The Near- and Far-field Evaluation for the Discharge from Back River Sewage Treatment Plant Effluent to the Sparrows Point in Baltimore Harbor

Final Report

Submitted To:

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I. Background

The Back River Wastewater Treatment Plant (BRWWTP) is owned and operated by City of Baltimore. It serves in a 140 square mile area of Baltimore City and County for 1.3 million residents. It was originally constructed as a primary sewage treatment plant and later was upgraded into a tertiary treatment to treat total of 180 million gallons per day of sewage. (https://publicworks.baltimorecity.gov/pw-bureaus/water-wastewater/wastewater/back-river). Beginning about 1940's, approximately seventy percent of the total effluent was discharged into Back River and the remaining thirty percent was diverted through two 6-mile long pipelines to Sparrows Point, where the Bethlehem Steel Mill Corporation used the water as the cooling waters. After the industrial usage, the water is discharged into the Bear Creek, a tributary of Patapsco River in the western Sparrows Point, primarily through outfall 012 and 014 (Figure 1). Sparrow's Point was the site of a very large industrial complex owned by Bethlehem Steel. During the 1970s and 1980s, changes in the steel industry, including a rise in imports and a move toward the use of simpler oxygen furnaces and the recycling of scrap, led to a decline in the use of the Sparrow's Point complex. After Bethlehem's bankruptcy in 2005, the site of the former Bethlehem Sparrows Point Shipyard and steel mill is renamed Tradepoint Atlantic in a revitalization program to clean up the environment and make it one of the largest ports on the East Coast of the United States. Now that the steel mill has left, the effluents still discharge to Sparrows Point in meeting the discharge permit issued to BRWWTP. The City of Baltimore has a license agreement with Sparrow Point's new owner - Tradepoint Atlantic and pays a monthly fee to divert approximately 50 million gallons of the treated BRWWTP effluent through the Sparrow's Point piping system to the Bear Creek. The City is examining an alternative for dealing with the water diversion issue. However, any solution would need to satisfy EPA's NPDES (National Pollutant discharge Elimination System) regulation, a primary US federal law under Clean Water Act, which governs water pollution for restoring and maintain the chemical, physical, and biological integrity of the nation's waters in US.

On February 19, 2019, the Baltimore City Department of Public Works (DPW), Whitman, Requardt and Associates, LLP (WRA) and Virginia Institute of Marine Science (VIMS) met with the Maryland Department of the Environment (MDE) to discuss a possible increase in the effluent discharge to the Back River main proper, which would reduce or possibly eliminate the need to discharge effluent to Sparrows Point. Evidences of water quality improvement was also presented as a result of recently implemented Enhanced Nutrient Removal (ENR) at Back River WWTP. However, MDE decided that, although substantial improvement was made in the effluent (by ENR), the 50 MGD water diverted to Sparrows Point should not be discharged to Back River on the ground that Back River is still not sufficient to assimilate the additional nutrient load via such discharge. On June 12, 2019's meeting, the City again urged MDE to resolve the issue for the diversion of the BRWWTP waters as soon as possible for the old piping system such as outfalls 012 and 014 in the western side of Sparrow Point (to Bear Creek) are obsolete and, without a proper maintenance, can potentially fail anytime without a warning. In the same meeting, WRA presented the technical details of "Evaluation of the discharge of Back River WWTP effluent to Sparrows Point" in which it was discussed about the potential use of the old outfall 001 (in the eastern side of the Sparrows Point) as the new discharging point for the diverted water.

The concern of MDE for the old outfall 001, however, was that it is too close to the Jones Creek located in the north of the Old Road Bay, as shown by the square box in the Figure 1 that the discharge of the effluent could potentially be trapped inside the Old Road Bay and affects the Jones Creek's community. After numerous discussions, the consensus for a viable solution was to build a new submerged outfall extended from the land into the Patapsco River southwestward off the tip of the eastern edge of the Sparrows Point, at about 4 meter depth water. As a result of the meeting, Trade Point Atlantic, in principle, agreed with approved the recommendation. The goal of this report is to conduct near and far-field evaluation for the new proposed effluent outfall in Sparrows Point. Section II illustrates the need for NPDE permit and gives detail of the site characteristics. Section III describe the use of CORMIX model for the near field evaluation. Section IV introduce the SCHISM (Semi-implicit, Hydroscience, Integrated System Model), and its calibration and verification for use as a Eulerian modeling. Section V uses SCHISM and the particle tracking module together to conduct Lagrangian Particle tracking to address additional concerns by MDE and Section VI concluded the report.

Figure 1: The legacy outfalls of the Sparrows Point, the proposed new outfall, and the outfall 001, the Old Road Bay and Jones Creek neighborhood region.

II. The need for NPDE permit and survey of the site characteristics

When an effluent is discharged into a receiving water body, the mixing process occurring in two separate zones. In the first zone, it is the near-field mixing zone characterized by effluent's own jet mixing of momentum flux and buoyancy flux (due to density difference). The second zone is the far-field zone, characterized by a plume influenced primarily by the ambient conditions such as flows, wind stress, stratification, geometry, and various boundaries surround, as shown in Figure 2. The NPDES permit is established so the effluent concentration beyond the mixing zone should not violate the ambient water quality criteria. For a permit application, both near field mixing zone and evaluation of the far-field water quality standard are required by Maryland's Departments of the Environment and the Natural Resources. The detail of the Maryland Department of the Environment guidance can be found in http://www.dsd.state.md.us/comar/comarhtml/26/26.08.02.05.htm).

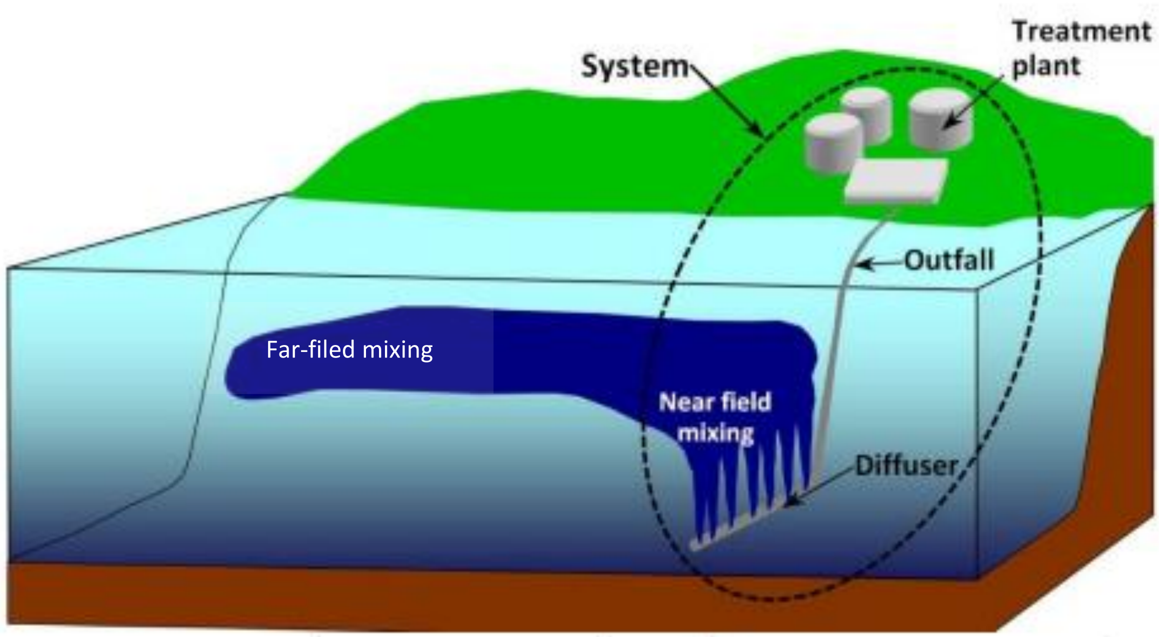


Figure 2: A wastewater disposal outfall: Sewage treatment plant, outfall pipe, diffuser, near-field and far-field mixing

<u>The Topo-bathymetry Surrounding Sparrows Point</u>

As described in section I, the consensus for selecting the site for a new outfall is in the southwest direction off the tip of the eastern edge of Sparrow Point. Figure 3 (a) shows the proposed outfall seen from the Google Earth. The red line on the top panel is the orientation of the outfall extended straight from the tip of Sparrow Point southwestward. The length is 304 meter (~1002 feet) and the bathymetric profile along the outfall drops from 0 to about 10 feet. If the outfall length is increased to 1200 feet, the depth will be increased to 14 feet, as shown in Figure 3 (b). The detail bathymetric contour line of the waterbody in the Sparrows Point region is shown in Figure 4. The data used to plot the contour can be obtained from https://www.usgs.gov/core-science-systems/eros/coned based on USGS 2019 surveyed in Sparrow Point

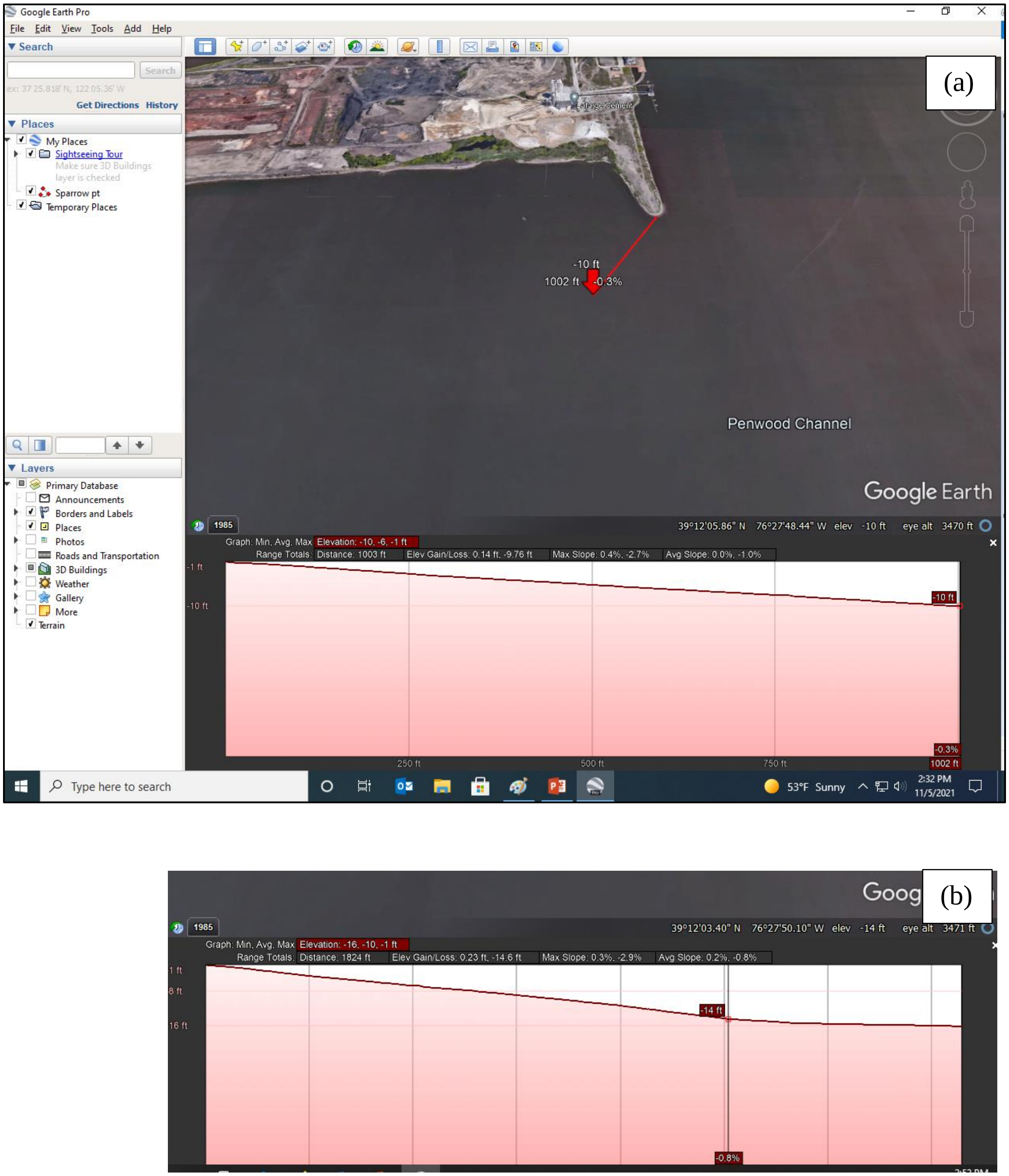


Figure 3: (a) The Google Earth view of the proposed outfall location and the cross-section bathymetry profile within 1000 feet (b) In 1200 feet, the depth increased from 10 to 14 feet

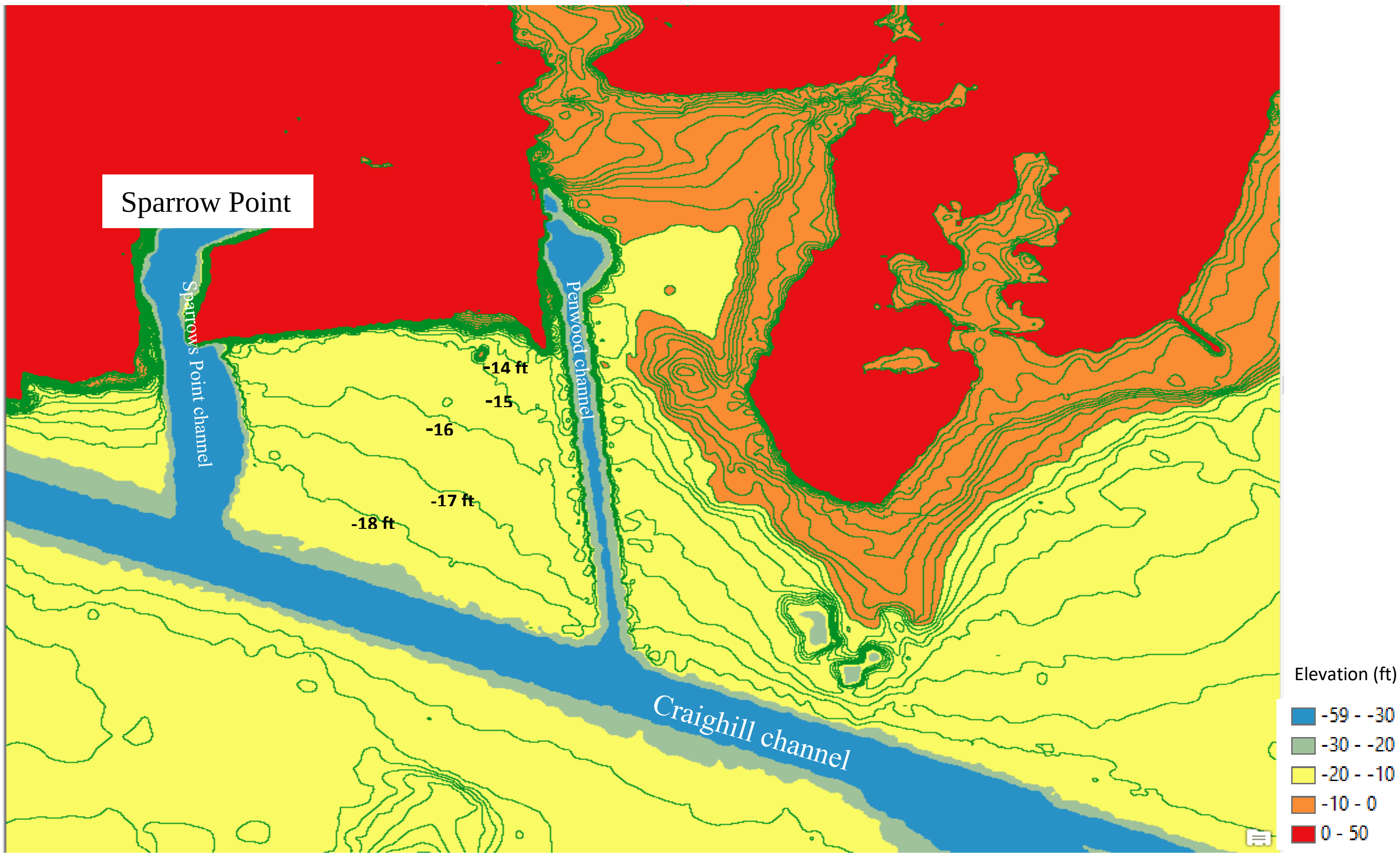


Figure 4: The bathymetry contour line in the vicinity of Sparrow Point including Sparrow Point, Penwood and Craighill channels

III A near-field mixing zone evaluation using CORMIX

The hydrodynamics for an effluent continuously discharging can be conceptualized as a mixing process occurring in two separate regions. As indicated in section II, the initial jet characteristics of momentum flux, buoyancy flux and outfall geometry influence the jet trajectory and mixing in the first zone. This region is referred to as the "near-field", and encompasses the jet subsurface flow and any surface or bottom interaction, or in the case of a stratified condition, the terminal layer interaction.

III-1 Description of CORMIX

Based on EPA's technical support document, mixing zone is defined as "that portion of a water body adjacent to an effluent outfall, where mixing results in the dilution of the effluent with the receiving water. Within the mixing zone, water quality criteria may be exceeded as long as acutely toxic conditions are prevented". The dilution factor is a key parameter for the mixing. A simple case of dilution in the presence of waste-field can be understood with the wastewater discharged horizontally as a jet from a single round port, as shown in Figure 5. Two forces shape the immediate nature of the plume. The first is the exit velocity of the discharge which would move the plume along the exit angle of the discharge. The second force is due to density differences between the discharge and the ambient. If the wastewater has a lower density than the surrounding water, then the resulting buoyancy force will deflect the jets upward forming a plume which is swept downstream by the current. The plumes entrain ambient water as they rise, causing them to be diluted and decreasing the density difference between them and the ambient. Assuming C_p is the plume concentration of a pollutant (or a dye) after the mixing and C_a , C_e are the ambient concentration and the effluent concentrations of the pollutant before mixing (or a dye), respectively, then $DF = \frac{C_e - C_a}{C_p - C_a}$ If the ambient concentration is 0, then $DF = \frac{C_e}{C_p}$ Where DF is the dilution factor.

