN (mg/L) measured at various stations in West Falmouth Harbor as part of the Mass. Estuaries Project (see also Table 1). Station names are listed above each station location. The concentration at the Snug Harbor sentinel station is underlined. Also shown is the averaged (2007-2017) TN concentration at the Buzzards Bay Coalition mid-bay buoy (BBC, Figure 1)



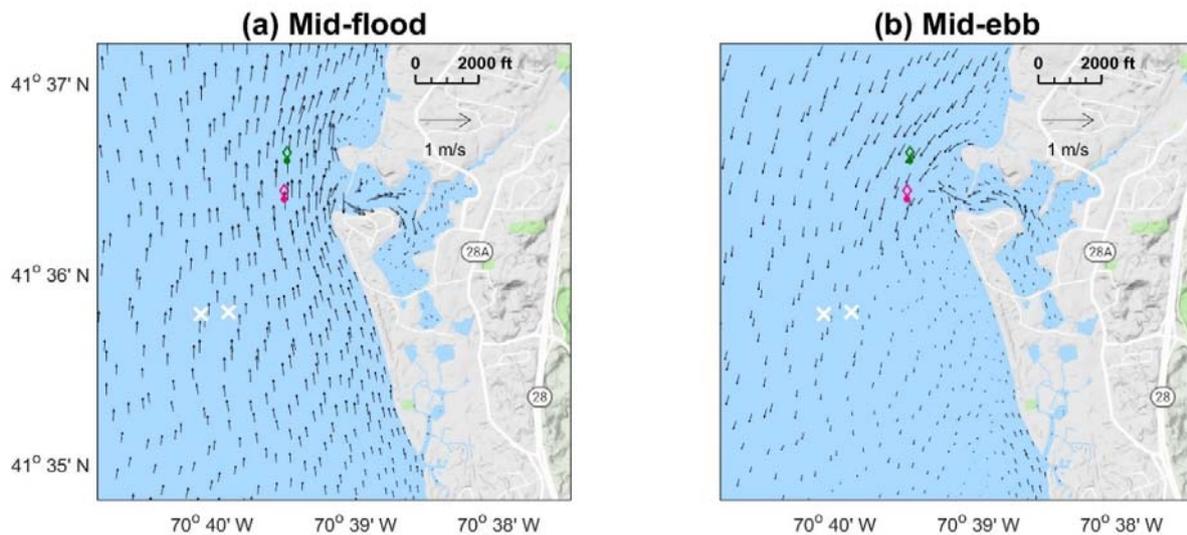
**Figure 3.** High-resolution bathymetry of the area of eastern Buzzards Bay considered for open water effluent discharge. The proposed discharge sites, D1 and D2, are situated within a basin with a mean depth of roughly 52 ft. Also shown are the locations of navigation buoys marking the entrance to West Falmouth Harbor.



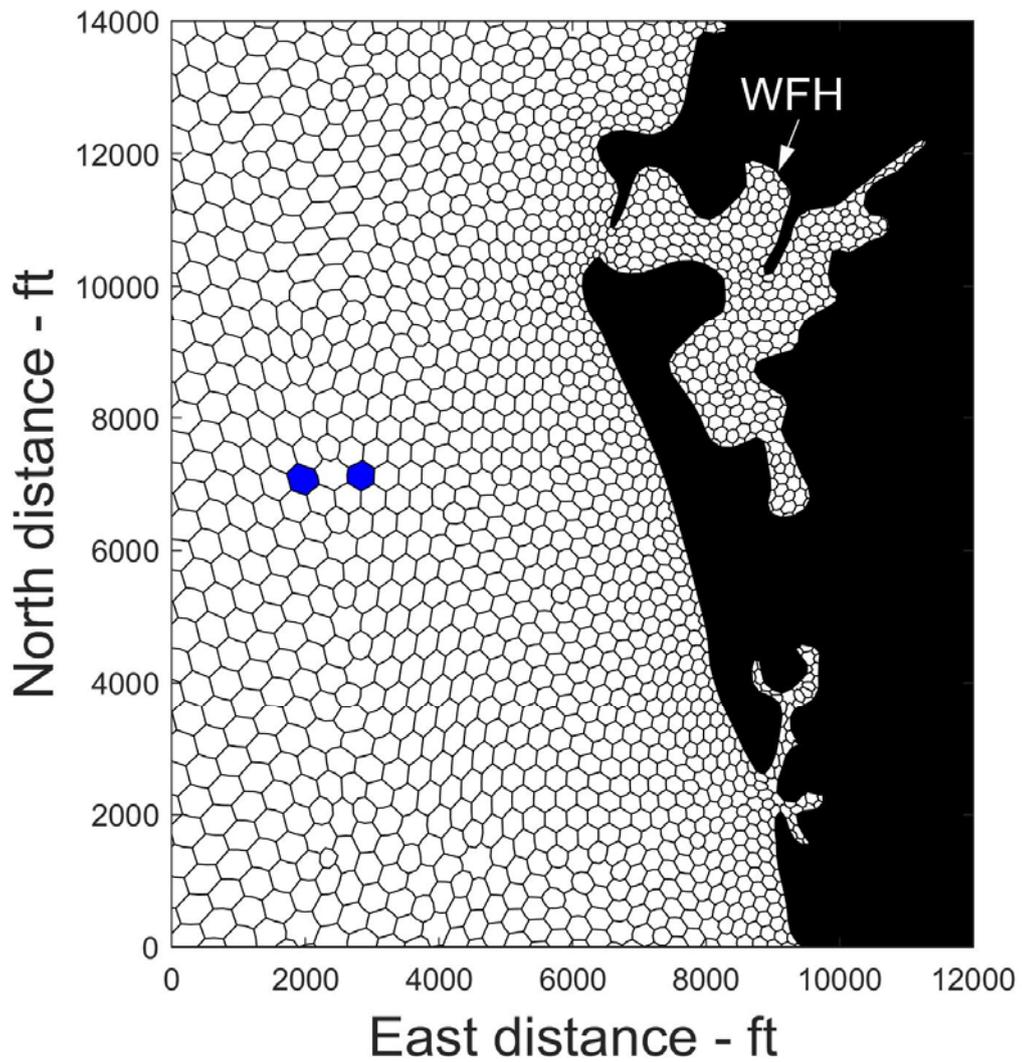
**Figure 4.** Profile of bottom depth along a line (shown in Figure 3) that extends offshore from West Falmouth and intercepts the proposed discharge sites D1 and D2.



