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Article

Exploring Localized Mixing Dynamics during Wet Weather in a Tidal Fresh Water System

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Abstract: A recently validated 3-dimensional implementation of the Environmental Fluid Dynamic Code (EFDC) for the tidal-fresh portions of the Delaware Estuary was exercised against the results of a dye release from a sewer outfall during a storm. The influence on dye distribution in the estuary resulting from variations in wind and local storm water discharges in an urban area is investigated. The modeled domain stretches 116 km from the head of tide and includes hydrologic input from 33 streams and a number of municipal and industrial discharges. Bottom roughness was parameterized from sedimentological and geophysical surveys. Model validation to-date relies upon field observations and tidal harmonics for sea level and currents derived from the NOAA-NOS 1984–1985 circulation survey and a current survey conducted by the Philadelphia Water Department (PWD). Model representation of dye distribution compared favorably for observations of concentrations in the dye plume from 10 cross-sections spanning the extent of the plume over seven tidal cycles. The dye distribution was characterized by an initial period of high local storm water and stream inflows with low wind conditions, lasting for several tidal cycles, followed by a period of reduced fresh water input and increasing wind stress. The dye experiment provided a unique opportunity to observe the performance of the model through the transition between these two very different meteorological periods, and to explore the physical conditions driving the hydrodynamics through both observations and numerical experiments. The influences of local meteorological forcing and channel morphology on lateral mixing, dispersion and longitudinal dynamics are characterized.

Keywords: hydrodynamic numerical model; dye study; wind

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1. Introduction

During the City of Philadelphia's development in the 19th and 20th centuries, a combined sewer system was built, which conveys stormwater runoff and sewage together in the same pipe network [1]. Today about 60% of the City's sewered area is still served by combined sewers, especially in the older sections of the city. The remaining 40% is served by separate sewers for sewage and stormwater respectively [2]. High intensity rainfall within the City causes the combined sewers to reach their maximum capacity, and a mixture of stormwater and untreated sewage is released into rivers and tributaries.

The City of Philadelphia is regulated by the Pennsylvania Department of Environmental Protection for discharges from combined sewer overflows and storm water outfalls to the Delaware and Schuylkill Rivers. The Philadelphia Water Department (PWD) is developing a water quality model of the tidal Delaware and Schuylkill Rivers to quantify the effects of City of Philadelphia discharges on these waterbodies and meet regulatory requirements.

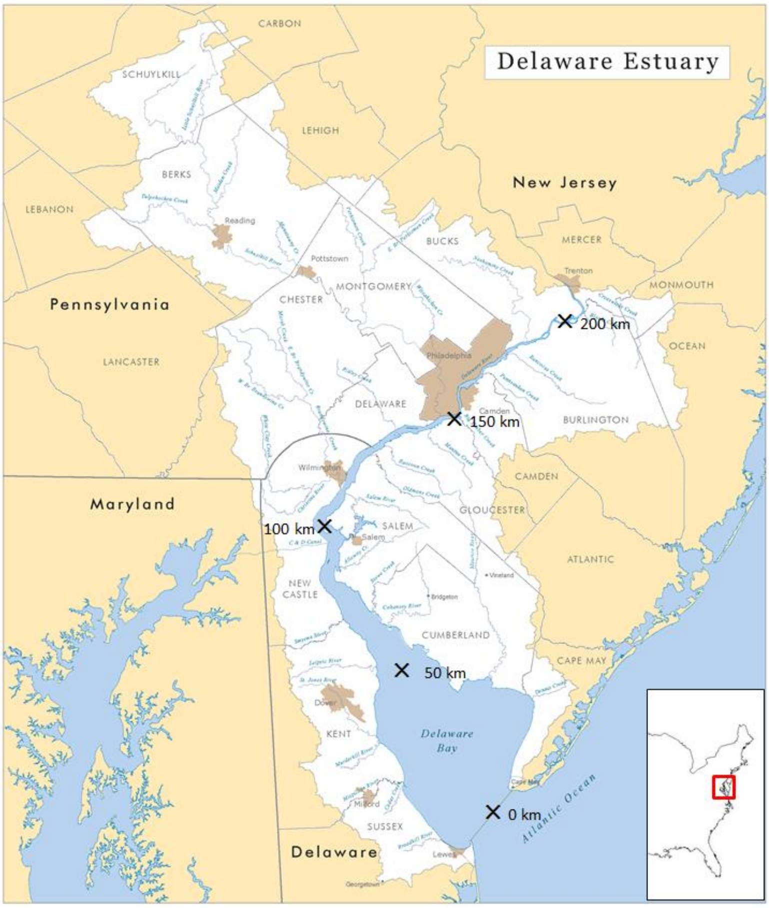
For this purpose a 3-dimensional hydrodynamic numerical model was developed using the Environmental Fluid Dynamics Code (EFDC) [3]. It was hydrodynamically validated against observations from the 1984 NOAA-NOS circulation survey and contemporary ongoing long term current surveys conducted by the PWD that started in August 2012. The following study shows a first attempt on assessing the model's transport capabilities by exercising it against a dye study conducted by Ocean Surveys, Inc. (OSI) for the Delaware River Basin Commission (DRBC) [4].

2. Methods

2.1. Study Area

The Delaware Estuary is located on the East Coast of the United States between Washington, D.C. and New York, NY, USA (Figure 1). The estuary spans 215 km from its mouth between Cape May, NJ, USA and Lewes, DE, USA to the head of tide at Trenton, NJ, USA. The City of Philadelphia is situated at River 147–180 km. The model domain includes the Delaware River section from 99 to 215 km and the tidal Schuylkill River. The model area begins north of the Chesapeake and Delaware Canal confluence, where a tidal gauge at Delaware City, DE, USA provides observed water levels for model forcing. The turbidity maximum zone of the Delaware Estuary reaches from 50 to 120 km. With the mean salt intrusion reaching 97 km, the model domain is generally considered to be tidal fresh water. Significant levels of salinity are only reached within the model domain during severe drought conditions when upstream river discharges are low.

Figure 1. Overview over Delaware River Estuary.