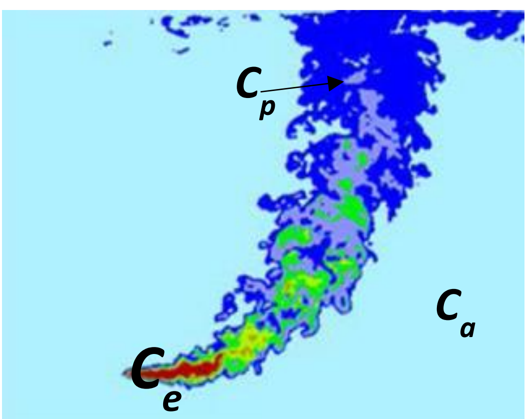


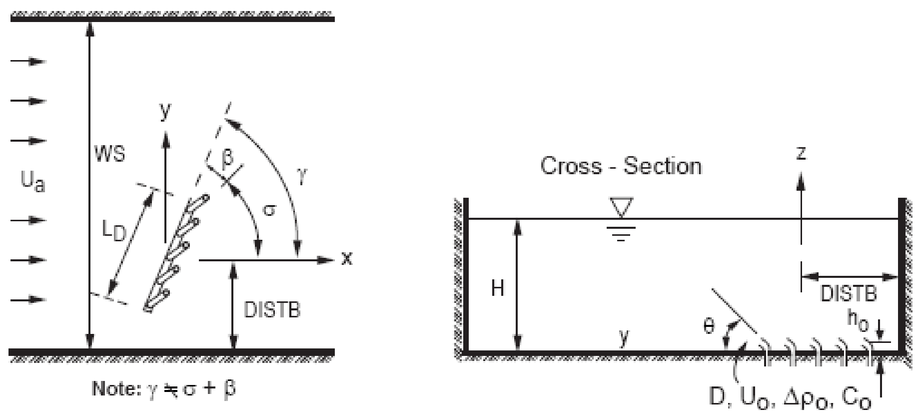
Figure 5: The cartoon drawing for the conceptual effluent outfall associated with the its calculation for the dilution factor

The actual mixing of effluent discharged in a real environment with ambient receiving waters, however, there are other factor coming into play. Those include

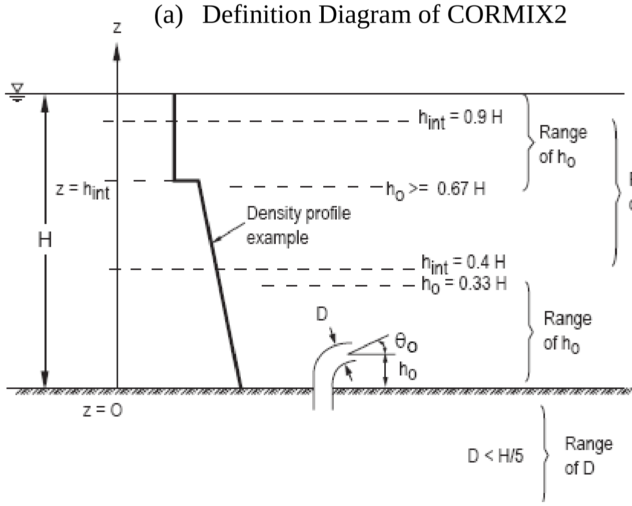
(i). Discharge characteristics, whether it is a "pure jet" (buoyancy is negligible) or it is a "pure plume" (exit velocity is negligible); or whether it is a combination of the two.
(ii) Ambient characteristics, whether the receiving water is stratified or not. This would govern whether discharge would be trapped below the surface or not.
(iii) Whether the characteristics of ambient receiving waters is an open ocean, a tidally reversing flow (as in an estuary), or predominantly uni-directional flow in a river.
(iv) Whether the effluent is rapidly and uniformly vertically mixed or lateral mixing dominate
(v) Boundary effects such as attachment of discharge plume to bank, bottom, surface, or a stratified terminal layer
(vi) Buoyant upstream intrusions caused by upstream density currents and weak ambient crossflow current
(vii) Re-entrainment of discharge in the nearfield due to surface or bottom interactions of plumes and local recirculation patterns, which can reduces dilution.

CORMIX (Jirka et al. 1996; Doneker et al. 2008) is a hydrodynamic model supported by US EPA which can used to simulate dilution and mixing zone in the near-field region. It addresses the full range of discharge geometries and ambient conditions, and predicts flow configuration ranging from internally trapped plumes, buoyant plumes in uniform density layers with or without shallow water instabilities. A flow classification system based on hydrodynamic criteria and empirical knowledge for field experiment enable the user to distinguish different flow classes with distinct hydrodynamic properties. The use-interface CORMIX modeling system implemented on Windows computers is available commercially (http://www.mixzon.com/). The core of CORMIX consists of four integrated hydrodynamic models: CORMIX 1 for single port discharge, CORMIX 2 for multiport diffuser discharges, CORMIX 3 for buoyant surface discharges, and DHYDRO for dense and sediment discharges in coastal environments. The proposed Sparrows Point effluent discharge is likely through a multiport diffuser, which is a linear structure consisting of many more or less closely spaced ports or nozzles which inject a series of turbulent jets at high velocity into the ambient receiving water body, as shown in Figure 6. These ports or nozzles may be connected to vertical risers attached to an underground pipe, tunnel or may simply be openings in a pipe lying on the bottom. CORMIX2 assume uniform discharge conditions along the diffuser line that include local ambient receiving water depth (HD) and discharge parameters such as port size, port spacing and discharge per port, and can analyze discharges from the three major diffuser types used in common engineering practice: (1) unidirectional diffuse (2) the staged diffuser, and (3) alternating diffuser. The key input parameters to the CORMIX2 include: (a) location of the nearest bank (left or right) (b) average distance to the nearest bank (c) average diameter of the discharge ports (d) contraction ratio for the port/nozzle (e) average height of the port center above the bottom (f) average vertical angle of discharge (g) the average horizontal angle (h) approximate straight-line diffuse length (i) distance from the shore to the first and last ports (j) number of ports (k) average alignment angle (l) relative orientation angle.

CORMIX2 performs a number of consistency checks to ensure the user does not make arithmetical errors in preparing and entering the data. It also checks the specified



(a) Definition Diagram of CORMIX2



(b) Limits of applicability of CORMIX2

Figure 6: CORMIX2 discharge geometry and limits of applicability of CORMIX2 for multi-port diffuser

geometry for compliance with criteria to prevent an inappropriate system application. it should be noted that CORMIX2 is a smaller-scale model that predicts dilution of an effluent plume in the near field under steady state conditions with significant influence by the vertical stratification and the surrounding boundaries.

III-2 Setup CORMIX2 in Sparrow Point

Based on WRD's design, a submerged multiport diffuser is to be placed at a site located offshore of eastern edge of Sparrows Point southwest-ward into the Patapsco River. The pollutants considered here are effluents from the Back River Waste Water Sewage Treatment Plant, which when discharged is required to meet the NPDES (National Pollutant Discharge Elimination System) permit regulation for the near-field mixing zones. Figure 7 (a) shows the plain view of a submerged multiport diffuser consisting of several closely spaced port or nozzles, which injects turbulent jet in to the ambient receiving water body. The length of the diffuser is L and the ambient current is U Figure 7 (b) shows the side view of the diffuser and the current with the length of the initial mixing region marked by Xi . At the end of Xi is the boundary of the mixing zone, where *he* is the thickness of the plume, *Zm* is the height of the top concentration, *Ze* is the rise height of the plume at the boundary. When the effluent was discharged into the ambient water with the presence of density stratification, it exhibits a plume feature involving (1) Momentum jet (2) Buoyancy (3) Turbulent dispersion, where the self-induced turbulence collapse under the influence of the ambient stratification.

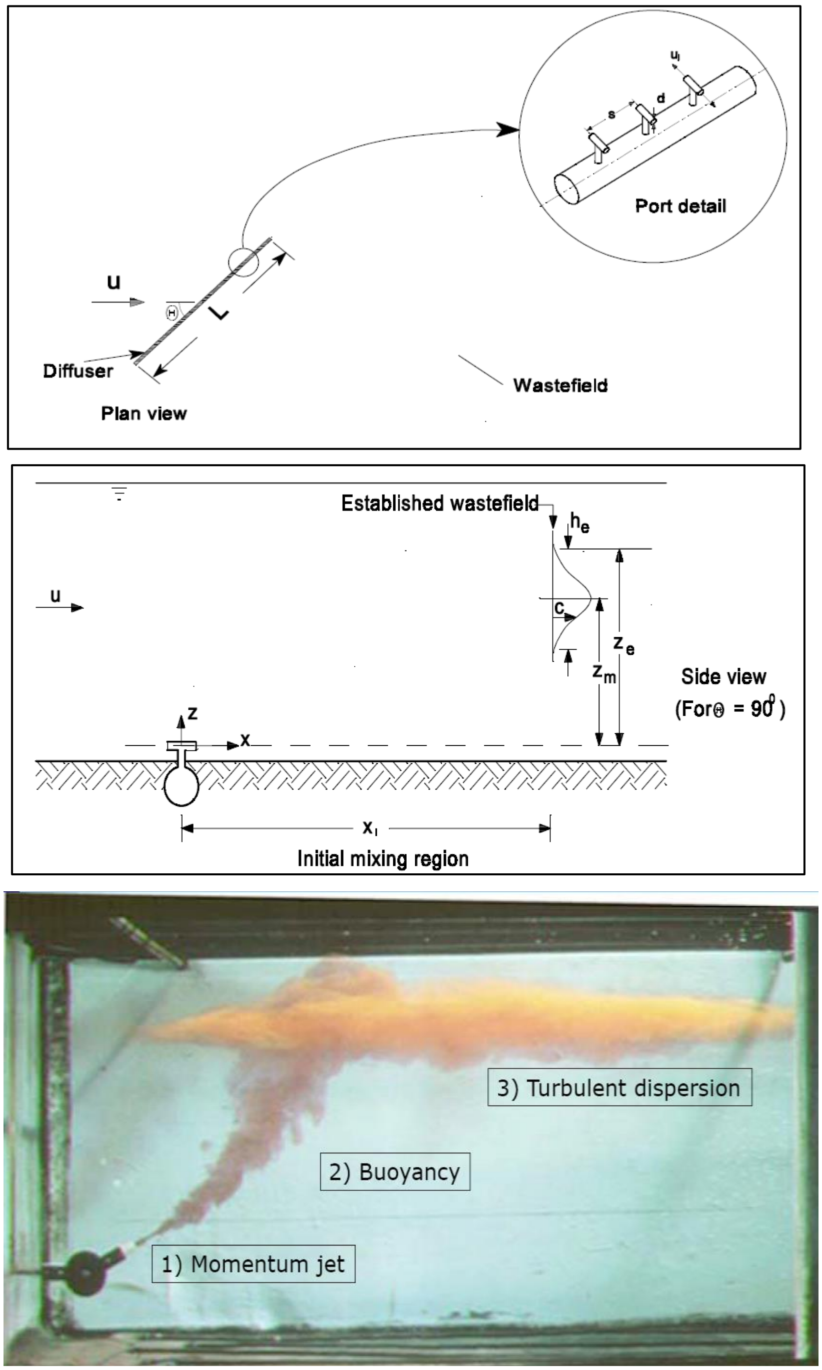


Figure 7: (top panel) The plain and side view of multiport diffuser port and its parameters used in CORMIX 2 (middle panel) The side view of the multiport diffuser port and its parameters. (bottom panel): The dynamics involved for a effluent discharge shown by dye tracer

The MDE COMAR D (2)(b) (i) requirement required 'specific data, when available, for the mean water level and average tidal velocity". Rigorously calibrated and verified 3D, baroclinc, unstructured grid Eulerian model: SCHISM provided tidal elevation and current velocity at Sparrow Point , as shown in Figure 8. The calibration and verification (against observed data) are in Figures 13, Figure 14 of section IV-2 and Figure 20, V-1 which has more detail description.

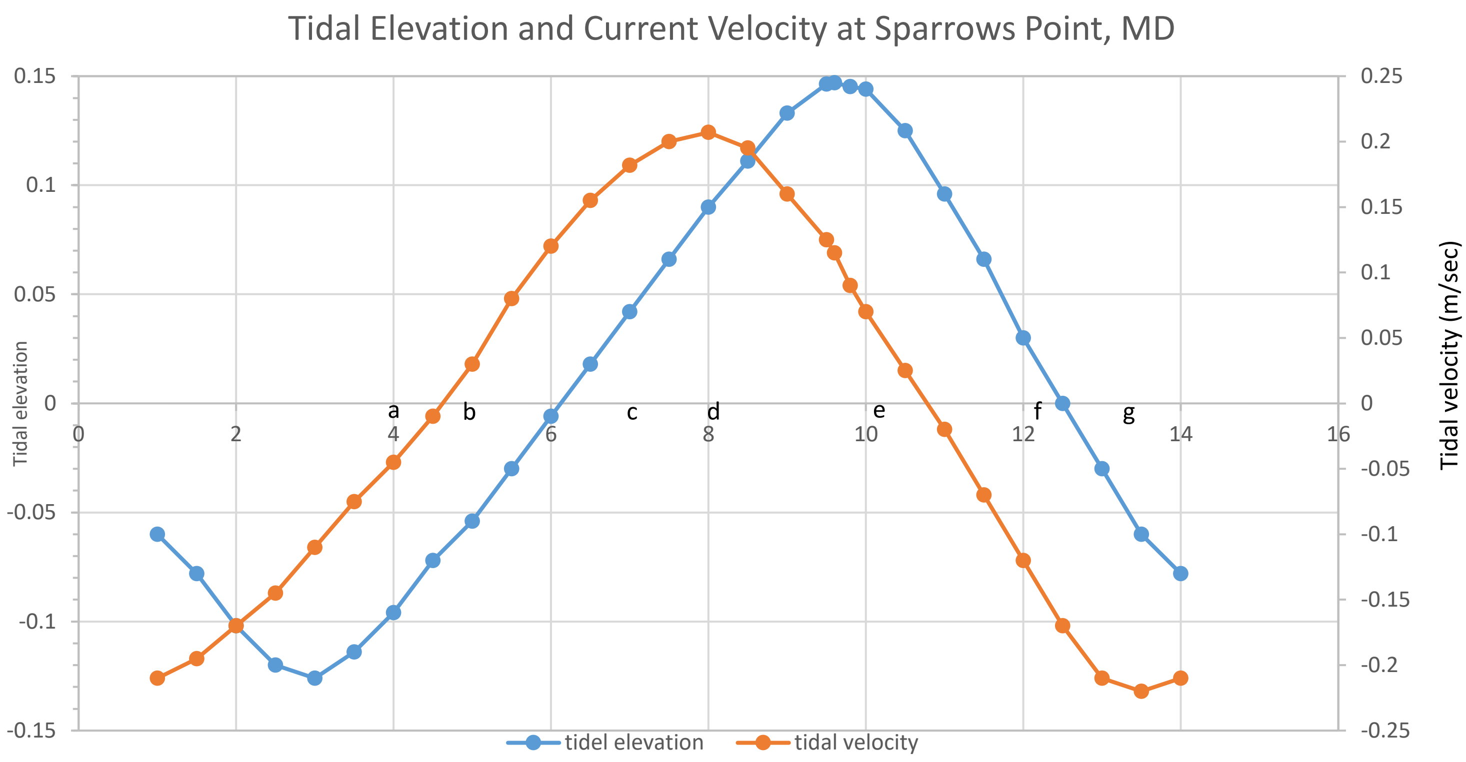


Figure 8: A mean tide elevation and averaged tidal velocity for the proposed outfalls location (in a full tidal cycle) was created by calibrated and verified 3D unstructured grid SCHIM model for use with CORMIX2. This satisfies MDE COMAR D(2)(i)) requirement.

The second requirement of COMAR D (2)(b) (ii) required “specific data on wastewater dispersion or dilution, when available for a specific discharge”. The wastewater dispersion and dilution are carried out by CORMIX2 under different tidal stages and tidal currents conditions marked by a, b , c, d , e, f, and g in Figure 8. This is required because the tidal stage and the associate tidal current can greatly affect the DF. Furthermore, the dilution factor could vary under different parameter setting such as (a) port angle, (b) diameter of opening of the port, and (3) number of ports attached to the diffusion pipe. A base case and 4 scenario were constructed and the DF was calculated by CORMIX2 for each case under 7 different tidal stage. The results are in tabulated form shown in Table 1 through Table 5.

The different parameter for Base and scanrio run are as follows:
1.. Base run: the diffusion pipe is 150 m long and 54 in in diameter. There are 20 ports attached to it with diameter 10 in and the port angle is 90 degree upward.
2.. Scenario 1: the same as base run, except the port angle is 45 degree to the horizontal axis
3. Scenario 2: the diffusion pipe is 150 m long and 54 in in diameter. There are 15 ports attached to it with diameter 15 in and the port angle is 90 degree upward.
4. Scenario 3: the diffusion pipe is 150 m long and 54 in in diameter. There are 10 ports attached to it with diameter 14 in and the port angle is 90 degree upward.
5. Scenario 4: the diffusion pipe is 150 m long and 54 in in diameter. There are 5 ports attached to it with diameter 20 in and the port angle is 90 degree upward

The diluation facotr obtained from Table 1 – Table 5 are summarized and provided in the following table:

Summary table for dilution factor at Sparrow Point

Dilution Factor	Tidal stages						
Cases	a (near slack)	b	c	d	e	f	g
Base case	8.1	11.4	47.4	36.8	20.7	31.9	53.0
Scenario 1	10.0	10.2	22.4	24.9	12.3	16.4	24.9
Scenario 2	8.1	11.4	47.4	59.2	20.7	31.9	53.2
Scenario 3	8.1	11.4	47.5	59.3	21.7	31.3	53.3
Scenario 4	8.1	11.4	47.4	56.8	21.0	31.3	53.3

Table 1: CORMIX Mixing Results for a Multiport Diffuser – Base case (54in , 150 m long, 20 ports, port angle 90 degree)

Category	**At a proposed outfall location off the Sparrows Point**						
Tidal stage (see Figure 1)	'a' LWS (1/2 hr before)	'b' ⅓ between 'a' and 'd'	'c' ⅔ between 'a' and 'd'	'd' Peak Flood	'e' HWS (1/2 hr before)	'f' ½ between 'e' and 'g'	'g' Peak Ebb
Tidal elevation relative to MSL: m	-0.096	-0.054	0.15	+0.04	+0.144	0.03	-0.03
Tidal velocity: m/sec (- flood + ebb)	-0.045	0.03	0.182	0.207	0.07	-0.12	-0.21
Effluent discharge duration time: hr or continuous	continuous	continuous	continuous	continuous	continuous	continuous	continuous
Total effluent rate from the outfall (through diffusion line): mgd (m^3/sec)	50 (2.19)	50 (2.19)	50 (2.19)	50 (2.19)	50 (2.19)	50 (2.19)	50 (2.19)
Type of effluent outfall	Multi-port diffusion line	Multi-port diffusion line	Multi-port diffusion line	Multi-port diffusion line	Multi-port diffusion line	Multi-port diffusion line	Multi-port diffusion line
Diameter of the diffusion line; meter (in)	1.37 (54)	1.37(54)	1.37(54)	1.37(54)	1.37 (54)	1.37 (54)	1.37(54)
Length of a diffusion line (meter)	150	150	150	150	150	150	150
Angle of the diffusion line from the horizontal plan: degree	Θ=90	Θ=90	Θ=90	Θ=90	Θ=90	Θ=90	Θ=90
Number of ports/nozzles in a diffusion line	20	20	20	20	20	20	20
Diameter of the port/nozzle, meter (inch)	0.254 (10)	0.254 (10)	0.254 (10)	0.254 (10)	0.254 (10)	0.254 (10)	0.254 (10)
Cross-sectional area of the individual port: m^2 (ft^2)	$5.06x10^{-2}$ (0.545)	$5.06\ x10^{-2}$ (0.545)	$5.06x10^{-2}$ (0.545)	$5.06\ x10^{-2}$ (0.545)	$5.06\ x10^{-2}$ (0.545)	$5.06\ x10^{-2}$ (0.545)	$5.06\ x10^{-2}$ (0.545)
The jet velocity from individual port; m/sec	2.16	2.16	2.16	2.16	2.16	2.16	2.16
The total discharge from the port (outfall discharge): m^3/sec	2.19	2.19	2.19	2.19	2.19	2.19	2.19
Ambient water slainiity: psu (1m) Ambient water salinity: psu (2m) Ambient water salinity: psu (3m) Ambient water salinity: psu (5m)	5.3 5.4 5.9 6.0	5.3 5.4 5.9 6.0	5.3 5.4 5.9 6.0	5.3 5.4 5.9 6.0	5.3 5.4 5.9 6.0	5.3 5.4 5.9 6.0	5.3 5.4 5.9 6.0
Ambient water density: kg/m^3 (1m) Ambient water density: kg/m^3 (2m) Ambient water density: kg/m^3 (3m) Ambient water density: kg/m^3 (5m)	1002.2 1002.3 1002.7 1002.9	1002.2 1002.3 1002.7 1002.9	1002.2 1002.3 1002.7 1002.9	1002.2 1002.3 1002.7 1002.9	1002.2 1002.3 1002.7 1002.9	1002.2 1002.3 1002.7 1002.9	1002.2 1002.3 1002.7 1002.9
CORMIX results:							
(1) In-Pipe Mixing DF_{vol} (Dilution Factor)	8.1	11.4	47.4	36.8	20.7	31.9	53.0
(2) Flow classification at the Mixing Boundary	MU8	MU8	MU8	MU8	MU8	MU8	MU8

