Application of Hydrodynamic Modeling to Predict Viral Impacts from Wastewater Treatment Plant Discharges Adjacent to Shellfish Growing Areas

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Abstract

Since the inception of the National Shellfish Certification Program in 1925, now the National Shellfish Sanitation Program (NSSP), dilution analysis has been used as a means to minimize the presence of enteric pathogenic microorganisms in shellfish growing areas. Today failures and bypasses at wastewater treatment plants (WWTPs) and combined sewer overflows (CSOs) that release untreated or partially treated sewage into shellfish receiving waters are of particular interest to shellfish control authorities and public health officials. Additionally, events that cause high flows into the WWTP resulting in a degradation of efficiency to reduce enteric viruses are also a significant concern. Since 2008, the U.S. Food and Drug Administration (FDA) has conducted numerous hydrographic dye studies assessing WWTP impacts to shellfish growing areas supplemented with the testing of shellfish sentinels for enteric viruses and their surrogates (Goblick et. al, 2008, 2015). The findings from these studies demonstrate that achieving a steady-state 1000:1 dilution level in waters adjacent to WWTP discharges established as prohibited (no shellfish harvest allowed) appears to be adequate for mitigating the impacts of viruses on shellfish when WWTPs have typical treatment and disinfection practices and when operating under normal conditions. However, these studies also indicate that when a WWTP is operating outside of normal operation the efficiency may be reduced and additional shellfish growing area may need to close in a timely manner during these events. To assess these events, which may be triggered by wet weather or high flow, FDA has used hydrodynamic models to predict the extent of sewage impacts on receiving waters under a various range of conditions not achieved through dye studies.

Background

Shellfish growing and harvestable waters have been recognized as a designated use under EPA's Clean Water Act (CWA) section 305(b). In 2010, FDA conducted a hydrographic dye study in shellfish growing waters in conjunction with a bioaccumulation study of pathogens in shellfish adjacent to a WWTP discharge in Yarmouth, Maine during dry weather. The objective of the study was to determine the buildup of dye tagged sewage effluent and steady state dilution in tidal waters to size a prohibited zone preventing the harvest of shellfish in proximity to the WWTP. During the study period, the average WWTP flow rate was 0.66 MGD; less than the 1.31 MGD design flow which is also the permitted flow under the Maine Pollutant Discharge Elimination System (MEPDES) permit. To assess the growing area under higher flows and adverse conditions, FDA led a shoreline survey source identification study in 2012 under a heavy rainfall event (3.99 inches) resulting in an increased flow rate at the WWTP (2.5 MGD) and exceeding the design flow and permit. Hydrodynamic modeling was performed to assess the wet weather event using MIKE 21 developed by the Danish Hydraulic Institute (DHI), a sophisticated two-dimensional computer model used to predict contaminant transport and dispersion in coastal estuaries. MIKE 21 incorporates pollutant concentrations (e.g. viruses) and flow data from wastewater treatment discharges, freshwater inputs, tidal current effects, bathymetry, and other environmental factors. The MIKE 21 model used by FDA was calibrated and validated using the 2010 hydrographic dye studies and microbiological analyses.