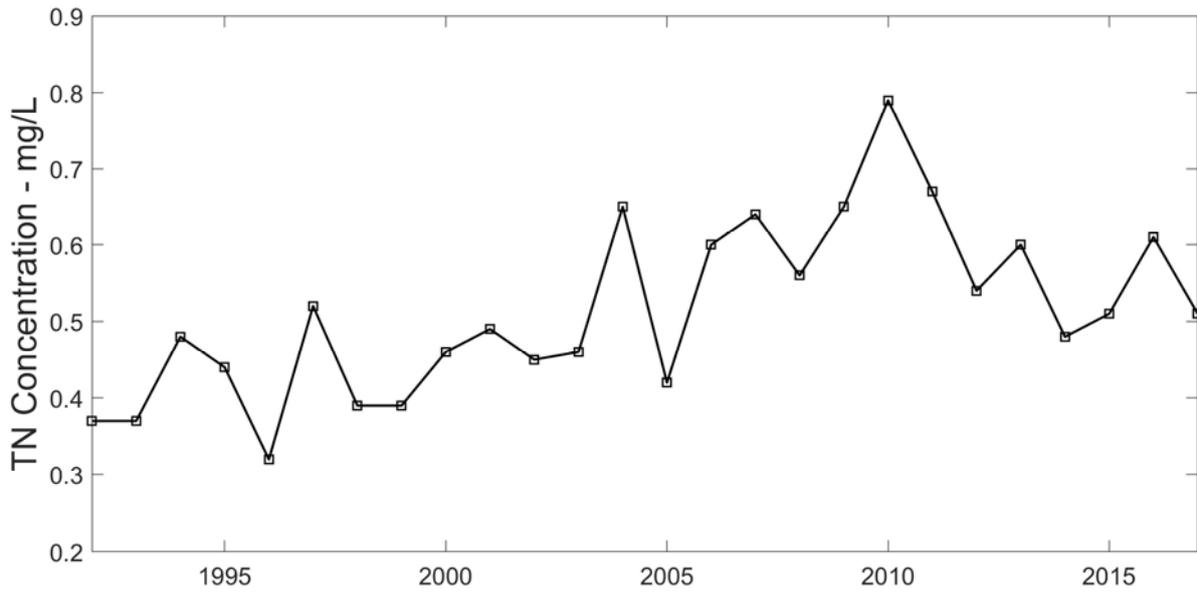
**Figure 5.** (a) Grid cells of the Southeastern Mass. hydrodynamic model (SEMASS-FVCOM) used to generate the velocity fields used in this study. The grid contains 284305 cells with increased resolution (smaller cell size) in the coastal zone. (b) A view of the SEMASS grid in our study region. The cells in the area of the proposed open water discharge sites, blue x's, measure roughly 350 ft in the N-S and E-W directions. The near-shore cells and those in West Falmouth Harbor (WFH) have horizontal dimensions of 100-200 ft.



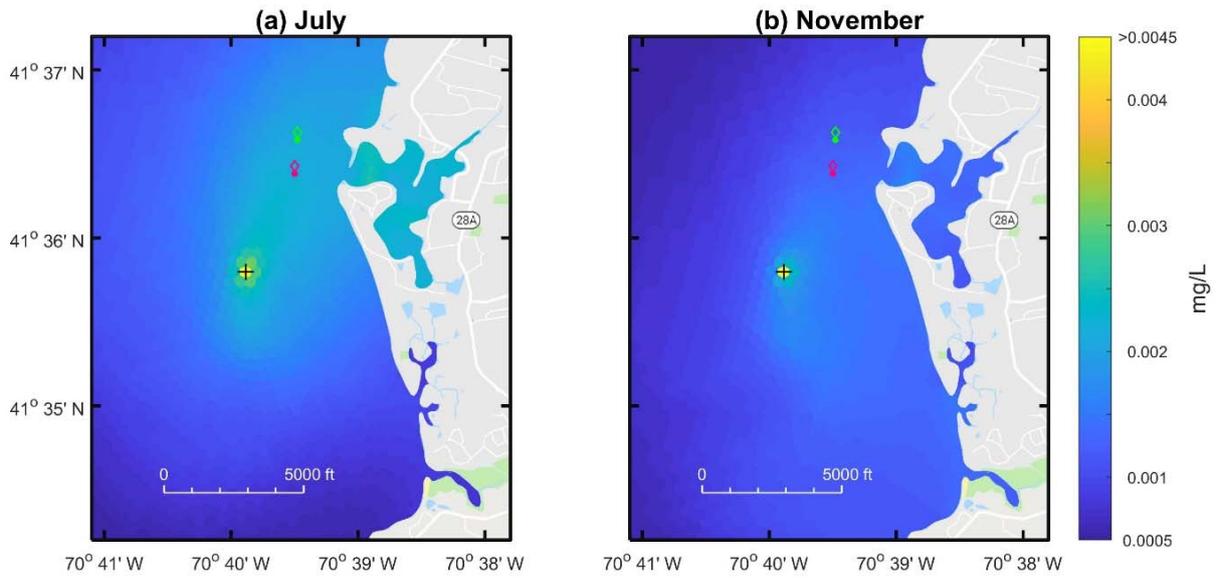
**Figure 6.** Sample fields of surface current (from 14-15 July 2015) during mid-flood (a) and mid-ebb (b) flow in West Falmouth Harbor. The proposed discharge sites are marked with white x's.