Table 2: CORMIX Mixing Results for a Multiport Diffuser – Scenario_1 (54in , 150 m long, 20 ports, port angle 45 degree)

Category	**At a proposed outfall location off the Sparrows Point**						
Tidal stage (see Figure 1)	**'a'** LWS (1/2 hr before)	**'b'** ⅓ between 'a' and 'd'	**'c'** ⅔ between 'a' and 'd'	**'d'** Peak Flood	**'e'** HWS (1/2 hr before)	**'f'** ½ between 'e' and 'g'	**'g'** Peak Ebb
Tidal elevation relative to MSL: m	-0.096	-0.054	0.15	+0.04	+0.144	0.03	-0.03
Tidal velocity: m/sec (- flood + ebb)	-0.045	0.03	0.182	0.207	0.07	-0.12	-0.21
Effluent discharge duration time: hr or continuous	continuous	continuous	continuous	continuous	continuous	continuous	continuous
Total effluent rate from the outfall (through diffusion line): mgd (m^3/sec)	50 (2.19)	50 (2.19)	50 (2.19)	50 (2.19)	50 (2.19)	50 (2.19)	50 (2.19)
Type of effluent outfall	Multi-port diffusion line	Multi-port diffusion line	Multi-port diffusion line	Multi-port diffusion line	Multi-port diffusion line	Multi-port diffusion line	Multi-port diffusion line
Diameter of the diffusion line; meter (in)	1.37 (54)	1.37 (54)	1.37(54)	1.37(54)	1.37 (54)	1.37 (54)	1.37(54)
Length of a diffusion line (meter)	150	150	150	150	150	150	150
Angle of the diffusion line from the horizontal plan: degree	Θ=45	Θ=45	Θ=45	Θ=45	Θ=45	Θ=45	Θ=45
Number of ports/nozzles in a diffusion line	20	20	20	20	20	20	20
Diameter of the port/nozzle, meter (inch)	0.254 (10)	0.254 (10)	0.254 (10)	0.254 (10)	0.254 (10)	0.254 (10)	0.254 (10)
Cross-sectional area of the individual port: m^2 (ft^2)	$5.06x10^{-2}$ (0.545)	$5.06\ x10^{-2}$ (0.545)	$5.06x10^{-2}$ (0.545)	$5.06\ x10^{-2}$ (0.545)	$5.06\ x10^{-2}$ (0.545)	$5.06\ x10^{-2}$ (0.545)	$5.06\ x10^{-2}$ (0.545)
The jet velocity from individual port; m/sec	2.16	2.16	2.16	2.16	2.16	2.16	2.16
The total discharge from the port (outfall discharge): m^3/sec	2.19	2.19	2.19	2.19	2.19	2.19	2.19
Ambient water slainiity: psu (1m) Ambient water salinity: psu (2m) Ambient water salinity: psu (3m) Ambient water salinity: psu (5m)	5.3 5.4 5.9 6.0	5.3 5.4 5.9 6.0	5.3 5.4 5.9 6.0	5.3 5.4 5.9 6.0	5.3 5.4 5.9 6.0	5.3 5.4 5.9 6.0	5.3 5.4 5.9 6.0
Ambient water density: kg/m^3 (1m) Ambient water density: kg/m^3 (2m) Ambient water density: kg/m^3 (3m) Ambient water density: kg/m^3 (5m)	1002.2 1002.3 1002.7 1002.9	1002.2 1002.3 1002.7 1002.9	1002.2 1002.3 1002.7 1002.9	1002.2 1002.3 1002.7 1002.9	1002.2 1002.3 1002.7 1002.9	1002.2 1002.3 1002.7 1002.9	1002.2 1002.3 1002.7 1002.9
CORMIX results:							
(1) In-Pipe Mixing DF_{vol} (Dilution Factor)	10.0	10.2	22.4	24.9	12.3	16.4	24.9
(2) Flow classification at the Mixing Boundary	MU2	MU2	MU2	MU2	MU2	MU2	MU2

Table 3: CORMIX Mixing Results for a Multiport Diffuser - Scenario_2 (54in, 150 m long, 15 ports, port angle 90 degree)

Category	**At a proposed outfall location off the Sparrows Point**						
Tidal stage (see Figure 1)	**'a'** LWS (1/2 hr before)	**'b'** ⅓ between 'a' and 'd'	**'c'** ⅔ between 'a' and 'd'	**'d'** Peak Flood	**'e'** HWS (1/2 hr before)	**'f'** ½ between 'e' and 'g'	**'g'** Peak Ebb
Tidal elevation relative to MSL: m	-0.096	-0.054	0.15	+0.04	+0.144	0.03	-0.03
Tidal velocity: m/sec (- flood + ebb)	-0.045	0.03	0.182	0.207	0.07	-0.12	-0.21
Effluent discharge duration time: hr or continuous	continuous	continuous	continuous	continuous	continuous	continuous	continuous
Total efflueent rate from the outfall (through diffusion line): mgd (m^3/sec)	50 (2.19)	50 (2.19)	50 (2.19)	50 (2.19)	50 (2.19)	50 (2.19)	50 (2.19)
Type of effluent outfall	Multi-port diffusion line	Multi-port diffusion line	Multi-port diffusion line	Multi-port diffusion line	Multi-port diffusion line	Multi-port diffusion line	Multi-port diffusion line
Diameter of the diffusion line; meter (in)	1.37 (54)	1.37 (54)	1.37(54)	1.37 (54)	1.37 (54)	1.37 (54)	1.37(54)
Length of a diffusion line (meter)	150	150	150	150	150	150	150
Angle of the diffusion line from the horizontal plan: degree	Θ=90	Θ=90	Θ=90	Θ=90	Θ=90	Θ=90	Θ=90
Number of ports/nozzles in a diffusion line	15	15	20	15	15	15	15
Diameter of the port/nozzle, meter (inch)	0.305 (12)	0.305 (12)	0.305(12)	0.305 (12)	0.305 (12)	0.305 (12)	0.305 (12)
Cross-sectional area of the individual port: m^2 (ft^2)	$7.31x10^{-2}$ (0.785)	$7.31\ x10^{-2}$ (0.785)	$7.31x10^{-2}$ (0.785)	$7.31\ x10^{-2}$ (0.785)	$7.31\ x10^{-2}$ (0.785)	$7.31\ x10^{-2}$ (0.785)	$7.31\ x10^{-2}$ (0.785)
The jet velocity from individual port; m/sec	2.00	2.00	2.00	2.00	2.00	2.00	2.00
The total discharge from the port (outfall discharge): m^3/sec	2.19	2.19	2.19	2.19	2.19	2.19	2.19
Ambient water slainiity: psu (1m) Ambient water salinity: psu (2m) Ambient water salinity: psu (3m) Ambient water salinity: psu (5m)	5.3 5.4 5.9 6.0	5.3 5.4 5.9 6.0	5.3 5.4 5.9 6.0	5.3 5.4 5.9 6.0	5.3 5.4 5.9 6.0	5.3 5.4 5.9 6.0	5.3 5.4 5.9 6.0
Ambient water density: kg/m^3 (1m) Ambient water density: kg/m^3 (2m) Ambient water density: kg/m^3 (3m) Ambient water density: kg/m^3 (5m)	1002.2 1002.3 1002.7 1002.9	1002.2 1002.3 1002.7 1002.9	1002.2 1002.3 1002.7 1002.9	1002.2 1002.3 1002.7 1002.9	1002.2 1002.3 1002.7 1002.9	1002.2 1002.3 1002.7 1002.9	1002.2 1002.3 1002.7 1002.9
CORMIX results:							
(1) In-Pipe Mixing DF_{vol} (Dilution Factor)	8.1	11.4	47.4	59.2	20.7	31.9	53.2
(2) Flow classification at the Mixing Boundary	MU8	MU8	MU8	MU8	MU8	MU8	MU9

Table 4: CORMIX Mixing Results for a Multiport Diffuser – Scenario_3 (54 in, 150 m long, 10 ports, port angle 90 degree)

Category	**At a proposed outfall location off the Sparrows Point**						
Tidal stage (see Figure 1)	**'a'** LWS (1/2 hr before)	**'b'** ⅓ between 'a' and 'd'	**'c'** ⅔ between 'a' and 'd'	**'d'** Peak Flood	**'e'** HWS (1/2 hr before)	**'f'** ½ between 'e' and 'g'	**'g'** Peak Ebb
Tidal elevation relative to MSL: m	-0.096	-0.054	0.15	+0.04	+0.144	0.03	-0.03
Tidal velocity: m/sec (- flood + ebb)	-0.045	0.03	0.182	0.207	0.07	-0.12	-0.21
Effluent discharge duration time: hr or continuous	Continuous	continuous	continuous	continuous	continuous	continuous	continuous
Total efflueent rate from the outfall (through diffusion line): mgd (m^3/sec)	50 (2.19)	50 (2.19)	50 (2.19)	50 (2.19)	50 (2.19)	50 (2.19)	50 (2.19)
Type of effluent outfall	Multi-port diffusion line	Multi-port diffusion line	Multi-port diffusion line	Multi-port diffusion line	Multi-port diffusion line	Multi-port diffusion line	Multi-port diffusion line
Diameter of the diffusion line; meter (in)	1.37 (54)	1.37 (54)	1.37(54)	1.37(54)	1.37 (54)	1.37 (54)	1.37(54)
Length of a diffusion line (meter)	150	150	150	150	150	150	150
Angle of the diffusion line from the horizontal plan: degree	Θ=90	Θ=90	Θ=90	Θ=90	Θ=90	Θ=90	Θ=90
Number of ports/nozzles in a diffusion line	10	10	10	10	10	10	10
Diameter of the port/nozzle, meter (inch)	0.356 (14)	0.356 (14)	0.356 (14)	0.356 (14)	0.356 (14)	0.356(14)	0.356 (14)
Cross-sectional area of the individual port: m^2 (ft^2)	0.1 (1.07)	0.1 (1.07)	0.1 (1.07)	0.1 (1.07)	0.1 (1.07)	0.1 (1.07)	0.1 (1.07)
The jet velocity from individual port; m/sec	2.19	2.19	2.19	2.19	2.19	2.19	2.19
The total discharge from the port (outfall discharge): m^3/sec	2.19	2.19	2.19	2.19	2.19	2.19	2.19
Ambient water slainiity: psu (1m) Ambient water salinity: psu (2m) Ambient water salinity: psu (3m) Ambient water salinity: psu (5m)	5.3 5.4 5.9 6.0	5.3 5.4 5.9 6.0	5.3 5.4 5.9 6.0	5.3 5.4 5.9 6.0	5.3 5.4 5.9 6.0	5.3 5.4 5.9 6.0	5.3 5.4 5.9 6.0
Ambient water density: kg/m^3 (1m) Ambient water density: kg/m^3 (2m) Ambient water density: kg/m^3 (3m) Ambient water density: kg/m^3 (5m)	1002.2 1002.3 1002.7 1002.9	1002.2 1002.3 1002.7 1002.9	1002.2 1002.3 1002.7 1002.9	1002.2 1002.3 1002.7 1002.9	1002.2 1002.3 1002.7 1002.9	1002.2 1002.3 1002.7 1002.9	1002.2 1002.3 1002.7 1002.9
CORMIX results:							
(1) In-Pipe Mixing DF_{vol} (Dilution Factor)	8.1	11.4	47.5	59.3	21.7	31.3	53.3
(2) Flow classification at the Mixing Boundary	MU8	MU8	MU8	MU8	MU8	MU8	MU8

Table 5: CORMIX Mixing Results for a Multiport Diffuser – Scenario_4 (54 in, 150 m long, 5ports, port angle 90 degree)

Category	**At a proposed outfall location off the Sparrows Point**						
Tidal stage (see Figure 1)	**'a'** LWS (1/2 hr before)	**'b'** ⅓ between 'a' and 'd'	**'c'** ⅔ between 'a' and 'd'	**'d'** Peak Flood	**'e'** HWS (1/2 hr before)	**'f'** ½ between 'e' and 'g'	**'g'** Peak Ebb
Tidal elevation relative to MSL: m	-0.096	-0.054	0.15	+0.04	+0.144	0.03	-0.03
Tidal velocity: m/sec (- flood + ebb)	-0.045	0.03	0.182	0.207	0.07	-0.12	-0.21
Effluent discharge duration time: hr or continuous	Continuous	continuous	continuous	continuous	continuous	continuous	Continuous
Total effluent rate from the outfall (through diffusion line): mgd (m^3/sec)	50 (2.19)	50 (2.19)	50 (2.19)	50 (2.19)	50 (2.19)	50 (2.19)	50 (2.19)
Type of effluent outfall	Multi-port diffusion line	Multi-port diffusion line	Multi-port diffusion line	Multi-port diffusion line	Multi-port diffusion line	Multi-port diffusion line	Multi-port diffusion line
Diameter of the diffusion line; meter (in)	1.37 (54)	1.37 (54)	1.37(54)	1.37(54)	1.37 (54)	1.37 (54)	1.37(54)
Length of a diffusion line (meter)	150	150	150	150	150	150	150
Angle of the diffusion line from the horizontal plan: degree	Θ=90	Θ=90	Θ=90	Θ=90	Θ=90	Θ=90	Θ=90
Number of ports/nozzles in a diffusion line	5	5	10	10	10	10	10
Diameter of the port/nozzle, meter (inch)	0.508 (20)	0.508 (20)	0.508 (20)	0.508 (20)	0.508 (20)	0.508(20)	0.508 (20)
Cross-sectional area of the individual port: m^2 (ft^2)	0.202 (2.18)	0.202 (2.18)	0.202 (2.18)	0.202 (2.18)	0.202 (2.18)	0.202 (2.18)	0.202 (2.18)
The jet velocity from individual port; m/sec	2.17	2.17	2.17	2.17	2.17	2.17	2.17
The total discharge from the port (outfall discharge): m^3/sec	2.19	2.19	2.19	2.19	2.19	2.19	2.19
Ambient water slainiity: psu (1m) Ambient water salinity: psu (2m) Ambient water salinity: psu (3m) Ambient water salinity: psu (5m)	5.3 5.4 5.9 6.0	5.3 5.4 5.9 6.0	5.3 5.4 5.9 6.0	5.3 5.4 5.9 6.0	5.3 5.4 5.9 6.0	5.3 5.4 5.9 6.0	5.3 5.4 5.9 6.0
Ambient water density: kg/m^3 (1m) Ambient water density: kg/m^3 (2m) Ambient water density: kg/m^3 (3m) Ambient water density: kg/m^3 (5m)	1002.2 1002.3 1002.7 1002.9	1002.2 1002.3 1002.7 1002.9	1002.2 1002.3 1002.7 1002.9	1002.2 1002.3 1002.7 1002.9	1002.2 1002.3 1002.7 1002.9	1002.2 1002.3 1002.7 1002.9	1002.2 1002.3 1002.7 1002.9
CORMIX results:							
(1) In-Pipe Mixing DF_{vol} (Dilution Factor)	8.1	11.4	47.4	56.8	21.0	31.3	53.3
(2) Flow classification at the Mixing Boundary	MU8	MU8	MU8	MU8	MU8	MU8	MU8

CORMIX2 expert system also provide valuable information about Sparrow Point outfall

```
CORMIX2 PREDICTION FILE:
2222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222222
                         CORMIX MIXING ZONE EXPERT SYSTEM
                 Subsystem CORMIX2: Multiport Diffuser Discharges
                               CORMIX Version 11.0GT
                        HYDRO2 Version 11.0.1.0 August 2019
---------------------------------------------------------------------------------------------
---------------------------------------------------------------------------------------------
CASE DESCRIPTION
 Site name/label:   Sparrows Point
 Design case:       Multi port
 FILE NAME:         C:\...le Files\Sparrows Pt\Multiport\Spt_multi_vl_c.prd
 Time stamp:        09/26/2019--11:43:45

ENVIRONMENT PARAMETERS (metric units)
 Unbounded section
 HA    =       6.00 HD    =       5.00
 Tidal Simulation at TIME =       1.000 h
 PERIOD=    12.40 h UAmax =       0.400 dUa/dt=      0.182 (m/s)/h
 UA    =       0.182 F     =       0.017 USTAR =0.8459E-02
 UW    =       2.000 UWSTAR=0.2198E-02
 Density stratified environment
 STRCND=  A         RHOAM = 1002.9500
 RHOAS = 1002.2000  RHOAB = 1003.7000  RHOAH0= 1002.9500  E     =0.2931E-02

DIFFUSER DISCHARGE PARAMETERS (metric units)
 Diffuser type:     DITYPE= alternating_perpendicular
 BANK  =  RIGHT     DISTB =    350.00  YB1   =    300.00  YB2   =    400.00
 LD    =    100.00  NOPEN =    5       NRISER=    5       SPAC  =     25.00   NPPERR =    1
 D0    =       0.480 A0    =       0.181 H0    =       1.00  SUB0  =      4.00
 D0INP =       0.480 CR0   =       1.000 B0    =0.7238E-02
 Nozzle/port arrangement:   near_vertical_discharge
 GAMMA =      90.00  THETA =      90.00  SIGMA =       0.00  BETA  =     90.00
 U0    =       2.420 Q0    =       2.190 Q0A   =0.2190E+01
 RHO0  =  998.0000  DRHO0 =0.4950E+01  GP0   =0.4840E-01
 C0    =0.1000E+02  CUNITS=  mg/l
 IPOLL =  1         KS    =0.0000E+00  KD    =0.0000E+00

FLUX VARIABLES - PER UNIT DIFFUSER LENGTH (metric units)
 q0    =0.2190E-01          SIGNJ0=      1.0
 m0 =U0^2*B0 =0.4241E-01   j0 =U0*GP0*B0 =0.8480E-03   (based on slot width B0)
 m0 =U0*q0   =0.5301E-01   j0 =q0*GP0    =0.1060E-02   (based on volume flux q0)
 Associated 2-d length scales (meters)
```

The input files are divided into 3 categories: (1)..environmental parameters (2). diffuser discharge parameter (3) flux variable – per unit diffuser length

```
-----------------------------------------------------------------------------
MIXING ZONE / TOXIC DILUTION ZONE / AREA OF INTEREST PARAMETERS:
  Toxic discharge                           = no
  Water quality standard specified          = no
  Regulatory mixing zone                    = yes
  Regulatory mixing zone specification      = distance
  Regulatory mixing zone value              = 1000 m (m^2 if area)
  Region of interest                        = 1000 m
*****************************************************************************
HYDRODYNAMIC CLASSIFICATION:
  *------------------------*
  | FLOW CLASS    = MU8 |
  *------------------------*
  This flow configuration applies to a layer corresponding to the full water
  depth at the discharge site.  The ambient density stratification at the
  discharge site is relatively weak and unimportant so the discharge flow
  penetrates to the surface and/or breaks down the existing stratification
  through vigorous mixing.
  Applicable layer depth = water depth = 5 m
*****************************************************************************
MIXING ZONE EVALUATION (hydrodynamic and regulatory summary):

-----------------------------------------------------------------------------
X-Y-Z Coordinate system:
  Origin is located at the BOTTOM below the port/diffuser center:
    350 m from the right bank/shore.
  Number of display steps NSTEP = 20 per module.
-----------------------------------------------------------------------------
NEAR-FIELD REGION (NFR) CONDITIONS :
Note: The NFR is the zone of strong initial mixing.  It has no regulatory
  implication.  However, this information may be useful for the discharge
  designer because the mixing in the NFR is usually sensitive to the
  discharge design conditions.
  Pollutant concentration at NFR edge  c = 0.2728 mg/l
  Dilution at edge of NFR              s = 36.7
  NFR Location:                        x = 58.87 m
    (centerline coordinates)           y = 0 m
                                       z = 5 m
  NFR plume dimensions:  half-width (bh) = 53.36 m
                         thickness (bv) = 4.90 m
  Cumulative travel time:       158.9648 sec.
```

The output files are divided into (1) mixing zone parameters (2) flow class (MU8) (3) mixing zone evaluation (4) near-field region conditions

IV. A far-field Eulerian transport modeling for effluent discharge at Sparrow Point

After the effluent flow interacts with the water surface, bottom, pycnocline (or terminal layer) and has thus completed its near-field mixing phase, the far-field mixing begins. In the far-field, advection and diffusion determine the plume dilution. Advection is a bulk transport process dominated by the mean current and diffusion is the results of combination effects of molecular diffusion, turbulence, and shear instabilities. Typical time and length scales are on the order of hours-days and 1-100 kilometers (see Figure 9).

