Tracking the discharge of the Yarmouth Waste Water Treatment Plant in Casco Bay, Maine with a numerical coastal model.

May 2014

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Abstract

The Maine Department of Marine Resources (MDMR) is responsible for establishing zones where commercial shellfish harvesting is prohibited near waste water treatment plant discharge areas. Two methods for determining the prohibitive zone around the Yarmouth Waste Water Treatment Plant (WWTP) are compared here. One method was a dye study conducted by the U.S. Food and Drug Administration (FDA) in May, 2010. The other method applies a numerical coastal model that provides the velocity field for the currents around the treatment plant. Such a model that includes a diffusion equation to simulate dye dispersion from a point source is used to determine the prohibitive zone that MDMR seeks. The finite-volume numerical coastal model (FVCOM) is applied to the circulation of currents in Casco Bay, Maine. The discharge from the waste water treatment plant in Yarmouth, Maine flows into the Royal River in Casco Bay. The coastal model incorporates bathymetry, tidal forcing, wind stress and river discharges from various sources. The horizontal resolution of coastline and island boundaries used in the study is sufficient to capture small eddy production and decay, and identify local circulation dynamics. 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. In addition, the numerical model is able to show dye concentrations in regions outside the Royal River where sampling was not conducted by the FDA.

1. Introduction and background

One of the many responsibilities of the MDMR is to establish zones around wastewater treatment plants where shellfish harvesting is prohibited. Shellfish filter large volumes of water and can concentrate toxic microorganisms from human sewage. MDMR uses criteria from the National Shellfish Sanitation Program (NSSP) to determine safe areas for commercial shellfishing. The NSSP sets standards for shellfish sanitation in interstate commerce, which is supported by the United States Food and Drug Administration (FDA). One of the methods used by the MDMR to establish safe shellfishing areas near a wastewater treatment plant is to conduct a dye study. A fluorescent dye such as Rhodamine WT is injected into the discharge outflow pipes of the treatment plant as a tracer to represent the potential fecal coliform concentration of post-treatment, prechlorinated effluent. The dye is then tracked by boats or recorded at profile sites over a period of several days to measure the dilutions, dispersion and residence times in the surrounding waters.

In May, 2010, the FDA Center for Food Safety and Applied Nutrition conducted a dye study at the Yarmouth Wastewater Treatment Plant (WWTP) in the Royal River (U.S. Food and Drug Administration, 2010). On May 24, dye was injected for 12.4 hours at a continuous flow into the final mixing chamber of the effluent stream of the treatment plant. During that period, the average plant flow discharge was taken to be 600,000 gallons per day, or 0.0263 cubic meters per second, and the mean dye concentration was measured to be 1924 parts per billion (PPB) at the outfall pipe. On May 20, 5 stations(cages) were set out in the Royal River (see Fig.1), equipped with WET submersible fluorometers to measure dye concentrations, along with about 50 oysters submerged in cages at each station. The cages stayed in the water until June 2, 2010. The two cages farthest from the discharge pipe were also equipped with a CTD to measure temperature and salinity. On May 24, 25 and 26, two boats equipped with fluorometers ran transects in the Royal River during the ebb tide to measure dye concentrations at locations within the river and out into Casco Bay.

The data that was recorded at the 5 stations and boat transects are described in the FDA report. The complete details of the dye study, including instruments, calibration, preliminary measurements and charts from boat transects are also in the FDA report, and will not be reproduced here.

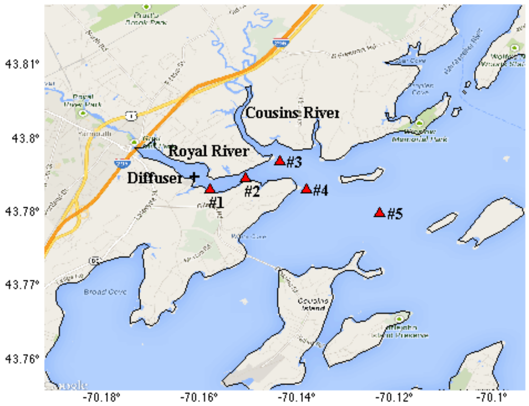

Figure 1. Royal River computational zone, with diffuser and 5 station locations.