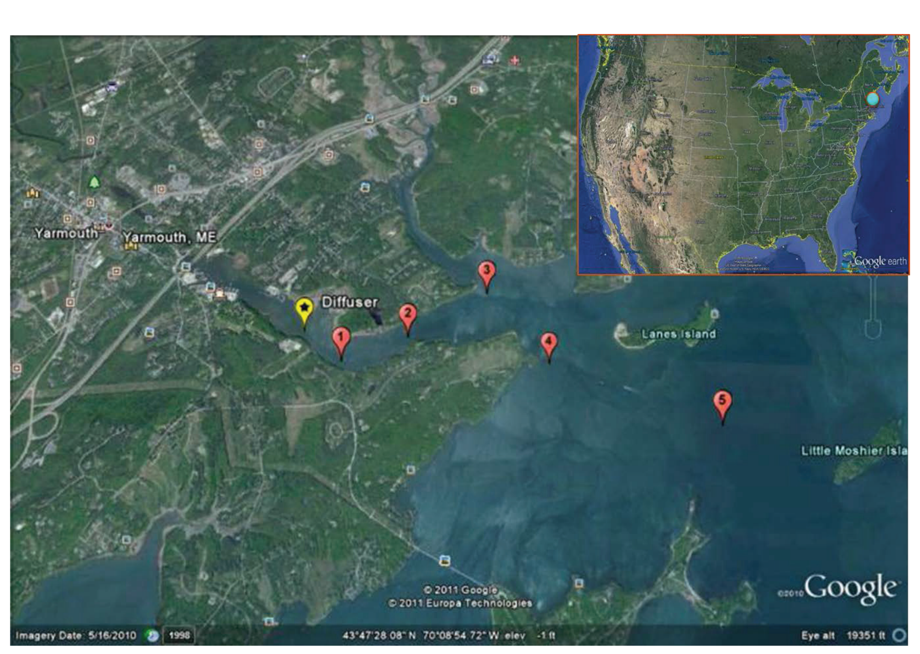

Figure 1: Model area showing five stations used in the assessment – Yarmouth, ME

Methods

Tide Measurements

- During 2010 dye study, two CTDs were attached to shellfish sentinels positioned in Royal River and the estuary to continuously collect water level data near Yarmouth WWTP outfall and between Lanes Island and Little Moshier Island to evaluate a specific tidal condition for 7 days.
- NOAA Portland, ME tidal station (Station ID: 8418150) water level data was also used for comparison.

Flow Conditions

- A time series hourly flow rate was used from Yarmouth WWTP during the study period in 2010 to simulate average dry weather condition of 0.66 MGD
- A real-time hourly flow rate was used from Yarmouth WWTP to simulate wet weather condition of 2.5 MGD in 2012
- A 5.41 m^3/s of flow rate was assigned as the freshwater inflow from the upper Royal River under dry weather conditions while a 20 m3/s flow rate was applied under wet weather conditions based on USGS gage location historical data of the Royal River at Yarmouth, Maine (Station ID: USGS 01060000).

Pollutant Simulation

Rhodamine WT was used in the simulation as the conservative source discharged from the Yarmouth WWTP to determine the location of a 1000:1 dilution under both dry weather conditions (based on the 2010 hydrographic study) and wet weather conditions (based on the 2012 wet weather study). To determine the location of a1000:1 dilution under dry weather conditions a 21 day injection period was simulated to determine the build-up to steady state conditions. To determine the location of a 1000:1 dilution under wet weather conditions a 12 hour injection period was simulated to reflect the short lived storm event period.

Model Mesh

Mesh development for this study was generated based on shoreline 1/3 arc-second cell size MHW Digital Elevation Model (DEM) of Portland, ME from National Oceanic and Atmospheric Administration (NOAA), NOAA nautical charts. The mesh horizontal references the UTM North American Datum of 1983 (NAD83) Zone 19. In addition, Google Earth historical images showing the location of the river channel area was used to aid in the construction of the quadrangular mesh reflecting real condition (Figure 2).