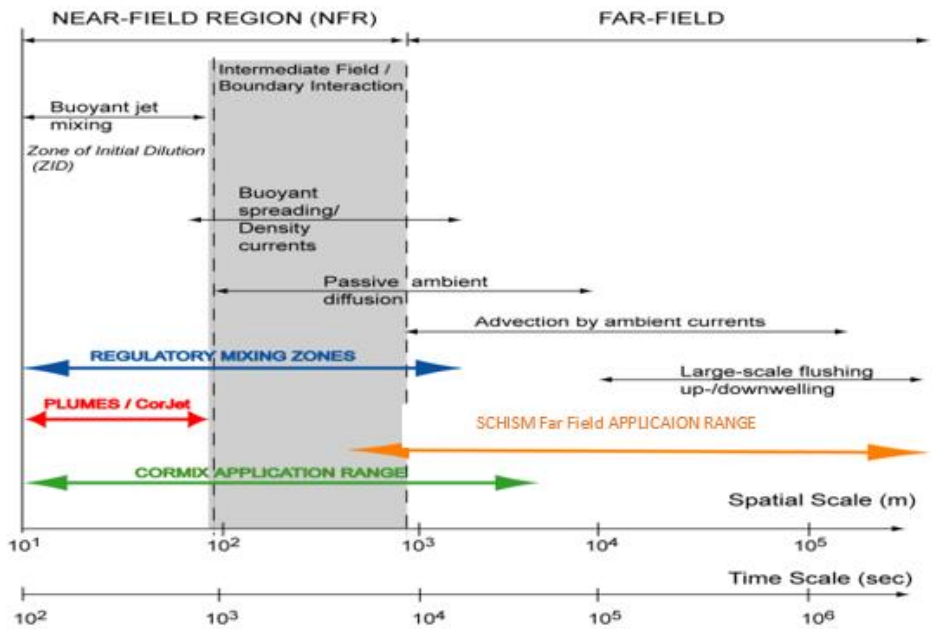


Figure 9: The temporal and spatial scales for physical mixing process

IV-1 The high-resolution SCHISM model

Application of three-dimensional Eulerian modeling in estuaries has been used to predict far-field dilution. Eulerian numerical models solve the advection-diffusion equation, or transport equation, for a given input of tracer (i.e., effluent). These models can simulate continuous unsteady flows and treats the ambient waterbody as a very fine 3-D mesh. The scale of the mesh is of the same order as the dimension of the discharge plume. Therefore, these models are time intensive requiring powerful computers and long simulation time. One such model system is being used here in the Sparrow Point is SCHISM (Semi-implicit Cross-scale Hydroscience Integrated System) and ICM (Integral Compartment Model) originally developed by Zhang et al. (2006). The core of hydrodynamic model SCHISM is a 3D baroclinic, unstructured grid model. It uses efficient semi-implicit Eulerian-Lagrangian scheme coupling with different system models and was designed for effectively simulating 3-D baroclinic circulation and associated processes in the estuaries and coastal waters across river-shelf-ocean scales. using unstructured grids in the horizontal and hybrid terrain-following S coordinates and shaved Z coordinate in the vertical. The horizontal grid structure uses finite-element discretization comprised of mixed quadrilateral and triangular grids without limiting by the orthogonality of the grid property. The vertical grid structure uses hybrid vertical coordinates including spatially-varying LSC^2 vertical grid based on local water depths (Zhang et al., 2015). The entire SCHISM system was efficiently parallelized via domain decomposition and MPI (Message Passing Interface) and has been tested widely against standard ocean/coastal benchmarks. The SCHISM model first solves the barotropic pressure gradient term in the momentum equation with a semi-implicit schematization. The unknown velocities (defined at side centers) are first eliminated from the equations with the aid from the bottom boundary layer, resulting in an integral equation for the unknown elevations alone, which can be efficiently solved with a parallel solver (by Jacobian Conjugate Gradient). The time stepping is done using a 2nd-order Crank-Nicolson method, i.e., with the implicitness factor being 0.5 (in practice a value slightly larger than 0.5 is used for robustness). The SCHISM then solves the momentum equation along each vertical column at the center of each element side. A semi-implicit Galerkin finite-element method is used, with the pressure gradient and the vertical viscosity terms being handled implicitly with all other terms treated explicitly.

Once all velocities at every element side are determined, the velocity at each node is computed by a weighted average of all surrounding sides evaluated by proper interpolation in the vertical. The velocity at each node is computed within each element from the three sides using a linear shape function as an averaging technique and is kept discontinuous between elements. This method can introduce parasitic oscillations, so a Shapiro filter is built into the model code as a smoothing function to suppress the static measurements. A finite-volume approach is applied to the continuity equation, to solve for vertical velocity. In this case, vertical velocity is solved from the bottom to the surface, in conjunction with the bottom boundary condition. Solution of the two-equations turbulence closure equations and update of the vertical grid including the marking of wetting and drying nodes/sides/elements constitute the remaining operations in a time stepping loop. Along with the governing equation are initial and boundary conditions. Surface boundary condition is applied mainly by surface wind stress over the water at the air-sea interface. At the bottom boundary, the 3-D SCHISM model is balanced between bottom friction stress and internal stress. Open ocean boundary in SCHISM model usually consists of elevation, velocity, river flux, salinity, and temperature which need to be specified at the surrounding boundaries of the model domain. Major features of SCHISM are highlighted as follows:

(1) Finite element/finite volume formulation.
(2) Unstructured mixed triangular/quadrangular grid in the horizontal dimension.
(3) Hybrid SZ coordinates or new LSC^2 in the vertical dimension.
(4) Polymorphism: a single grid can mimic 1D/2DV/2DH/3D configurations.
(5) Higher-order Eulerian-Lagrangian treatment of momentum advection.
(6) Semi-implicit time stepping (no mode splitting): no CFL stability constraints.
(7) Robust matrix solver including an implicit solver for transport equations.
(8) Natural treatment of wetting and drying processes for inundation studies.
(9) Mass conservative, monotone, higher-order transport solver: TVD^2; WENO.

(10) No bathymetry smoothing is required.

The upper Chesapeake Bay SCHISM model domain started from the southern boundary near Solomon's Island (of Maryland) in the middle section of the Bay and expands northward to the head of the Bay near Chesapeake City in C&D canal and to the Conowingo Dam where Susquehanna freshwater inputs was specified, as shown in Figure 10 (left). The bathymetry associated with the upper Chesapeake Bay was assigned to the grid, as shown in Figure 10 (right). It can be seen that the depths for most of the upper Bay are shallower than 7 m except for the shipping channel where it can go deep from 10- 25 m. The uniqueness of the Upper Chesapeake Bay SCHISM model grid presented here is that it was

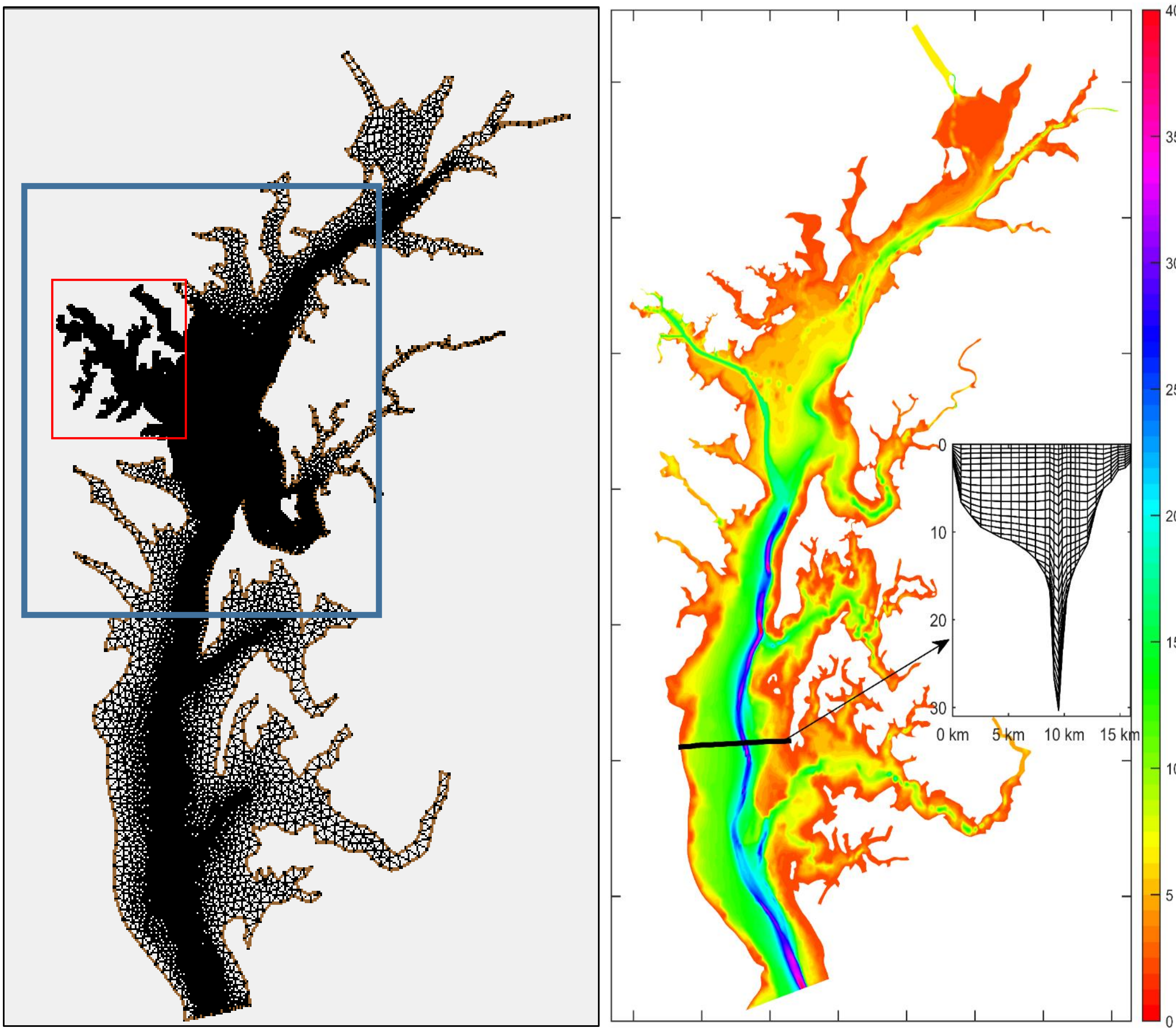


Figure 10: (left) The SCHISM modeling domain and grid (right) the bathymetry and the example of the cross section

configured such that the domain is large enough that Upper Bay dynamics is properly captured and, at the same time, tailored for a very fine grid in the Baltimore Harbor, particularly at those area around the Bear Creek and Sparrow Point in the lower Harbor where outfalls are located , as shown in Figure 11. In so doing, it is hopeful to satisfy the requirement that the model mesh to be on the same order as the dimension of the discharge plume for the effluent discharge modeling applications. More detailed of the model grid built around the proposed outfall is shown in section V-2 Particle tracking modeling.

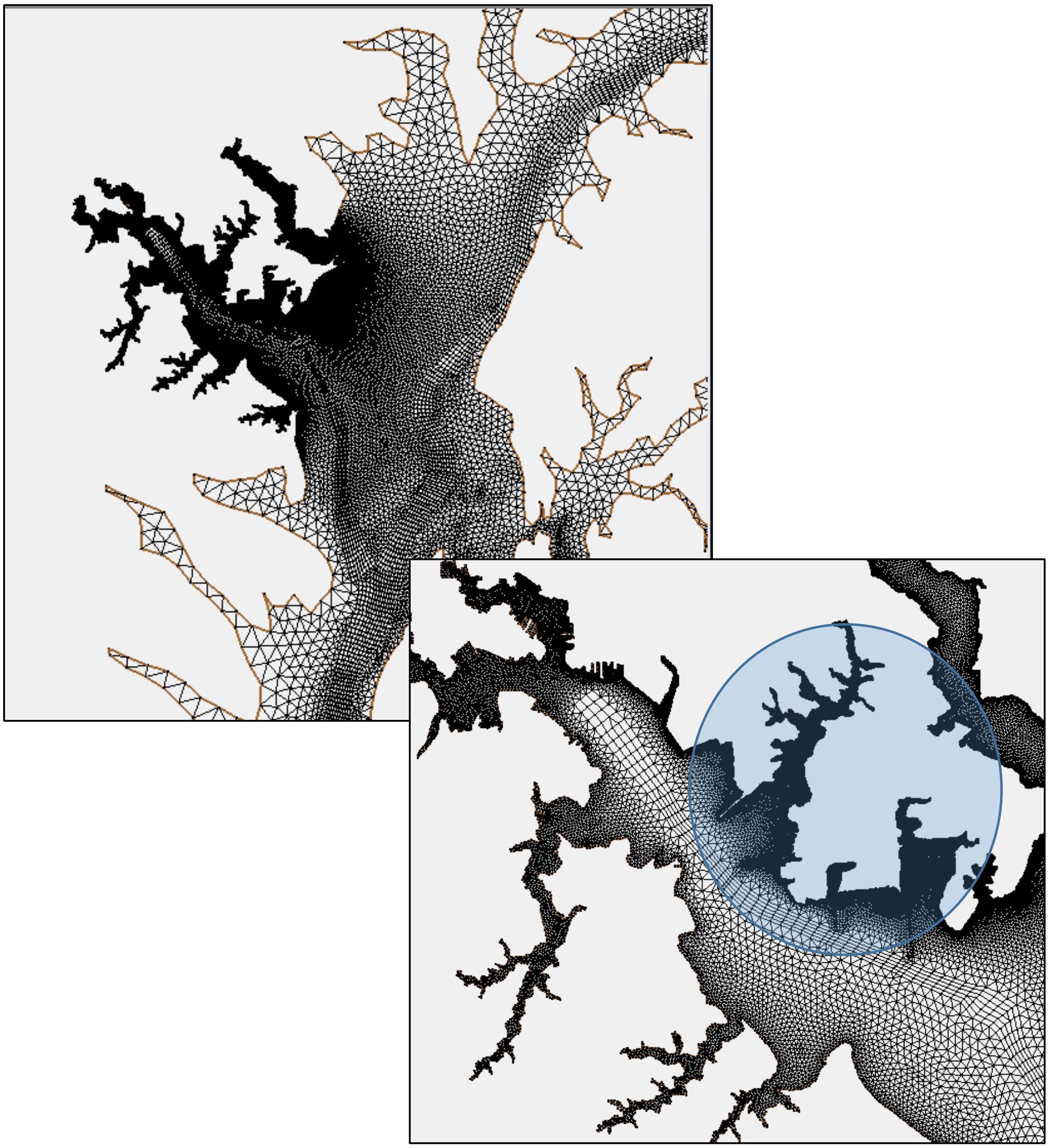


Figure 11: The high-resolution SCHISM model grid in Baltimore Harbor and in the vicinity of Sparrow Point

Initial and boundary conditions

The observation data are used to setup the initial and boundary conditions for the model. Those include:
(i).. The bathymetry data (http://www.ngdc.noaa.gov/mgg/gdas/gd_designagrid.html) from NOAA.
(ii) The Chesapeake Bay salinity and temperature survey data from EPA https://www.chesapeakebay.net/what/data
(iii).. Bi-weekly salinity/temperature profiles measured at the station CB 4.1 in the southern boundary from the Chesapeake Bay Program (CBP) Water Quality Database
iv) 6-min free-surface elevation from at Solomon's Island NOAA tidal gauges.
v) Daily Susquehanna discharge at Conowingo Dam from USGS (https://waterdata.usgs.gov/md/nwis/uv?site_no=01578310)
vi) Surface wind stress obtained from NOAA NCEP/NCAR Phusical Science Laboratory Reanaluysis: https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html

Execution of the model

Once the model grid is built and the model initial condition, and boundary condition are setup, the model is submitted to High Performance Computing (HPC) center of William & Mary's for execution. The facilities include three main clusters of computers, named SciClone, Storm, and Chesapeake, providing over 2600 computing cores. The upper Chesapeake Bay model simulation was executed on SciClone HPC cluster with 200 computation cores. With the high-resolution grid consists of 788,915 nodes and 1,524,968 elements, it took the coupled SCHISM and ICM model 3.5 days to finish one-year simulation, approximately 100 times speed up of the real-time.

IV-2 Model calibration and verificaiton

Model calibration and verificaiton required observation data. There are 4 observed variables which were used for comparing with the modeled results. They are: water levelvation, current velocity, salinity and tempeature. The elevation and currents are from NOAA station https://tidesandcurrents.noaa.gov/map/index.html?region=Maryland; the salinity and temperature are from EPA Chesapeake Bay water qaulity monitoring Program https://www.chesapeakebay.net/what/downloads/. The station distibution in the upper Bay of above variables is shown Figure 12.

The model simulation period was from January 01, 2012 through 12/31/2012. The results for elevation during June period are shown in Figure 13 for staitons: Annapolis, Cambridge, and Tolchester (Solomon's Island is the bounary condition). It can be seen that semi-diurnal tide is superposed on sub-tidal, low frequency varation driven by wind. In particular, on days 165 and 178, there are a large drop of water level for the entire Upper Bay, presumbly by the passing of the storm. The model produced tidal as well as sub-tidal variability truthfully. The statistics of R square are above 0.92 for all stations, the absolute errors around 0.050 m, and the root mean square error 0.070 m.