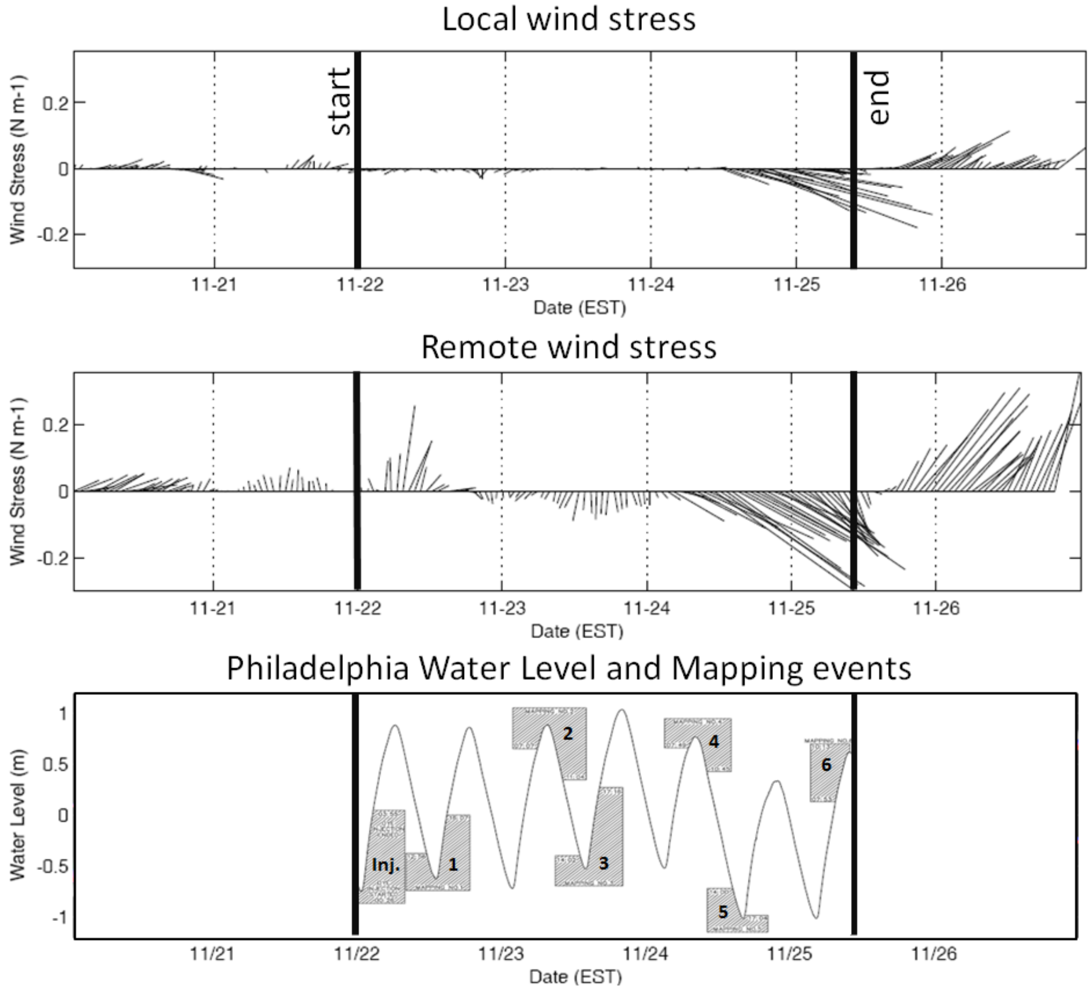
Within the City of Philadelphia, there are 4800 km of sewer pipe, 455 storm water outfalls and 164 combined sewer outfalls (CSO). Most outfalls discharge directly into the Delaware and Schuylkill Rivers. Some are located along smaller non-tidal tributaries in the city area, the Cobbs, Frankford and Pennypack Creeks, which are connected as boundary conditions to the tidal model.

2.2. 1997 CSO Mixing Zone Study

The aim of the mixing zone study was to characterize a CSO discharge during a wet weather event, to identify initial dilution and mixing, and to determine the far-field impact of CSOs [4]. The study was conducted by OSI on behalf of DRBC and HydroQual, Inc. (HQI) during the period of 21–25 November 1997. Rhodamine WT dye was injected over a period of 3.5 h into a trunk sewer upstream of CSO D-39 shortly after midnight on 22 November 1997, while the CSO was actively overflowing due to a 1.1 inch storm in the region. Dye tracer concentrations were recorded during six plume mappings on the following days that coincided with either high or low slack tides (Figure 2). Contour lines of the plume during each mapping were determined by interpolation of the measured track lines.

Mappings of the observed dye data showing the interpolated dye plume projections were created by OSI. The dye concentration quickly declined with the beginning of a strong local wind event that led to a setdown of the mean sea level as can be seen in Figure 2 during 24 November 1997.

Figure 2. Wind conditions and time table of dye injection and mapping events (shaded areas).



2.3. Model Setup

The EFDC model used for this study was developed at the Virginia Institute of Marine Science and has been applied for a wide range of environmental studies. The EFDC model solves the 3-dimensional, vertically hydrostatic, free surface, turbulent averaged equations of motion using stretched or sigma vertical coordinates and Cartesian or curvilinear, orthogonal horizontal coordinates. It solves the equations using a combination of finite volume and finite difference techniques, and allows for wetting and drying in shallow areas. Dynamically coupled transport equations for turbulent kinetic energy, turbulent length scale, salinity and temperature are also solved. Additionally, an arbitrary number of Eulerian transport-transformation equations for dissolved and suspended materials can be solved simultaneously [3,5].