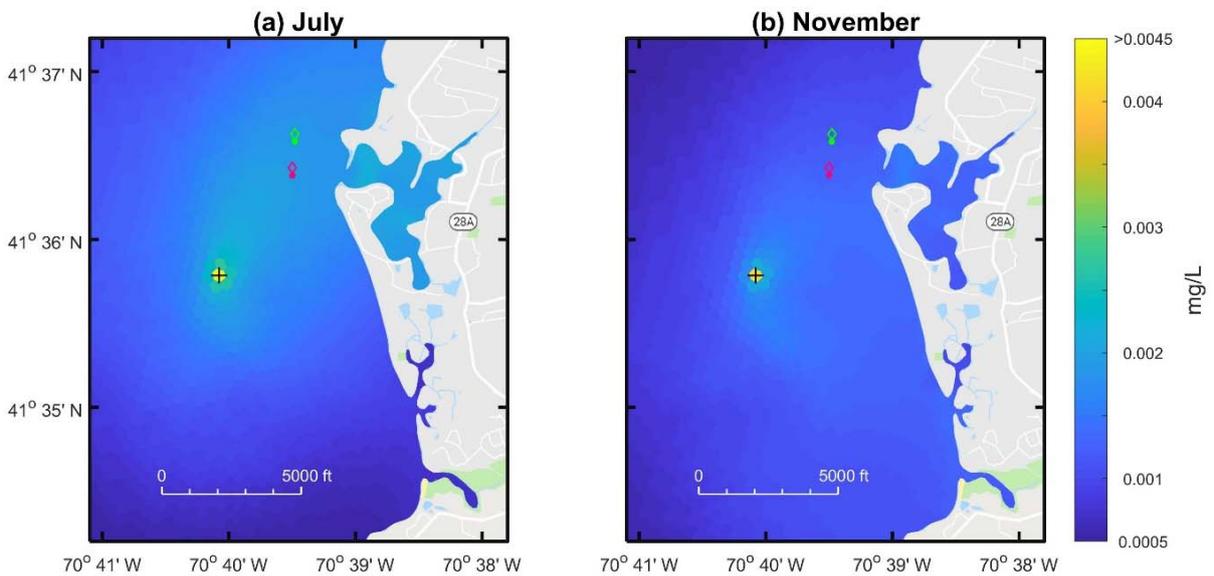
**Figure 7.** Cells of the water quality model grid in our region of interest. This grid is linked (but not identical) to the grid of the hydrodynamic model (Figure 5), which supplies velocities for the effluent transport simulations. The cells containing the proposed open water discharge sites, shaded in blue, measure roughly 430 ft in the N-S and E-W directions. The near-shore cells and those in West Falmouth Harbor (WFH) have horizontal dimensions of 100-200 ft.



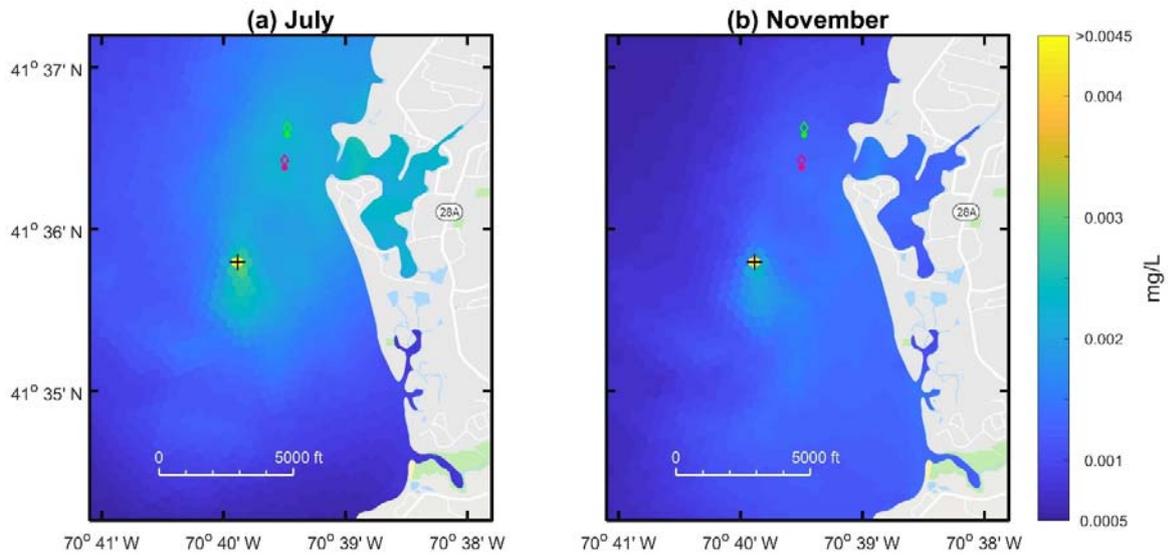
**Figure 8.** Yearly averaged TN concentrations at the Snug Harbor Sentinel (WF5 in Figure 2) in West Falmouth Harbor.



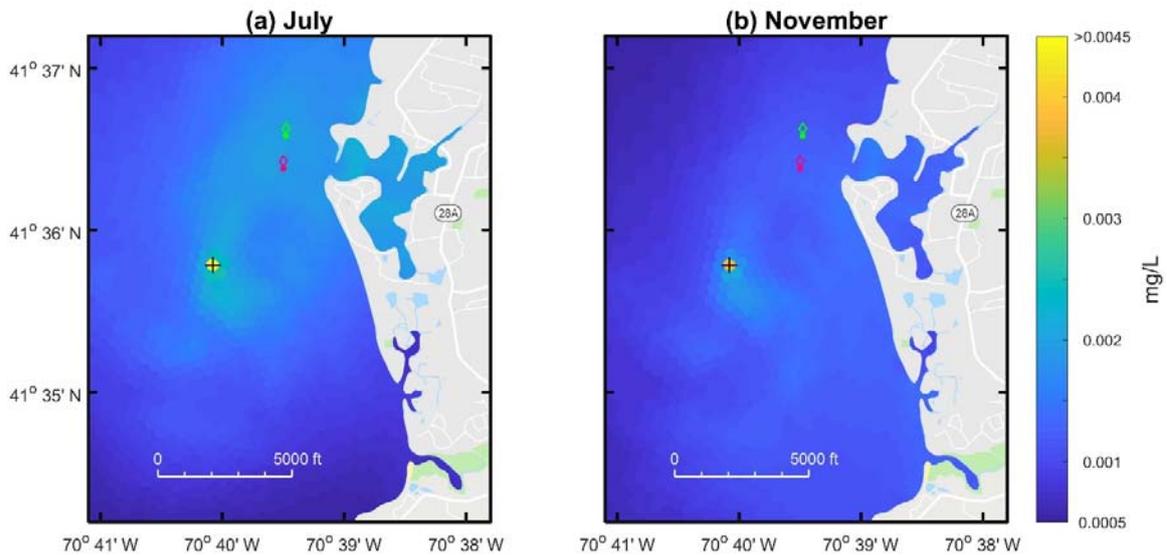
**Figure 9.** Fields of vertically averaged concentration of effluent TN discharged at site D1 (Figures 3 and 4) and averaged over July (a, when winds are predominately from the SW) and November (b, with predominately N winds). In both fields, the averaged effluent TN exceeds 0.0031 mg/L only in the cell containing the discharge (marked by a cross).