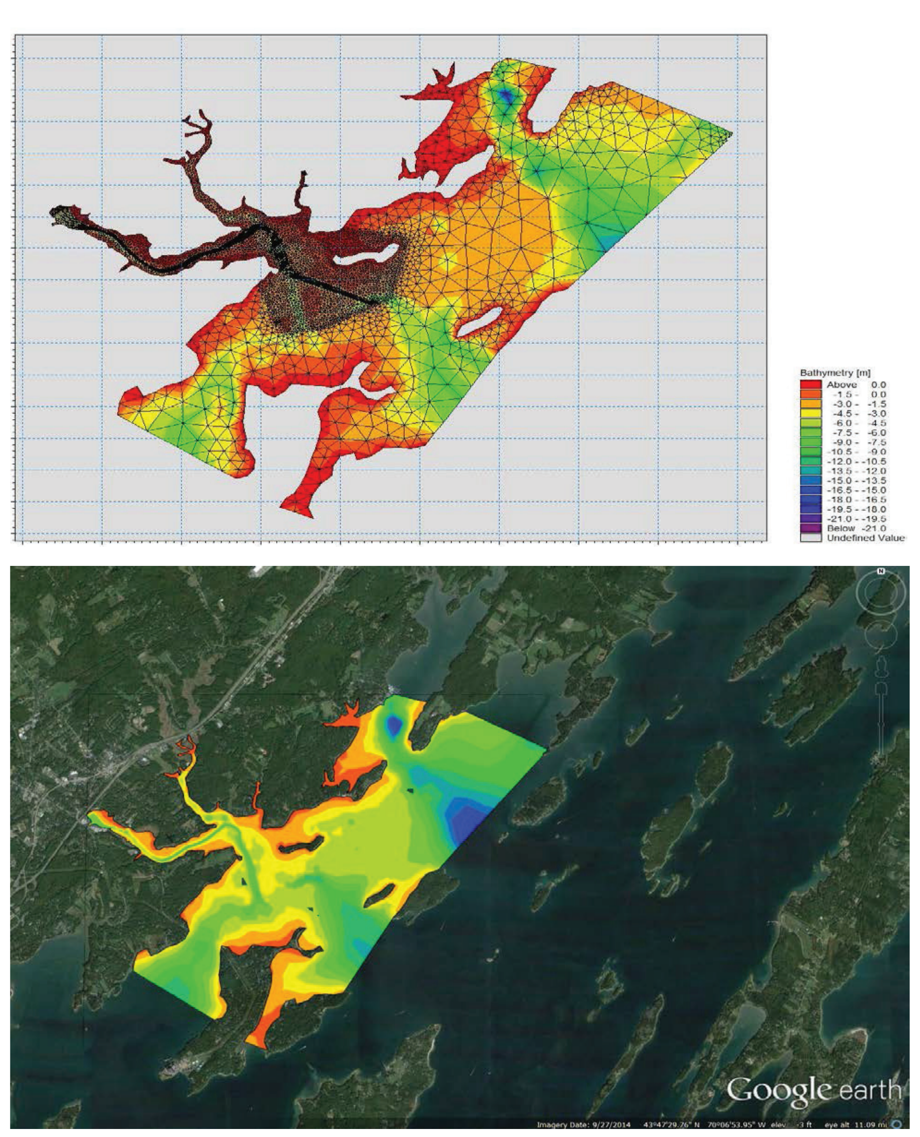

Figure 2: Grid and bathymetry (in Google Earth) used in the Flexible Mesh model for Yarmouth, Maine

Results

Model Calibration

Model Calibration consisted of iterative adjustments to model parameters to match with the measured data. The calibrated HD model parameters included a Manning number of 32 $m^{1/3}/s$ for all estuary and rivers; a Smagorinsky formulation of 0.28; and a CFL number of 0.8. Tidal information (Station ID: 8418150) and measured water level from CTDs (Stations 1 and 5) were used for HD model calibration. Figures 3 and 4 show a comparison of the measured water level from CTDs and model simulated water surface elevation at Stations 1 and 5, respectively over 10 days covering the study period. All surface water elevation levels are relative to Mean Sea Level (MSL). Except for a slightly over estimate of high and low tides, both figures shows a strong agreement between measured/ NOAA station data and model simulated water surface elevations.