The model and the dye study were used to characterize the hydrodynamics of the tidal Delaware River and the impact of stormwater and CSO discharges. A strong wind event at the end of the dye study period appeared to have considerable influence on the rate of dilution. Three model scenarios were performed to analyze the impact of wind on dye transport in the model:

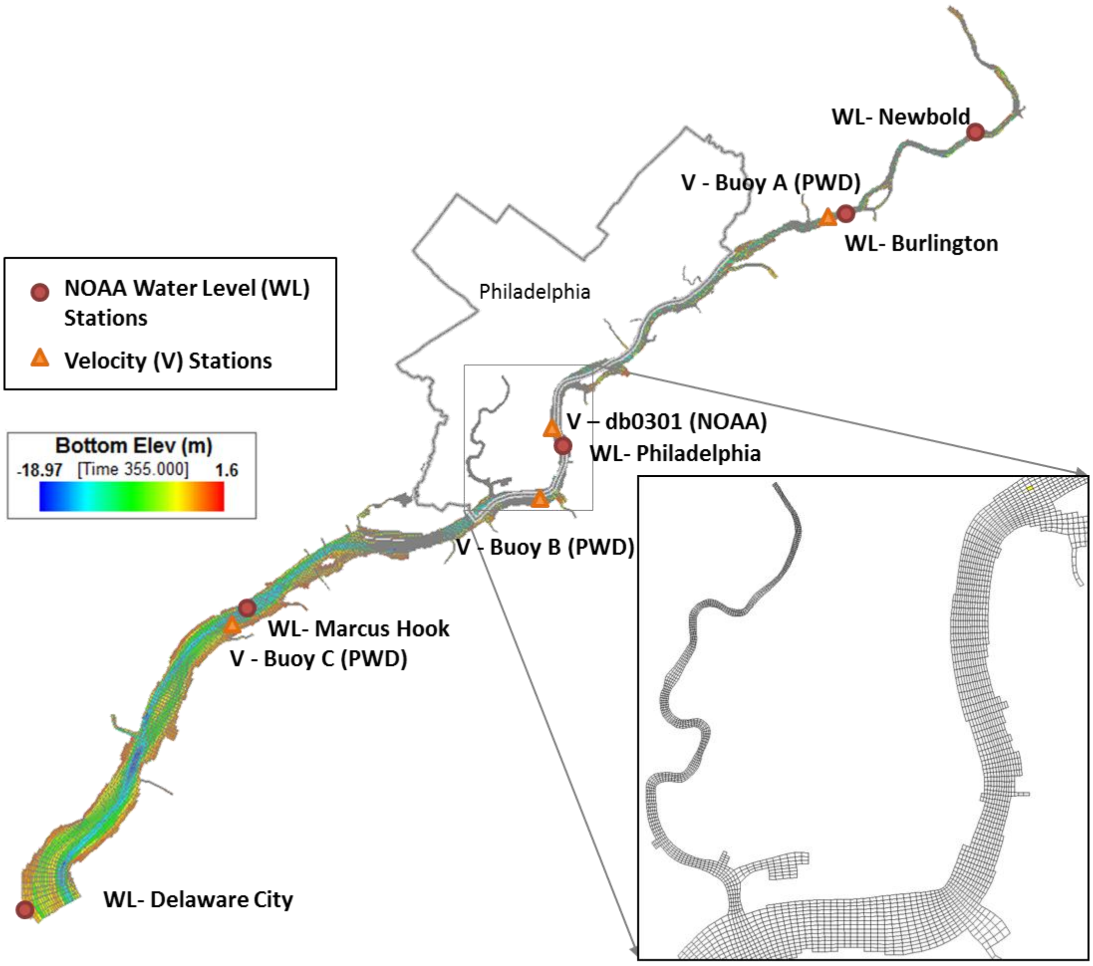
(i) tidal only: forcing with predicted water level at the open boundary, no wind field;
(ii) no wind: forcing with observed water level at the open boundary, no wind field;

(iii) wind: forcing with observed water level at the open boundary and wind field inside the model domain.

2.3.1. Model Grid

The model grid was generated using RGFgrid from the Delft3D software package [6] (Figure 3). The domain spans 116 km of the tidal Delaware River from the downstream water level open boundary at Delaware City, DE, USA to the head of tide at Trenton, NJ, USA. The tidal extents of the Schuylkill River and three tributaries (Cobbs Creek, Frankford Creek, Pennypack Creek) that receive City of Philadelphia CSO discharges are represented in the model. The grid contains 9746 elements with lengths ranging from 17 m in the lateral direction in small tributaries to 650 m longitudinally in the Delaware River, and has five vertical sigma layers that follow the bottom geometry.

Figure 3. Model domain and grid.



2.3.2. Initial and Boundary Conditions

2.3.2.1. Model Validation

Initial model calibration and validation were performed using data from the NOAA-NOS 1984–1985 circulation survey [7]. An "astronomical tides only" scenario was used to assess the model's capability of accurately representing the tidal dynamics. The model was further calibrated using observed data from 1984 to 2012 for model forcing and comparison. Roughness calibration was performed based on information from a sedimentological survey of the upper Delaware Estuary [8], leading to local roughness parameters ranging from 0.001 m in the downstream section of the model to 0.015 m in the coarser upstream section.

NOAA/NOS Survey 1984

The National Oceanic and Atmospheric Administration and National Ocean Service (NOAA/NOS) conducted a Delaware Bay and River circulation survey in 1984/1985. Stations within the model domain upstream of the Chesapeake and Delaware Canal were used for this study. The majority of measurements were conducted from February through April 1984. Five water level stations and seven current stations were available for model forcing, as reference, and to develop tidal constituents. In the tidal-only scenario the downstream open boundary was forced using the predicted water level for Delaware City based on 37 tidal constituents from contemporary water level data. The flow boundaries were forced using annual mean discharge from 23 USGS river gauges.

No observed water level was available for Delaware City in 1984 to force the hindcast scenario, thus the water level time series from the nearby Reedy Point station was shifted in phase to match the timing at Delaware City. Observed discharge from 23 USGS stations provided data for the flow boundaries. The bathymetry used for grid generation was assembled from individual sounding datasets downloaded from the NOAA National Geophysical Data Center, Digital Elevation Model Discovery Portal [9] and converted to NAVD88 using VDATUM [10]. Additional soundings of smaller tributaries of interest were conducted by PWD and integrated into the bathymetry data set.