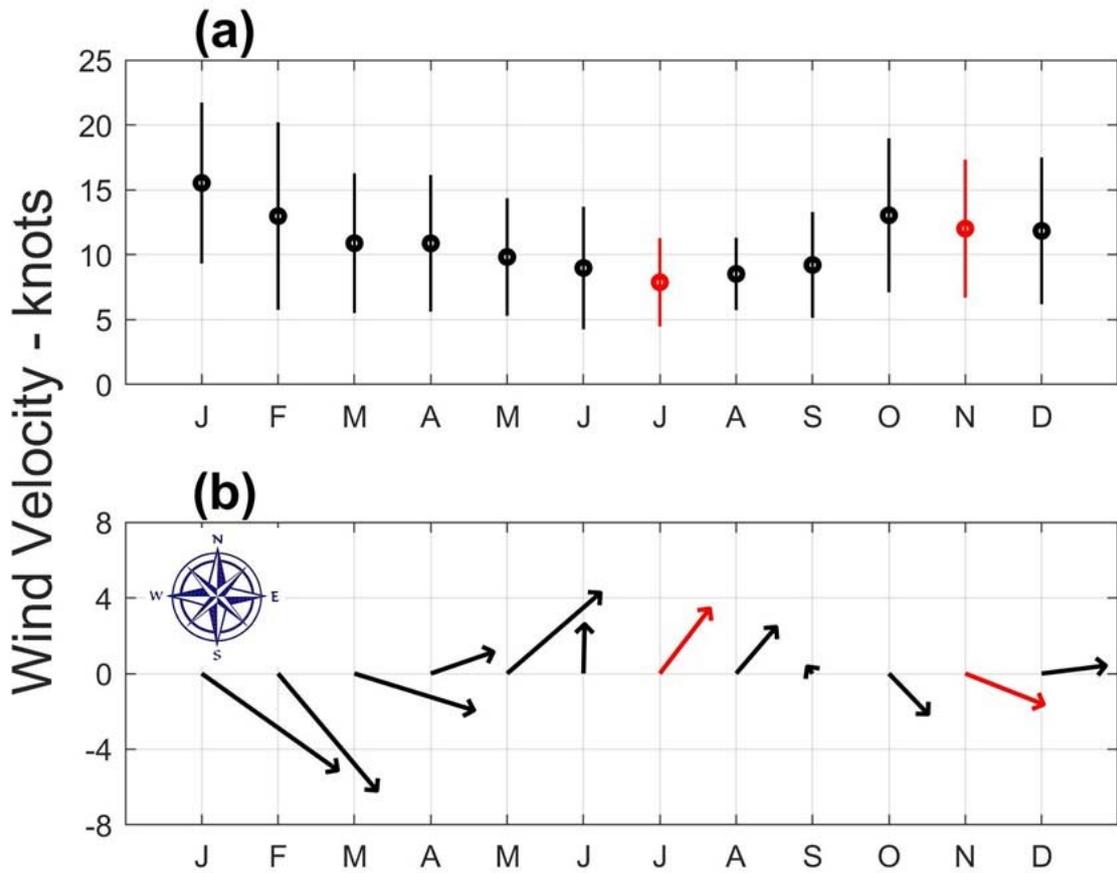
**Figure 10.** Same as Figure 9 except showing fields of vertically averaged concentration of effluent TN discharged at site D2 (Figures 3 and 4).



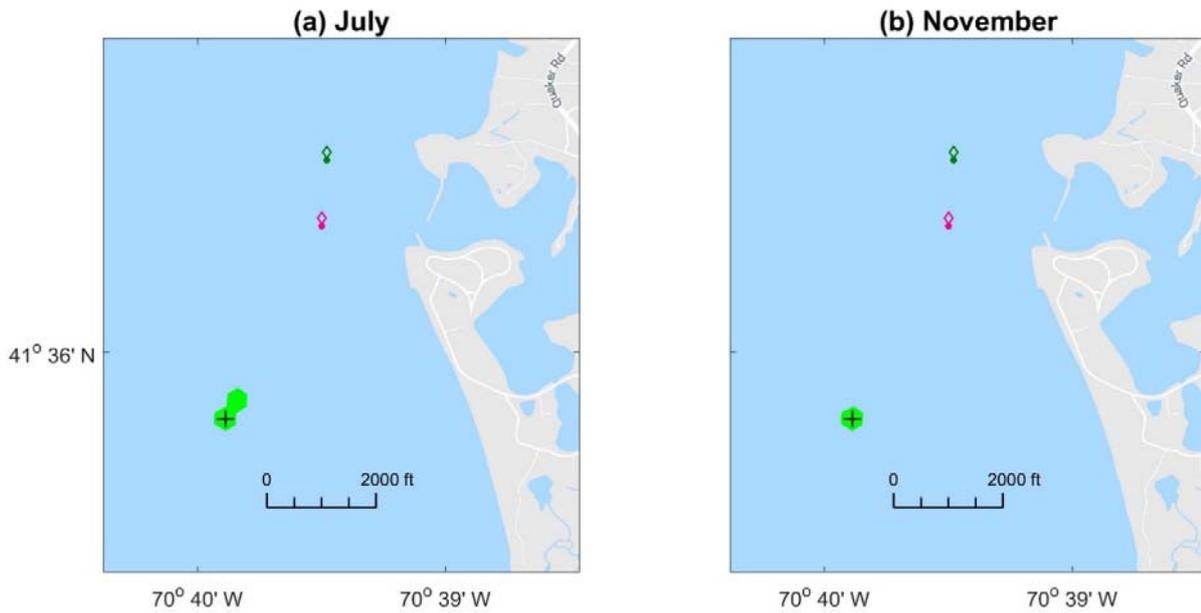
**Figure 11.** Fields of surface concentration of effluent TN discharged at site D1 (Figures 3 and 4) and averaged over July (when winds are predominately from the SW) and November (with predominately N winds). In both fields, the surface effluent TN exceeds 0.003 mg/L only in the cell containing the discharge (marked by a cross).