2. The Numerical Model

For this study, the FVCOM numerical model is applied on an unstructured triangular grid of Casco Bay. FVCOM, developed by Chen et al. (2003), is a prognostic, unstructured grid, finite-volume, free surface, three dimensional primitive equation coastal and estuarine model. 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 model allows for a wet/dry treatment in the intertidal zone, river discharge as a point source with separate temperature/salinity assignments, and hourly wind stress applied uniformly across the surface of the computational domain. The computational domain for this study is a triangular unstructured mesh consisting of two zones: the outer zone which includes all of Casco Bay (see Fig. 2), and a higher resolution nested zone which covers the Royal and Cousins Rivers (see Fig. 3). The Royal River zone consists of triangles whose sides are of length 50 meters or less. The triangular grid was created using Triangle (Shewchuk) and BATTRI (Smith et al.*),* a graphical Matlab interface for Triangle. The domain is enclosed by the boundary curves as shown in Figure 2. 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 minutes. 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 (DEM) of Casco Bay, Maine (DEM, 2008). This high resolution bathymetric data provides water depths on 10 m squares for all of Casco Bay. The bathymetry for the numerical model used here is derived from this data.

3. Initializing the Model

The hourly wind data from the NOAA buoy # 44007 in Casco Bay for May, 2010 is applied

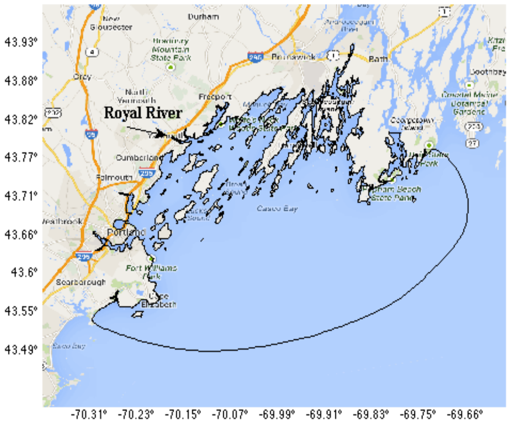

Figure 2. Casco Bay, Maine

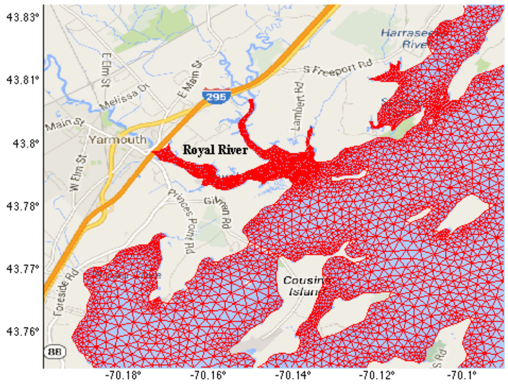

Figure 3. Portion of Casco Bay mesh with nested high resolution mesh of Royal and Cousins Rivers.

uniformly across the computational domain. During May 24-26, average wind speed was a mild 4.0m/sec (9mph) 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 (http://tidesonline.nos.noaa.gov/). The major tidal constituent in Casco Bay is the semi-diurnal lunar tide (M2) with a period of 12.42 hours. The water levels at this gauge can range up to 2.3 m above mean sea level. The amplitudes and phases for seven tidal constituents, S2, M2, N2, K1, K2, O1, 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 ten stations maintained by the Friends of Casco Bay (FOCB) provide a synoptic survey of temperature and salinity for Casco Bay. The FOCB data for May 2010 was kriged onto the nodes of the numerical model to initialize temperature and salinity on the computational domain.