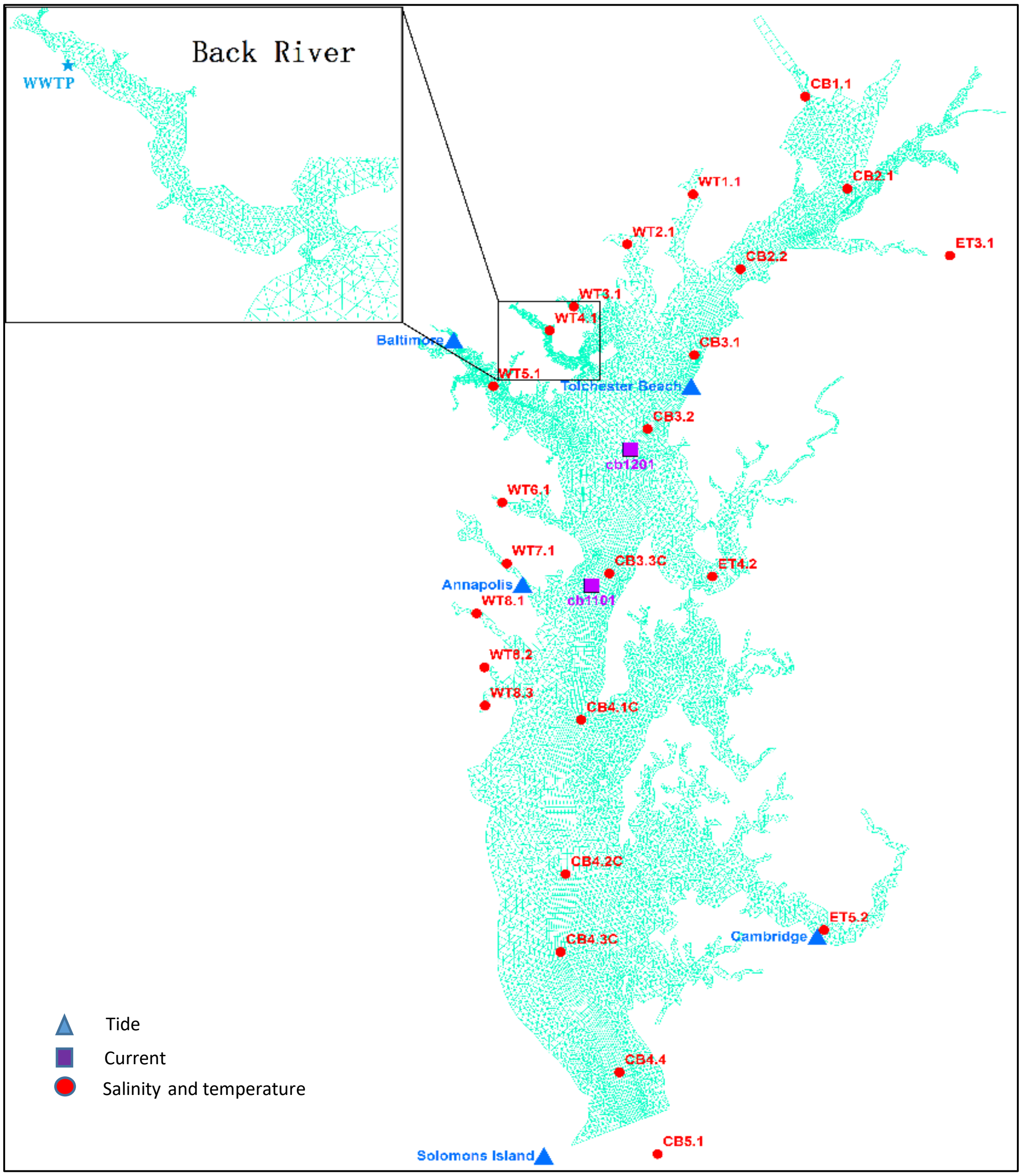


Figure 12: The Upper Bay SCHISM modelding grid with various observation statons locations

The next comparison was for vertial profile of the along-channel veloicty for modeled and the ADCP observed velocity, as shown in Figure 14. The period for the comparison was from Juy 1 – July 31, 2012 at station 1101 and station 1201 off Annapolis and the west of Baltimore Harbor repectively. It can be see obviously the velocity with semi-diurnal period and the sub-tidal oscillation. Also seen is spring tide in early July and neap tide in the midle of July. The veloicty comparisons were at multiple depths (available from cb1101 for 12 layers and cb1201 for 9 layeres), in which the storm induced variability in July 15 - 17 and 26-27 are visiable in that the surface velocity flows southward while the bottom veloicty flow northward, a baroclinic response. The mean surface velocity is sourthward while mean bottm veloicty is northward. The modeled water veloicty mimics the observaton quite well including the reversal of the mean velocity at surface and bottom, and the veloicty response during the storm conditoin.

Figure 15 show the comparsion of the surface and bottom salinity at stations CB1.1, CB21., CB2.2, CB3.1 CB3.2, CB3.3C, CB4.1C, CB4.2C, CB4.3C, CB4.4 and WT5.1 from Janunary 1 through June 1, 2012. The stations listed above covered the entire Upper Bay including a station WT5.1 inside Baltimore Harbor. The modeled surface salinity shown as blue line and the bottom salinity by a red line are compaed with the observations marked by colored circle with blue on the surface and red at the bottom. Note that the observation was available only once in March, April, May and twice in June in discrete times. Overall, the comparison was very good in that modeled blue line on the surface always touch the bottom of the observaiton in low saliinity regime and in contrast the red line at the bottom top off the obsevation in high salinity. It seems that the only place that mis-match occurs was at CB2.2 where model over-predict the bottom salinity, possibly caused by the uncertainties of the dischage from Susquehanna River. Figure 16 is for tempeature at the same stations for salinity. The simulation period is from Jaunary 1 to June 30, 2012 and can be seen obviously the temperauter is increased over the period. In this case, the modeled surface tempeature shown as blue line and the bottom tempeiature by a red line are compaed with the observations marked by colored circle with blue on the surface and red at the bottom. The observation was available only once in March, April, May and twice in June in a discrete time. Overall, the comparison was again very good in that modeled blue line on the surface always touch the blue of the observaiton at higher temperuater and in contrast the red line touch the red circle at the bottom of the low tempeautre observation. It can ben seen that surface tempeature is more variable than the bottom one due to larger fluctuation of atmospheric tempeautre.

Furthermore, the dynamics of the Baltimore Harbor was also exmained. Baltimore Harbor is located on the western shore of the Upper Chesapeake Bay and connected with the main Bay via a dredged channel of ~15 m deep. The most distinctive feature of Baltimore Harbor is a three-layered sub-tidal circulation (Schubel and Pritchard, 1986; Stroup et al., 1961) during high flow season. This pattern often occurs after the spring freshet of the Susquehanna River. The results generated by SCHISM in April shown in Figure 17 are in close agreement with the observations. When three-layer circulation occurs, the salinity contours from the head of the harbor to the adjacent bay are funnel-shaped, with higher surface salinity and lower bottom salinity in the harbor than in the bay. As the water input from the Susquehanna River decreased through May, the three-layered circulation pattern weakens: the surface inflow and mid-layer outflow are still present, but the bottom flow is significantly weakened and even reversed, resembling an inverse estuary (Figure 17 top). The inverse estuary fades away in July, as the bay salinity increases through summer. The circulation inside the harbor is eventually restored as a normal exchange flow, with surface outflow and bottom inflow (Figure 17 bottom). The confirmation of the circulation pattern in the Baltimore Harbor lend the credibility to the SCHISM model which is to be used for evaluating the effect of BRWWTP effluent discharge diverted to the proposed new outfall in Sparrows Point.

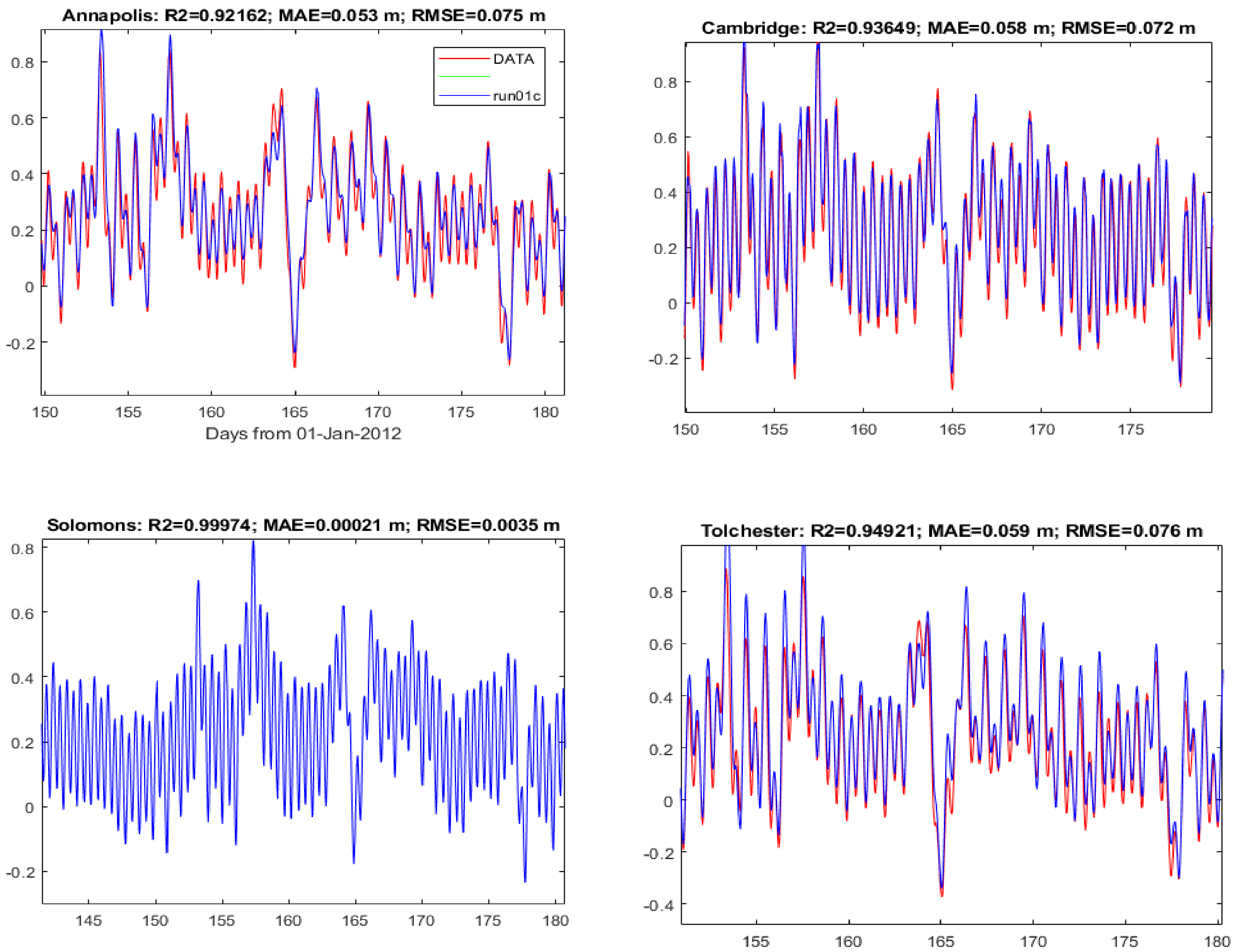


Figure 13: The modeled versus observed water elevation during June and July, 2012

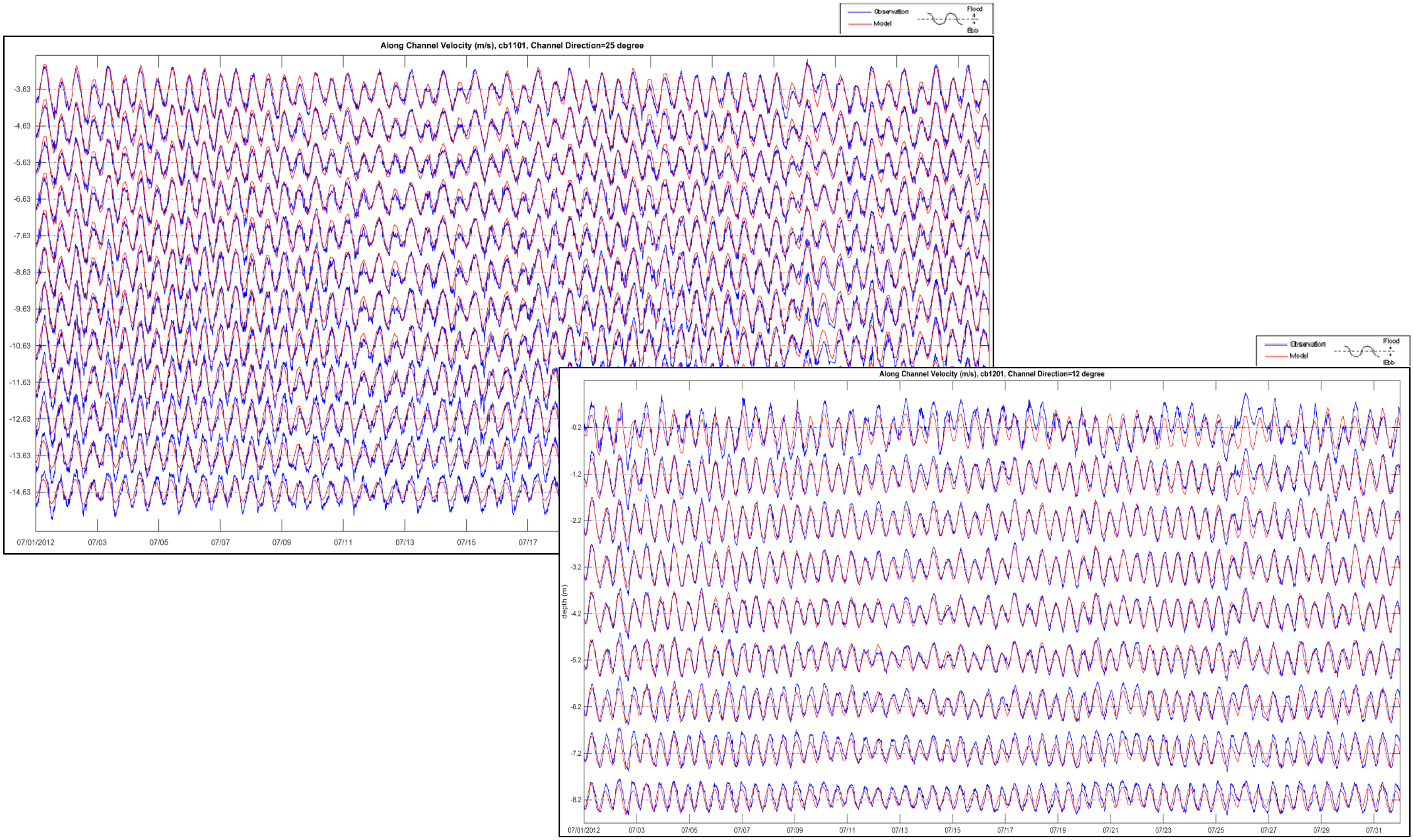


Figure 14: The modeled versus observed ADCP along channel current velocity during June and July, 2012 (top) at station cb1201 (bottom) at cb1101.

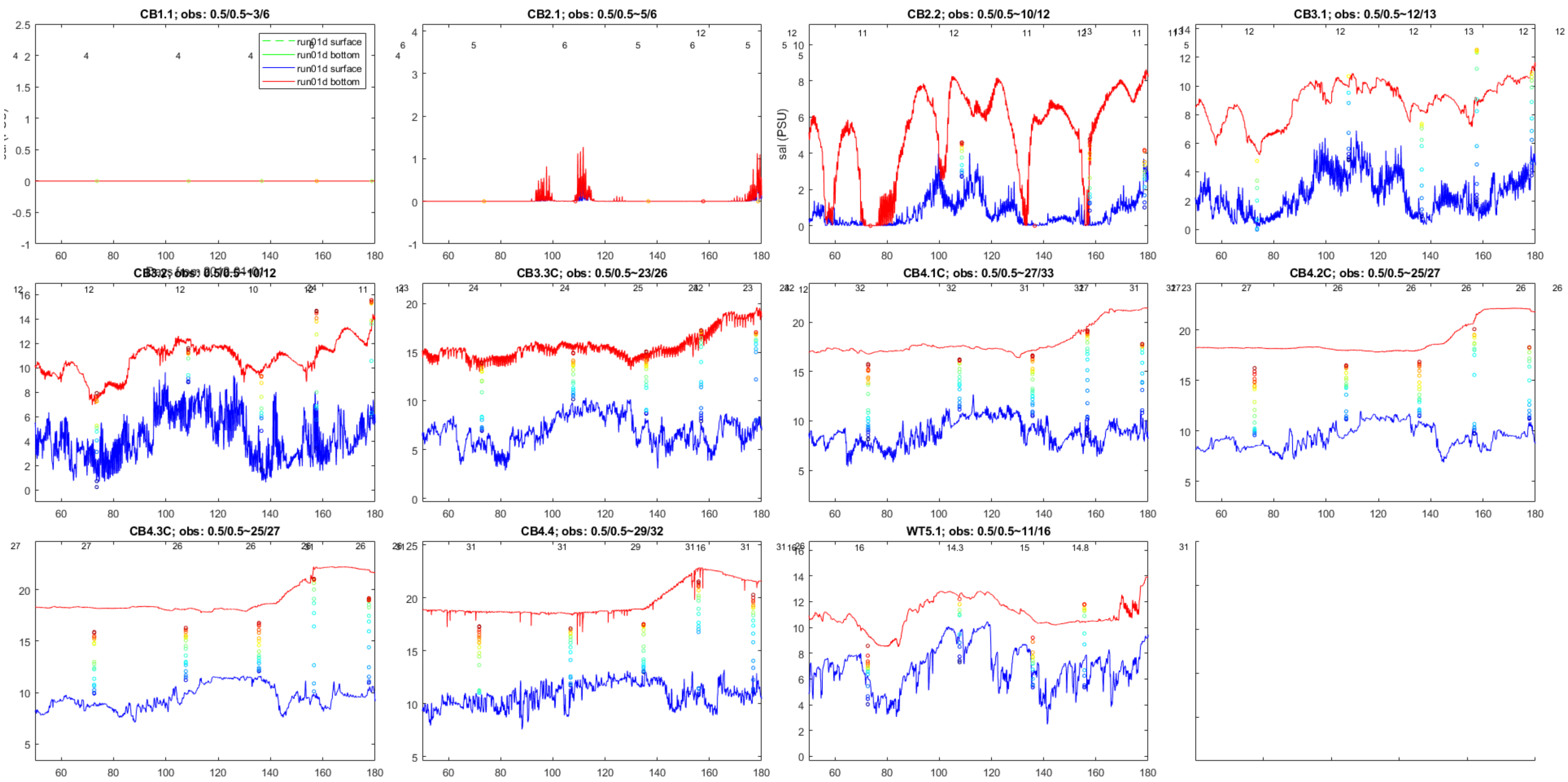


Figure 15: The modeled versus observed surface and bottom salinity in the upper Bay for year 2012