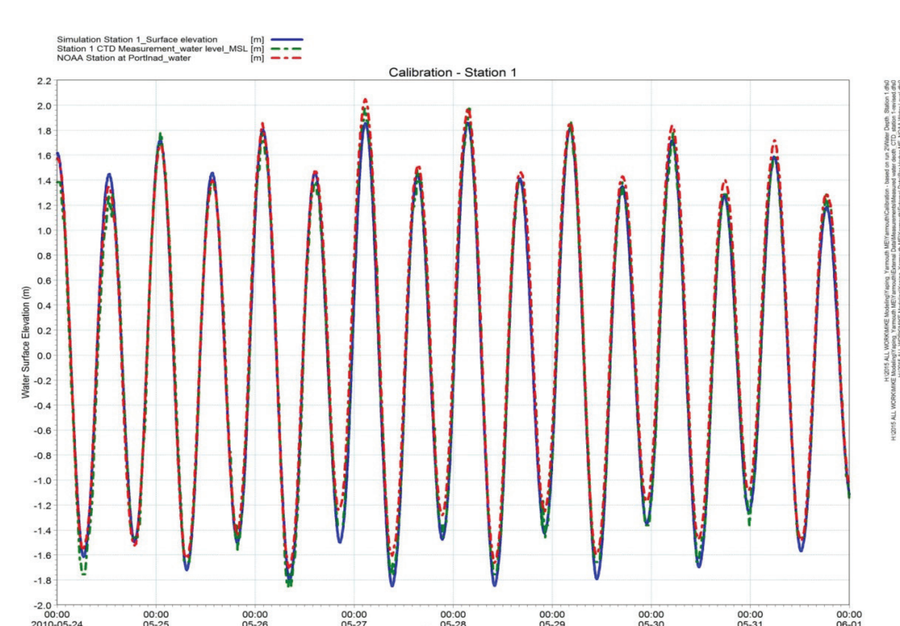

Figure 3: Comparison of measured water level, tidal ranges from NOAA tidal station, and simulated surface water elevation from MIKE 21 model at station 1

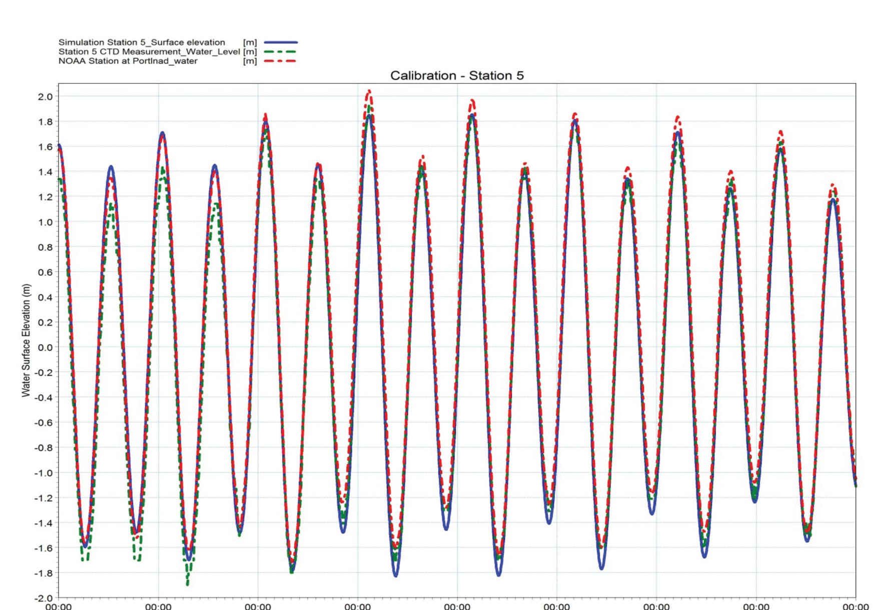

Figure 4: Comparison of measured water level, tidal ranges from NOAA tidal station, and simulated surface water elevation from MIKE 21 model at station 5

Model Validation

In order to validate and verify the model, dye measurements collected in the dye study were applied. The measured dye concentrations on the surface and in-depth show a slight difference than MIKE 21 model simulation results as MIKE 21 is a two-dimensional model averaging the depth of water column. The modeled paths, travel time, and viral levels over flooding and ebbing tidal excursions matched well with FDA 2010 hydrographic dye study and microbiological results (Figure 5). Two scenarios are applied based on calibrated and validated model at Yarmouth, Maine area. Comparing the predicted model results of the location of the steady state 1000:1 under dry weather with dye study results indicate that the model results are more conservative (Table 1). This may be due to an underestimate of the natural loss of dye that may occur whereas the model reflects a completely conservative tracer assuming no decay to determine dilution based entirely on physical dilution processes and not accounting for pollutant decay.