For small volumes of water, freshwater input from rivers and streams can influence current flows, temperature and salinity. There is some historical stream flow data for the Royal River in Yarmouth, available at the Gulf of Maine Watershed Information and Characterization System (http://gm-wics.sr.unh.edu). The data covers the years 1949-1998. An effort was made to correlate stream flow for the Royal River for May 2010 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 6 m^3/sec. There are also 2 small streams flowing into the north area of Harraseeket River. No flow rates could be found for these, but based on comparative size with the Royal River, a flow rate of 0.25 m^3/sec was assigned to each of these streams. Finally, the wastewater treatment plants in Yarmouth, Freeport and Portland discharge an average fresh water flow which are taken to be 0.0263 m^3/sec, 0.014 m^3/sec and 0.876 m^3/sec respectively.

4. Results

The volume of water in the Royal and Cousins River can be estimated quite accurately from the model. Beginning at the last dam on the Royal River near Route 295 and extending to a line about half way from the River mouth to Lanes Island, the volume of water at mean sea level is about 2,094,044m^3, and at low tide the volume is only about 216,491m^3. The FDA study used an average discharge from the Yarmouth treatment plant to be 600,000 gallons per day (2,272m^3/day) and this same rate was used in the numerical model.

The FVCOM numerical model was run to simulate one month of the circulation in the Royal River beginning May 1, 2010. The model provides a dye tracer module, which was used to replicate the dye experiment conducted by the FDA during May 24-26, 2010. The dye was inserted in the model beginning at 2:15AM, EDT of May24, as it was in the FDA study.

A. Comparison of dye concentrations at the five stations.

In the FDA study, the dye was only injected in the discharge pipe for 12.4 hours. Following Kilpatrick (1993), a superposition principle with a five point moving average was then applied to the dye concentrations that were recorded at the 5 stations. This method was used to reduce the cost of injecting the dye over three or more days. The superposition method was then used to predict the dye concentrations for the period May 24-31 to determine when the dye concentrations at each station reach a steady state. By contrast, in the numerical model the dye was injected into the effluent at the discharge pipe continuously for four days. As an example, Figure 4. compares the four day dye injection in the numerical model with the actual FDA 12.4 hour dye injections at station 4 as recorded by the fluorometer at that station. The model shows how the dye concentration rises at station 4 to a near steady state at a maximum of about 6 PPB.

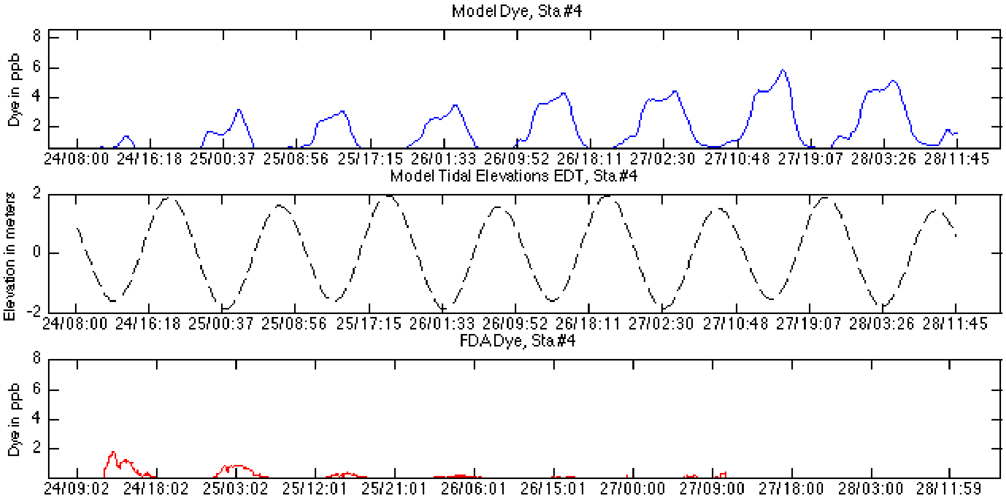

Figure 4. Dye concentrations in PPB at station #4. Top: model dye injected for 4 days. Bottom: FDA dye injected for 12.4 hours.