PWD Long Term Current Survey 2012/13

In May 2012 PWD installed three buoy mounted ADCPs within the model domain to collect long term current measurements for additional model calibration and validation. The NOAA Physical Oceanographic Real-time System (PORTS) for the Delaware Bay provided current data at a station near Philadelphia (db0301) and water levels at five stations within the domain [11] (Figure 3). Observed water level data for Delaware City and discharge data from all gauged tributaries along the model domain were used to force the open boundaries. An area ratio based approach was used to estimate discharge for ungauged tributaries and for run off areas downstream of USGS gauges and along the Delaware River. Wind forcing data were generated from measurements at five stations within the domain obtained from the National Climatic Data Center [12].

2.3.2.2. Dye Study 1997

The dye study was conducted in November 1997. Observed water levels were available for stations at Reedy Point and Philadelphia at this time. Reedy Point water level data was shifted in phase to be used as open boundary forcing and the Philadelphia water level data was compared to model results for validation. Observed discharge from USGS gauges were used as available and discharge for ungauged tributaries and runoff areas were estimated using an area ratio based approach. Since the dye study’s main goal was to observe a wet weather event, all Philadelphia CSO inputs were included in the model forcing. The PWD Hydrologic and Hydraulic (H&H) modeling group maintains a validated Stormwater Management Model (SWMM) of each of Philadelphia's three wastewater plant drainage districts. The SWMM model utilizes precipitation data, geospatial data of the land cover of the contributing service area, and numeric representation of the combined sewer system to simulate CSO flows. A range of flow estimates for each of the City's 164 CSO regulators and reported flows from the three wastewater treatment plants were provided for the dye study simulation exercise.

For the study, dye was injected into the sewer line 180 m back from the end of pipe. An average dye concentration of 236 parts-per-billion (ppb) was measured downstream of the injection point at the end of the pipe. The dye was injected upstream of a regulator that directs flow to a treatment plant during dry weather and allows for overflows into the river during storms. Thus, a considerable amount of dye was likely redirected to the plant and did not reach the outflow where the concentration was measured. The reported discharge was back calculated based on the measured concentration and the total amount of dye injected. Application of the reported discharge resulted in overprediction of dye concentrations in the river. As an alternative, the modeled CSO discharge for this sewer line was used, which resulted in good agreement with observed dye concentrations in the river. Wind fields were generated from observed data of three NCDC stations within the model domain.

3. Results and Discussion

3.1. Model Validation

For the astronomic tidal-only simulation in February through April 1984, water level results at Philadelphia showed good agreement with predicted time series as shown in Table 1 below. Amplitude errors range from 0 to 6 cm for water level. A slight shift in phase exists compared to observed data, which explains higher values for the RMSE. The RMSE and Skill by Willmott [13] are 12 cm and 0.98, respectively. Results for all water level stations range from 9 to 15 cm for RMSE and 0.98 to 0.99 for Skill.

Table 1. Tidal-only harmonic constituents: predicted *vs.* model for water level and major velocity at Philadelphia NOAA stations 8545530 and C51.

	Water Level—Amplitude (m) Phase (h)						Major Velocity—Amplitude (m/s) Phase (h)					
Tidal Const	Amp Pred	Amp Mod	Amp Err	Phase Pred	Phase Mod	Phase Err	Amp Pred	Amp Mod	Amp Err	Phase Pred	Phase Mod	Phase Err
M2	0.86	0.86	0.00	6.42	6.47	0.05	0.94	0.86	−0.07	4.14	3.91	−0.23
S2	0.10	0.12	0.02	7.56	8.07	0.51	0.07	0.12	0.05	5.33	5.67	0.33
N2	0.15	0.19	0.04	5.99	5.90	−0.09	0.11	0.18	0.07	3.48	3.28	−0.19
K1	0.11	0.06	−0.06	18.70	19.34	0.65	0.07	0.03	−0.05	13.22	13.68	0.46
M4	0.09	0.07	−0.02	4.57	4.71	0.14	0.15	0.13	−0.02	4.11	4.07	−0.03
O1	0.09	0.07	−0.02	18.86	18.52	−0.34	0.05	0.03	−0.01	13.86	12.44	−1.41
M6	0.06	0.05	−0.01	2.88	2.80	−0.08	0.10	0.08	−0.02	2.52	2.33	−0.19

Velocity results also showed good agreement with predicted time series at Philadelphia station C51 from the NOS Delaware River and Bay Circulation Survey. Velocity data were measured 8.5 m above bottom corresponding to model results from the second layer below surface. Amplitude errors ranged from 1 to 7 cm/s as shown in Table 1. The RMSE and Skill are 11 cm/s and 0.98 respectively. Results for currents range from 7 to 17 cm/s for RMSE and 0.42 to 0.98 for Skill at all stations.

For the hindcast simulation in August through September 2012, water level results showed good agreement with predicted time series with amplitude errors smaller than 3 cm as shown in Table 2 below. The RMSE and Skill are 7.7 cm and 0.99.

Velocity results also showed good agreement with predicted time series as shown in Table 2 below. Amplitude errors range from 0 to 7 cm/s. The RMSE and Skill are 8.5 cm/s and 0.98.

Table 2. Hindcast harmonic constituents, August–September 2012: observed *vs.* model for water level and major velocity at Philadelphia NOAA stations 8545240 and PWD Buoy B, layer 4.