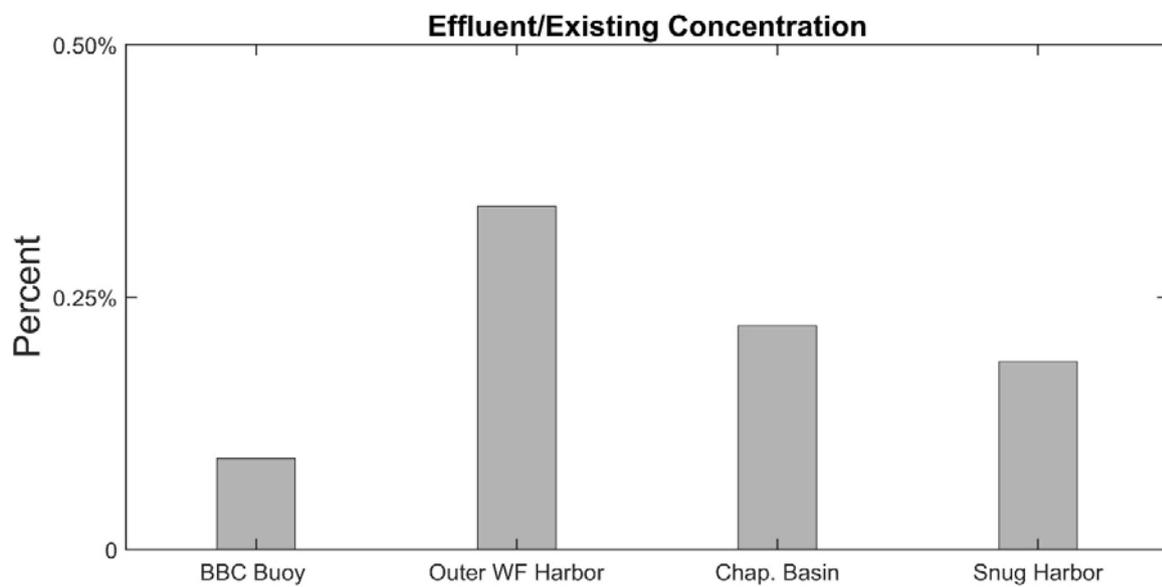
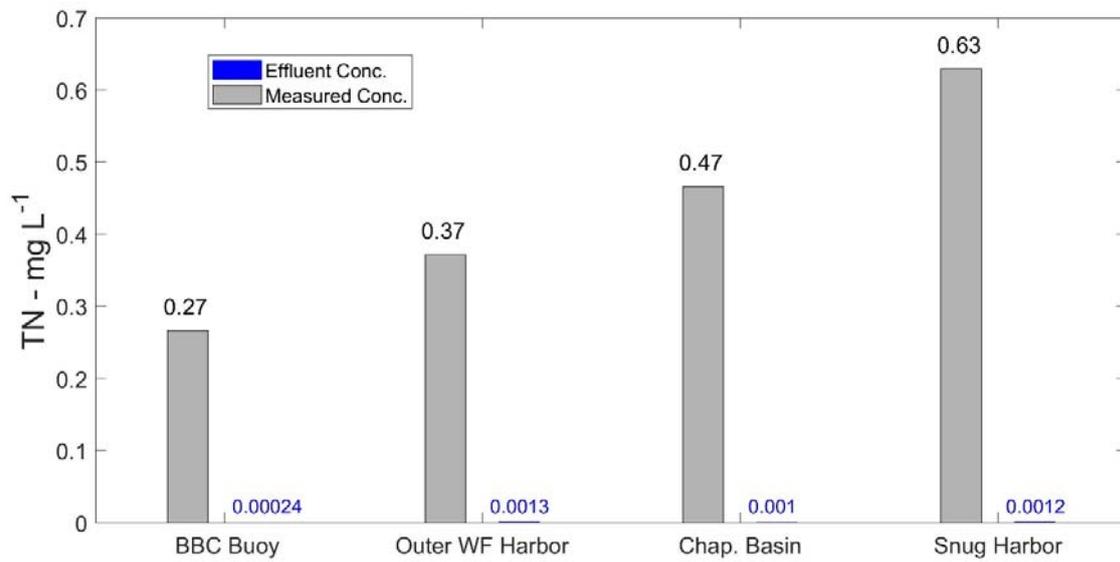
**Figure 12.** Same as Figure 11 except showing fields of the surface concentration of effluent TN discharged at site D2 (Figures 3 and 4).



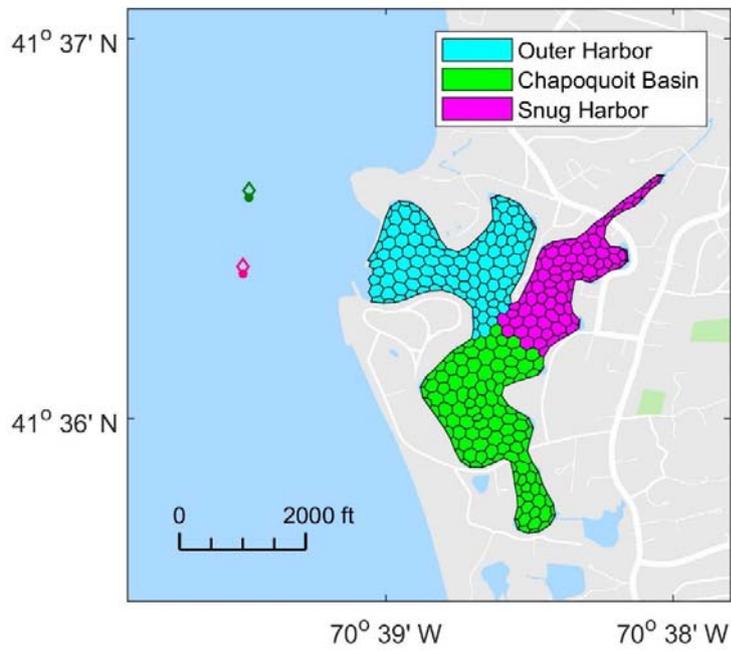
**Figure 13.** Graphical representation of the monthly statistics of the model winds off of West Falmouth (in the region of the proposed open water outfalls). The filled circles in (a) mark the monthly mean wind speeds, while the lines bracketing each circle span the range of  $\pm$  one standard deviation about the mean winds. Shown in (b) are the monthly mean wind vectors in a geographic coordinate system. Statistics of the winds of July and November (the months of the mean TN concentration fields of Figures 9-12) are shown in red.