The FDA report shows the superposition concentrations for half tidal day maximum, half tidal day peak 1 hour, and half tidal day average dye concentrations for each of the 5 stations, assuming a constant injection of dye for 6 days. After 6 days, the half tidal day maximum dilution levels at stations 1 through 5 were computed in the FDA report to be 223, 222, 307, 426 and 640. These numbers are determined by dividing the average 1924 PPB dye concentration at the diffuser discharge pipe by the number of PPB derived from the superposition method. Thus a dilution of 223 is equivalent to 1924/223 = 8.63PPB. The corresponding dilutions from the numerical model at the 5 stations were 224, 240, 275, 384, and 583. The model shows dilutions at stations 1 and 2 to be higher than the superposition method used in the FDA study, and lower at stations 3,4, and 5. The largest difference of 57 occurs at station 5. The corresponding differences in dye concentrations at stations 1 through 5 are 0.04, 0.65, 0.73, 0.49, and 0.29 PPB respectively. These differences may be due to a number of factors: the variability in the volume discharge at the diffuser, the variability of the flow in the Royal River, especially during May when evening and daytime volume flows can change dramatically. The historical gauge data for the Royal River from 1950 to 1998 during May shows a mean discharge rate that varies from 2.6m^3/s in 1985 to 30.7m^3/s in 1989. This data is at (http://www.gmwics.sr.unh.eduhtml/Points/Data_ud01060000.txt). In the model, the river discharge was taken to be 6m^3/s. The model locations for the 5 stations may be as much as 25m from the FDA stations, and the time difference between observed and model samples can be up to 8 minutes. These differences in space and time can contribute to slight differences between observed and model readings. The superposition method may also be predicting slightly lower concentrations as well. Note the difference in tidal range in Figure 4. between one 12.42 hour cycle and the next. The difference in tidal ranges from one 12.42 hour period to the next can be as much as 0.5m. The superposition method assumes all tidal ranges are the same.

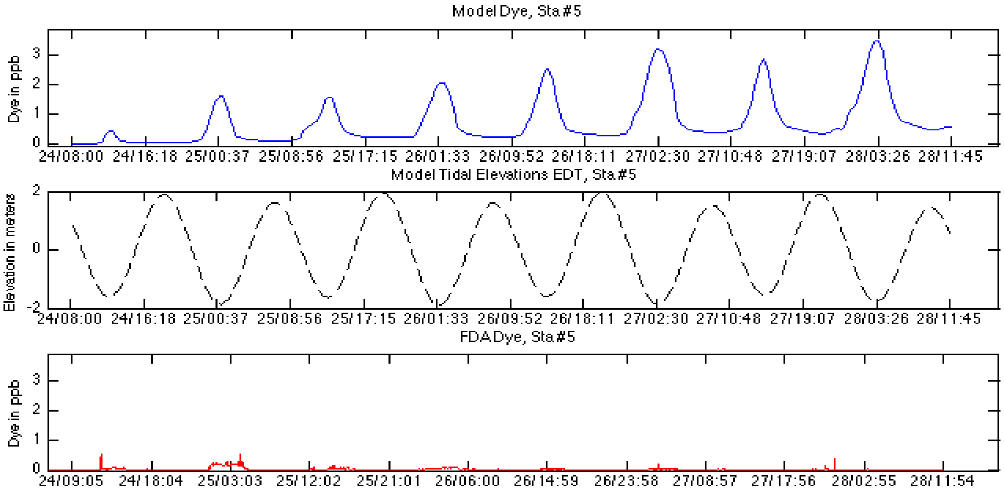

Figure 5. Dye concentrations in PPB at station #5. Top: model dye injected for 4 days. Bottom: FDA dye injected for 12.4 hours.

Of particular interest is the comparison of the model and superposition method for dye concentrations at station 5, as shown in Figure 5. Station 5 is about 1 mile southeast of the mouth of the Royal River. The currents there are more complex. On the ebb tide, water from the Royal River fans out as it leaves the river, with much of it passing through station 5 and continuing southeasterly through a narrow channel between the north end of Cousins Island and Little Moshier Island. 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 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 free of effluents from the Yarmouth treatment plant, and contributes to the dilution of effluents in the Royal River. The model dye concentration in Figure 5 compares well with the superposition method; the half tidal day maximum concentration of the model is approximately 3.29PPB, while the FDA value is 3PPB. The results in Figure 5 also show that the dye concentration at station 5 remains above about 0.5PPB.