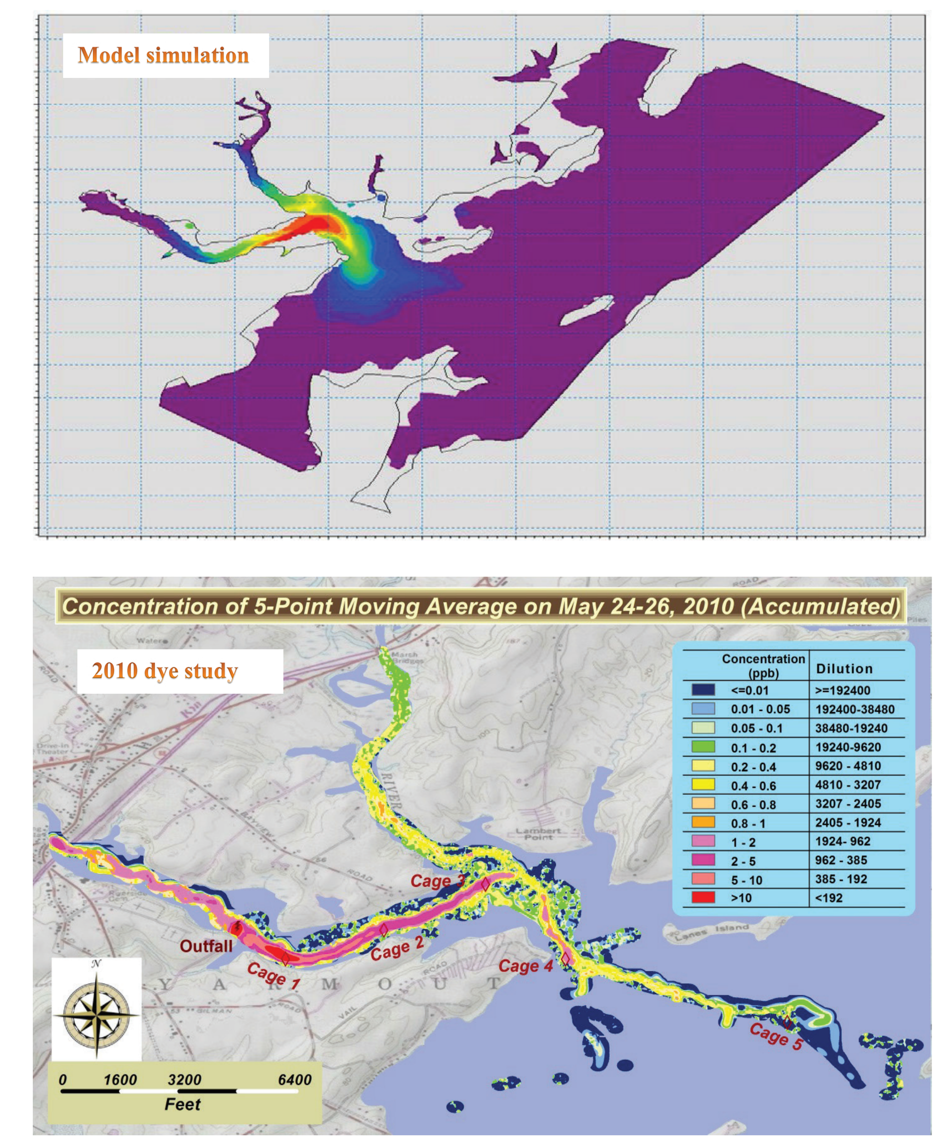

Figure 5: A comparison of model simulated results and FDA 2010 dye study results

Modeling the wet weather event (2.5 MGD flow rate)