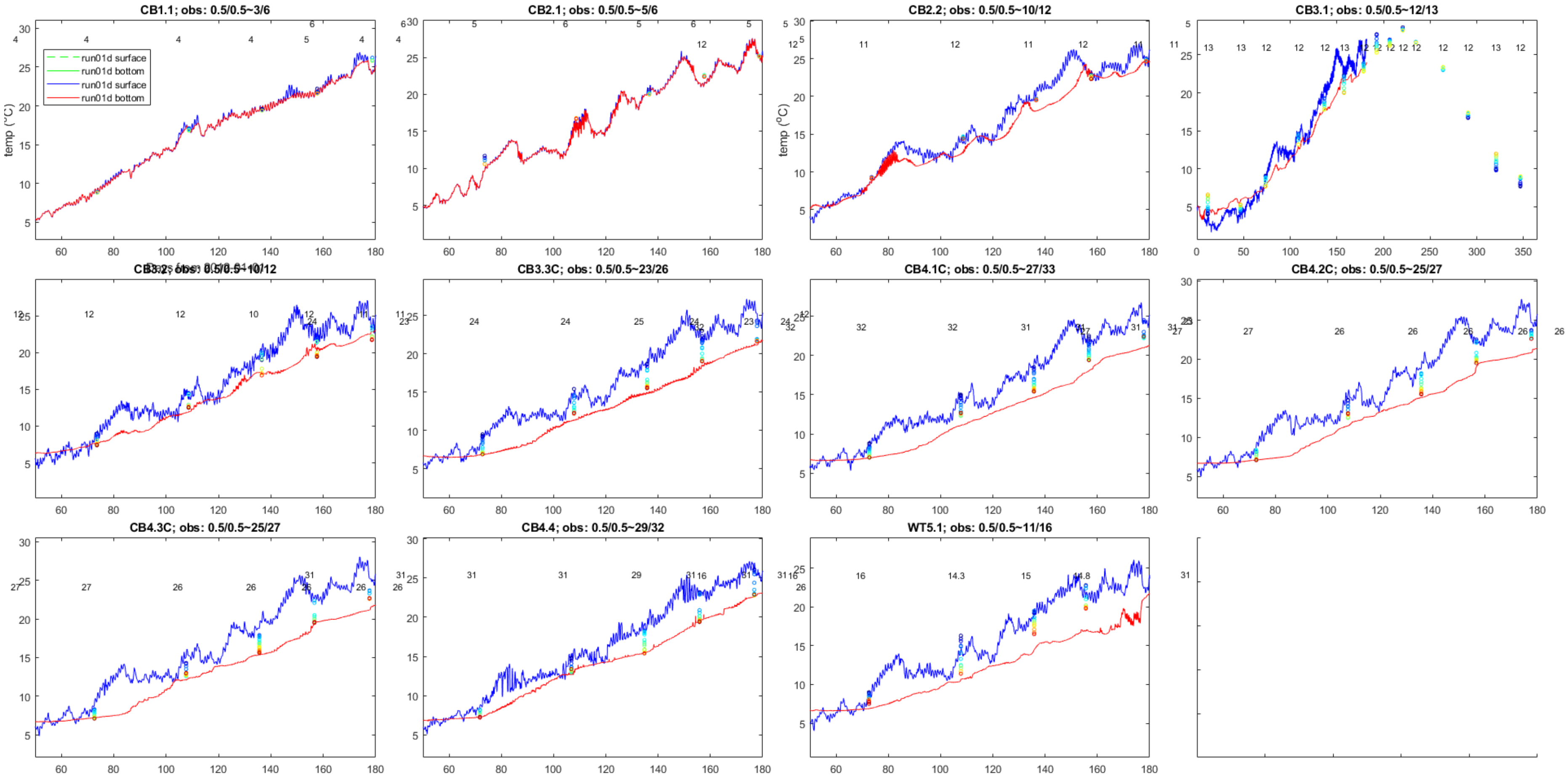


Figure 16: The modeled versus observed temperature in the Upper Bay during 2012

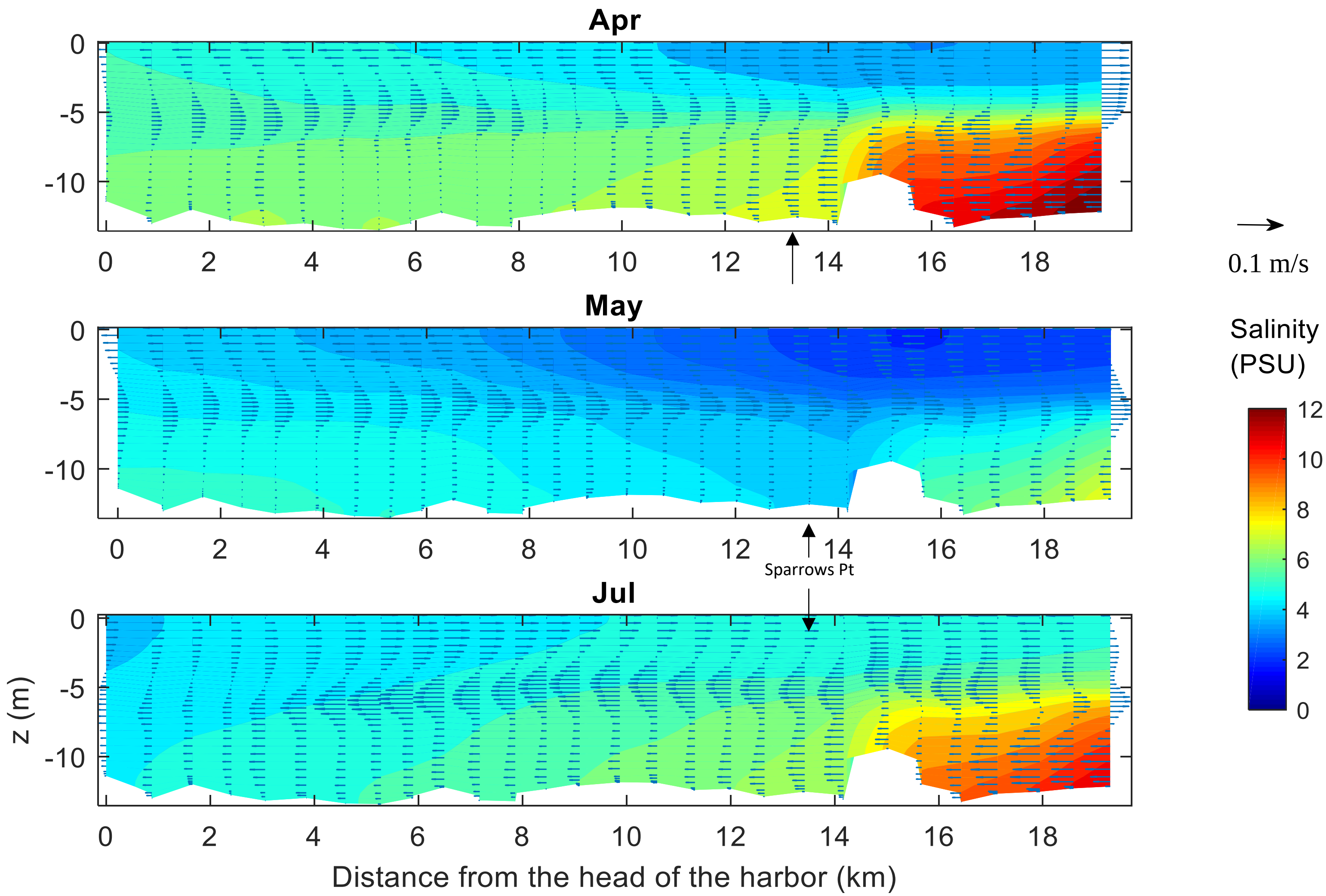


Figure 17: Monthly averaged salinity distribution and circulation patterns inside the Baltimore Harbor (0~15 km) and the adjacent bay (15~19 km): (a) funnel shaped salinity contours, and a three-layer circulation inside the harbor; (b) salinity decreasing from the head to the mouth of the harbor (15 km), and an inverse two-layer circulation inside the harbor; (c) salinity increasing from the head to the mouth, and a normal two-layer exchange flow.

V. Far-field Lagrangian Particle tracking modeling

V-1 A Lagrangian particle tracking method applied to the proposed outfall in Sparrows Point

Lagrangian Particle Tracking refers to the process of determining long 3-Dimensional trajectories of small neutrally buoyant particles (or flow tracers). In computational fluid dynamics, the **Lagrangian particle tracking** is a numerical technique for simulated tracking of particle within an Eulerian filed. It is also commonly referred to as Discrete Particle Simulation (DPS). Lagrangian particle tracking, based on the simulated velocity field derived from hydrodynamic models, is an important tool in quantifying transports in the ocean and, in this case, for track the pollutant released from the outfall in the estuary. Particle tracking in the unstructured grids typically used in coastal regions is computationally slow and only limiting the number of particles and ranges of behaviors that can be modeled. Techniques used in a new offline particle tracker "OceanTracker" developed by Vennell et at. (2021) of New Zealand Cawthron Institute) are shown to be two orders of magnitude faster than those used in an existing ocean particle tracker for unstructured grids when run on a single computer core. More significantly, its computational speed can exceed that achieved when particle tracking on a regular grid. The techniques for unstructured grids make it possible to routinely calculate the trajectories of millions of particles. This large number of particles allows much better estimates of dispersion and transport statistics. It also enables wider exploration of parameter sensitivity and particles' bio-physical behaviors to provide more robust results. The speed increases result largely from exploiting history and reuse within the spatial interpolation of the hydrodynamic model's output. When multiple computer cores are used, it further increased the speed to track a given number of particles. Given the Innovative technology developed by Dr. Ross Vennell and his group, VIMS has decided to cooperate with of Cawthron Institute in New Zealand to conduct the Lagrangian particle tracking on the proposed discharge outfall in Sparrows Point.

The first step in carrying out the Lagrangian particle tracking method in the context of applying for the discharge from an outfall is to create a fine mesh which is comparable to the scale of the outfall openings. Figure 18 show the unstructured mesh generated in the lower Baltimore Harbor, consisting of main ship channel – Craighill channel with depth of 11-13 meter and shallow shoal on the sides. Also the two channels: Sparrow Point channel in the west adjacent to the Port and Penwood channel in the east adjacent to Old Road Bay. The grid size used for this area are about 30-50 meter. Figure 19 further zooms-in to the grids surrounding the opening of the outfall which has a shape of a circle with a radius of 300 meter and were blended with the unstructured grid nearby. The resolution of the grid within the circle, ranging from 3-5 meter, is the finest we can tackle, and is small enough to simulate the characteristics of the plume near the discharge opening of the outfall. These fine grid covers the southwest portion of the cape off the eastern edge of the Sparrow Point for the purpose of encompassing the region where outfall is to be built and the mixing zone wlhich can be created by the discharge from the outfall. The velocity simulated by this fine grid was compared with the ADCP measurement at the buoy cb1201. Figure 20 shows excellent comparison of along channel velocity from the modeled results versus every 10 minutes observation by ADCP at 8 different layer in the vertical. It can be seen that the averaged mean flood and ebb tide in this region are about + and - 0.8 m/sec and the error statistics for the comparison is 0.08 m/sec MAE and 0.11 m/sec RMS. That translates to about 10% of error, which is considered to be excellent skill in terms of velocity comparisons. The spatial plot of the sub-tidal velocity field averaged over 29 days (56 tidal cycle) in the month of June, 2012 was generated and shown in Figure 21(left) for the surface current and in Figure 21(right) for the bottom current. It can be seen that the surface current in general moves from the harbor toward the Bay and the bottom current from the Bay into the Harbor in the summer, although three-layered circulation may occur when the Susquehanna flow is at the peak in the spring. In the Sparrow Point, the velocity pattern infers that there exist a counter clock-wise gyer, as shown by the blue arrow.

Once the velocity field is determined, the next step was to prepare release of the effluents from the outfall at the center of the circle 300 meter from the shore. Two types of the effluents are considered: (i) particulate matter (ii) dissolved matter. For particular matter, the one-time controlled release of neutral buoyant particles was performed. As many as 50 neutral buoyant particles were released simultaneously at the outfall with particular focus to examine whether all the particles are flushed out of the Harbour and the time it took to reach the Bay. For dissolved matter, the continuous release of dissolved tracers from the outfall and recorded as animation every 30 minutes was conducted. The source flux set at the origin of the discharge outfall is 2.19 m**3/sec (corresponding to 50mgd) and the concentration for the release was set at 2.5 mg/l (or 2.5 kg/m**3) at the submerged outfall. The initial snapshot release test was conducted for dissolved matter shown in Figure 22: Figure 22 (c) shows the released location at Sparrows Point, (a) show the presence of the stratified condition in the Harbour, and (b) shows the vertical profile of the effluent evolving with time. Owing to the presence of stratification, the intense initial mixing oscillated up and down until minutes 10 the plume became more steady and the top of the plume breaks the pycnocline to reach to the surface. It should be note that the use of 2.5 mg/l as the initial concentration of the pollutant is to mimic treated BWWTP ammonia concentration ranging between 1 – 5 mg/l for a typical effluent delivered to Sparrow Point. The vertically averaged background value monitored by the EPA Bay water quality monitoring program in WT5.1 for the period of spring, summer and fall in 2012 yield 0.21 mg/l, 0.18mg/l and 0.24 mg as mean, median and mode respectively. In terms of statistical distribution, the 10 percentile and 5 percentile are 0.1 mg/l and 0.05 mg/l respectively. For the modelling purpose for the far-field mixing at Sparrow Point, we use 2.5 mg/l as the effluent concentration released from the outfall, and use 0.1 mg/l (the 10 percentile) as the ambient background value.

V-2: Results from the particle tracking modeling

<u>The snapshot release of multiple neutral-buoyant particles</u>

As described earlier, this experiment, treating the neutral buoyant particles like a drogue, is intended to mimic the particular matter released from the effluent. Total of 50 particles were released simultaneously on March 5, 2012 during the ebb at the center of the outfall and the map updates to display the days and the location of all the

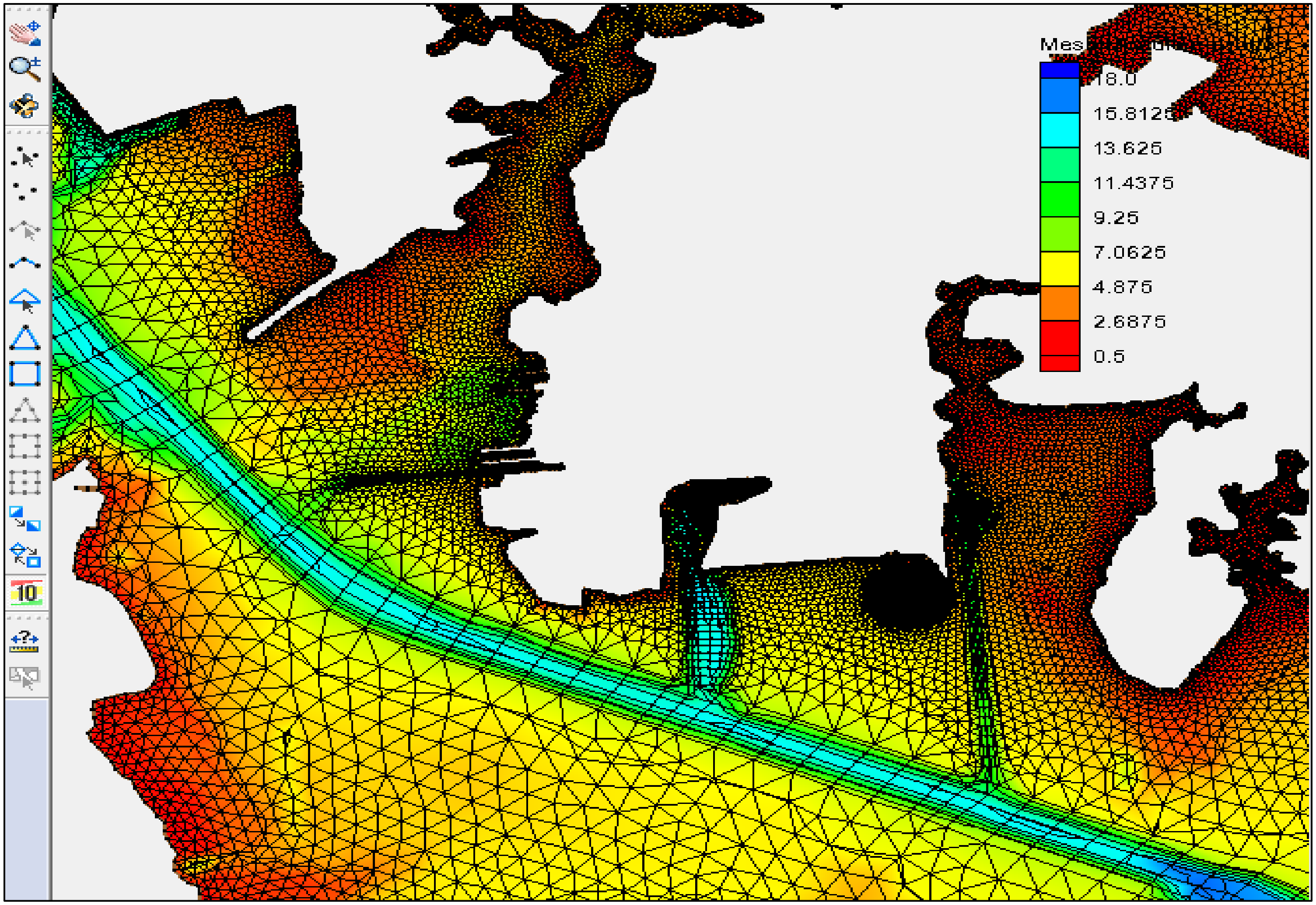


Figure 18: The SCHISM model grid with bathymetry in the Sparrow Point and the Bear Creek of the Baltimore Harbor. The proposed outfall location was discretized with a circular grid.

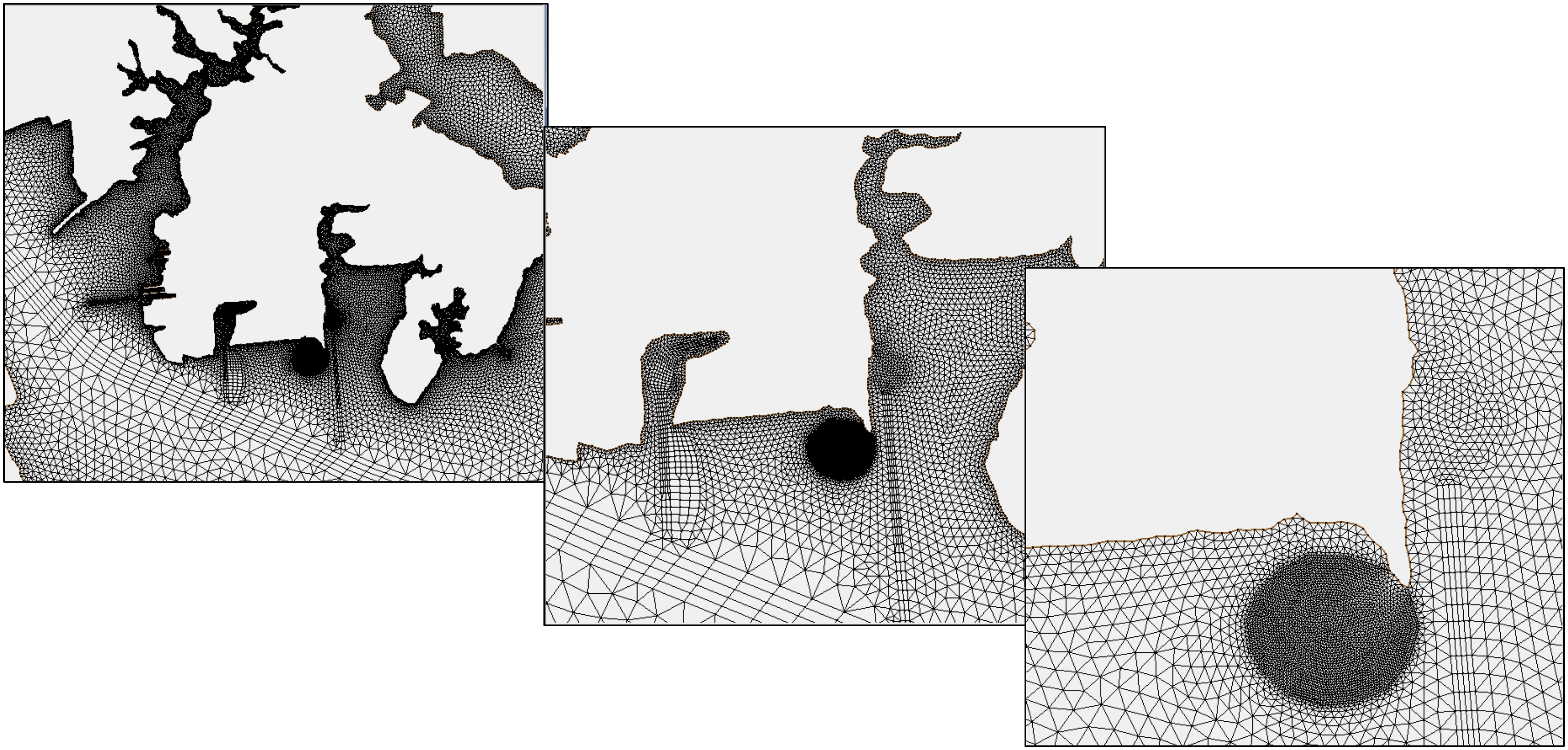


Figure 19: The Sparrows Point in the Baltimore Harbor where grid resolution is to be refined around Bear Creek, outfall 012, the proposed new outfall location, and the Old Road Bay.

