Establishing Nitrogen Endpoints for Three Long Island Sound Watershed Groupings:

Embayments, Large Riverine Systems, and Western Long Island Sound Open Water

Subtask E. Summary of Hydrodynamic Analysis

Submitted to:

U.S. Environmental Protection Agency
Region 1 and Long Island Sound Office

Submitted by:

Tetra Tech, Inc.

March 27, 2018

This Tetra Tech technical study was commissioned by the United States Environmental Protection Agency (EPA) to synthesize and analyze water quality data to assess nitrogen-related water quality conditions in Long Island Sound and its embayments, based on the best scientific information reasonably available. This study is neither a proposed TMDL, nor proposed water quality criteria, nor recommended criteria. The study is not a regulation, and is not guidance, and cannot impose legally binding requirements on EPA, States, Tribes, or the regulated community, and might not apply to a particular situation or circumstance. Rather, it is intended as a source of relevant information to be used by water quality managers, at their discretion, in developing nitrogen reduction strategies.

Subtask E. Summary of Hydrodynamic Analysis

Contents

Introduction

The purpose of this Subtask was to relate tributary loads to areas of influence using both System Wide Eutrophication Model (SWEM)[1] outputs and other work. To accomplish this, Tetra Tech calculated (1) the areas of influence of the Connecticut, Housatonic, and Thames rivers and their contributions to selected embayments and throughout Long Island Sound (LIS) and (2) the relative mixing between LIS open water and individual embayments. The results allowed Tetra Tech to estimate the contribution of nitrogen loads from the Connecticut, Housatonic, and Thames rivers and the open waters of LIS to each embayment and, consequently, the amount of mixing between LIS and embayments. Subtask E supports Subtasks F and G (developing estimated nitrogen endpoints for each selected embayment that are protective of seagrass and that do not show adverse effects related to macroalgae and dissolved oxygen) by defining the areas of influence of the three rivers that need to be protected. These estimated levels and estimated contributions can then be used by states to estimate nitrogen reductions needed by various sources in the watershed. This Subtask also supports Subtask H (calculating reductions), because it provides estimates of mixing or dilution of embayment water with LIS water, explained in detail below. There are several options available to simulate mixing that range from simple estimates of dilution and endpoint nutrient contributions (less resource intensive) to developing more complex, individual hydrodynamic models for each embayment (more resource intensive).

Relative mixing estimates for embayments provide an indication of the extent to which local nutrient loads are diluted by tidal and dispersive processes. Dilution of salinity within estuaries can be used as a proxy for nitrogen dilution under the assumption that nitrogen within embayments is approximately conservative. There are several assumptions for this analysis, which are detailed in this memo and in the New York Harbor Observing and Prediction System (NYHOPS) documentation, including validation information. There will be some settling and volatilization losses, but total nitrogen (TN) is likely to be nearly conservative or conservative enough on the spatial and temporal scales being considered to merit comparison. Larger losses are likely expected within the watershed, which should be considered in allocation. With this assumption, the following equation can be used to estimate reductions based on seasonal average nitrogen concentrations:[2]

$$Percent\ Reduction = \frac{(C_t - C_w)}{\left\{C_w - \left[C_{LIS} \times \left(\frac{S_e}{S_{LIS}}\right)\right]\right\}} \times 100 \qquad \text{(equation 1)}$$

where:

C_t = target TN endpoint concentration

C_w = receiving waterbody TN concentration

C_{LIS} = TN concentration in LIS boundary outside the embayment mouth

S_e = embayment salinity

S_{LIS} = LIS boundary salinity

This equation uses existing concentrations of an embayment, the boundary (LIS), and the target endpoint concentration to calculate reductions. The S_e/S_{LIS} component of the equation is the relative

[1] As discussed later in this memo, NYHOPS (not SWEM) was chosen as the most appropriate model.
[2] Equation provided by Joe Costa, Executive Director of the Buzzards Bay National Estuary Program.

mixing between the open sound and individual embayments and is available from an LIS hydrodynamic model (selection of the model is described below).

A hydrodynamic model of LIS is also appropriate to address the areas of influence of the Connecticut Housatonic, and Thames rivers, which are major sources of freshwater to LIS. Their areas of influence are those regions within which water from the rivers exerts a predominant effect on water quality conditions and, consequently, designated use attainment. For this Subtask, we identified the areas of influence for the three rivers for the purposes of setting TN endpoints for those waters. Moreover, the Connecticut, Housatonic, and Thames rivers contribute TN load to embayments influenced by their individual flows. If TN reductions from sound-side TN loads are needed for those embayments, then it is necessary to know the contribution from each of the rivers in order to allocate reductions to those sources.

Given the resources available and the timeline of the project, Tetra Tech and EPA decided to use existing hydrodynamic models of LIS, preferably with salinity models already completed on an appropriate timescale (ideally hourly or daily during the summer critical season) rather than developing such models *de novo*. Local universities and groups continue to model LIS and individual embayments. In the future, those models might be more appropriate once more site-specific data have been gathered and more analyses have been conducted. Additionally, those models might potentially improve model-estimated areas of influence. More information about the research Tetra Tech conducted and used to select a final model is provided in the section on hydrodynamic model selection, specifically in Table E-1 and Table E-2.

The first part of the Subtask E analysis involved selecting an appropriate hydrodynamic model and extracting the salinity modeling component to estimate mixing between LIS and the selected embayments. As mentioned above, Tetra Tech used salinity to measure dilution by LIS and then dispersion of that salinity as a reasonable surrogate for nitrogen dilution and nitrogen dispersion from freshwater streams into the embayments. The second part of the analysis consisted of applying a particle-tracking model to the hydrodynamic model output to calculate the area of influence and percent contribution from the Connecticut, Housatonic, and Thames rivers. The particle-tracking model analysis estimates the percent dilution of water from each of the three rivers within each selected embayment. This information can be used to estimate how much of the nitrogen load from the rivers contributes to nitrogen concentrations in any of the selected embayments.