	Water Level—Amplitude (m) Phase (h)						**Major Velocity—Amplitude (m/s) Phase (h)**					
Tidal Const	Amp Pred	Amp Mod	Amp Err	Phase Pred	Phase Mod	Phase Err	Amp Pred	Amp Mod	Amp Err	Phase Pred	Phase Mod	Phase Err
M2	0.84	0.87	0.03	1.41	1.27	−0.14	0.64	0.58	0.07	11.13	11.10	0.04
S2	0.09	0.11	0.02	2.52	2.49	−0.03	0.09	0.08	0.01	0.20	0.13	0.07
N2	0.15	0.12	−0.02	0.93	1.52	0.59	0.09	0.08	0.01	11.69	11.63	0.05
Kl	0.10	0.10	0.00	13.86	14.11	0.26	0.05	0.03	0.02	9.33	8.21	1.12
M4	0.08	0.09	0.01	5.63	5.78	0.15	0.07	0.08	−0.01	5.41	5.06	0.36
O1	0.08	0.11	0.03	13.91	13.04	−0.87	0.04	0.03	0.01	5.60	6.79	−1.19
M6	0.05	0.04	−0.01	2.00	1.82	−0.18	0.06	0.06	0.00	3.33	1.17	2.15

3.2. Dye Study 1997

Dye simulation results were compared to in-situ fluoroscopy observations that were converted to ppb by weight. The most fully-developed plume is represented by Mapping 3, which is comprised of survey observations interpolated over the 3.5 h of Day 2, low-slack tide (Figure 4). Figure 5 below shows contour plot visualizations of simulated dye results for the corresponding Mapping 3-time, which successfully characterized the observed plume. The extent of the 0.01 ppb contour line, thus the total detectable plume, matched the observed extent very well.

Transect plots of the dye results are shown in Figure 6 in which generally good agreement with observed concentrations are shown. Less dye was transported in the downstream extent of the plume in the model simulation than was measured in the survey as seen at profile P2, but this result is within an acceptable range.

A strong wind co-aligned with the Delaware Bay longitudinal axis led to a setdown throughout the estuary, which is visible at the Philadelphia NOAA water level station as a drop in mean water level of approximately 0.6 m. This resulted in a barotropic emptying of the upper estuary that transported much of the dye mass out of the domain of the original study. The model response to this setdown showed good agreement by matching the outflow of volume as seen in a plot of the subtidal water level at Philadelphia (see Figure 7).

Figure 4. Mapping 3 contour plot of low-slack, Day 2 survey results. Inset shows location of dye-injection point. Model results of profiles P2, P3, P4 and P5 are shown in Figure 6.

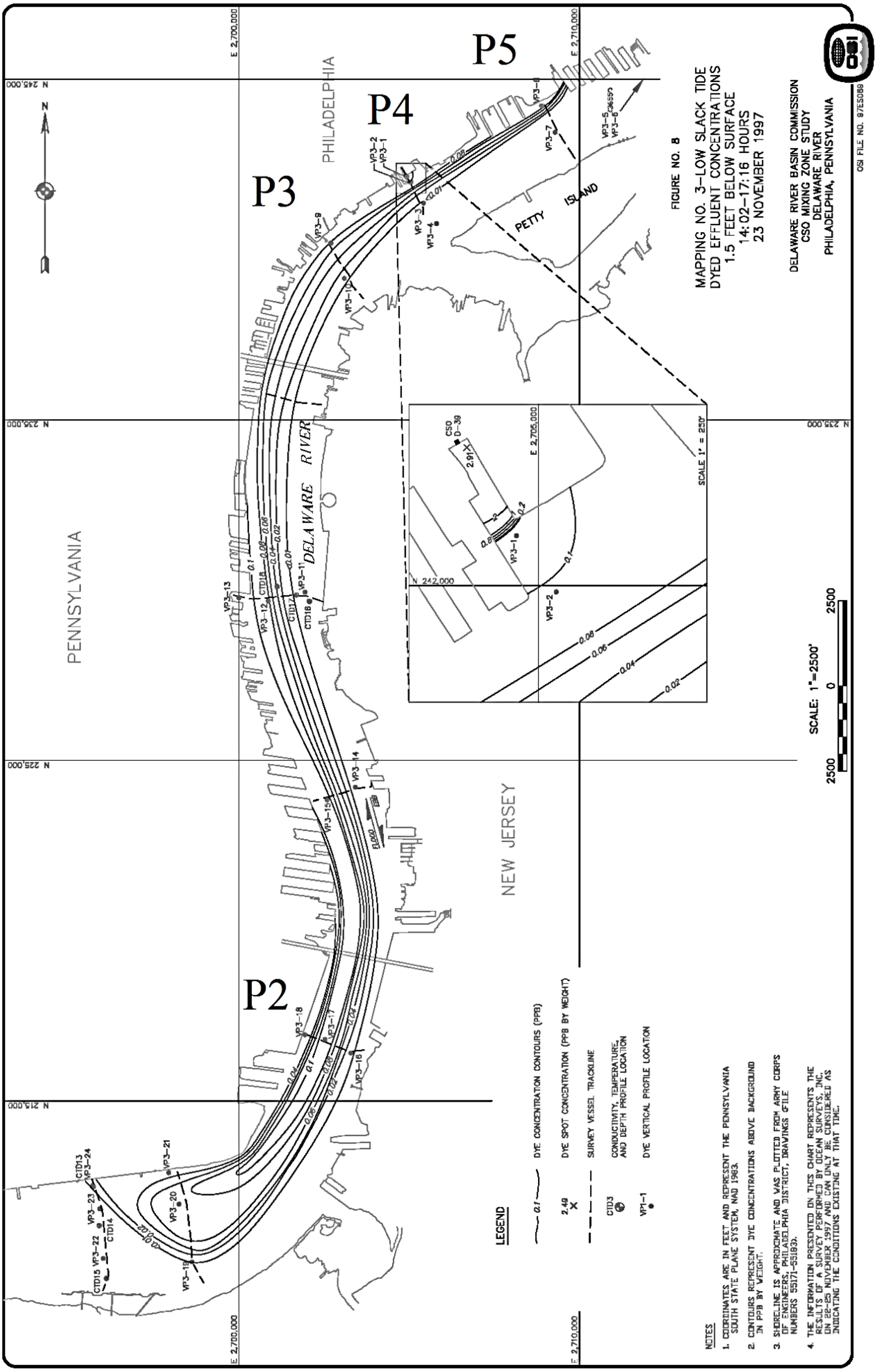


Figure 5. Contour plots of simulated dye injection, at time of Mapping 3. Axes in kilometer, dye in ppb, and time in Julian days.

