

Attention

This article has been delivered to you using an automated system. If there are any problems with this copy, please let us know as soon as possible so we can get you a better copy.

Questions regarding this ILL should be directed to nuill@norwich.edu.
Be sure to include the TN number and/or the article title.

Please also note:

WARNING CONCERNING COPYRIGHT RESTRICTION The copyright law of the United States (Title 17, United States Code) governs the making of photocopies or other reproductions of copyrighted material.

Under certain conditions specified in the law, libraries and archives are authorized to furnish a photocopy or other reproduction. One of the specified conditions is that the photocopy or reproduction is not to be "used for any purpose other than private study, scholarship, or research." If a user makes a request for, or later uses, a photocopy or reproduction for purposes in excess of "fair use," that user may be liable for copyright infringement.

This institution reserves the right to refuse to accept a copying order if, in its judgment, fulfillment of the order would involve violation of copyright law.

Rapid #: -13739539

CROSS REF ID: **68215**

LENDER: **CS1 :: Electronic**

BORROWER: **NRU :: Kreitzberg Library**

TYPE: Article CC:CCG

JOURNAL TITLE: Water, air and soil pollution

USER JOURNAL TITLE: Water Air Soil Pollution

ARTICLE TITLE: Using a numerical model to track the discharge from a wastewater treatment plant in a tidal estuary

ARTICLE AUTHOR: Ernest D. True

VOLUME:

ISSUE: Aug. 2018

MONTH: August

YEAR: 2018

PAGES: 229-267

ISSN: 0049-6979

OCLC #:

Processed by RapidX: 9/27/2018 5:39:45 PM



This material may be protected by copyright law (Title 17 U.S. Code)

Using a Numerical Model to Track the Discharge of a Wastewater Treatment Plant in a Tidal Estuary

Ernest D. True 

Received: 13 April 2018 / Accepted: 19 July 2018 / Published online: 31 July 2018
© Springer Nature Switzerland AG 2018

Abstract Along the coast of Maine, USA, there are numerous wastewater treatment plants that discharge their treated effluents into a river estuary which is shared by commercial fishing and shellfish harvesting. Occasionally, there can be failures or bypasses of treatment plants that lead to untreated or partially treated sewage flowing into shellfish harvesting waters. To prevent any toxic contamination of harvested shellfish, a prohibitive zone is established around the treatment plant where shellfish harvesting is prohibited. The U.S. Food and Drug Administration has conducted numerous dye studies on both coasts of the USA to determine these prohibitive zones, based on the guidelines of the National Shellfish Sanitation Program. In May 2010, the FDA conducted such a dye study at the Yarmouth, Maine wastewater treatment plant. The results are compared with a numerical coastal model that provides the velocity field for the currents around the treatment plant. This model includes a diffusion equation to simulate dye dispersion from a point source which is used to determine the prohibitive zone. The numerical model shows good correlation with the FDA dye study report and establishes a prohibitive zone for commercial harvesting in keeping with that of the FDA study. The benefits of the numerical model include sampling at thousands of locations simultaneously, seasonal changes in river volumes, and changes in plant discharge volumes.

Keywords Wastewater treatment · Numerical modeling · Dye studies · Particle tracking · Transit time · Physical-biogeochemical

1 Introduction/Background

Every wastewater treatment plant in the USA is subject to strict federal and state regulations. The National Pollutant Discharge Elimination System (NPDES) is a program within the U.S. National Environmental Protection Agency (EPA). The NPDES issues permits to wastewater treatment plants which establish discharge limits and conditions based on the standards of the U.S. Clean Water Act of 1972 and the Water Quality Act of 1987. The Maine Department of Environmental Protection (MDEP), Division of Water Quality Management, has been authorized by NPDES to issue permits for operating a wastewater treatment plant in Maine, which must be renewed every 5 years (<https://www.epa.gov/npdes-permits>). The Maine Department of Marine Resources (MDMR n.d.), Bureau of Public Health, is ultimately responsible for ensuring that the receiving waters around a wastewater plant meet all standards of the U.S. Clean Water Act of 1972 and State water quality standards as described in Maine's Surface Water Classification System (<https://www.maine.gov/dep/water/wqs/index.html>). MDMR also uses criteria from the National Shellfish Sanitation Program (NSSP) to determine safe areas for commercial shellfishing (<http://www.issc.org>). Shellfish filter large volumes of water and can concentrate toxic microorganisms from nearby sewage

E. D. True (✉)
Department of Mathematics, Norwich University, Northfield, VT
05663, USA
e-mail: true@norwich.edu

systems. The treatment plant in Yarmouth, Maine is typical of many plants that discharge their effluent into a tidal estuary where commercial fishing and shellfish harvesting share the same waters and mud flats. Yarmouth's treatment plant permit requires the plant to monitor and sample all operations on a regular basis to ensure that the receiving waters of the effluent are not being polluted as a result of faulty discharges, such as a loss of disinfection (see Permit-Yarmouth 2017). A Google Earth map of all wastewater treatment plants in Maine is at <http://www.maine.gov/dep/gis/datamaps/index.html>.

A treatment plant that is operating normally is capable of reducing fecal and total coliform to levels well below the standards set by the NPDES. But some enteric viruses such as Norwalk-like viruses are not adequately reduced during the plant's disinfection process. Consequently, the MDMR must provide zones around the outfall of a treatment plant in an effort to maximize the harvesting area for shellfish, while satisfying all growing area standards of the NSSP. A zone may be classified as Approved, Conditionally Approved, Restricted, Conditionally Restricted, or Prohibited. The descriptions of these zones are available at the MDMR website (Maine.gov/dmr: <http://www.maine.gov/dmr/shellfish-sanitation-management/programs/growingareas/howclassified.html>). The FDA, after numerous studies related to wastewater treatment plants, has established a prohibitive zone for shellfish harvesting around a treatment plant outlet based on a dilution of 1000 parts of receiving waters to every part of effluent. In addition to the 1000:1 dilution criteria, there must also be an alarm system and notification procedures in place in the event of a plant failure to close the area to harvesting before the discharged untreated effluent can travel to the boundaries of the prohibitive zone. The identification of this prohibitive zone and conditionally approved zone is the focus of this work. It should be established to protect consumers from infected shellfish, but minimize the area that would be off limits to shellfishing.

The United States Food and Drug Administration (FDA) Center for Food Safety and Applied Nutrition participates in monitoring the operations of wastewater treatment plants (WWTP) along the coasts of the USA to ensure that the standards established by the NSSP are fulfilled. In May 2010, at the request of the MDMR, the FDA conducted a hydrographic dye study of the wastewater treatment plant in Yarmouth, Maine (Goblick

et al. 2017), which discharges its effluent into the Royal River which, in turn, flows into Casco Bay (Fig. 1). The study consisted of injecting the water-tracing red dye Rhodamine WT into the outflow pipe of the treatment plant at a continuous rate for one tidal cycle of 12.42 h, beginning at 7:15 UTC on May 24. The dispersion of the dye throughout the estuary was then tracked during the daylight hours of May 24–26 with two boats operating towed fluorimeters and Trimble GPS units to record the dilution of the dye at various locations. For this study, FDA also deposited oysters in cages at the five stations shown in Fig. 1 along the river. Each station also had a submersible fluorometer so that a microbiological analysis of the oysters could later be compared with the dye dilution at that location to determine if a relationship exists between dilution and viral impacts on shellfish. An outside firm collected soft-shell clams from three other locations near the outflow pipe which were later tested for fecal coliforms (FC), male-specific coliphage (MSC), and Norovirus (NoV). Three days prior to the study, three winged drogues made of two perpendicular aluminum sheets attached to a PVC pipe and two other winged drogues with GPS units attached were placed in the river near the plant outflow pipe to determine the path of the effluent plume and select the best locations for their five stations. The drogues were deployed at a depth of 1 to 2 ft at different times near the beginning of ebb tide for about 3 h. The FDA report for this study addresses four objectives: (1) determine the bacterial conditions that could arise under a short-term lapse in treatment and disinfection, (2) determine the steady-state bacterial conditions in the shellfish growing waters that could arise in the event of a long-term elimination or lapse in disinfection, (3) attempt to determine the location of a 1000:1 dilution area and provide guidance to the MDMR regarding WWTP closure zones, and (4) research the dilution level needed to achieve a sufficient reduction in viruses to ensure the safety of shellfish harvested in proximity to WWTPs as part of FDA's dilution policy guidance. The questions to answer here relate to objective 3: Is it possible to implement a numerical coastal ocean model to reproduce the same prohibitive zone of the Yarmouth WWTP that was established by the FDA study of May 2010? Can the sampling of fluorometer readings by two boats over 3 days to determine the prohibitive zone by the FDA be replaced with the results of a numerical hydrographic model? Can such a model provide more temporal and spatial information than that sampled by the FDA and be

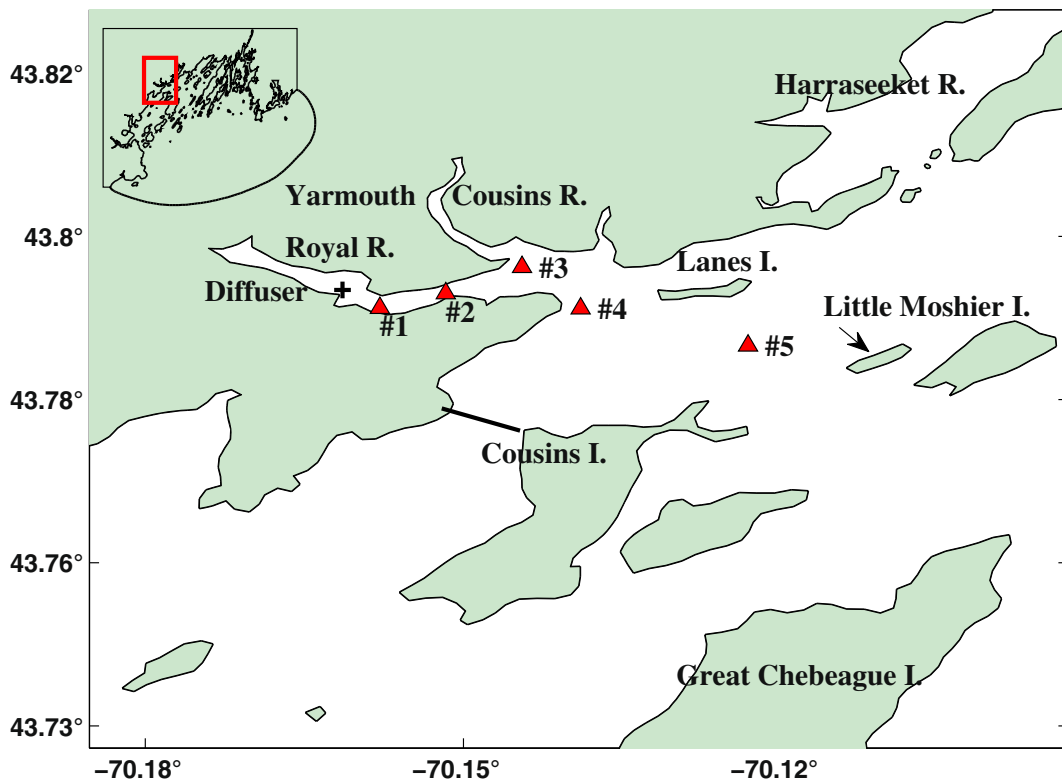


Fig. 1 The five FDA station and diffuser locations in the Royal River. The inset is Casco Bay, Maine

used to determine a prohibitive zone when the discharge from the plant meets or exceeds its capacity, or if river volume discharges change with precipitation or snow melt? The data available from this comprehensive study by the FDA provides an ideal opportunity to assess the results of a hydrodynamic numerical coastal model using the same local forcing that occurred during May 2010.