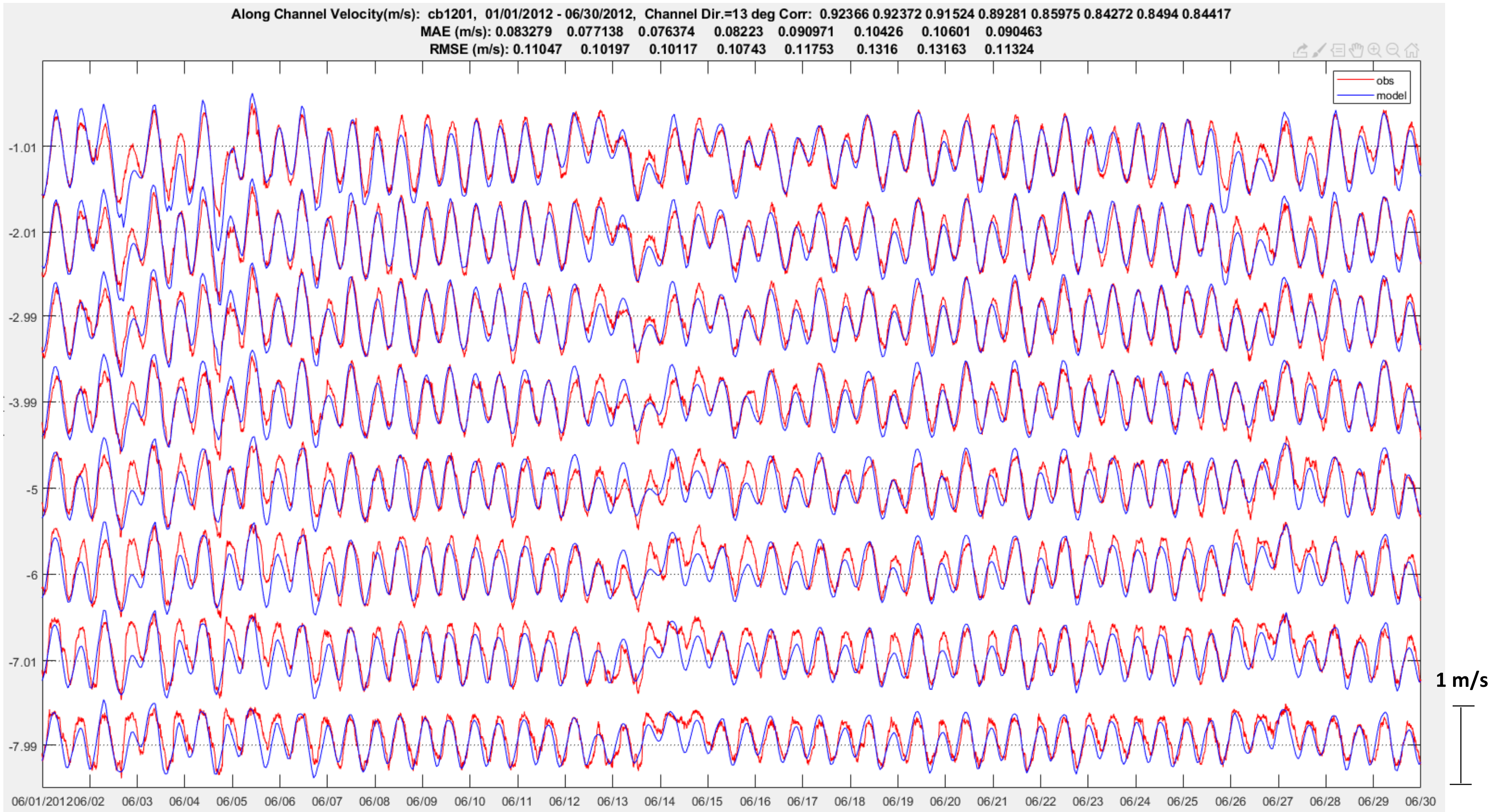


Figure 20: The modeled versus observed ADCP along channel velocity vertical profile at station cb1201 during June , 2012

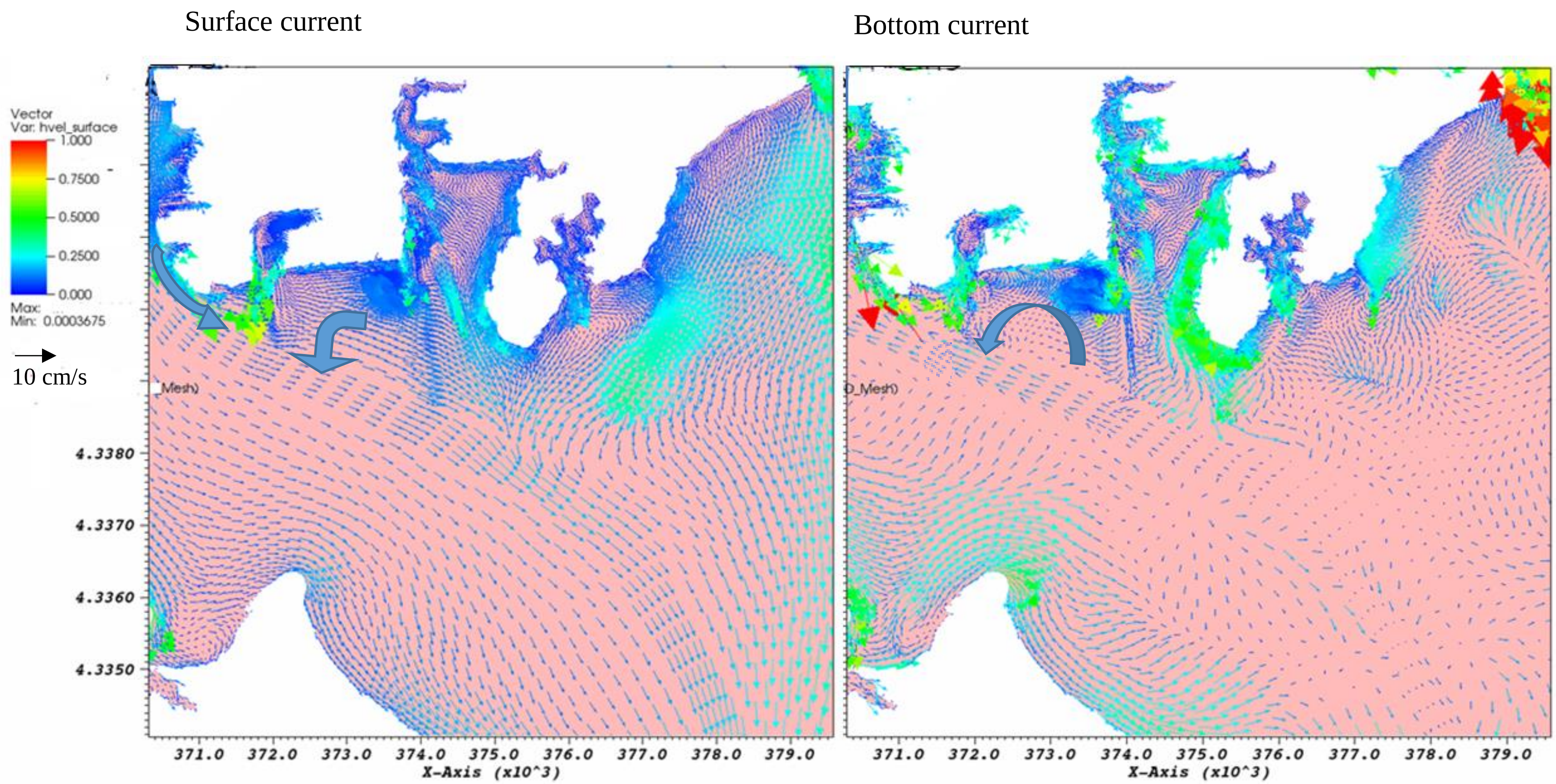


Figure 21: (left) high-resolution monthly averaged surface current (right) high-resolution monthly averaged bottom current in Sparrow Point, MD

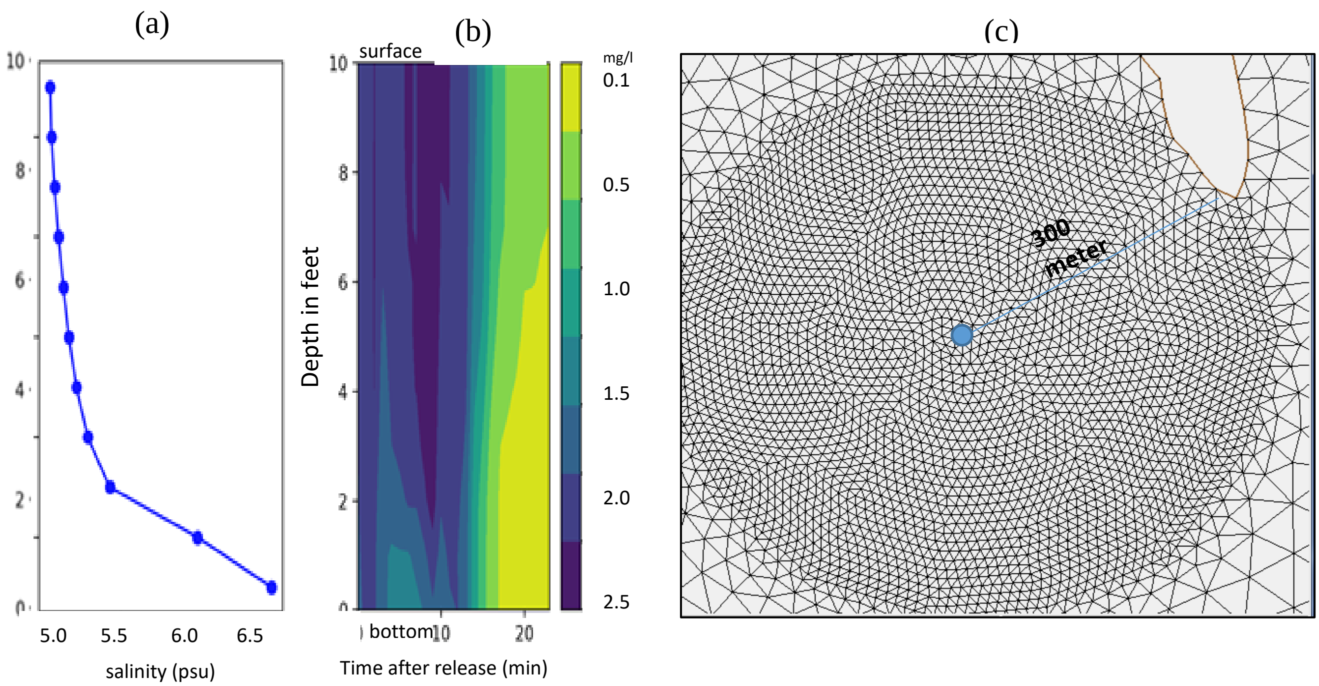


Figure 22: (left) the vertical profile for salinity and trace in the effluent release experiment. (right) the circular modeling domain with the proposed outfall located at the center 300 meter offshore.

particles. The results are shown in Figure 23 from day 1 to day 6. The associated annotation for the particle dispersion map is as follows:

Day 1: the particles are dispersed around Sparrow Point region.

Day 2: the leading edge of the particle cloud reached the Craighill ship channel where the current velocity is greater.

Day 3: The particle cloud continues to move southeastward. Some particles are reaching to the mouth of the Baltimore Harbor and beyond.

Day 4: Further dispersion of the particle cloud toward the Bay proper and the south side of the Harbor. There are 50% of the particles were out of Baltimore Harbor.

Day 5: The dispersion further accelerates. Now 94% of the particle are out into the Bay proper and 6% are still inside the Baltimore Harbor.

The particle dispersion map indicated that, after 5 days of release, the majority (96%) of the buoyant particulate matter move out of the Harbor. The dispersion pattern in general is not uniformed, but skewed toward the southeast direction toward main Bay. There is no indication that any single particle (out of 50) ever move into Old Road Bay and trapped.

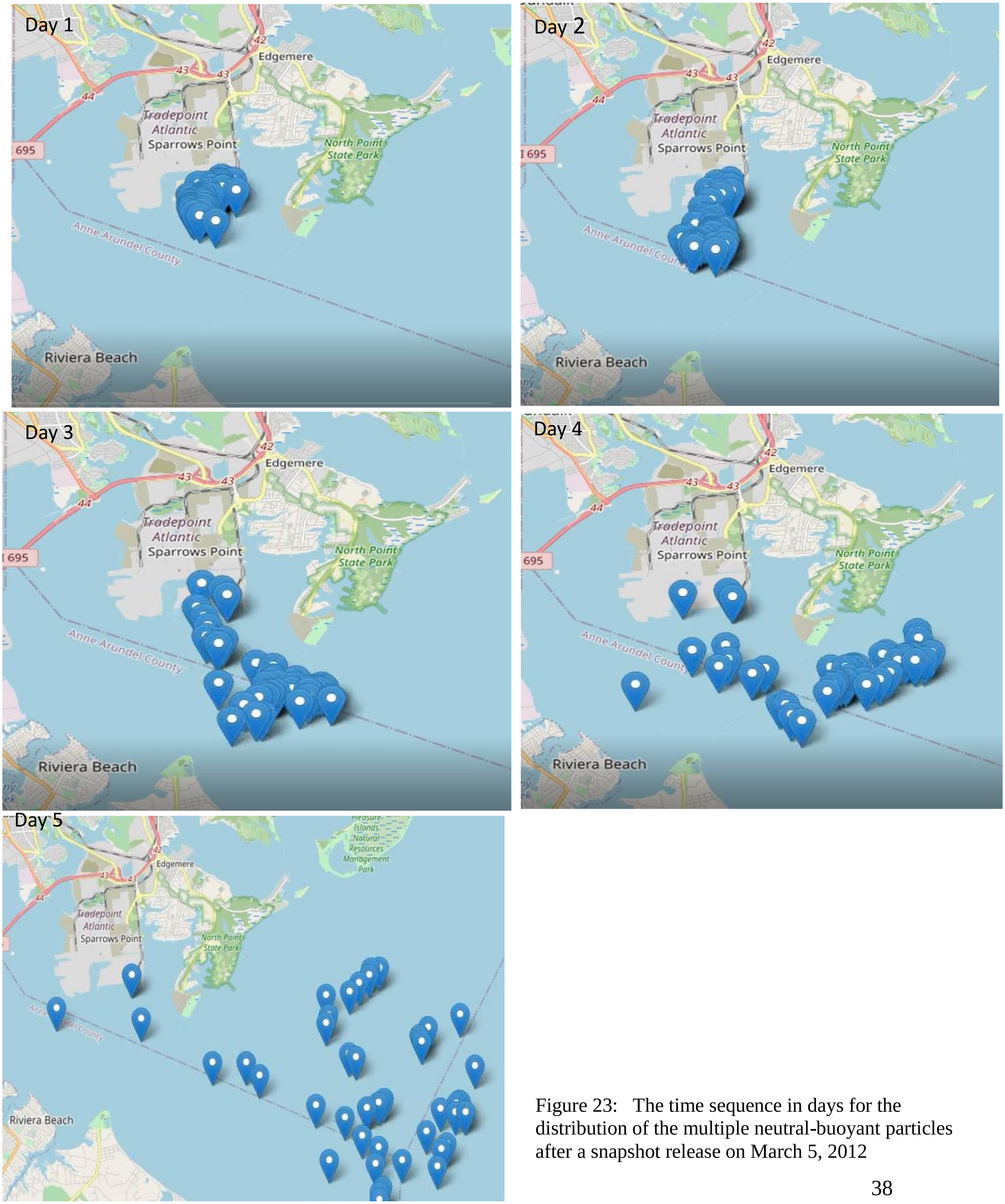


Figure 23: The time sequence in days for the distribution of the multiple neutral-buoyant particles after a snapshot release on March 5, 2012

The continuous release of soluble tracers

Using effluent concentration calculated by SCHISM and the particle tracking algorithm: ptrack.f90, a Python/jupyterlab note book was used to generate animated video file named: “Sparrow Point tracer animation.mp4” to be the companion product of the written report. The animation of the continuous release of soluble tracers from the proposed Sparrow Point outfall started from March 5, 2012 and ended on March 21, 2012 for 17 days, and the time stamp registered on the lower righthand corner of the animation runs from 07:39:00 backward to 00:00:00. The gray area shown on the animation map of Figure 24 (a) is the outline of the land mass around Sparrow Point region. The water surround the land mass is shown as the dark blue indictive of very low tracer concentration below 0.005 mg/l, considered to be pristine condition. When the effluent discharge is activated, the colors around the outfall will be turned on to represent different level of dilution, scaled from 1/500 (dark blue), 1/200 (blue), 1/100 (light blue), 1/50 (green), 1/20 (brown) to 1/10 (yellow). The concentration of effluent is set at 2.5 mg/l. When the dilution reaches 1/50, the effluent is gradually blended into blue which is the 10 percentile of ambient concentration: 0.1 mg/l based on the statistics of the observation data. Also included in the map are the current vectors whose motions move the effluent around and a separated wind vector recorded at Baltimore International Airport shown in Figure 25, from 3/5 – 3/10 as a reference.

Annotation for day 1 (with continuous release of tracers)
The release started at an ebb tide with the presence of northwesterly wind which advect the plume in the direction from northwest toward southeast against North Point like a line

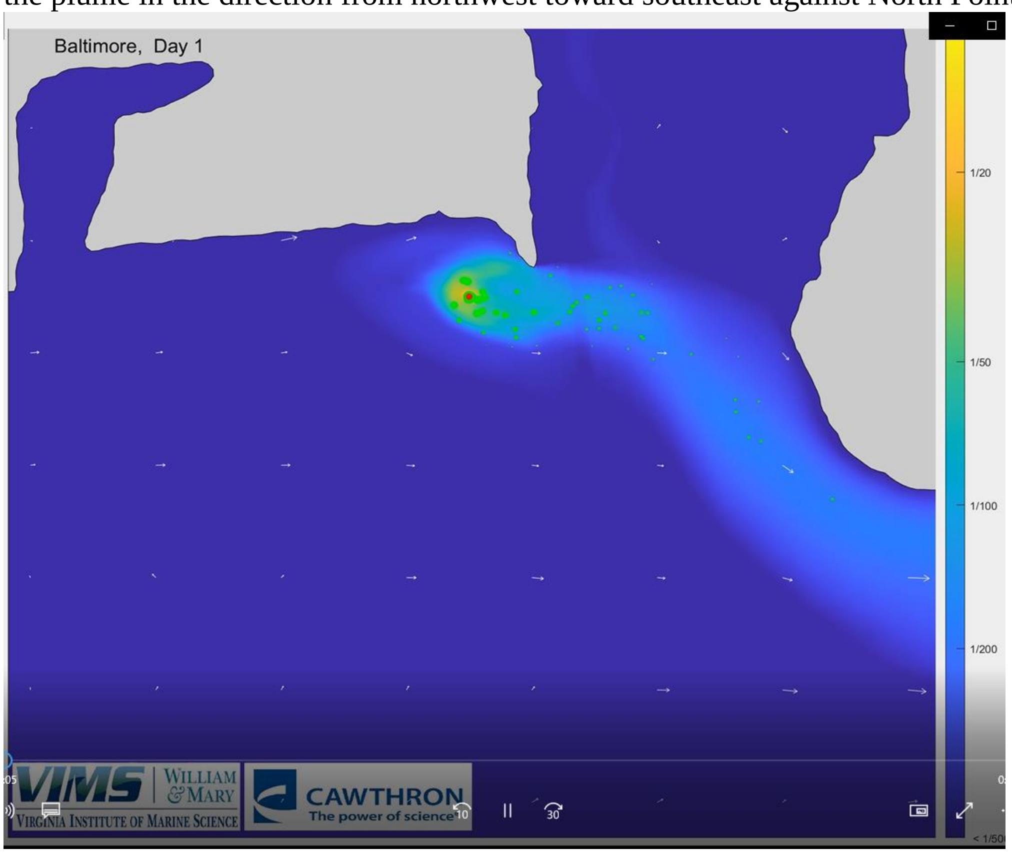


Figure 24 (a): Highlight of day 1 for the continuous release of soluble tracers source as see Figure 24 (a). As the tide change its phase, the plume turns slightly back to the land mass, but was disrupted by a northwesterly wind again which turn the plume back to the ebb tide direction. It can be seen that green particles are moving around which represent the 1/50 dilution or 0.05 mg/l, representing the conservative estimate of the ambient concentration. The screen shot of Figure 24 (a) highlights the effect of wind in orienting the plume position.