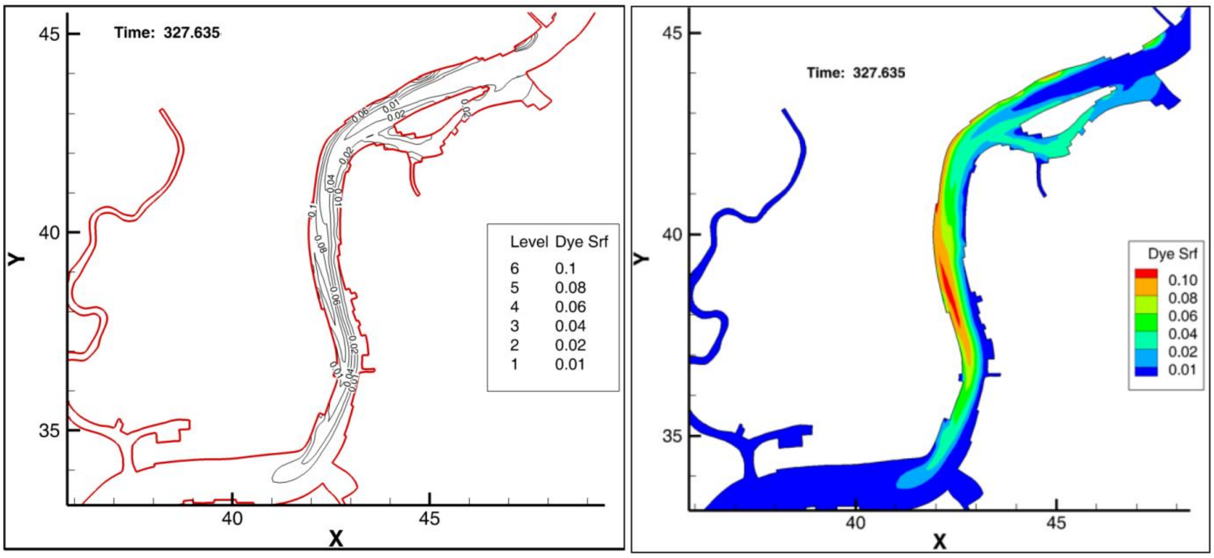


Figure 6. Model results *vs.* observed concentrations for profiles P2, P3, P4 and P5.

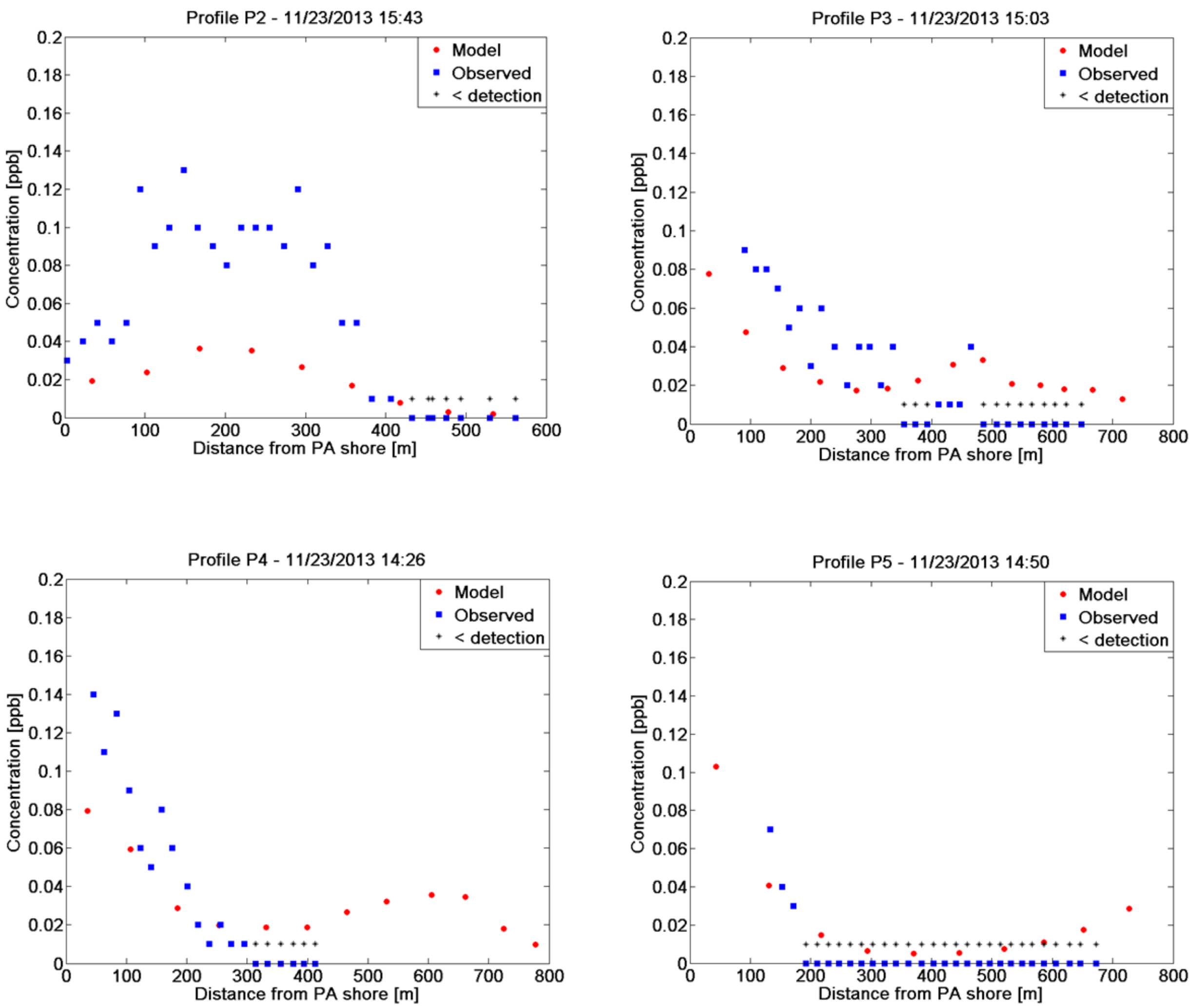
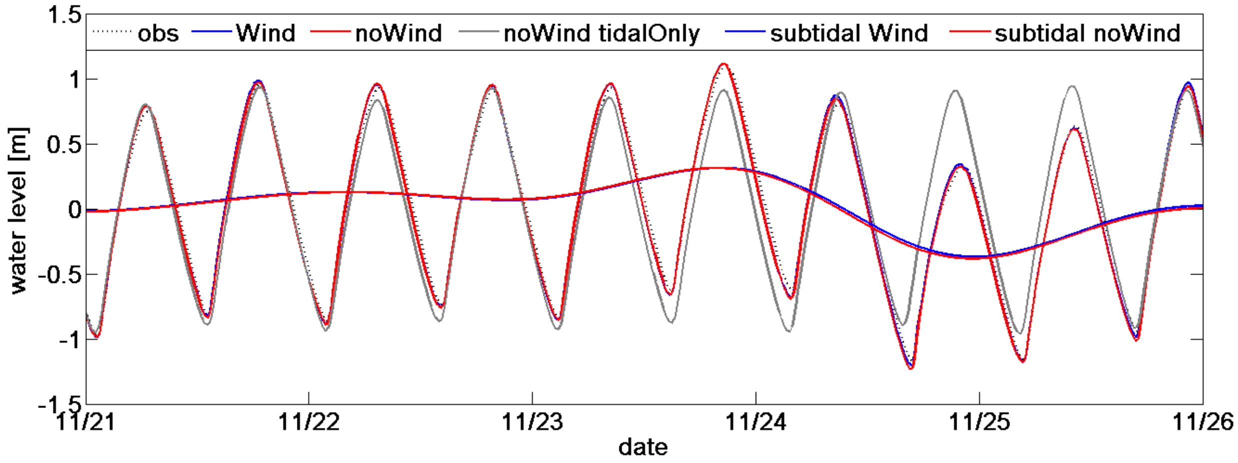