In the past decade, numerical hydrodynamic and ecological ocean models have made major advances in accuracy, complexity, and robustness. They have been applied to a large variety of coastal applications throughout the world with impressive success (for example, see Ganju et al. 2016). Liu et al. (2007) applied the three-dimensional hydrodynamic eutrophication model, HEM-3D (Hamrick 1996), to study the marine outfall in Keelung Harbor, Taiwan, and recommended an optimal offshore location for a wastewater treatment plant to handle discharges on the order of $1.47 \text{ m}^3/\text{s}$. Some large treatment plants discharge their treated effluents far offshore with long lines of diffusers. In Antalya City, Turkey, the treatment plant discharges about $1 \text{ m}^3/\text{s}$ of effluent to Antalya Bay about 2.6 km

offshore at a depth of 48 m. The diffuser system is 315 m long with 120 ports. Muhammetoglu et al. (2012) applied the model set Visual Plumes (Frick et al. 2003; Frick 2004) to determine bacteriological pollution from the Antalya outfall. Visual Plumes provides separate models for both near-field and far-field dynamics. In Worli village, Mumbai, India, Gupta et al. (2006) used the DIVAST model (Depth Integrated Velocity and Solute Transport) developed by Falconer (1984, 1986) to study dispersion patterns and far-field dilutions around the outfall which discharges about $5 \text{ m}^3/\text{s}$ through a pipe that extends 3.5 km offshore into the Indian Ocean. Gupta used a radio tracer and Rhodamine WT dye in his model to investigate the plume dynamics, but the 2-dimensional model was not able to provide acceptable results far from the outfall.

One of the most comprehensive modeling investigations of large treatment plants has been with the relocation of the Boston, Massachusetts outfall from Boston Harbor to a new site 15 km offshore at a depth of 30 m in Massachusetts Bay in September, 2000. Signell et al. (1996, 2000) applied the semi-implicit version ECOM-si of the three-dimensional hydrographic model ECOM

(Blumberg 1991) to examine and recommend the benefits of moving the Boston sewage effluent discharge from Boston Harbor to the new site. Later, Zhao et al. (2016) applied a local version of Finite Volume Community Ocean Model (FVCOM) to drive the circulation for the water quality model UG-RCA. The many papers regarding the Boston Harbor Project are available at <http://www.mwra.state.ma.us/harbor/enquad/trlist.html>. One very important by-product of the Boston Harbor Project is the ideal opportunity for modelers to use over 20 years of comprehensive time-series data to repeatedly calibrate and validate their models, which has greatly improved performances that are being applied to other investigations.

For every large wastewater treatment plant, there are hundreds of smaller plants that serve towns along the east and west coasts of the USA. The lessons learned by modelers on the larger plants described earlier are incorporated in this study to monitor and predict the performance of these smaller plants. For this study, the Yarmouth WWTP discharges its effluent through its outfall pipe into the Royal River in Yarmouth, Maine. The Royal River is a narrow channel that flows into Casco Bay. Tidal excursions are restricted by a dam near Route 88 through Yarmouth. The distance from this dam to a line about halfway from the River mouth to Lanes Island in Casco Bay is about 3.86 km (Fig. 1). The plant outfall pipe is 1.24 km downstream from the dam. The River is mostly protected from wind and waves from the dam to the River mouth. At high tide, the width of the river bed near the plant outfall pipe is about 245 m, and 480 m wide at the River mouth. However, the main channel is only about 50 m wide at depths of 4 m or less. The flow in the Royal River can vary greatly in May, even during the course of a day, due to snow melt and precipitation. The historical gauge data for the River is available at the Gulf of Maine Watershed Information and Characterization System (<http://www.gm-wics.sr.unh.edu>). The data only covers the years 1950–2004 and shows a monthly mean discharge for May that varies from 2.6 m³/s in 1985 to 30.7 m³/s in 1989. The mean of the monthly discharges for May during 1950–2004 is 9.2 m³/s. For May 2010, an effort was made to correlate stream flow for the Royal River by comparing its flows with the Kennebec flow rates which are known for May 2010. By comparing flow rates at times when monthly data is available for both rivers, an estimate is made for a flow rate of 9 m³/s for the Royal River for May 2010, nearly the same as the May monthly mean

discharge rate for 1950–2004. The mean tidal range in the river in spring is about 3.4 m. From the dam to the river mouth, the volume of water at mean sea level is about 10,497,160 m³ and only about 3,101,397 m³ at low tide. By comparison, the daily effluent volume from the treatment plant is about 2272 m³. One can expect considerable variation in dilution values of the outflow from the treatment plant into the estuary over each tidal cycle. This section of the river is mostly vertically mixed by the tides with a slightly fresher surface flow during ebb tide. The dynamics of the outfall discharge are mainly dominated by river flow, tidal excursions, and dispersion.

1.1 FDA Studies

Two major reports through the FDA are used here to compare the results of a numerical model with the FDA study. The final report submitted to the MDMR (U.S. Food and Drug Administration 2013) includes all biological and hydrographic findings of the study during May 24–31, 2010. The second report by Goblick et al. (2017) addresses an improvement of the superposition method that leads to an update of some of the data from the 2013 study. The results and methods from this later work are used here when comparing FDA results with the numerical model. The MDMR has provided all the FDA data sets that were collected by the boat transects, CTD, and fluorometer readings from the five stations.

There are some differences in the distances of the five FDA stations from the diffuser (Fig. 1). In the FDA study, the five stations, after converting from miles to kilometers, are at distances of 0.48, 1.45, 2.41, 3.86, and 5.79 km, respectively, from the treatment plant diffuser (Table 1). Apparently, these were the original distances laid out in the design stage and appeared in the final study document. The final latitude/longitude locations for each station are included in the MDMR data set. These distances have since been checked by the FDA (personal communication with G. Goblick), corrected, and found to be 0.40, 1.04, 1.77, 2.62, and 4.06 km from the diffuser. These distances also coincide with the same distances used in the model calculations. When comparing FDA distances with model distances, adjustments in the FDA study will be made where possible. These distances were measured along the narrow Royal River channel to each station, where current speeds are maximum.

Table 1 Station distances and dye comparisons between FDA and model results. Numbers in parentheses in the last column are the ratios of the model 1.5 to 0.6 MGD dye concentrations

Station	Distance from the diffuser (km)		Steady-state peak 1-h dye concentrations (ppb) 0.6 MGD		Steady-state peak 1-h dye concentrations (ppb) 1.5 MGD	
	FDA	Model	FDA	Model	FDA	Model
1	0.48	0.4	7.51	7.92	18.78	20.2 (2.55)
2	1.45	1.04	7.73	7.07	19.33	16.76 (2.37)
3	2.41	1.77	4.47	4.76	11.18	6.64 (1.39)
4	3.86	2.62	3.23	3.67	8.08	7.75 (2.11)
5	5.79	4.06	0.44	1.23	1.10	1.78 (1.45)

2 Methods

2.1 Numerical Model

For this study, FVCOM is applied on an unstructured triangular grid of Casco Bay, Maine. FVCOM, developed by Chen et al. (2003), is a prognostic, unstructured grid, finite-volume, free surface, three-dimensional primitive equation coastal and estuarine model. It has been tested and applied to oceans and estuaries all over the world with very satisfactory results. The default setup applies the Mellor and Yamada (1982) level 2.5 turbulent model scheme for vertical mixing and the Smagorinsky (1963) scheme for horizontal mixing. The wet/dry treatment in the intertidal zone is available in FVCOM and is applied in this study. The computational domain is a triangular unstructured mesh consisting of two zones: the outer zone which includes all of Casco Bay and a higher resolution zone which covers the Royal/Cousins Rivers (Fig. 2). The Royal/Cousins zone consists of triangles whose edges are of length 50 m or less. The triangular grid was created using Triangle (Shewchuk n.d.) and BatTri (Smith and Bilgili n.d.), a graphical Matlab interface for Triangle. The vertical structure is represented by using 11 terrain-following equally spaced levels at each nodal depth. This means that the dye concentration, as well as temperature and salinity, is being computed at 10 depths at each node and saved every 15 min. Likewise, the current velocities are also computed at the center of each triangle at each of the 10 depths. The shoreline and islands of the outer zone are sampled with nodes at intervals of 150 m or less and generally at intervals of 900 m along

the outer boundary. The National Geophysical Data Center (NGDC), an office of the National Oceanic and Atmospheric Administration (NOAA), developed an integrated topographic-bathymetric digital elevation model of Casco Bay, Maine (DEM, <https://www.ngdc.noaa.gov/metaview/page?xml=NOAA/NESDIS/NGDC/MGG/DEM/iso/xml/606.xml&view=getDataView&header=none>). This high-resolution bathymetric data provides water depths on 10-m squares for all of Casco Bay and provides the bathymetry for this numerical model study.

FVCOM includes a tracer tracking module to simulate the injection of a dye at one or more point sources. The equation for the dye tracing as described in the FVCOM manual is similar to the temperature equation and is of the form

$$\begin{aligned} \frac{\partial DC}{\partial t} + \frac{\partial DuC}{\partial x} + \frac{\partial DvC}{\partial y} \\ + \frac{\partial \omega C}{\partial \sigma} - \frac{1}{D} \frac{\partial}{\partial \sigma} \left(K_h \frac{\partial C}{\partial \sigma} \right) - D F_c \\ = D C_0(x, y, \sigma, t) \end{aligned} \quad (1)$$

where the normalized σ coordinate is a linear transformation of water depth and varies from -1 at the bottom to 0 at the surface. C is the concentration of the dye as a function of x, y, σ, t ; D is the total water depth; u, v , and ω are the x, y , and σ components of water velocity at time t ; K_h is the vertical thermal diffusion coefficient calculated here with the Mellor-Yamada 2.5 closure scheme; F_c is the horizontal diffusion term calculated with the Smagorinsky eddy parameterization method; and C_0 is the concentration of dye injected from one or more point sources over a specified time period.