Annotation for day 2 (with continuous release of tracers)

In Day 2, we see the plume expands its lateral extent when the ambient flow is more or less quiescence, as shown in Figure 24 (b). We also see the light blue region can impinge onto the southern area of Old Road Bay. The light blue color equivalent of 1/100 dilution line representing the concentration of 0.025 mg/l which is below the observed ambient concentration obtained by the water quality data. That is to say, the water movement did enter into the area, but the concentration is so low near the background concentration that it does not have any impact. In the screen shot, the outline of the green particle is clear enough and can be use it to estimate the width of the plume. MDE COMAR did point out that the width of the plume should not exceed 10% of the receiving water cross-section width.

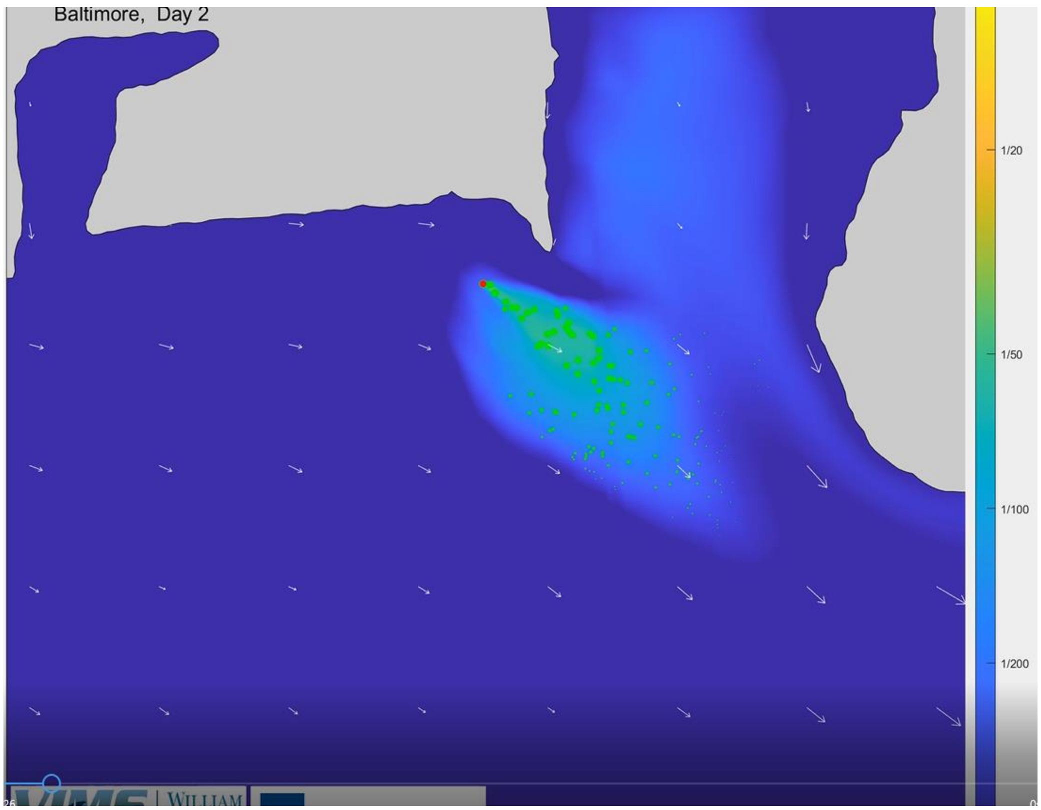


Figure 24 (b): Highlight of day 2 for the continuous release of soluble tracers

Annotation for day 3 (with continuous release of tracers)

In day 3, the plume is mostly restricted to the corner of the eastern cape from the south toward north, as shown in Figure 24 (c). It sweeps back and forth between northeastward and northwestward when the plume seems to generate enough shear to dissipate the high concentration region. This direction of flow is dictated by the wind as the prevailing wind is from the south (refer to wind record in Figure 25).

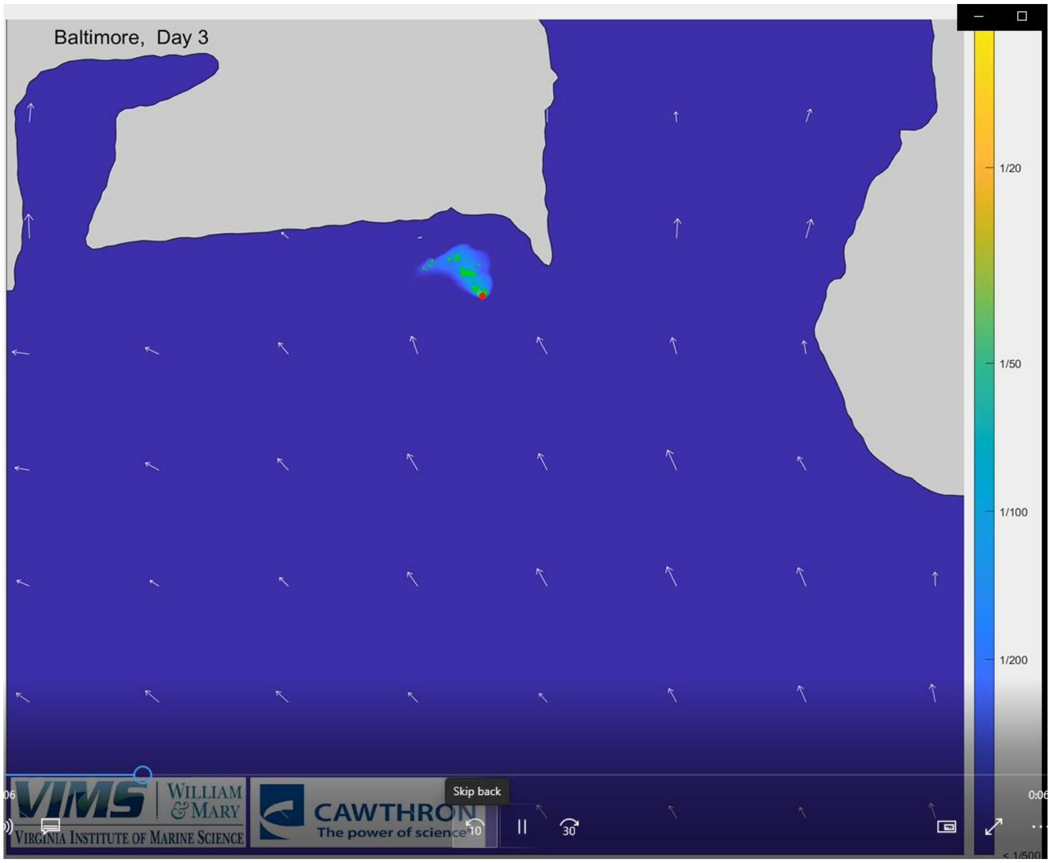


Figure 24 (c): Highlight of day 3 for the continuous release of soluble tracers

Annotation for day 4 (with continuous release of tracers)

In day 4, the southeasterly wind combined with flood generate a strong current toward the coast, which push the plume against the southern coast (of Sparrow Point) and the plume further spilled over to the west toward Port of Sparrow Point, as the screen shot Figure 24 (d) displayed.   This is the case where the boundary of shoreline actually blocked the plume and the concentration was building up. Fortunately, the phenomena is short lived. As the tide turned, so did the plume move away. Again we see it is influenced by the wind from the south and southeast.

Annotation for day 5 (with continuous release of tracers)

In day 5, it was seen that the plume orientation turned toward south, this is obviously affected by the wind from the north that day. Near noon, however, the pattern is more circular around the center of the release, as shown in Figure 24 (e). This, I believe, is the results of astronomical tide because the wind has died down significantly around noon. Later, when the northly wind pick up again, the plume become aligned to the southeast again.

In summary, after inspecting many animation for time-varying plume concentration, one can see the action of the wind can accelerate, streamline, stretch, twist the path line of concentration resulted in dilution and mixing. When compared the old outfall 012 in the Bear Creek with the new proposed site in Sparrow Point, it is obvious that the latter has more open water space and thus more fetch distance for the effect of wind to be more effective.

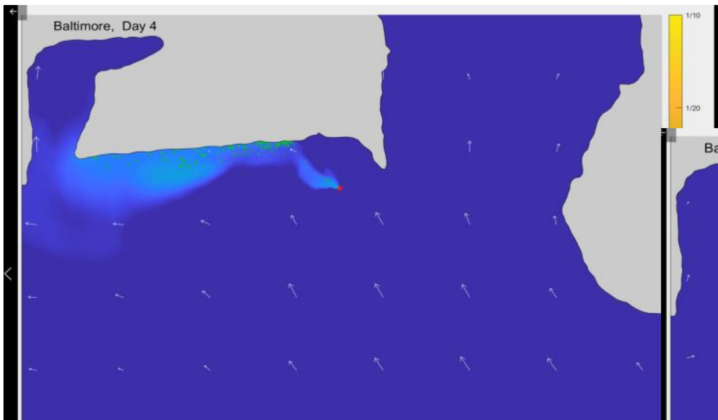


Figure 24 (d): Highlight of day 4 for the continuous release of soluble tracers

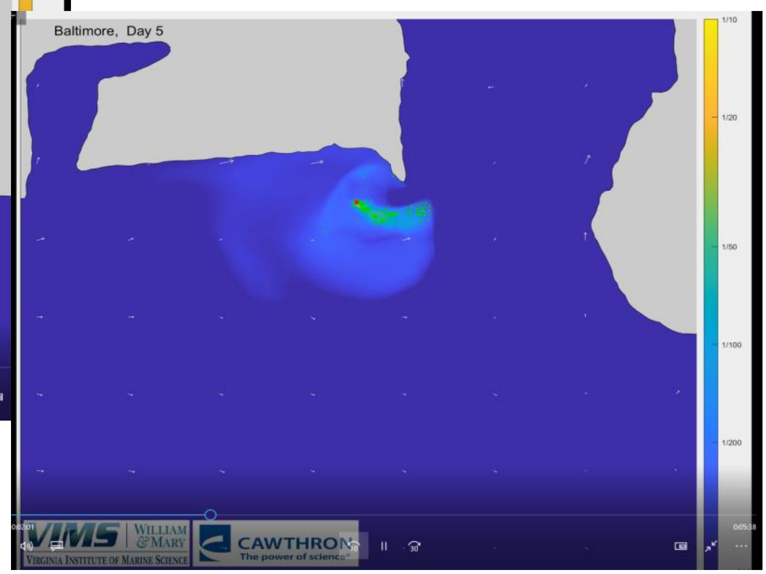


Figure 24 (e): Highlight of day 5 for the continuous release of soluble tracers

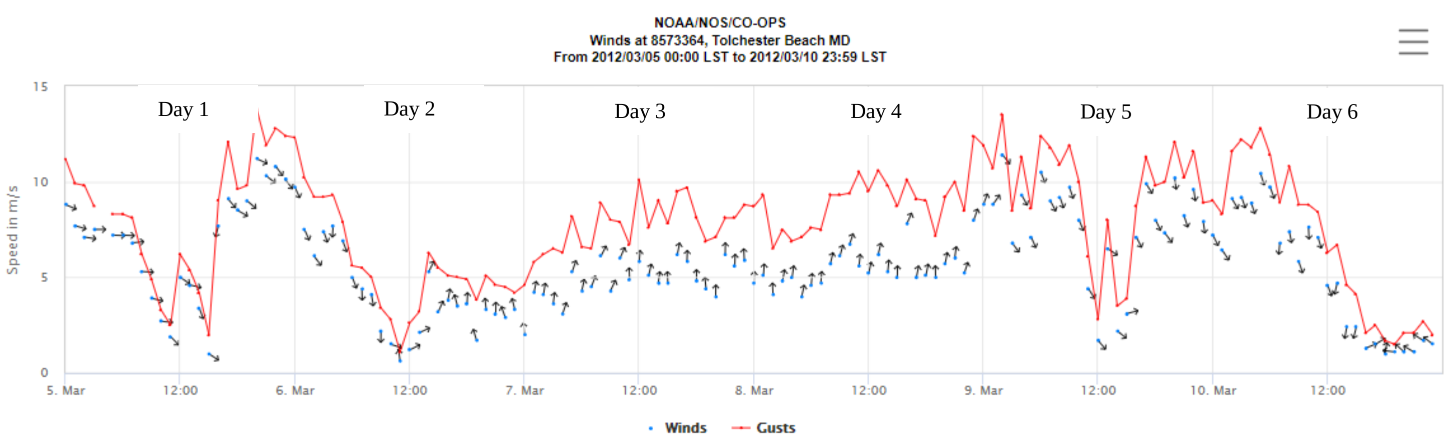


Figure 25: wind vectors for March 5-20, 2012 recorded at Baltimore International Airport

VI. Conclusion

For NPDES regulation, the permit guideline for the State of Maryland is MDE COMAR 26.08.02.05, as shown in table 6. There are two major categories in the CODE:

Table 6: COMAR 26.08.02.05

C. Application of Toxic Substance Acute Criteria for the Protection of Aquatic Life.
(1) In intermittent streams, the acute criterion shall be applied at the end of the discharge pipe.
(2) In other water bodies, achievement of the acute criterion to protect aquatic life shall be provided:
(a) Within a very short distance from the outfall using:
(i) A high velocity discharge with an initial velocity of 3 meters per second or more, and
(ii) A mixing zone limited to 50 times the discharge length scale in any direction, where the discharge length scale is defined as the square root of the cross-sectional area of any discharge outlet;
(b) Without a high velocity discharge, within a short distance from the outfall using the most restrictive of the following conditions:
(i) Meeting the acute toxicity criterion within 10 percent of the distance from the edge of the outfall structure in any direction to the edge of the mixing zone used for application of toxic substance chronic criteria,
(ii) Meeting the acute toxicity criterion within a distance of 50 times the discharge length scale in any direction, when the discharge length is defined as the square root of the cross-sectional area of any discharge outlet, or
(iii) Meeting the acute toxicity criterion within a distance of five times the local water depth in any horizontal direction from the discharge outlet, where appropriate; or
(c) By demonstration or calculation that a drifting organism may not be exposed to a 1-hour average concentration exceeding the acute aquatic life criterion.

D. Application of Toxic Substance Chronic Criteria for the Protection of Aquatic Life.

(1) Any mixing zone may not exceed the following:

(a) In freshwater streams and rivers, a mixing zone width may not exceed 1/3 of the width of the surface water body;

(b) In lakes, the combined area of all mixing zones may not exceed 10 percent of the lake surface area; and

(c) In estuarine areas, the maximum cross-sectional area of the mixing zone may not exceed 10 percent of the cross-sectional area of the receiving water body.

(2) The flows used shall be:

(a) For freshwater streams and rivers, the 30Q5 value; and

(b) For estuaries and the open ocean, determined from:

(i) Specific data, when available, for the mean water level and average tidal velocity and, when appropriate, the 30Q5 stream flow,

(ii) Specific data on waste dispersion or dilution, when available for a specific discharge, or

(iii) Dispersion or dilution studies required at the Department's discretion.

(i) C. Application of toxic substance acute criteria for the protection of aquatic life (ii) D. Application of toxic substance chronic criteria for the protection of aquatic life.

For (i), CORMIX was used for modeling near-field dilution. Specifically, CORMIX2 of the CORMIX Version 10.0 was used for proposed Sparrows Point submerged multiport diffusers outfall. The capability of CORMIX2 allows to analyze the size of mixing zone, the discharge length scale, and dilution factor under different ambient tidal stage, currents and stratification conditions found in the lower Baltimore Harbor. The size of mixing zone and the discharge length scale are all satisfied the acute criteria. The only assumption used was that the flow begins from a long slot discharge with equivalent dynamic characteristics, which was frequently used by many studies, The dilution factor under different tidal stage looks promising. The table reproduced from section III below showed the dilution factor (DF) at 7 different tidal stages are all above 10 except for the critical tidal period “a” which is during the slack water, the DF is 8, and is blow 10. Since the pollutant concerned here are eutrophication variables, such as ammonia, phosphorus, dissolve oxygen which ae not toxic substance. Its exposure criteria should be chronic (time scale of days) not acute (on hours). Thus, the short period low DF during slack is tolerant.   In correspondence with Dr. Yen-Der Cheng, Chief of Municipal discharge permit division, he pointed out   COMAR 26.08.02.05 D (2) for chronic criteria in protecting aquatic life, should be applied.

Dilution Factor	Tidal stages						
Cases	a	b	c	d	e	f	g
Base case	8.1	11.4	47.4	36.8	20.7	31.9	53.0
Scenario 1	10.0	10.2	22.4	24.9	12.3	16.4	24.9
Scenario 2	8.1	11.4	47.4	59.2	20.7	31.9	53.2
Scenario 3	8.1	11.4	47.5	59.3	21.7	31.3	53.3
Scenario 4	8.1	11.4	47.4	56.8	21.0	31.3	53.3

As for the issue whether the plume will impact the Jones Creek and Old Road Bay (on the east side of Sparrow Point), based on section V-2 “The snapshot release of multiple neutral-buoyant particles”, 96% of the neutral buoyant particle released at Sparrow Point have moved out of the Harbor into the main stem Bay after 5 days of release. The same experiments were conducted many times repeatedly, for example, on different releasing time, but it achieved the similar results. In no time even a single release buoyant particle has move into the Old Road Bay. For the V-2 “The continuous release of soluble tracers” at the proposed outfall site in Sparrow Point, the light blue color code for the concentration (against the background of dark blue) was seen occasionally impinges on the southern edge of the Old Road bay in a transient fashion. It should be reminded that the light blue color code represents the 100:1 dilution line which translates to 0.025 mg/l is way below the background ambient concentration of 0.1 mg/l (for 10% percentile) and 0.05 mg/l (for 5% percentile). Thus, occasionally some water can mov toward Old Road Bay. The water movement can occur, but the effluent concentration it carries is too low to have any impact. Essentially, it is a ambient water with background value.

In “The continuous release of soluble tracers” numerical experiment, the lateral extent of the plume marked by the green color with a 50:1 dilution line has been observed well-organized. We recast the plume onto the Google Earth map and estimated the width is about 200 meter in a 3.56 mile width of the lower Baltimore Harbor, as shown in Figure 26. Assuming the depth is the same, the cross-section area of the plume is about 3.5% of the receiving water cross-section, which is below the10% threshold the criteria required.

Figure 26: Google view for the cross-section of the effluent versus the cross-section for the receiving water

Lastly, our examination of the continuously evolving soluble tracers using animation have found that wind stress and the induced currents can play an important role in stretching, streamlining, accelerating the concentration of the path line and thus produce shear for active mixing. Part of the reason, the wind becomes much effective in produce mixing is because the long unobstructed fetch it has in the open water near Sparrow Point. When comparing the old outfall 012 located in the Bear Creek and the new proposed Sparrow Point site, it becomes obvious that the former is in a much confined region adjacent to the Bear Creek and thus does not possess the benefit of the long fetch (for wind induced mixing) that Sparrow Point has. This provide additional justification for the move of the old outfall to the new proposed location.

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