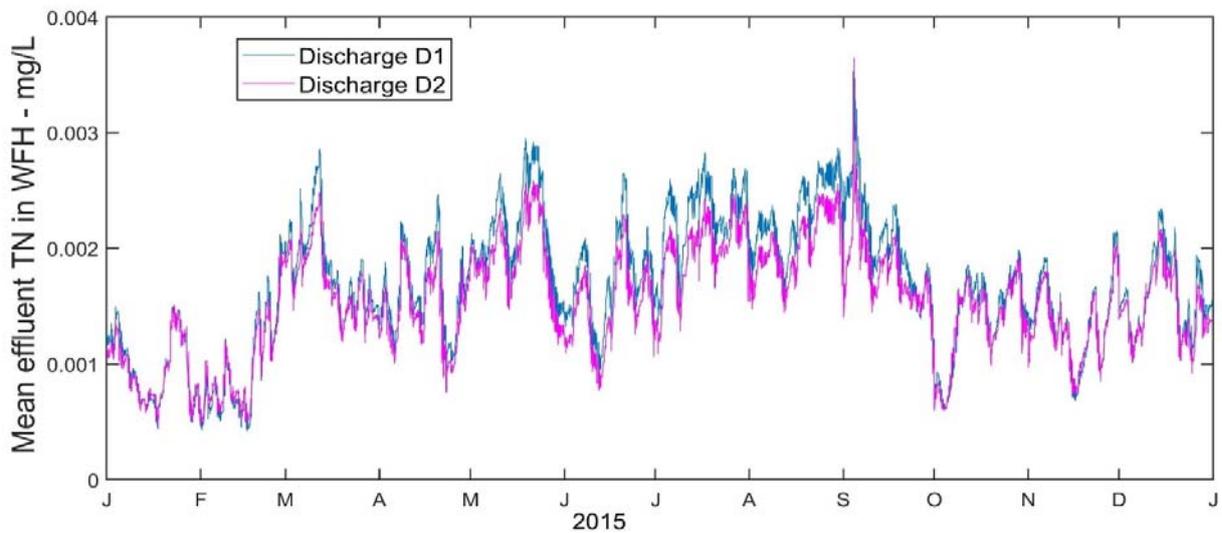
**Figure 14.** The green-shaded areas depict the model cells over which the dilution factor (the ratio of discharged to vertically averaged effluent TN concentration) is equal to or less than 1000:1 for the TN concentration fields of July (a) and November (b). Note that the mean dilution factor for these months exceeds 1000:1 for all but 1-2 cells at or adjacent to the discharge, which is the case for all months.



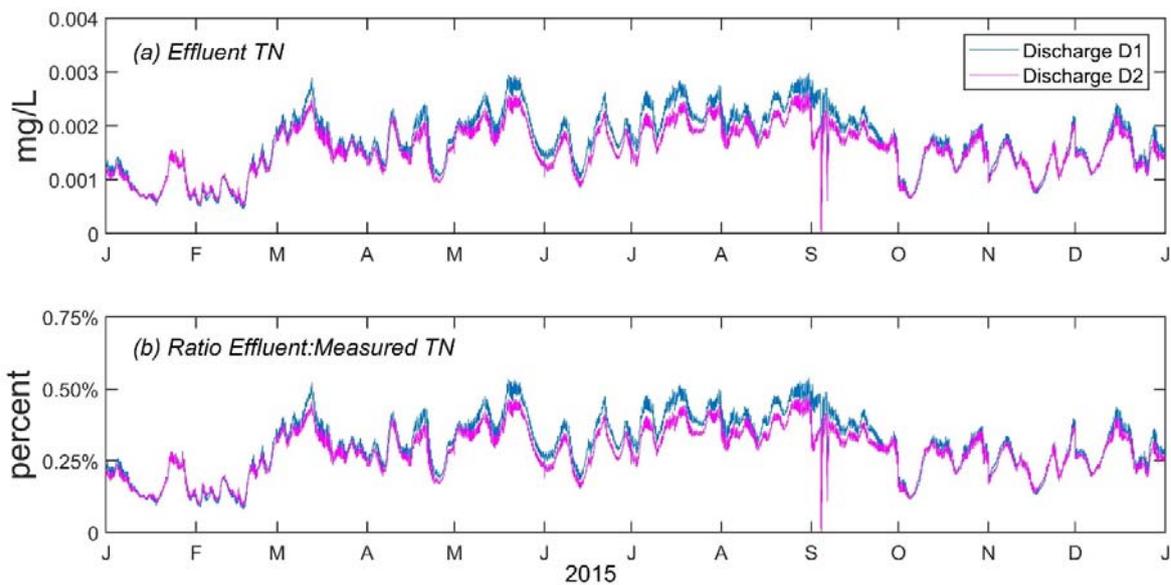
**Figure 16.** Ratio of the modeled effluent TN to the measured TN at the BBC buoy (Figure 1) and the indicated regions in West Falmouth Harbor (Figure 17). The ratios (in percent) were determined from the TN values shown in Figure 15.



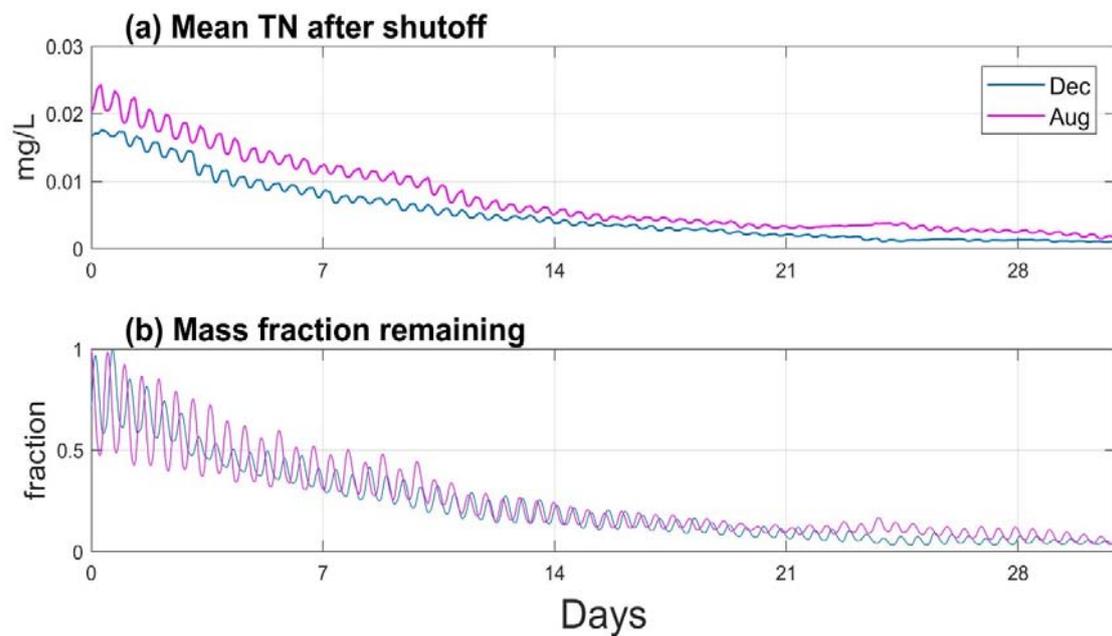
**Figure 17.** Water quality model cells in West Falmouth Harbor divided into three regions: Outer Harbor, Chapaquoit Basin and Snug Harbor.