A Lagrangian particle tracking module is also included in FVCOM. It applies the explicit Runge-Kutta fourth-order scheme to solve a coupled system of ordinary differential equations. The 3-dimensional velocity field from an FVCOM run is used to passively move a particle from some initial position to a final position in the velocity field through a sequence of time steps. The tracking module can be used offline, which is convenient for experimenting with numerous initial particle positions and time intervals while using the same velocity field generated with FVCOM. A particle tracking module that is coupled with a hydrodynamic model has become an important tool in estuarine studies to

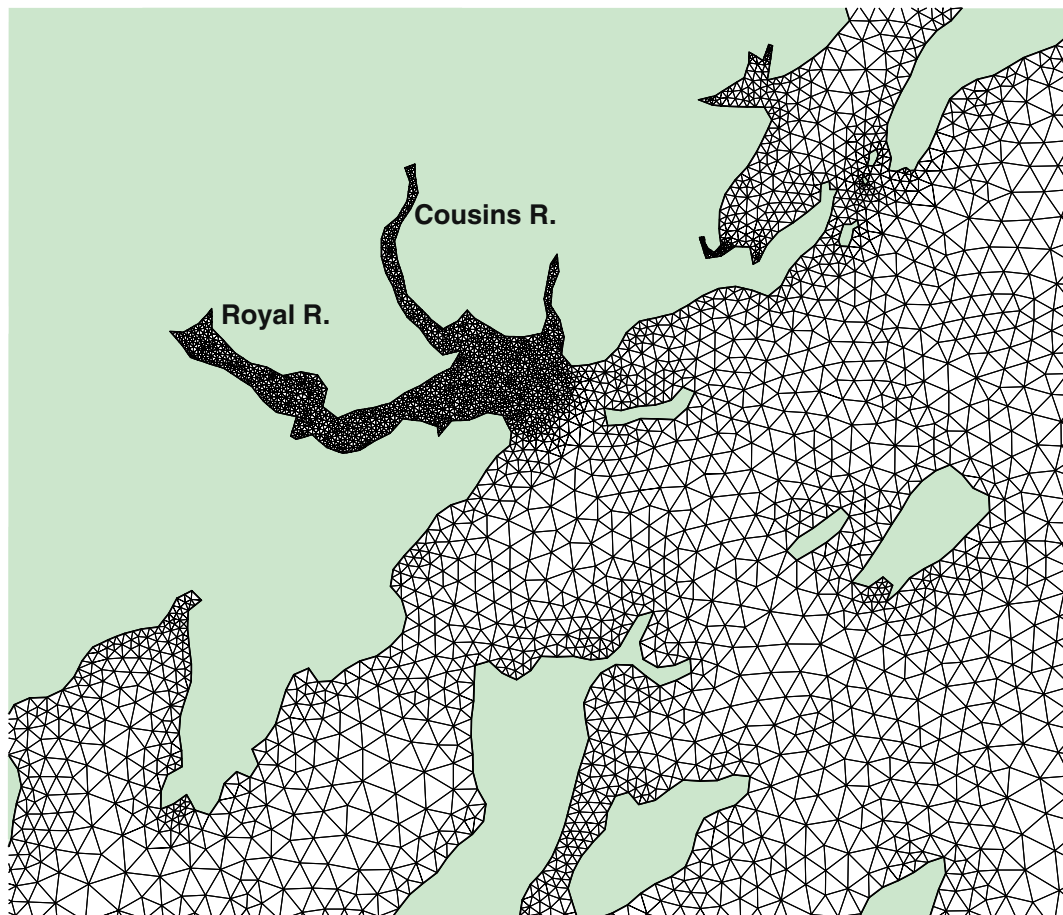


Fig. 2 The FVCOM mesh of the Royal/Cousins estuary and outlet to Casco Bay

determine such parameters as transit times, flushing times, turnover time, and other timescales with different freshwater and tidal flow rates (Lemagie and Lerczak 2015). In particular, particle tracking is used to determine residence times of a pollutant entering an estuary, which would then need to be closed to shellfish harvesting until the estuary is sufficiently cleansed. Here, particle tracking is being used with the objective of estimating travel times of particles through the estuary.

2.2 Model Forcing

The FVCOM model provides the inclusion of river discharge as a point source with separate temperature/salinity assignments, hourly wind stress applied uniformly across the surface of the computational domain, and surface heat flux. Hourly wind data from the NOAA buoy # 44007 in Casco Bay for May 2010 is applied uniformly across the computational domain. During

May 24–26, average wind speed was a mild 4.0 m/s primarily from the southwest. The National Ocean Service Center (NOS) of NOAA provides historical hourly tidal recordings at the Portland tide gauge (NOS station 8418150), which is located on the Maine State Pier in Portland harbor (<https://tidesandcurrents.noaa.gov/waterlevels.html?id=8418150>). The major tidal constituent in Casco Bay is the semidiurnal lunar tide (M2) with a period of 12.42 h. The water levels at this gauge have a range of about 3.4 m. The amplitudes and phases for seven tidal constituents, S2, M2, N2, K1, K2, O1, and Q1, were interpolated from the ADCIRC Tidal Constituent Database (Mukai et al. 2002) onto the 97 nodes of the outer boundary of the model domain. The ADCIRC tidal data slightly overestimates the M2 and K1 amplitudes at the Portland tide gauge, so these amplitudes were adjusted accordingly.

The Friends of Casco Bay (FOCB [n.d.](#)) maintains 10 profile stations that provide a synoptic survey of

temperature and salinity for Casco Bay, as well as 30 shoreline sites where surface temperature and salinity are recorded monthly. Temperature/salinity data from two fixed buoys in Casco Bay (see Buoys-BowdoinD02, NDBC44007, <http://gyre.umeoce.maine.edu/data/gomoos/buoy/html/D02.html>; http://www.ndbc.noaa.gov/station_page.php?station=44007) are also included. All this *T/S* data for May 2010 was krigeed onto the nodes of the numerical model to initialize temperature and salinity throughout the computational domain, including the open boundary. Heat flux files were acquired from the National Centers for Environmental Information (NCEI) Climate Forecast System Reanalysis (CFSR) at <https://nomads.ncdc.noaa.gov/data/cfsr/>. This data set has a horizontal resolution of about 56 km and provides surface heat flux data over two locations in Casco Bay.

For small volumes of water, freshwater input from rivers and streams can influence current flows, temperature, and salinity. As explained earlier, a flow rate of 9 m³/s for the Royal River is used in this study. The May monthly mean river discharges into Casco Bay from the Cousins, Presumpscot, and Androscoggin/Kennebec rivers are also included in the model. Finally, the wastewater treatment plants in Yarmouth, Freeport, South Portland, and Portland discharge freshwater into Casco Bay and their mean flows of 0.0263, 0.014, 0.274, and 0.876 m³/s, respectively, are included in the model. Constant temperature and salinity assignments from all river and treatment plant input are continuously injected in the model. Throughout Casco Bay for May, the density is fairly uniform offshore, with sigma-*t* values ranging from 22 to 25 kg/m³. In The Royal River, the surface sigma-*t* varies from 5.5 kg/m³ near the dam to 16 kg/m³ at the river mouth.

2.3 Model Initialization and Execution

FVCOM applies a mode-split method, using an internal/external time step. These two time steps must be chosen to ensure mass conservation at each time step. Here, the internal/external time steps are 4/0.5 s, respectively. The model is ramped up for 2 days. The density field and velocity field reach near steady state in about a week before the model is applied beginning May 24, 2010. The results of temperature, salinity, velocity field, and dye concentrations are saved at 15-min intervals.

2.4 Dye Injections and Comparisons

The records of the Yarmouth WWTP during May 2010 show that the average discharge to the Royal River was about 0.60 million gallons per day (MGD) or 0.0263 m³/s. The permit allows the plant to process and discharge 1.31 MGD. The conditions during this period were somewhat dry with little rainfall, so the amount of stormwater that is also treated by the plant was easily managed. The treatment plant was recently improved with a new 20-in. outfall pipe leading to a new diffuser at the end with seven ports 6 in. in diameter spaced about 10 ft apart at a depth of 4 m. The new diffuser is able to disperse the plant outflow to the estuary and improve dilution near the outfall. For this study, a mixture of three gallons of the Rhodamine WT dye and three gallons of deionized water was injected at a constant rate into the plant effluent pipe following dechlorination for 12.4 h beginning at 7:15 UTC on May 24 near the beginning of ebb tide. This resulted in a continuous discharge with a mean dye concentration of 1924 parts per billion (ppb) as measured at the diffuser.

In some earlier dye studies of treatment plants by the FDA, the dye might be injected at a rate proportional to the volume flow of the plant in order to attempt to maintain a uniform dye concentration at the outflow pipe. The dye might be injected steadily for 3 days, and two or three boat crews with fluorimeters would follow the dye and record readings that would then be used to establish the prohibitive zone for that plant. But in this study, the FDA injected the dye during the first 12.4 h only, and then used the fluorometer readings at the five stations to initialize a superposition principle developed by Yotsukura and Kilpatrick (1973) and Kilpatrick (1993) to estimate the dye concentrations for the period May 24–31. This superposition method was used to reduce the cost of injecting the dye over many days and also to determine when the dye concentrations at each of the five stations would reach a near steady state. Briefly, the superposition method is based on a linear convective diffusion equation whose solution provides the dye concentration at a specific location. The equation itself is not solved. The superposition principle relies on the knowledge that, since the equation is linear and homogeneous, any sum of solutions is also a solution to the equation. For each of the five stations, the fluorometer readings during the first 12.4 h are used as the solution to the diffusion equation

for this time interval. This solution, along with the fluorometer readings for the next 12.4 h, is used to initialize and extend the solution for the next 12.4-h period. The process is continued until May 31, when a near steady state is achieved at each station.

The dye from the model was injected into the Royal River at a single node nearest the plant diffuser, whereas the FDA dye was dispersed more uniformly through the seven ports of the diffuser. Since the distance between model nodes near the diffuser is about 37 m (121 ft), it seemed better to inject the dye at a single node in the model. The dye in the numerical model was injected continuously during May 24–31 with a concentration of 1924 ppb.

3 Results

3.1 Variability in Model Initial Conditions

As described earlier, the flow in the Royal River can vary greatly in May. Flow rates may also vary during the course of a day due to snow melt and precipitation, but data is not available on such short time intervals. The volume flow through the outfall pipe of the treatment plant also varies throughout the day. Goblick et al. (2017) reports that average daily flow rates from the plant can range from 0.022 to 0.088 m³/s. During the dye injection period, the flow rate from the plant reached as high as 0.0577 m³/s. The model assumes a constant mean flow rate of 0.0263 m³/s. These hourly fluctuations about the mean can lead to differences when dye concentrations from the FDA study are compared with those of the numerical model in space and time. Smoothing of bathymetry near FDA stations, bottom friction, and horizontal diffusion parameters can also have an effect on circulation.

3.2 Comparison of Dye Concentrations with FDA Boat Transects

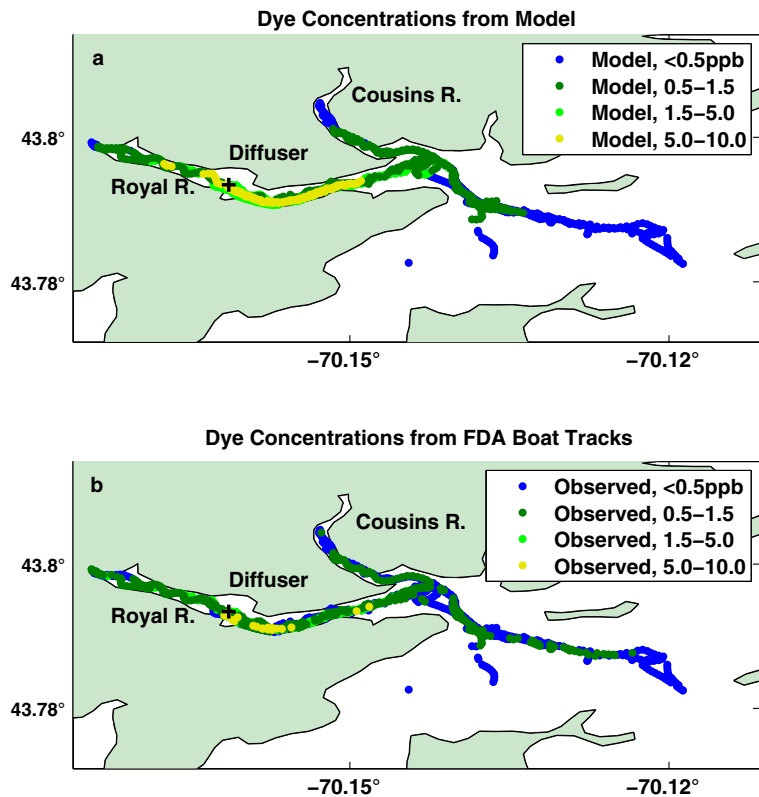
Since the superposition method was used in this study, the actual dye concentrations in the receiving waters can only be compared with the results of the numerical model during the first 12.4 h from 7:15 to about 19:40 UTC on May 24 when the FDA injected the dye into the outflow pipe of the treatment plant. At about 13:15 on May 24, two boats with fluorometers and GPS began tracking the dye along the Royal/Cousins Rivers above

and below the outfall pipe to locate the leading edge of the dye. Fluorometer readings were recorded near the surface usually every second for a total of about 13,000 readings. A five-point moving average was then applied to smooth the data. A method for comparing the fluorometer readings with model results was performed. For each node of the numerical model, the dye concentrations from the boat tracking fluorometer readings were searched to find the corresponding fluorometer dye concentration at the nearest node and nearest time. The comparison between the boat surface fluorometer readings and the numerical model are shown in Fig. 3. The mean difference between fluorometer readings and model readings was 0.74 ppb, with a standard deviation of 1.7 ppb, so model dye readings on this first day overall are slightly higher than the FDA fluorometer readings. However, Fig. 3 shows that the FDA readings include higher dye concentrations in the interval 0.5–1.5 ppb extending out to station 5. Since the model dye was injected at a single node nearest the plant diffuser, this may partly explain the larger differences in dye concentrations within about 200 m of the diffuser. Beyond 200 m, the model results were within 1 ppb farther upstream and downstream of the diffuser. Overall, these results are encouraging and show consistent dispersion agreement in space and time downstream from the outfall pipe, which is where the prohibitive zone is to be determined.