B. Determine the distance from the outfall where effluent dilutions of 500:1 and 1,000:1 occur.

In order to examine a prohibitive shellfishing zone in the event of a long term elimination or lapse in disinfection, the numerical model computes the dye concentration at more than 1600 locations (nodes) in the Royal River and Cousins River alone, each at 10 depths from surface to bottom below each node for a total of over 16,000 locations, and is saved every 15 minutes. The entire computational domain includes over 30,000 nodes for a total of 300,000 locations where dye concentrations can be determined. The model provides the concentrations in PPB. The corresponding dilution is obtained by dividing the mean injected flow rate (1924 PPB) by the concentration at a particular location. The concentration associated with a dilution of 500:1 or less would be 3.85 PPB or higher. During the period May 24-28, the entire model output data set is searched for all those locations where the dye concentration is below the 500:1 dilution at least once. Figure 6 shows that the 500:1 dilution area covers the Royal and Cousins rivers and extends beyond the outlet with a few readings between the outlet and station 5.

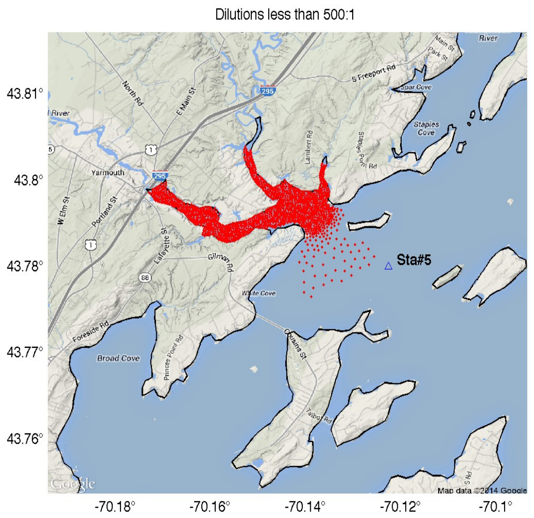

Figure 6. Dilutions below 500:1

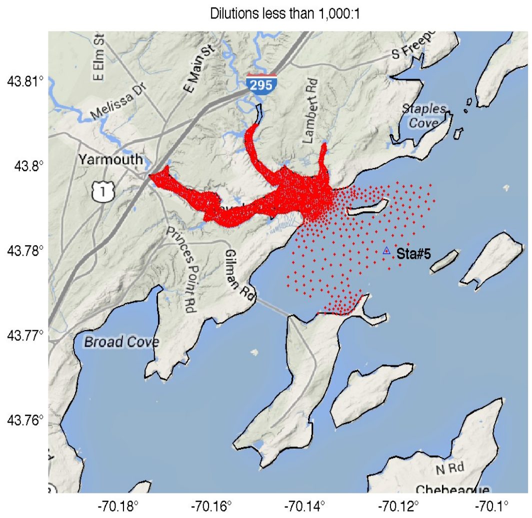

Figure 7. Dilutions below 1,000:1

In order for the MDMR to select an acceptable zone around the Yarmouth WWTP during normal operating conditions, one criteria is that a minimum dilution of 1,000:1 must be met. In the FDA report, two scenarios are described for determining the size of a prohibitive zone for commercial shellfishing. In order to reduce the size of the prohibitive zone to a conditionally approved zone, a dilution of 1000:1 must be met, along with enough time to close the area to harvesting in the event of a treatment plant failure. To satisfy the first criteria for a conditional zone, the model output was again searched for locations where dilutions of 1000:1 or less are met at least once during the 4 day dye injection. The results are shown in Figure 7. The conditional zone would have to extend to the outer boundary of the red dots in the figure, with occurrences from the north end of Cousins Island to above Lanes Island. This outer boundary is in good agreement with the FDA report, except that the model results also include the area above Lanes Island. The FDA study did not sample that region.