The wet weather scenario simulation predicted the increased flow from WWTP which exceeds 1.31 MGD of Yarmouth WWTP permit flow rate and exceeds the design flow. The furthest distance from outfall to 1000:1 dilution line was 3.7 km (Figure 9 and Table 1). The model results indicate that although the event may produce higher loadings due to increased flow, the event is short lived and thus the extent of build-up is not significant compared to a continuous dry weather discharge at the same concentration. Thus, the size of the prohibited zone simulated under dry weather (4.6 km) is sufficient for the short lived event. However, if the concentration significantly increases, as did the MSC levels in the effluent during the 2012 study (Goblick et. al, 2013), then 1000:1 may not be sufficient. During the 2013 study, MSC reached as high as 38,200 PFU/100 ml in the effluent. To reach a level of MSC of <1 PFU/100 ml in the shellfish growing area, a level of >38,200:1 would need to be achieved in order to reduce the viral risk in shellfish (assuming shellfish bio-accumulate 50 fold from levels in the water column and reach a level of <50 PFU/100 ml, which is the established criteria in the NSSP).

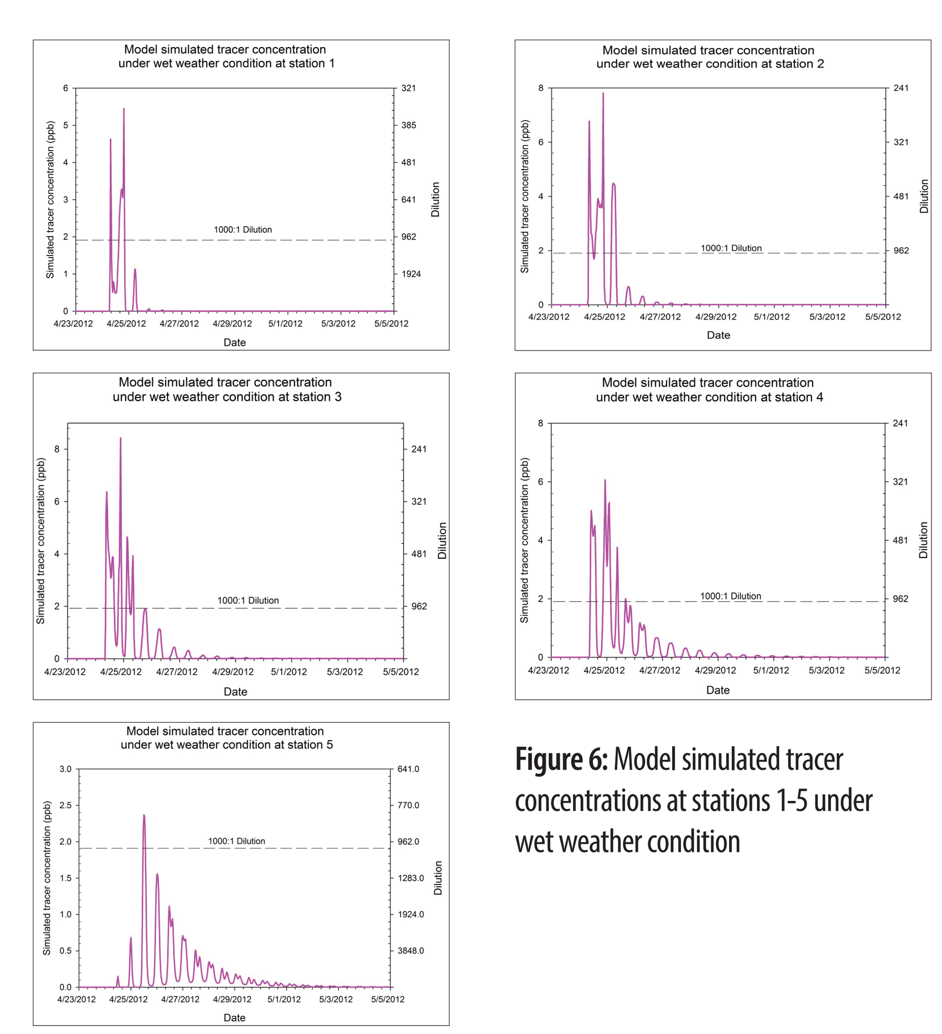

Figure 6: Model simulated tracer concentrations at stations 1-5 under wet weather condition