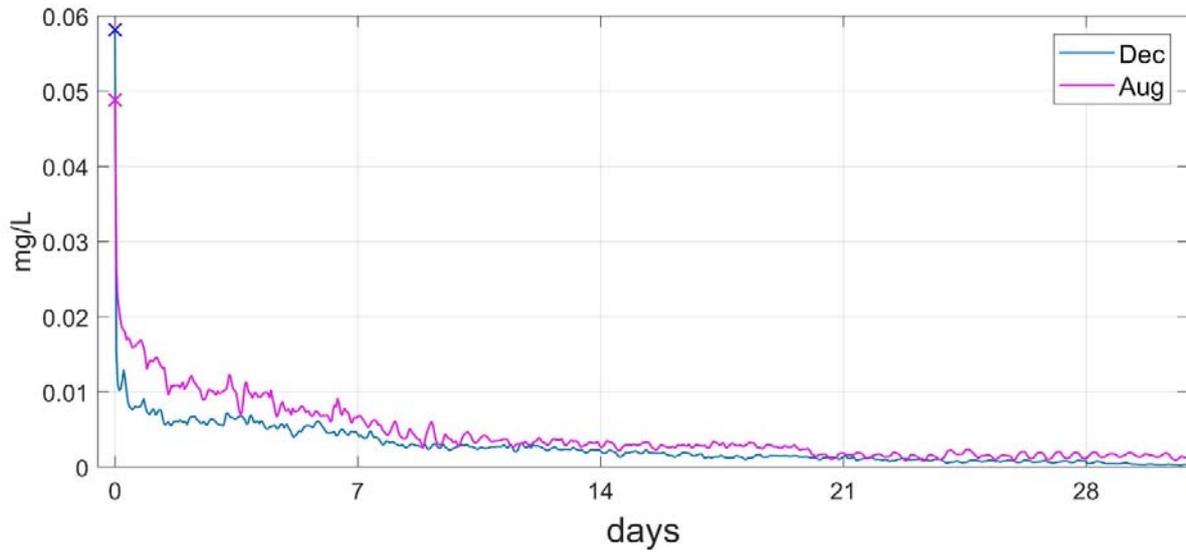
**Figure 18.** Year-long time series of the mean concentration of effluent TN within West Falmouth Harbor (encompassing all of the colored cells of Figure 17) resulting from effluent discharge from site D1 (blue line) and site D2 (magenta). Note that except for a brief period in early September, the mean effluent TN concentration is  $< 0.003$  mg/L, close to the TN detection limit (see Methods).



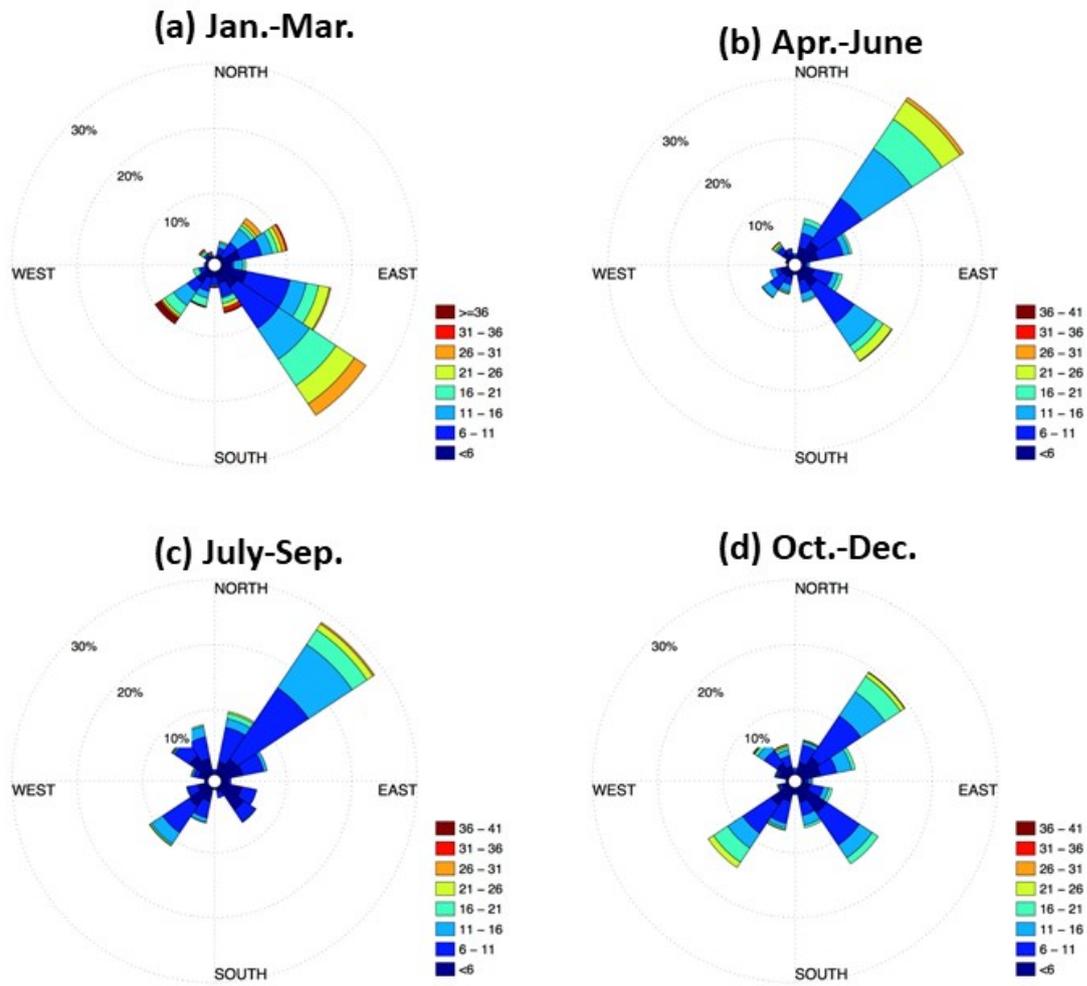
**Figure 19.** (a) Year-long time series of the vertically averaged effluent TN concentration at the Snug Harbor sentinel station (Figure 2) resulting from effluent discharge from site D1 (blue line) and site D2 (magenta). (b) Ratio (in percent) of the model effluent TN concentration to the mean TN concentration at the Snug Harbor sentinel station (Table 1). Note that both panels show little difference in the impact of discharge at D1 relative to D2.