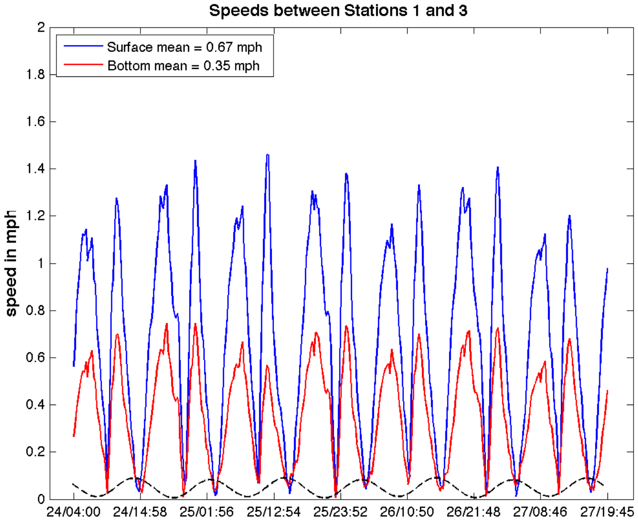

Figure 8. Surface and Bottom speeds between stations 1 and 3. Tidal elevations are shown in black.

C. The time it takes for the effluent to travel various distances from the outfall.

The second condition requires a determination of the travel time it takes for effluents to move from the treatment plant to the prohibitive zone. In the event of a malfunction at the WWTP which may lead to the release of partially treated or untreated effluent to the river, the MDMR would need time to announce a temporary closure of commercial harvesting near the outfall pipe. Of course, the movements of partially treated effluents depend on location and tides. For example, at a location midway between stations 1 and 3, the surface and bottom speeds are shown in Figure 8 in miles/hour to compare with the FDA report. At the surface, the mean speed is 0.67 mph, while the bottom mean speed is 0.35 mph. The FDA measured the time for the leading edge of the dye to move from station 1 to station 3 and determined a mean speed at the surface of 0.89 mph during ebb tide. On May 21, the drogue study conducted by the FDA showed a mean speed of 0.57 mph. Once a particle leaves a location, it enters another location in the velocity field and experiences a different speed and direction. This travel time depends on many factors; the effluent could be discharged during ebb tide or flood tide, and the current speeds and directions vary with time and space.

In an effort to determine an accurate travel time that it takes for effluent to move from the discharge pipe to the prohibitive zone, the particle tracking module in FVCOM that applies the model velocity field to track particles over time was used. A set of 50 particles was placed at the surface around the outfall pipe and released on May 24 at ebb tide. Most of the particles arrived near station 3 in about 1.5 hours. After 2 hours, most particles ended up just past station 3 toward station 4. If there is a management plan in place to notify shellfish control officers and shellfish harvesters within 2 hours, then the conditionally approved area would need to extend beyond station 3 to the outlet of the Royal River. But the dilutions along these paths can't be known if there is a faulty discharge without knowing the conditions at the plant and the degree at which the effluent is untreated. These travel times can only suggest a zone for temporary closure within a 2 hour window until more is known about a malfunction at the treatment plant.