3.3 Comparison of Model Dye Concentrations at the Five FDA Stations

As mentioned earlier, the FDA set out oyster cages at the five stations with submersible fluorometers to measure dye concentrations throughout the study. All five stations are downstream from the treatment plant. Station 5 is about 1.5 km southeast of the mouth of the Royal River. The velocity field from the numerical model shows that the currents there are more complex. On the ebb tide, water from the Royal River fans out as it leaves the mouth of the river, with much of it moving toward station 5 and continuing southeasterly through a narrow channel between the north end of Cousins Island and Little Moshier Island (Fig. 1). On the flood tide, this flow is reversed and water from offshore moves back through this channel between Cousins Island and Little Moshier Island toward the entrance to the Royal River. This particular current can return some effluent from the Yarmouth treatment plant back to station 5 and the

Fig. 3 Dye concentrations during the first day of dye injection from the model (a), compared with FDA dye readings from boat tracks (b)



Royal River. But another source of water between Cousins Island and the mainland flows northward on the flood tide under the Cousins Island bridge and joins the first flow as it enters the Royal River. This water is essentially free of effluents from the Yarmouth treatment plant and contributes to the dilution of effluents in the Royal River.

The FDA used the superposition principle to calculate the 12.4 tidal cycle maximum, peak 1 h, and average dye levels at each of the five stations. An extended application of the superposition method was also used to predict the dye concentrations for the period May 24–31 to determine when the dye concentrations at each station reached a near steady state, which was about 6 days. This is because the fluorometer readings at the five stations showed little or no dye concentrations after about 6 days, so no additional concentrations would be added to the initial conditions in the superposition method. By comparison, the numerical model was run for a full 3 weeks with continuous dye injection and is also in agreement that the dye concentrations for this estuary reached a near steady state after about 6 days. The week of May 24–31 is also the period of the spring tide when the tide reached about 2 m above mean sea level on

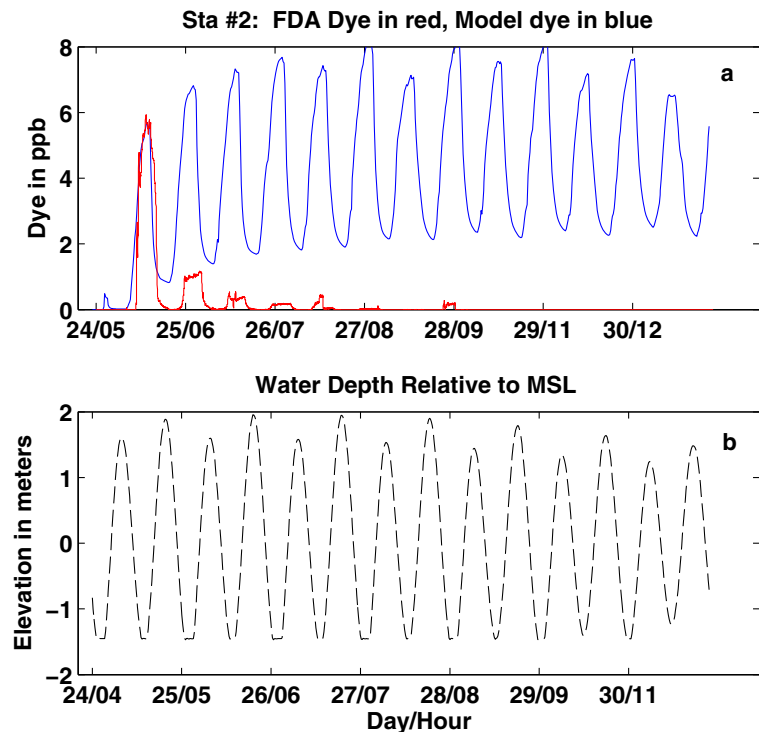
May 27, resulting in greater dye dilution and spreading farther from the diffuser. The neap tide followed during the first of June where the maximum tidal range only reached about 1.5 m above mean sea level, leading to less water volume for dye dilution in this tidal river. This led to some minor alterations due to current speeds and dispersion. The neap tide intrusion on the flood tide did not penetrate up the river as far as the spring tide. At the dam near Rte. 88, the fresher river water rose above the incoming tidal water, forming a more pronounced temporary wedge of length about 300 m at the surface. From the dam to the diffuser, the dye concentration increased slightly in the lower layers compared to the concentrations during the spring tide. However, there was little difference in dye concentrations at the five stations in the transition from spring to neap tide.

At each of the five FDA stations, the dye readings from the station fluorometers are compared with those of the numerical model. The fluorometers are positioned about 30 cm from the bottom, since the objective here is to determine the effect that effluent concentrations will have on shellfish harvesting. First, since the FDA dye was only injected during the first 12.4 h, the maximum dye concentrations at each station during this initial

period are compared with the corresponding maximum dye concentrations from the model. The maximum FDA dye concentrations at stations 1 through 5 were 6.10, 5.93, 2.80, 1.83, and 0.57 ppb, respectively. The corresponding maximum concentrations from the numerical model at the five stations were 5.92, 5.77, 2.81, 1.09, and 0.37 ppb. These initial dye values from the model compare favorably with the FDA data and indicate that the initializing process for the model is performing properly. Next, the FDA dye concentrations at each station as computed with the superposition method are compared with those of the model concentrations. As an example, Fig. 4 compares the 6-day dye injection in the numerical model with the FDA data at station 2 as recorded by the fluorometer at that station. Figure 4 also shows how the dye concentrations attain their maximum during low tide, and can vary by as much as 6 ppb during one tidal cycle. In the FDA study, the steady-state peak 1-h concentrations were more conservative and deemed to be preferred to the other measurements. Thus, the peak 1-h concentrations are compared in Table 1. At the end of 6 days, the FDA steady-state peak 1-h dye concentrations at stations 1 through 5 were computed in Goblick et al. (2017) to be 7.51, 7.73, 4.47, 3.23, and 0.44 ppb, respectively, using the

modified superposition method. It should be noted from Fig. 4 that the maximum model dye concentrations do not increase monotonically but fluctuate slightly up and down as a response to the tidal elevations from one 12.4 tidal cycle to the next. This means that the model calculated peak 1-h concentrations will also not increase monotonically through the May 24–31 time period. (In such a tidal environment, Yotsukura and Kilpatrick (1973) recommends that the dye should be injected for a full 24.8-h period to catch this oscillatory tidal behavior when using the superposition method.) By comparison, the superposition method can only increase the peak 1-h concentrations or leave them unchanged from one tidal cycle to the next. One way to determine the steady-state peak 1-h concentrations from the numerical model is to combine the last two peak 1-h concentrations after 6 days to obtain a mean peak 1-h concentration. Using this approach, the model results for stations 1 through 5 were 7.92, 7.07, 4.76, 3.67, and 1.23 ppb, respectively (Table 1). As expected, the model concentrations decrease with distance from the diffuser. Except for station 2, the model concentrations after 6 days are higher than the FDA data. The peak 1-h model reading of 7.92 ppb at station 1 is about 0.41 ppb higher than the FDA results, perhaps due to the model dye being

Fig. 4 Comparison of FDA and model dye concentrations at station 2 (a) and water depth relative to mean sea level (b)

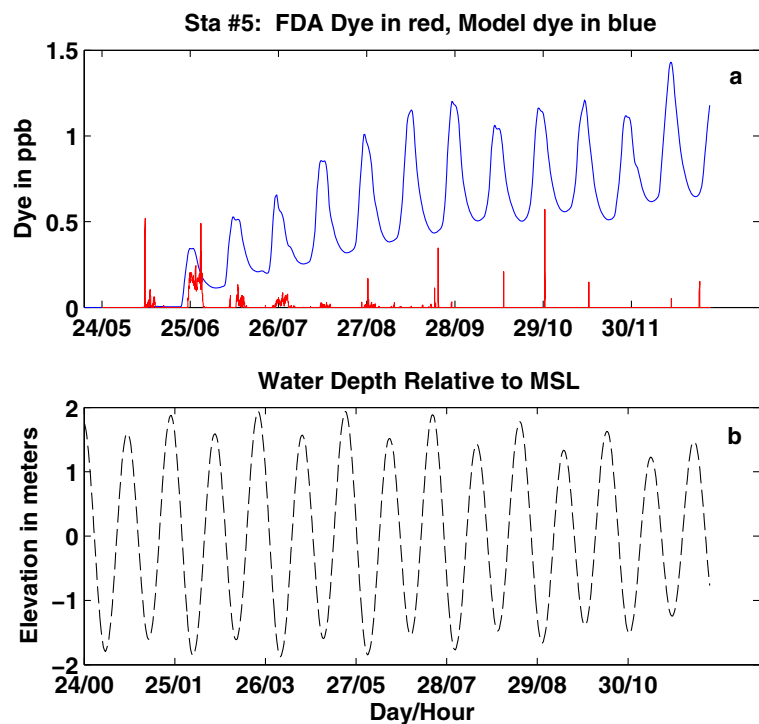


injected at a single point near the diffuser, rather than dispersed more uniformly by the seven ports from the diffuser. The model dye concentrations at stations 1, 2, and 4 are nearly identical at every depth throughout May 24–31, so this portion of the river channel is well mixed vertically. Some reasons for the differences between the FDA study and the model results are presented in Section 4. Considering the dramatic differences in the two methods used here, the model results are in close agreement with the FDA study, with the exception of the differences in steady-state peak 1-h concentrations at station 5. These differences play an important role in determining the prohibitive zone by the FDA.