Figure 7. Water level and subtidal water level scenarios: (1) tidal-only boundary forcing with no local wind (**solid gray**); (2) observed boundary forcing with no local wind (**red**); and (3) observed boundary forcing with local wind (**blue**).

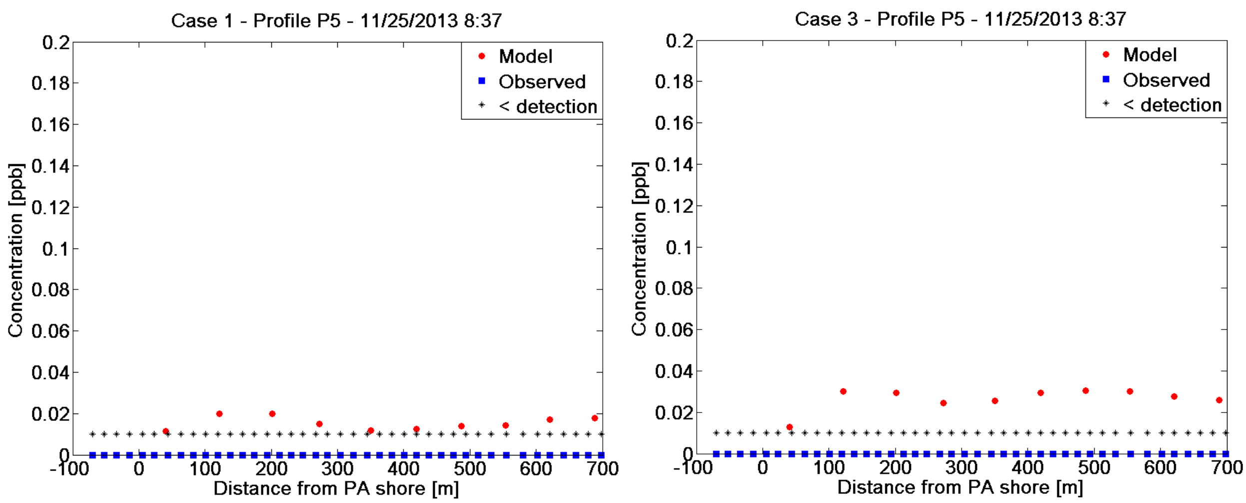


To demonstrate the impact of meteorological forcing on dye transport, three scenarios were simulated: (1) tidal-only boundary forcing comprised of harmonic constituents from the NOAA Delaware City station with no local wind; (2) observed water level that contained the down-bay setdown as a subtidal signal was applied at the lower model open boundary without a local wind field; and (3) the same observed boundary forcing was applied but along with a composite local wind field.

Comparison of the water level and subtidal plots between Scenarios 2 and 3 demonstrated the dominance of the down-bay subtidal set-down in both cases, but show only a very small impact on water levels from local wind within the model domain (Figure 7). This influence of along-estuary wind stress on subtidal fluctuations in the Delaware Estuary is consistent with the findings of Janzen and Wong [14].

Comparison of observed and simulated dye concentrations in Scenario 3 during the setdown event also showed good agreement (see Figure 8). Results from Scenario 1 with tidal-only boundary forcing shows the range of error that would be experienced without simulating the effects of the estuarine setdown.

Figure 8. Model dye results *vs.* observed: Scenario 1 and Scenario 3 showing impact of barotropic setdown on dye transport.



The influence of bathymetry on dye distribution can be seen in the extent of the plume. The mixing length, the length after which full lateral mixing can be expected in a channel, was previously estimated to be on the same order of magnitude as the tidal excursion in this area [15]. Thus, full lateral mixing could be expected within the first day of the dye study. Instead, the plume largely moved along the Pennsylvania shoreline, with its center of mass following the navigation channel (Figure 5). In areas where the navigation channel shifted between shores (Figure 9) or where the entire river cross section was deeper (Figure 10) the plume followed as well, further confirming bathymetrical steering induced by the presence of the navigation channel.

Figure 9. Modeled plume extent with shifting navigation channel. Bed elevation in meters, dye in ppb.