D. Determine the 1000:1 zone for a short term lapse in treatment and disinfection.

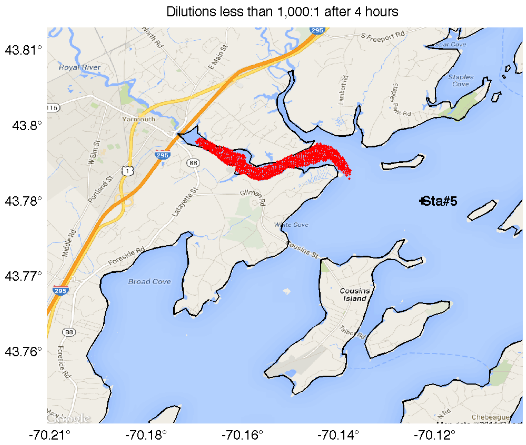

Figure 9. Dilutions during first 4 hours of dye injection

Another objective of the FDA study was to determine a prohibitive zone in the event of a short term lapse in treatment and disinfection at the treatment plant. For this case, a procedure similar to the steady state long term lapse can be used by tracking the dye injections for only a short period of time. In particular, if there was a failure that would go undetected for 4 hours, the numerical model output data set is searched for all those locations where the dye concentration is below the 1,000:1 dilution at least once during the first 4 hours that the dye was injected. The locations of 1,000:1 dilutions or less for the 4 hour period are shown as red dots in Figure 9. Dilutions of 1,000:1 or less can be seen almost out to station 4. The Cousins River area is not affected, since the dye enters that area later during the flood tide after the dye has left the outlet of the Royal River on the ebb tide. But the area from the discharge pipe of the treatment plant upstream to the Yarmouth Boat Yard below the dam near the bridge on route 88 does have dilutions less than 1,000:1.

These results, along with the previous steady state analysis described in **B** and **C** above, are in good agreement with the FDA report, which suggests a conditional zone from the outlet of the Royal River out to a line from Blaney Point on Cousins Island to the southern tip of Little Moshier Island.

5. Conclusions

The FVCOM numerical coastal model has been applied to the dispersion of the effluent from the Yarmouth WWTP in the Royal and Cousins Rivers. The dye study in the FDA(2010) report was used to compare the numerical model performance with observations. The model assumes a uniform flow from the treatment plant discharge pipe, and uniform injection of the dye over a 4 day period from May 24 to May 28. The FDA study on the other hand, performed a 12.4 hour dye injection, and used the superposition method on the diffusion equation to predict dye concentrations at five stations in the Royal River and beyond. The model manages to reproduce the general features of the FDA dye study. The important result to be obtained is the establishment of a safe zone about the outflow pipe in which shellfishing is to be prohibited. The zone produced by the model is in good agreement with the FDA recommendation. The model is capable of reproducing the data that was collected during the FDA study, but it also includes regions beyond the Royal River outlet that was not sampled in the FDA study. In particular, the model would include the region above Lanes Island as part of the conditionally approved zone. This region is part of the conditionally approved zone by the MDMR in their Classification-Notification of Changes, Oct. 2013(MDMR). The model also went beyond the sampling by the boat transects and was able to follow the dye on the ebb tide as it flowed beyond station 5 continuing southeasterly through a narrow channel between the north end of Cousins Island and Little Moshier Island, and then returning to the mouth of the Royal River.

A numerical coastal model can be used to predict an appropriate prohibitive zone around a waste water treatment plant. The information from the model results could also provide important features to consider prior to a dye study, such as designing careful boat transects to capture the main features of the dye dispersion, and select stationary buoy locations in the main stream of the dye dispersion for better data gathering. Another benefit of the numerical model study is that it is able to sample the dye at many more locations than is possible with transects and buoy locations. In particular, the dye concentrations can be determined from surface to bottom, where currents are very different. In the Royal River, the water is well mixed, but at other locations, there can be salt wedges, upwelling, and moving eddies that would distribute the dye concentrations in complex ways. Also, a number of various scenarios can be conducted to answer "what if" questions, such as determining the prohibitive zone for higher flow rates or strong persistent winds that can move surface waters of effluent to unexpected locations.

In order for such a numerical model to be applied, some local data should be obtained first to adjust the model to the particular region. The data to collect should include temperature and salinity profiles in key locations around the site. Temperature and salinity data for this experiment was available from the FDA report at stations 1 and 5 in addition to the monthly data provided by Friends of Casco Bay(FOCB). Temperature and salinity at the outer edges and near river outlets of the study site is important for interpolating and initializing the model. Since the water in the Royal River is well mixed, any density currents produced by salinity changes would be minimal compared with the tidally driven currents. Also, current measurements at various depths in a few locations should be taken to validate the model.

Acknowledgments

Alison Sirois, Growing Area Program Manager at MDMR, provided resources and information regarding the Yarmouth WWTP and the FDA study of May 2010. The particle tracking routine for this study was developed by the FVCOM team (Chen, 2003). The version used here includes some modifications kindly provided by James Churchill at the Woods Hole Oceanographic Institute.

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