The comparison of the model and superposition method for dye concentrations at station 5 is of particular interest (Fig. 5). The model steady-state peak 1-h concentration is 0.79 ppb higher than the FDA value of 0.44 ppb after 6 days. However, the dye data from the FDA boat tracks on the first day show higher dye concentrations ranging from 1.23 to 1.65 ppb within 0.2 km of station 5. As a check, the model peak 1-h concentrations were computed at several other locations near station 5 and found to be similar to the 1.23 ppb at station 5. Rhodamine WT dye is not a conservative substance. The dye concentration can

decrease over time due to photochemical decay from long daily exposures of sunlight, quenching agents such as chlorine which may have been released in small amounts from the treatment plant or other sources, and sediment absorption due to turbidity caused by tidal flows over the river bed. The details of the superposition method as described by Yotsukura and Kilpatrick (1973) allow for this dye decay in the superposition method and were applied in the FDA report. For an estuary like the Royal River, experimental investigations in similar estuaries suggest a dye loss of about 3% per tidal day. The FDA study adjusted for this decay in their calculations. In Fig. 5, a number of “spikes” are seen in the fluorometer readings at station 5. These are usually caused by turbidity (or bubbles) in the lower water column that can interfere with accurate fluorometer readings. Note that the spikes generally seem to occur at the beginnings of the flood and ebb tides. It is not clear if these spikes have a significant effect in the superposition method. By comparison, the numerical model dye concentrations are passive and are not affected by decay. Further discussion of the high steady-state peak 1-h concentrations from the model at station 5 will appear later.

Fig. 5 Comparison of FDA and model dye concentrations at station 5 (a) and water depth relative to mean sea level (b)



3.4 Conditions Required for a Prohibitive Zone

The FDA uses the following scenarios to establish the size of a prohibitive zone around a wastewater treatment plant when the plant is operating under normal conditions (see <http://www.issc.org/2015-nssp-guide>).

Scenario 1: In consideration of effluent discharged from a WWTP under *failure conditions* (such as a loss of disinfection), the prohibitive zone must provide a sufficient amount of dilution to dilute the effluent discharged under failure conditions to the fecal coliform standard of 14 MPN/100 ml within the prohibitive zone (MPN is most probable number, a statistical estimate of the number of organisms which most likely produced the laboratory results noted in a particular sample)

OR

Scenario 2: In order to reduce the size of the prohibitive zone, a conditionally approved zone may be operated if a factor of at least a 1000:1 dilution of effluent is achieved within the prohibited area, and there is sufficient amount of time to close the conditional area to the harvesting of shellfish before the effluent discharged at the onset of a failure can travel to the boundaries of the prohibitive zone.

Note: The additional area beyond the prohibitive zone to be closed under WWTP failure conditions must provide a sufficient amount of dilution to dilute the effluent discharged under failure conditions to the fecal coliform standard of 14 MPN/100 ml within the closed (due to failure) zone (consistent with scenario 1).

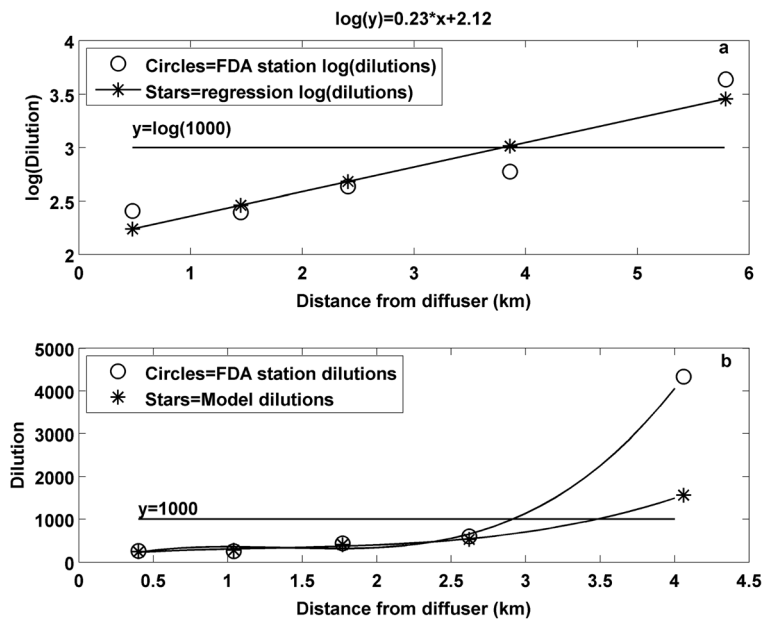
This study will focus on determining a prohibitive zone and a conditionally approved zone as described in these two criteria. The three properties to examine are the determination of the 1000:1 dilution zone, time of travel of effluents through a prohibitive zone in the event of a treatment plant failure, and amount of dilution necessary under failure conditions to meet the fecal coliform standard of 14 MPN/100 ml.

3.5 Determining the 1000:1 Dilution Zone

The first criterion for establishing a prohibitive zone for commercial shellfish harvesting around a treatment plant is that the effluent from the treatment plant must be diluted with 1000 units of receiving waters to every unit of effluent, a dilution of 1000:1. During the FDA study, a continuous discharge with a mean dye concentration of 1924 ppb was measured at the diffuser. The model provides the concentrations in parts per billion, so the corresponding dilution is obtained by dividing the mean injected flow rate (1924 ppb) by the concentration at a particular location. For a 1000:1 dilution at a particular location, the dye concentration would be 1.924 ppb. The FDA study used the near steady-state peak 1-h dye concentrations at stations 4 and 5, which were 3.23 and 0.44 ppb (Table 1), with the idea that the 1.924-ppb location would be somewhere between these two stations. The dilutions increase somewhat exponentially with distance from the diffuser. By using the original FDA station distances (Table 1), linear regression was performed in the FDA study on the log of the steady-state peak 1-h dilutions, y , versus station distance from the diffuser, yielding $\log(y) = 0.2328 * x + 2.1167$ with an R^2 value of 0.86, and x is the distance from the diffuser in kilometers. But with this regression line, when dilution = 1000, the distance from the diffuser would only be 3.8 km, which is closer to the diffuser than station 4 by 0.06 km (Fig. 6a). That is because this regression line does not adequately fit the logs of the dilutions at the five stations, and underestimates the distance from the diffuser for station 4. A better regression curve might be a cubic polynomial of the dilution, y , which was calculated to be $y = 80.64 * x^3 - 482.24 * x^2 + 851.59 * x - 88.14$, with an R^2 value of 0.99. When dilution = 1000 for this curve, the distance from the diffuser is 4.24 km, which is beyond station 4 by 0.38 km. For comparison, by using the corrected model station distances (Table 1), the regression equation becomes $y = 216.10 * x^3 - 884.42 * x^2 + 1118.84 * x - 96.57$, with an R^2 value of 0.99. When dilution = 1000, the distance is 2.9 km from the diffuser and 0.28 km beyond station 4. So regardless of which set of distances is used here with the FDA dilutions, note that the 1000:1 dilution line lies just beyond station 4 by about 0.28 to 0.38 km.

Finally, using the model station distances *and* model steady-state peak 1-h dilutions, the cubic regression equation becomes $y = 47.59 * x^3 - 182.12 * x^2 +$

Fig. 6 A log regression curve used by FDA (a) and the cubic regression curves (b) to estimate the distance from station 4 to the nearest boundary of the 1000:1 dilution zone



$308.28 * x - 127.54$, again with an R^2 value of 0.99. When dilution = 1000, the distance is 3.77 km from the diffuser and 1.1 km beyond station 4. These last two regression curves are compared in Fig. 6b. Using these last two regressions with the same distances between stations, the FDA study would recommend a prohibitive zone to include all waters within 2.9 km of the diffuser, while the model results would recommend a slightly larger prohibitive zone to include all waters within 3.77 km of the diffuser.

The model data can be used here to determine the prohibitive zone in a much more comprehensive, multidimensional way. The benefit of using a numerical model here is that the model computes the dye concentrations at more than 1600 locations (nodes) in the Royal/Cousins River estuary simultaneously, each at 10 depths for each node from surface to bottom for a total of 16,000 locations, and is saved every 15 min. The entire computational domain includes over 30,000 nodes in Casco Bay for a total of 300,000 locations where dye concentrations can be measured, if needed. As a minimum, the outer boundaries of the prohibitive zone must encompass all areas where the dilution is at least 1000:1, i.e., where the dye concentration would be 1.924 ppb or more. So the entire model output data for the period May 24–31 was searched for all those locations near the bottom where the dye concentration was 1.924 ppb or more at least once. In Fig. 7, each dot shows where the dye concentration was 1.924 ppb or

more, so the prohibitive zone would extend to the outer boundary of these dots, with occurrences from the north end of Cousins Island to Lanes Island. The figure also shows the two 1000:1 circular arcs of radii 2.9 and 3.77 km corresponding to the FDA and model boundaries, respectively. This zone of dots would extend around station 5 to a maximum of about 3.8 km from the treatment plant diffuser, almost identical with the previous model distance of 3.77 km obtained with the regression polynomial. This result is more convincing than the previous methods using just the dye readings at stations 4 and 5, because it identifies locations that were not recorded at the stations or in the boat tracking data. In a recent publication by Ao and Goblick (2016), the FDA applied the Mike 21 hydrodynamic model to the Yarmouth WWTP for the same period of May24–31, 2010, but with a lower Royal River flow of $5.41 \text{ m}^3/\text{s}$. The Mike 21 two-dimensional model also showed a more conservative prohibitive zone which extended about 3.4 km from the treatment plant diffuser.

The FDA also included the upper reaches of the Royal River as part of the prohibitive zone all the way to the dam near Route 88, which agrees with the model results seen in Fig. 7. The model results also include the area above Lanes Island, which was not sampled in the FDA study, but it is included in the official prohibitive zone that was established by the MDMR. To summarize, using the model distances between stations, the 1000:1 dilution zone by the FDA study would include

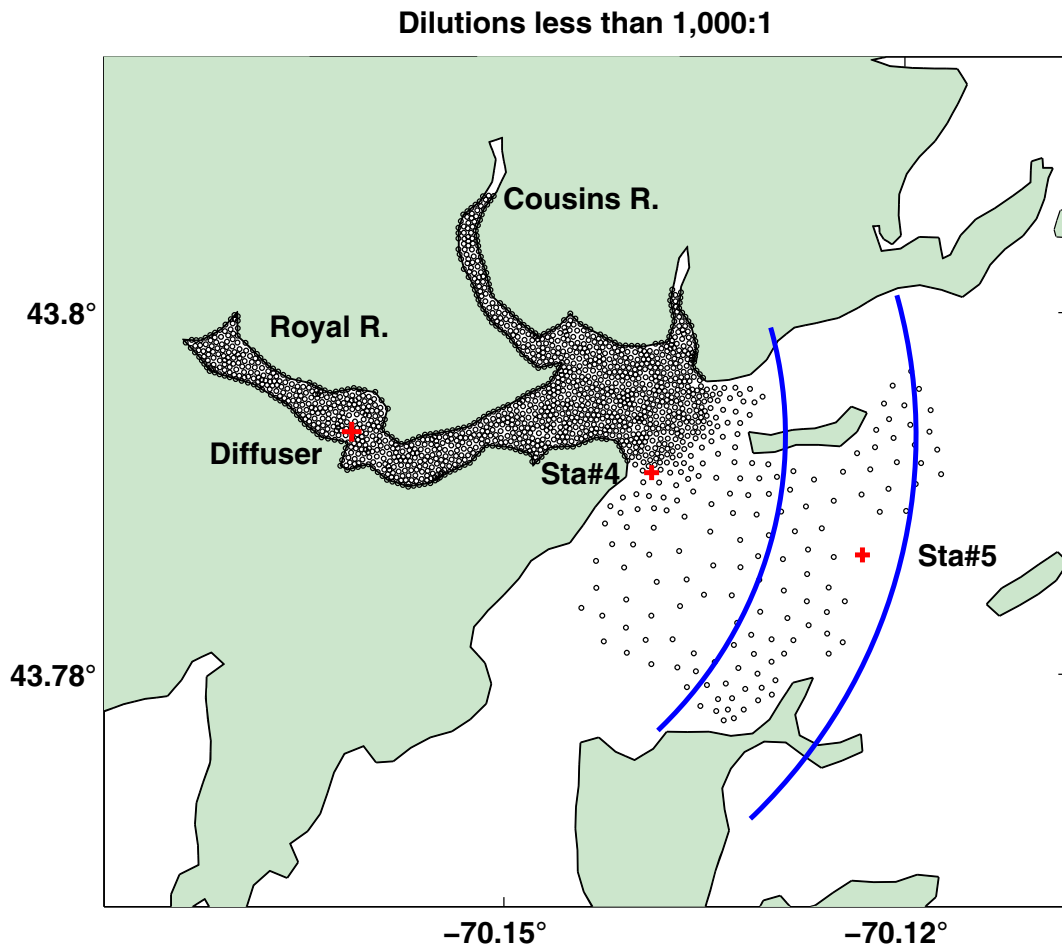


Fig. 7 Circles mark all locations where model dilutions are 1000:1 or less. Circular arcs mark the 1000:1 dilution boundaries of the FDA 2.9 km and model 3.77 km distances from the diffuser

all waters within 2.9 km of the WWTP diffuser, just beyond station 4. Using the results from Fig. 7, the model would include all waters within 3.8 km of the diffuser, just short of station 5.