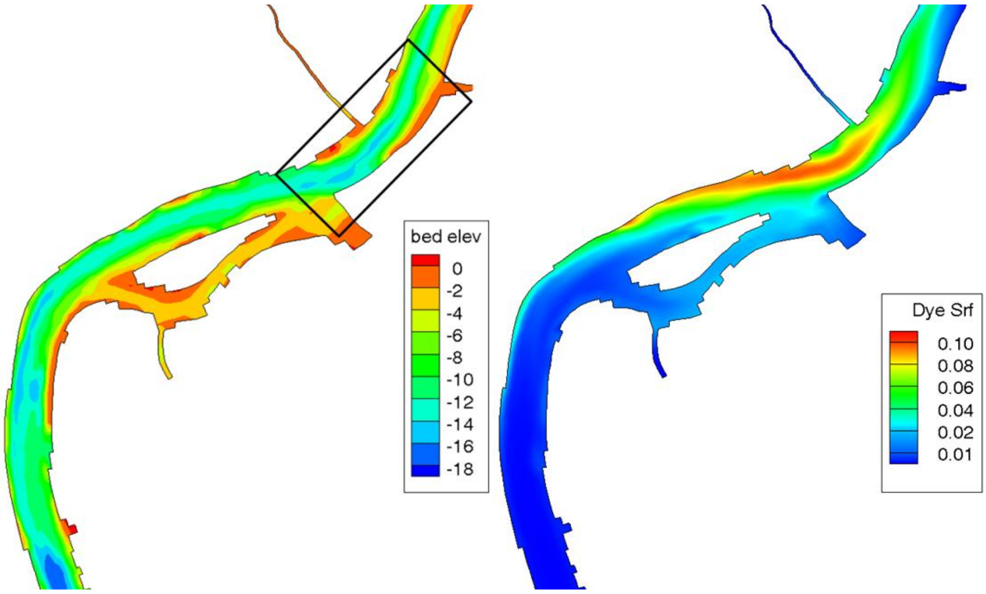
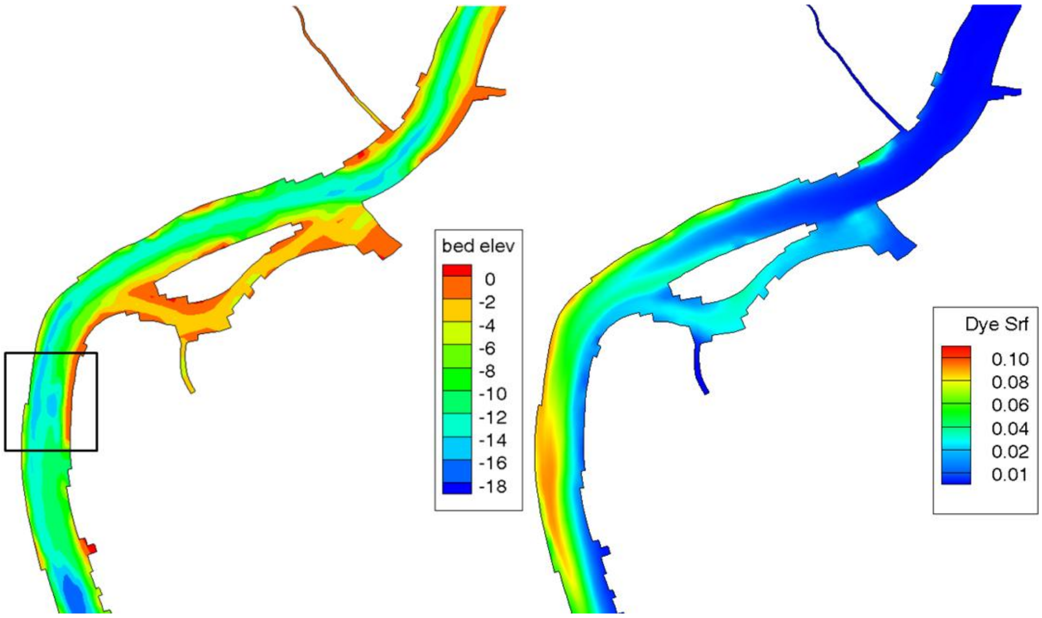


Figure 10. Modeled plume extent in deep river section.



4. Conclusions

To meet its regulatory obligations for combined sewer overflow control, the City of Philadelphia Water Department is developing a hydrodynamic and water quality model to determine if changes made to the stormwater infrastructure will result in improvements in receiving stream water quality. Validation of an EFDC hydrodynamic model was successfully completed as demonstrated through model skill metrics.

Exercising the model against the results of a dye study demonstrated that this tidal fresh water riverine system model, using a detailed and bathymetrically accurate grid, and forced at the downstream boundary with observed water levels, successfully represents the dynamics of the advection and dispersion of dye transport. The selected model domain proved to be appropriate with the observed water level forcing at Delaware City driving the model to adequately represent the tidal and subtidal (meteorologically-induced) effects, including those that originated down-bay, from the Chesapeake and Delaware Canal, and remotely from the continental shelf. Numerical experiments conducted with and without the application of wind showed that the model responded as expected to meteorological forcing through a local, down-bay stress and yielded results consistent with findings of other Delaware Estuary researchers. That is, large-scale wind stress forcing on the lower Delaware Bay caused a setdown at the model lower boundary, resulting in a barotropic response observed in both the dye study and the model. Local wind forcing internal to the model domain was shown to exert little influence on the hydrodynamics driving the dye advection and dispersion.

Bathymetric interactions play an important role in lateral mixing. With an estimated mixing length on the order of the local tidal excursion, full lateral mixing could theoretically be possible over the course of the dye study. Comparison of the dye plume to the bathymetry suggested that bathymetric steering forces the major part of the dye into the deep navigational channel preventing it from fully distributing laterally.

These validation and dye study exercises demonstrate that our model is a reliable tool for a broad range of applications for the City of Philadelphia. Future use of the model will include exploring more advanced mixing dynamics through a new dye study that includes a more complete plume coverage. Other applications include scenarios for early response to pollutant spills and strategic planning related to climate change impacts on infrastructure vulnerability and salt intrusion on the City's drinking water source.

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Authors Contributions

The authors contributed equally to research and manuscript writing.

Conflicts of Interest

The authors declare no conflict of interest.

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