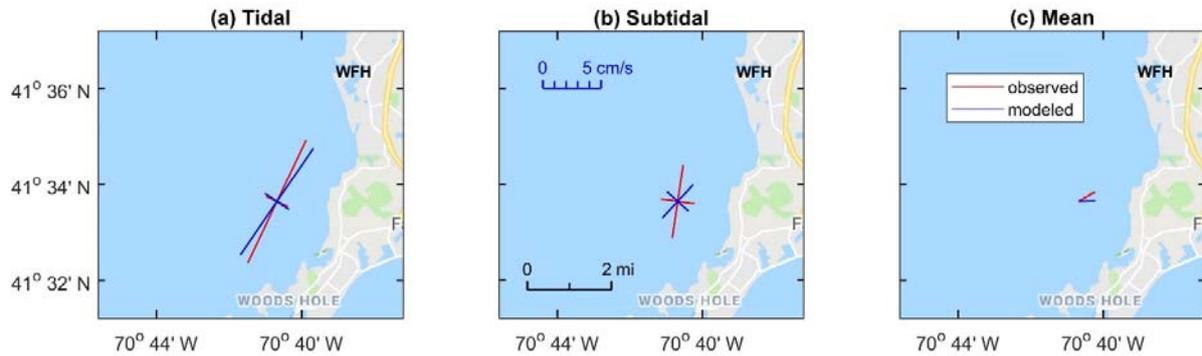
**Figure 20.** The results of model runs aimed at determining the flushing time of West Falmouth Harbor. (a) The mean concentration of effluent TN in West Falmouth Harbor after cessation of effluent discharge at the beginning of August (magenta) and December (blue). The starting TN fields were taken from simulations (in July and November) with discharge at site D1 set at a rate of 4 MGD and with TN concentration of 35 mg/L. (b) The fraction of TN mass in West Falmouth Harbor relative to the maximum mass after discharge cessation. For both months, the TN mass in West Falmouth Harbor is reduced by a factor of 10 in roughly 3 weeks after the cessation of discharge.



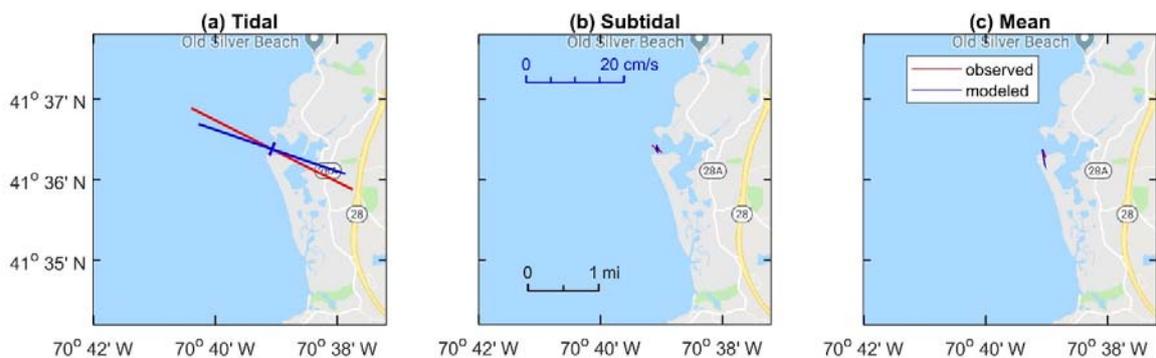
**Figure 20.** The vertically averaged effluent TN concentration at outfall D1 after cessation of effluent discharge at the beginning of August (magenta) and December (blue). The starting TN fields were taken from simulations (in July and November) with discharge at D1 set at a rate of 4 MGD and with TN concentration of 35 mg/L. Apparent is a rapid initial decline in effluent TN concentration immediately after the cessation of discharge. This is followed by a more gradual decline that brings the TN concentration to order 0.002 mg/L two weeks after the termination of discharge.



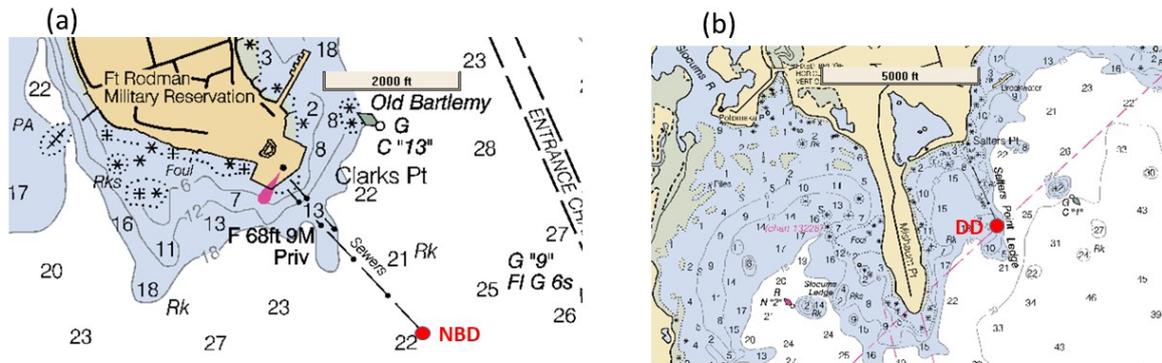
**Figure A1-1.** Graphical representation of the seasonal variation of the modeled wind field (knots) in eastern Buzzards Bay.



**Figure A1-2.** Comparison of the statistical properties of the vertically averaged modeled and measured currents at site in eastern Buzzards Bay roughly 3 nautical miles SSW of West Falmouth Harbor. The measured currents represented by the statistics are from a current meter (ADCP) deployed by the USGS over 13 August – 9 November 2009. The modeled currents are from the model cell with the center closest to the current meter location and from the period 13 August – 9 November 2015 (the year of the model simulations). Demarked by the lines in (a) and (b) are the standard deviations along the principal axes of the tidal and sub-tidal velocity signal [on the scale shown in (b)]. The overall mean velocities are shown in (c).



**Figure A1-3.** Same as Figure A1-2 except comparing the statistical properties of the vertically averaged measured (2 July – 8 September 2010) and modeled (2 July – 8 September 2015) currents at the entrance to West Falmouth Harbor.



**Figure A2-1.** Portions of navigation charts (enclosed by the boxes in Figure 1a) of the region near Clarks Point, New Bedford MA (a) and Mishaum Point Dartmouth MA (b) (soundings in feet). The red dots in (a) and (b) mark the locations of the open water discharge of the City of New Bedford (NBD) and Town Dartmouth (DD), respectively.