3.6 Travel Time

To satisfy the second criterion in scenario 2, it is necessary to determine the time of travel of the effluent from the treatment plant to the outer boundaries of the 1000:1 prohibitive zone. If a malfunction occurs at the plant which may release partially treated or untreated effluent to the river, the MDMR would need to be notified in time to announce a temporary closure of commercial harvesting perhaps beyond the prohibitive zone. In the FDA study, the leading edge of the dye was tracked on the ebb tide from stations 1 to 3, which took 0.93 h. Using this

and the distance between stations 1 and 3, a mean speed was computed at the surface of about 58 cm/s. At 58 cm/s, it would take about 1.4 h for sewage from the treatment plant to flow 2.9 km to reach the edge of the 1000:1 FDA dilution zone. By comparison, the numerical model provides a velocity field sampled near the same places as the dye readings. At a single node midway between stations 1 and 3, the model mean speeds during the first 2-h period at ebb tide were 55 cm/s at the surface and 38 cm/s near the bottom. The surface speed for this single node is in good agreement with the FDA speed. At 55 cm/s, it would take about 2.0 h for sewage from the treatment plant to flow the farther distance of 3.8 km to reach the boundary of the model 1000:1 dilution zone. It should be noted that these times are based on a plant discharge rate of $0.0263 \text{ m}^3/\text{s}$. A higher discharge rate could reduce the time of travel.

The two times of 1.4 and 2.0 h computed above are based only on surface speeds at a single location during ebb tide. But once a particle leaves a location, it enters another location in the velocity field and experiences a different speed and direction. A more comprehensive method to determine travel times can be accomplished with the FVCOM particle tracking module described earlier. To investigate the travel times from the diffuser with the particle tracking module, a set of 50 particles was placed around the diffuser, some just upstream and some downstream, and across the entire river bed to capture as much variability in flow rates as possible. The particles were released at the beginning of ebb tide, which is when a plant malfunction would have the greatest impact out to and beyond the mouth of the Royal River and into Casco Bay. The results in Fig. 8

show that 16 of the 50 particles moved beyond station 4 and the mouth of the Royal River in 3.0 h. All particles stayed within the FDA 1000:1 dilution zone. Other particles only moved a few meters, and the rest remained between the diffuser and station 4. The particle tracking module also showed that after 4 h all 50 particles stayed within the model 1000:1 prohibitive zone and terminated well short of station 5. The particle tracking result produces a longer travel time than the previous travel times that were based on speeds between stations 1 and 3. Once a particle moves past the river outlet, its speed can decrease by 10 to 20 cm/s, resulting in a longer time to reach the 1000:1 boundary. This means that the Yarmouth treatment plant would need a management plan with adequate monitoring, recording devices, and alarm systems to close a conditionally approved area to

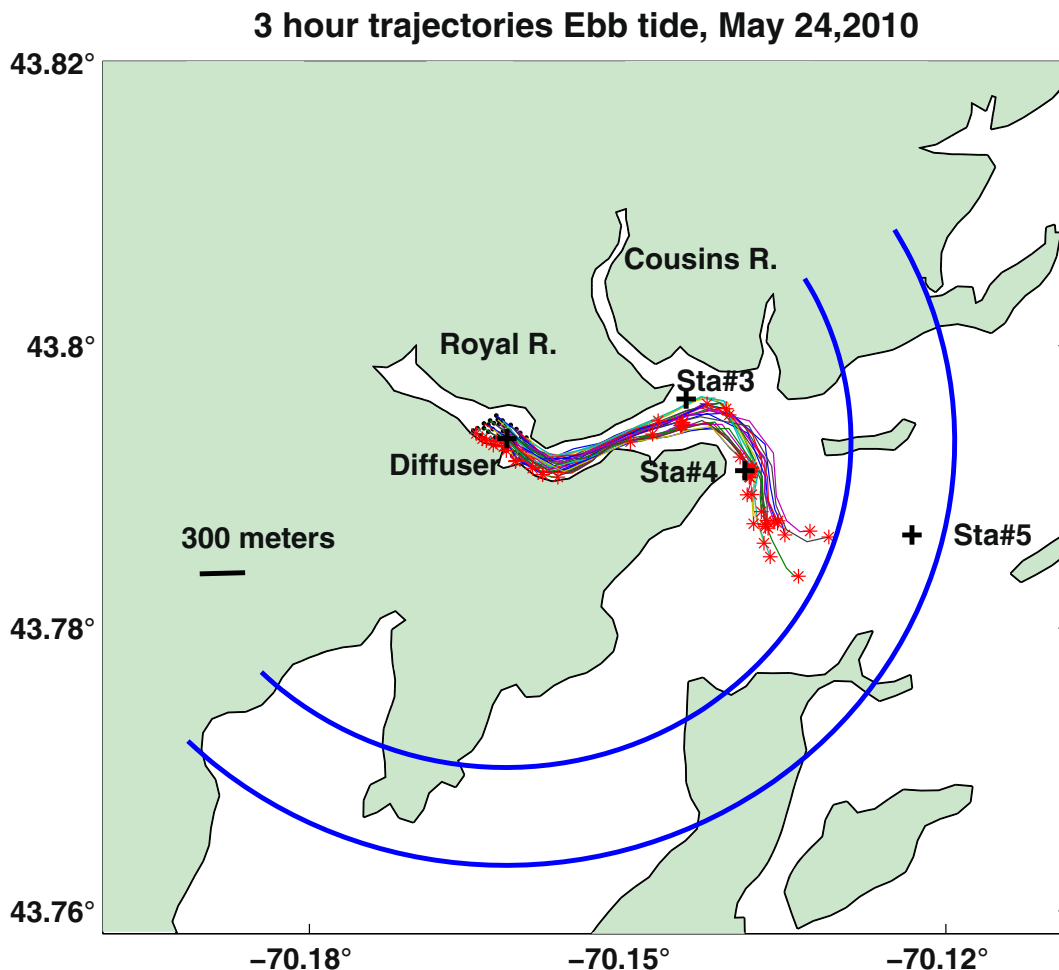


Fig. 8 Distances traveled by 50 particles from the diffuser in 3 h. Red asterisks mark the terminal points of each particle. Circular arcs mark the 1000:1 dilution boundaries of the FDA 2.9 km and model 3.77 km distances from the diffuser

harvesting shellfish in the event of a plant malfunction. Assuming a conservative notification time of 3.0 h or less, the transition from a prohibitive zone to a conditionally approved zone could occur just beyond the model 1000:1 dilution zone. Most treatment plants today are carefully monitored around the clock with personnel and current technologies. A faulty discharge, such as a loss of disinfection, can usually be identified in a matter of hours.

3.7 Meeting a Fecal Coliform Standard of 14 MPN/100 ml

Finally, there must be an adequate amount of dilution within the conditional area to dilute effluent discharged under failure conditions to meet the FC standard of 14 MPN/100 ml. In the event of a short-term failure, it is necessary to determine the distance from the diffuser where the FC concentrations are within the 14-MPN/100-ml standard. This may depend on the influent values coming into the plant before processing. The FDA uses a typical literature-based value of 1.4×10^6 FC MPN/100 ml of a fecal coliform count for raw, untreated wastewater for a worst-case total failure scenario. This is the typical anticipated FC count that would enter a treatment plant prior to processing (U.S. Food and Drug Administration 2013). Normally, the FC counts of the influent to a WWTP are not recorded periodically, but some samples were taken just prior to and during the FDA study. Six weeks before the FDA study, the plant records showed FC and *E. coli* (EC) influent readings of only 7×10^5 MPN/100 ml. During the FDA study, FC readings of 7×10^6 FC MPN/100 ml were recorded, five times the literature value, but a long-term mean is not available. In order to meet the 14-MPN/100-ml standard using the literature-based value, the corresponding dilution value would be $1.4 \times 10^6/14 = 100,000:1$, resulting in a dye concentration of 0.019 ppb. Again, as with the 1000:1 dilution zone, the entire model output data for the period May 24–31 was searched for all those locations near the bottom where the dye concentration was 0.019 ppb or more at least once. The 100,000:1 dilution zone is shown along with the 10,000:1 and 1000:1 dilution zones in Fig. 9. As expected, this zone is considerably larger than the 1000:1 dilution zone. It extends out to a line from the east coast of Great Chebeague Island to the southern tip of Whaleboat Island. It also extends

northward to include the lower half of the Harraseeket River and down the coast to the northern tip of Sturdivant Island. This is the conditional zone that would need to be closed under failure conditions of the treatment plant. The FDA study had a smaller conditional zone that extended out to a line from Blaney Point on the northern tip of Cousins Island to the southern tip of Little Moshier Island (U.S. Food and Drug Administration 2013). The model conditional zone extends beyond the region where the FDA 3-day study collected dye concentrations. In addition to the dye samples from the five fixed stations, the FDA boats also collected dye concentrations for 3 days. During this period though, the locations of the samples collected by the boats are essentially displayed in Fig. 3, which focuses on and around the channels of the Royal/Cousins Rivers out to about 300 m beyond station 5. As mentioned earlier, the dye data from the FDA boat tracks on the first day show dye concentrations ranging from 1.23 to 1.65 ppb within 200 m of station 5. These are more in line with the model steady-state peak 1-h concentration of 1.23 ppb at station 5. It is not known how much farther the FDA boundaries would have been for the conditionally approved zone if more data had been collected beyond station 5. With limited resources and only two boats, it would not have been possible for the FDA to cover all directions from the outlet of the Royal/Cousins Rivers out to a point where dye concentrations reached 0.019 ppb. Moreover, the limit of detection of the fluorometer instruments is close to 0.01 ppb, so it would be difficult for the boat fluorometers to map the outer boundaries for a conditionally approved zone. Thus, more observational dye data would be needed beyond station 5 to make a suitable comparison of the size of a conditionally approved zone with the results from the model. The conditionally approved zone as determined from the model may seem large, but the mean depth within this zone is only about 3.3 m at mean sea level, resulting in a low volume of water for a 100,000:1 dilution.