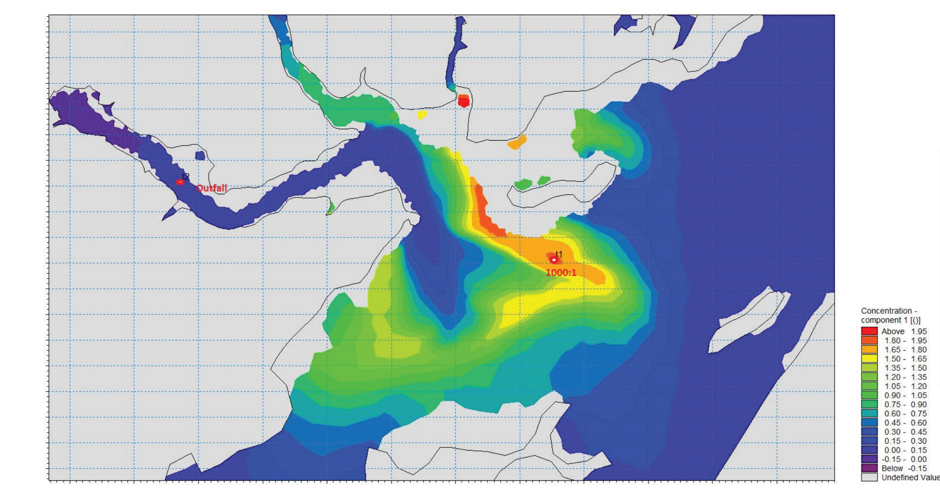

Figure 7: Modeled 1000:1 and 38,200:1 dilution under wet weather condition

Table 1: The furthest distance from outfall based on 1000: 1 dilution under dry and wet weather conditions

Scenarios	The furthest distance of 1000:1 from outfall (km)	The furthest distance of >38,200:1 from outfall (km)
Dry weather under steady state (simulated)	4.6	
Dry weather under steady state (dye study)	3.8	
Wet weather event (simulated)	3.7	>6.4 (purple contour area in estuary in Fig.7)

Conclusions

For State Shellfish Control Authorities to properly assess the risk of virus accumulation in shellfish adjacent to WWTP discharges, the build-up of viral contaminants in the receiving waters must be considered as well as the impact that also may occur under pollutant events such as wet weather. A prohibited zone established around a WWTP discharge must allow for sufficient dilution of viral contaminants to protect shellfish consumers from risk of viral exposure. Moreover, establishment of a prohibited zone needs to take into consideration not only a potential failure at the WWTP (e.g. such as a loss of disinfection) but also the persistence of viruses in treated effluents at all times. The appropriate sizing of the buffer zone depends on dilution analysis, i.e., determining the amount of dilution water needed to reduce a pollutant to levels that pose minimal risk in regard to shellfish safety. Thus, the simulated model results are extremely helpful for shellfish management authorities to assess appropriate classifications and management of shellfish growing areas under a range of conditions and factors. Hydrodynamic modeling has also proven to be a valuable tool in a current joint U.S./Canada quantitative norovirus risk assessment. FDA and National Oceanic and Atmospheric Administration (NOAA) will be collaborating on future efforts to develop eco-forecasting capabilities utilizing modeling and weather (precipitation) forecasts to predict sewage impacts on shellfish growing areas that occur from bypasses and CSOs during storm related events. The next step is to link MIKE model simulation results with the joint United States – Canada Risk Assessment on Norovirus in Bivalve Molluscan Shellfish model to determine norovirus impacts and compare results against field data of shellfish testing.

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