In some cases, the conditionally approved zone may be reduced, depending on the time the treatment plant has to notify the MDMR in case of a plant failure. If an untreated discharge remains within the 1000:1 zone during the first 4 h, and the plant has the ability to notify the MDMR to close the zone to harvesting, it may be possible to reduce the conditionally approved zone out to the 10,000:1 boundary (Fig. 9).

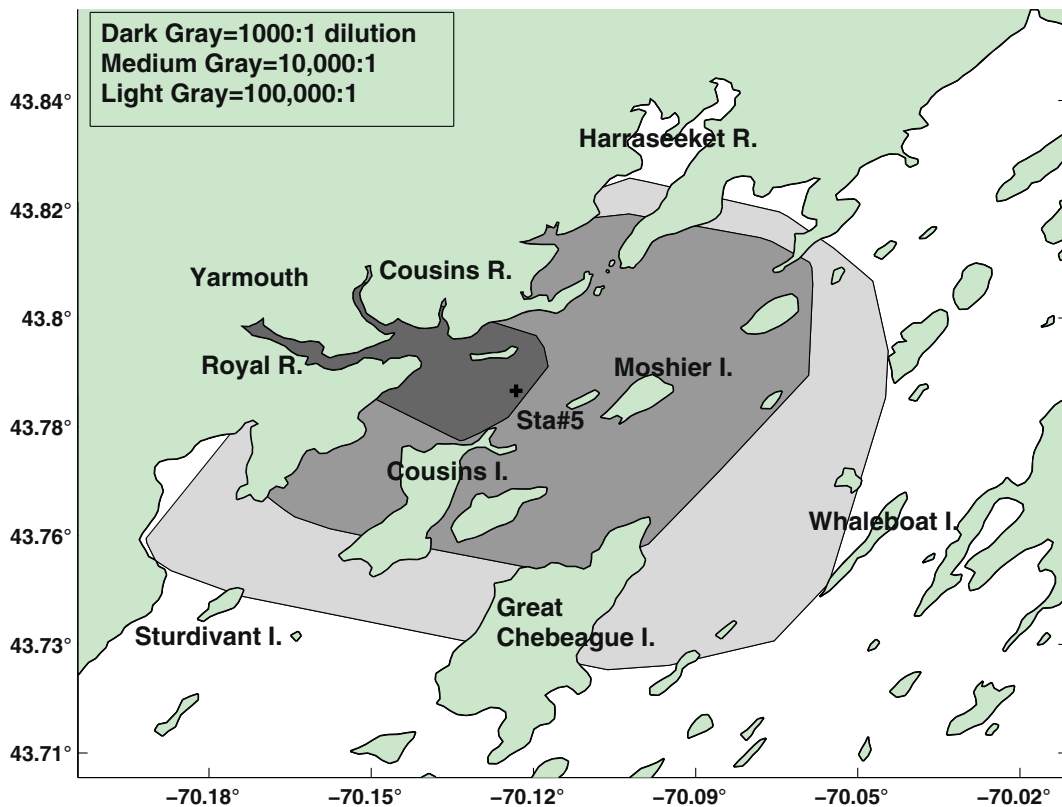


Fig. 9 A map of the three model dilution zones with a plant discharge rate of 0.6 MGD. The 1000:1 zone in dark gray is the model prohibitive zone

3.8 The Prohibitive Zone Under Higher WWTP Flow Rates

In the FDA study, a simple ratio was used to address dilutions at the five FDA stations for higher treatment plant discharge rates. For example, if the discharge rate at the plant increases from 0.6 MGD ($0.0263 \text{ m}^3/\text{s}$) to 1.5 MGD ($0.0657 \text{ m}^3/\text{s}$), this represents a 2.5-fold increase. Thus, the steady-state peak 1-h dye concentrations in Table 1 would be multiplied by 2.5 to obtain the concentrations for the higher rate. For example, at station 1, $7.51 * 2.5 = 18.78$ ppb. These new concentrations could then be used to determine the boundaries for the prohibitive zone. This method assumes that increases in the Royal/Cousins River flow would have minimal impact on downstream dilutions.

To compare this method of ratios, the model was run again with a discharge rate of 1.5 MGD ($0.0657 \text{ m}^3/\text{s}$) from the plant, just above the 1.3 MGD maximum permit rate. With this change, the model steady-state peak 1-h dye concentrations were computed again at each of the five stations (Table 1). The new concentrations at stations

1 through 5 are 20.2, 16.76, 6.64, 7.75, and 1.78 ppb. The ratios, however, are not consistent at 2.5, but instead are 2.55, 2.37, 1.39, 2.11, and 1.45 (last column of Table 1 in parentheses). Stations 1, 2, and 4 are close to the 2.5 ratio, but dye concentrations at stations 3 and 5 rose only slightly. Station 3 is located just north of the main channel of flow out of the Royal River (note in Fig. 8 how all particle tracks starting around the diffuser lie south of station 3). As a result, an increase in the plant discharge had only a small influence on dye concentrations at this station. The more complex velocity field dynamics around station 5 contributes to higher dilutions, which may explain only a slightly higher dye concentration there. To determine how the higher flow rates from the treatment plant affect the boundaries of the prohibitive zone, the cubic polynomial was used again to regress the new FDA dilutions at the five stations. When the dilution is 1000:1, the FDA distance from the diffuser to the outer boundary of the prohibitive zone moved from 2.9 to 3.5 km, an increase of 0.6 km. As before for the model results, the more comprehensive method of locating all model nodes where the dye concentrations were

1.924 ppb or higher was employed. The new 1000:1 dilution zone for the model would move from 3.8 to 4.6 km, an increase of 0.8 km. Figure 10 shows the 1000:1, 10,000:1, and 100,000:1 dilution zones for the higher plant discharge of 1.5 MGD.

4 Discussion

The comparison of the FDA study and model study presented here applies to a given wastewater treatment plant which discharges its effluent into the Royal/Cousins River estuary. The objective has been to determine the prohibitive zone around the Yarmouth WWTP using two very different methods.

In each method, dye concentrations were used to determine the boundaries of the prohibitive zone. There can be many causes for differences between model dye

readings and those of the FDA study. The model assumes a plant mean discharge of $0.0263 \text{ m}^3/\text{s}$, but there were times during the study when the flow rate increased to $0.0577 \text{ m}^3/\text{s}$. The flow rate in the Royal/Cousins River was assumed to be at $9 \text{ m}^3/\text{s}$ but could vary in the course of a day. In the model, the coefficient of bottom friction can alter dilutions and may be too small. The vertical and horizontal diffusion parameters in the tracer tracking module for this estuary may need further examination. The five FDA stations are in shallow waters close to the shoreline, and the model bathymetry, after smoothing, may not be exact there. This is an important consideration when comparing dye concentrations, which will vary with depth. In comparing model dye readings with the boat tracking fluorometers, a model node could be as much as 25 m from the corresponding fluorometer readings, with a maximum time difference of 8 min. There are also readings in the

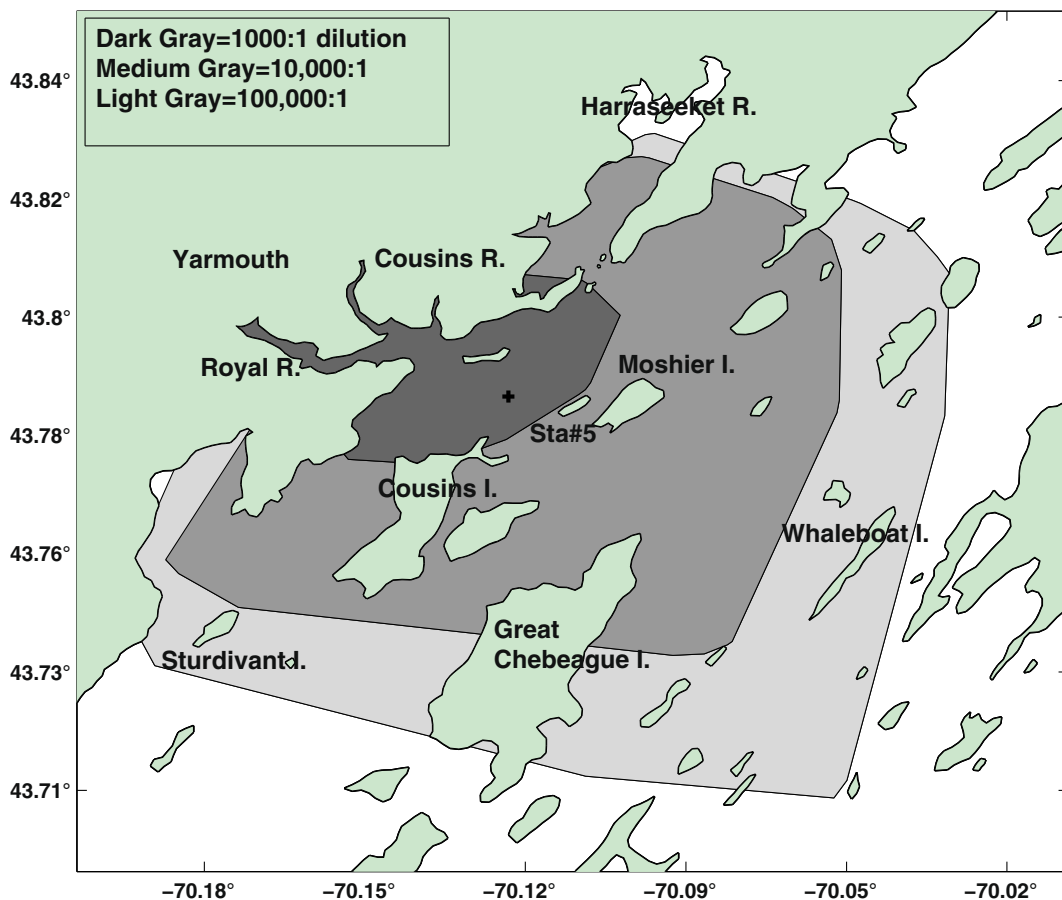


Fig. 10 A map of the three model dilution zones with a plant discharge rate of 1.5 MGD. The 1000:1 zone in dark gray is the model prohibitive zone

boat tracking data where dye concentrations vary greatly: one reading lists the dye concentration jumping from 8.6 to 13.1 ppb within 1 s. The discharge of dye from the plant diffuser is more uniformly distributed, whereas the model dye discharge is at a single node. The superposition principle does not fully address daily tidal variability, or any nonlinear effects that are included in the hydrodynamic equations of FVCOM. These are all typical of assumptions that are encountered when a model is applied to a changing environment. Nevertheless, the model results strongly coincide with those of the FDA study, where the major objective has been to determine a prohibitive zone around a treatment plant.

The FDA prepared a dilution model based on ratios to create a table of dilutions associated with changes in plant outfall flow rates. A major benefit of the model is that it can be run with different flow rates to construct a similar table, with corresponding graphs of the prohibitive and conditionally approved zones. A complete and applicable model study would need to include a number of model runs to encompass all possible events that can occur under different diffuser flow rates, river flow rates, precipitation, and other environmental conditions. Since these model runs would only repeat the same processes discussed so far, only the increase in the plant discharge rate to 1.5 MGD is included here as an example.

The locations of the five stations as chosen by the FDA appear to be very well placed for determining the prohibitive zone, at least when comparisons are made with the results of the model. Perhaps, station 3 was located north of the main channel of the Royal River to obtain more isolated readings from the Cousins River. The model prohibitive zone extends farther east than the FDA zone, but its outer edge is still between stations 4 and 5. However, a conditionally approved zone from the model is larger and extends farther east than that of the FDA conditional zone. As mentioned earlier, dye samples from the two boats stayed close to the river channels and stopped about 300 m east of station 5. If a hydrodynamic model for a treatment plant could be constructed and run first under various flow rates and environmental conditions, perhaps the resulting information could be used in preparing future FDA hydrographic studies that might, for example, include placing fluorometer stations in ideal locations where dilutions can reach as little as 100,000:1. The FDA is developing such hydrodynamic models (currently Mike 21) which will hopefully provide the preliminary information to prepare future treatment plant studies that produce more information at lower cost.

Supplementary material regarding this study can be found at the author's website, www.casconorwich.org/pages/YarmouthWWTP.html. One video displays the dye dispersion from the beginning of the injection to the final steady state. The 1000:1, 10,000:1, and 100,000:1 contours move with the tides; another shows a vertical transect of the dye from the dam at Route 88 to the diffuser, with the formation and decay of the salt wedge near the dam. The most recent shellfish closure map from the MDMR website is also available on this webpage. The MDMR must include additional criteria when constructing its closure maps, based on their own "sanitation survey" (see Sanitation-Survey 2018). It would have included the microbiological analysis of the oysters in the five FDA cages and the FC and MSC concentrations of the soft-shell clams that were harvested near the diffuser. Additional samples taken beyond the Royal/Cousins outlet would also be examine, and could alter the size of the conditionally approved zone. In addition to the discharge from the Yarmouth WWTP, there are 26 mi of the Royal River watershed above the dam where various agricultural runoff contaminants can affect water quality and be detrimental to commercial shellfish harvesting. These waters do not pass through any treatment plants, and the MDMR must also include these contaminants when preparing its closure map. The closure map displays the final official prohibitive and conditionally approved zones, including closing criteria related to precipitation and seasons. Part of the prohibitive zone is classified as conditionally restricted, which allows for harvesting subject to depurated and/or relay harvesting under specific environmental conditions, such as excessive rainfall or a sewerage treatment plant bypass.

5 Conclusion

An FDA hydrographic dye study and the numerical hydrodynamic coastal model FVCOM have been applied to a wastewater treatment plant in the Royal/Cousins river estuary in Yarmouth, Maine. The main objective has been to determine if the numerical model can reproduce the same prohibitive zone of the Yarmouth WWTP that was established by the FDA study. The FDA dye study aided in the calibration and validation of the model with regard to dye concentrations and diffusion. The dye concentrations from the two methods during the first day when the dye was injected in the FDA study were in close agreement at each of the five FDA stations and along the

transects of the boat tracking fluorometers. The superposition method applied by the FDA and the model results were in agreement that the near steady state of the dye distribution from the treatment plant diffuser was about 6 days for this estuary. The surface speeds at selected locations from both studies were within a few centimeters per second of each other. The outer boundary of the prohibitive zone for the treatment plant determined by the model was about 0.9 km farther from the diffuser than the FDA study. When the effluent discharge from the plant was increased to 1.5 MGD, the FDA data and methods would increase the distance from the diffuser to the outer boundary of the prohibitive zone by 0.6 km, whereas the model data would increase its distance by 0.8 km. For the conditionally approved zone that requires a 100,000:1 dilution, the dye data collected by the FDA was not available spatially to compare with the model.

An objective of this study has been to demonstrate the advantages of using the tools of a numerical model to provide a high-resolution velocity field vertically and horizontally where pollutants may be discharged to a coastal estuary. The results show that this numerical model is capable of replicating the observational data provided by the FDA study. The tracer tracking module is integrated with the velocity field to produce dye dispersion throughout an estuary with more spatial and temporal information than can be obtained with limited observational data. The particle tracking module provides important information about transit times and flushing times for the estuary. The model can easily be modified to alter river flow rates, discharge rates from a treatment plant, precipitation, and seasonal environmental factors to produce a comprehensive report on prohibitive and conditionally approved zones for the estuary.

Acknowledgements The author thanks Greg Goblick, FDA Consumer Safety Officer, for assistance in comparing model results with the FDA study. Also, thanks to Tom Connolly, Director, Yarmouth Wastewater Treatment Plant, for additional information on plant operation. Special thanks to the reviewers for their many helpful suggestions that greatly improved this work and made it more readable.

References

- Ao, Y., Goblick, G. N. (2016). Application of hydrodynamic modeling to predict viral impacts from wastewater treatment plant discharges adjacent to shellfish growing areas. Office of Food Safety Center for Food Safety and Applied Nutrition, U.S. Food and Drug Administration, 5100 Paint Branch Parkway, College Park, MD 20740. <https://www.epa.gov/sites/production/files/2016-06/documents/application-hydrodynamic-modeling.pdf>.
- Blumberg, A. F. (1991). *A primer for ECOM-si, technical report* (p. 66). Mahwah: HydroQual.
- Chen, C., Liu, H., & Beardsley, R. (2003). An unstructured grid, finite volume, three dimensional, primitive equations ocean model: application to coastal ocean and estuaries. *Journal of Atmospheric and Oceanic Technology*, 20(1), 159–186.
- Falconer, R. A. (1984). A mathematical model study of the flushing characteristics of a shallow Tidal Bay. *Proceedings of the Institute of Civil Engineers, Part 2*, 77, 311–332.
- Falconer, R. A. (1986). A water quality simulations study of natural harbour. *Journal of Waterway Port, Coastal and Ocean Engineering ASCE*, 112, 234–259.
- FOCB (n.d.). Friends of Casco Bay, 43 Slocum Drive, South Portland, Maine 04106. <http://www.friendsofcascobay.org/>.
- Frick, W. E. (2004). Visual plumes mixing zone modeling software. *Environmental Modeling & Software*, 19, 645–654.
- Frick, W.E., Roberts, P.J.W., Davis, L.R., Keyes, J., Baumgartner, D.J., George, K.P. (2003) Dilution models for effluent discharges (Visual Plumes). EPA/600/R-03/025, fourth ed. U.S. Environmental Protection Agency, Environmental Research Division, NERL, Standards and Applied Science Division, Office of Science and Technology, Athens, Georgia.
- Ganju, N. K., Brush, M. J., Rashleigh, B., Aretxabaleta, A. L., del Barrio, P., Grear, J. S., Harris, L. A., Lake, S. J., McCardell, G., O'Donnell, J., Ralston, D. K., Signell, R. P., Testa, J. M., & Vaudrey, J. M. P. (2016). Progress and challenges in coupled hydrodynamic-ecological estuarine modeling. *Estuaries and Coasts*, 39, 311–332.
- Goblick, G. N., Ao, Y., Anbarchian, J. M., & Calci, K. R. (2017). Determination of buildup and dilution of wastewater effluent in shellfish growing waters through a modified application of super-position. *Marine Pollution Bulletin*, 115, 164–171.
- Gupta, I., Dhage, S., Jacob, N., Navada, S. V., & Kumar, R. (2006). Calibration and validation of far field dilution models for outfall at Worli, Mumbai. *Environmental Monitoring and Assessment*, 114, 199–209.
- Hamrick, J. M. (1996). User's manual for the environmental fluid dynamics computer code. Special Report in Marine Science and Ocean Engineering No. 331, The College of William and Mary, Virginia Institute of Marine Science, VA. *Environmental Research*, 70, 150–161.
- Kilpatrick, F.A. (1993). Techniques of water-resources investigations of the United States Geological Survey: simulation of soluble waste transport and buildup in surface waters using tracers. *United States Geological Survey, Chapter A20, Book 3, Application of Hydraulics, Report Number: TWRI3A20*. Washington, DC: US Government Printing Office, Washington, DC: US Geologic Survey, pp. 2–14.
- Lemagie, E. P., & Lerczak, J. A. (2015). A comparison of bulk estuarine turnover timescales to particle tracking timescales using a model of the Yaquina Bay Estuary. *Estuaries and Coasts*, 38, 1797–1814.
- Liu, W. C., Kuo, J. T., Young, C. C., & Wu, M. C. (2007). Evaluation of marine outfall with three-dimensional hydrodynamic and water quality modeling. *Environmental Modelling Assessment*, 12, 201–211.

- MDMR (n.d.). Shellfish harvesting area classification-notification of changes, Oct. 2013 http://www.maine.gov/dmr/rm/public_health/closures/14.pdf.
- Mellor, G. L., & Yamada, T. (1982). Development of a turbulence closure model for geophysical fluid problems. *Reviews Geophysics Space Physics*, 20, 85–875.
- Muhammetoglu, A., Talcin, O. B., & Ozcan, T. (2012). Prediction of wastewater dilution and indicator bacteria concentrations for marine outfall systems. *Marine Environmental Research*, 78, 53–63.
- Mukai, A.Y., Westerink, J.J., Luettich, R.A., Mark, D. (2002). Eastcoast 2001, a tidal constituent database for western North Atlantic, Gulf of Mexico, and Caribbean Sea. Contract Number DACW 42-00-C-0006, U.S. Army Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), Vicksburg, MS.
- Permit-Yarmouth (2017). Website for Yarmouth WWTP Permit # ME0100765. <https://www.epa.gov/sites/production/files/2017-05/documents/draftme0100765permit.pdf>.
- Sanitation-Survey (2018). MDMR website for how shellfish areas are classified. <http://www.maine.gov/dmr/shellfish-sanitation-management/programs/growingareas/howclassified.html>.
- Shewchuk, J.R. (n.d.). Triangle. <https://www.cs.cmu.edu/~quake/triangle.html>.
- Signell, R. P., Jenter, H. L., Blumberg, A. F. (1996). Circulation and effluent dilution modeling in Massachusetts Bay: model implementation, verification and results. *USGS Open File Report 96-015*, U.S. Geological Survey, Woods Hole.
- Signell, R. P., Jenter, H. L., & Blumberg, A. F. (2000). Predicting the physical effects of relocating Boston's sewage outfall. *Estuarine, Coastal and Shelf Science*, 50, 59–72.
- Smagorinsky, J. (1963). General circulation experiments with the primitive equations. *Monthly Weather Reviews*, 1, 99–164.
- Smith, K. W., Bilgli, A. (n.d.) BafTri 2-D triangular grid generator. <http://www-nml.dartmouth.edu/Software/battri>.
- U.S. Food and Drug Administration (2013). Hydrographic study of waste water treatment plant effluent in the Royal and Cousins River of Yarmouth, Maine. Report on findings from the May 24–26, 2010 study period. U.S. Food and Drug Administration, Washington, D.C. (YarmouthStudy_Final.pdf at <http://www.casconorwich.org/pages/YarmouthWWTP.html>).
- Yotsukura, N., Kilpatrick, F.A. (1973). Tracer simulation of soluble waste concentration. Journal of the Environmental Division, *American Society of Civil Engineers*, vol. 99, no. EE4, *Proceedings Paper 9947*, pp. 499–515.
- Zhao, L., Chen, C., Beardsley, R.C., Codiga, D.L., Leo, W.S. (2016). Simulations of hydrodynamics and water quality in the Massachusetts Bay system during 2014 using the bays eutrophication model. Boston: *Massachusetts Water Resources Authority. Report 2016-03*. 103 pp. <http://www.mwra.state.ma.us/harbor/enquad/pdf/2016-03.pdf>.