Hydrodynamic Model Selection

Tetra Tech and EPA identified several candidate existing hydrodynamic models for potential use for Subtask E, including the NYHOPS, the Regional Ocean Modeling System (ROMS), the Estuarine, Coastal, and Ocean Model (ECOM), and the Finite Volume Community Ocean Model (FVCOM) (Table E-1).

Table E-1. Hydrodynamic Models Considered

Model	Source
New York Harbor Observing and Prediction System (NYHOPS)	Nikitas Georgas, Stevens Institute of Technology
Regional Ocean Modeling System (ROMS)	Michael Whitney, University of Connecticut
Estuarine, Coastal, and Ocean Model (ECOM)	Originally developed by Hydroqual with updates and management by James O'Donnell and Grant McCardell, University of Connecticut
Finite Volume Community Ocean Model (FVCOM)	James O'Donnell and Grant McCardell, University of Connecticut

Tetra Tech and EPA conducted a series of meetings with each of these model teams to discuss the characteristics, advantages, and disadvantages of each model. Model summaries resulting from those meetings are compiled in Table E-2.

Table E-2. Hydrodynamic Model Meeting Summaries

Model	Summary
NYHOPS	• Model built to predict hydrodynamics and any conservative pollutant transport primarily for New York Harbor, but extends to LIS and beyond. • While primary focus is on operational modeling for New York Harbor, Nikitas Georgas recently completed a successful effort to validate model performance for flow, temperature, and salinity in LIS. • Immediately available are hindcast hydrodynamics for 1979–2013 on a daily time step for a standard grid (500 x 500 m; 11 sigma levels) from Delaware Bay to Cape Cod, including LIS. More recent output is also available on the data server. • Available output includes daily and monthly average: wave height, currents, water level, temperature, salinity, and wind. • All data are freely available via a THREDDS data server from Stevens Institute of Technology. Access can be automated. • Finer temporal resolution output could be obtained through use of finer scale, nested models for embayments. They are not currently available, however, and implementing them would be resource intensive. • Small embayments may not be fully resolved on a 500-m grid. • Freshwater inputs to LIS are represented directly in NYHOPS for all gaged rivers and multiple ungaged areas between them (the exact methods for the ungaged areas do not appear to be thoroughly documented at this time, however). • Model is run every 6 hours in near real time.
ROMS	• Model framework calibrated and validated for LIS by Michael Whitney. • Similar spatial resolution to NYHOPS model. • Small embayments may not be well resolved by the grids. • Have explicitly modeled large freshwater tributaries, as well as many small river inputs along the estuary with the intent of looking at nutrient transport. • Temporal extent (years modeled) is unknown, but, unlike NYHOPS, ROMS is not run in near real time. • Model output data are very limited as far as public availability and what has been compiled is not at a daily time scale. • Norwalk Harbor fine-scale nested model output could be shared easily; other data would take more time and presumably resources to make available. • The output could not be provided in ready fashion by Dr. Whitney, and he recommended the NYHOPS model under these constraints.

Model	Summary
ECOM	• Model developed by Hydroqual for original LIS total maximum daily load (TMDL), model output managed for LIS by Jim O'Donnell and Grant McCardell. • ECOM is the hydrodynamic model for SWEM for which University of Connecticut researchers possess the output (also available on disks provided to EPA by Hydroqual). University of Connecticut researchers reviewed and updated the SWEM (eutrophication) model code in 2010. • Model is comparable to ROMS and NYHOPS. • Small embayments might not be well resolved in the coarse grids of ECOM. • Freshwater inputs from major tributaries are represented in models. • Temporal scales from ECOM output: 1988/1989, 1994/1995, and 1998–2002 (only output; no forcing files). • ECOM output available in older binary format. • Output is not hosted on a public server at this time.
FVCOM	• FVCOM is a newer updated hydrodynamic model calibrated and validated for LIS by Jim O'Donnell and Grant McCardell. FVCOM is a finite element model (as opposed to a gridded model) that has triangular grids more easily adapted to provide finer resolution in near-shore areas and embayments. • Model is comparable to ROMS and NYHOPS. • FVCOM has a more flexible grid structure but is still principally an open water model; some nested models could be used for smaller embayments, but only a few have currently been developed. • Freshwater inputs from major tributaries are represented in models. • Temporal scale for FVCOM output: 2014. • FVCOM output is in NetCDF format (easy to use) and could likely be made available. • Output is not hosted on a public server at this time. • In recapping the characteristics of available models, McCardell suggested that model skills were similar, but if there was a need to move on a quick schedule, NYHOPS would be the model of choice because of its hosting model output on a THREDDS server.

After meeting with each model team and discussing the pros and cons of each model as well as the availability of data, Tetra Tech and EPA selected NYHOPS as the best modeling framework currently available to accomplish Subtask E within the project schedule and budget. The models produce comparable output, but the NYHOPS output is readily available for the project schedule; covers a longer temporal scale than any other model (so one can account for temporal variability), including resolution during critical summer conditions; and provides sufficient spatial resolution comparable to other model output datasets. The NYHOPS archive provides lateral flow vectors and salinity predictions at a daily time step. The salinity model output can be used to calculate dilution/exchange for each embayment, and the flow vector output can be used to run particle-tracking models for the Connecticut, Housatonic, and Thames rivers to identify the areas of influence and to trace contribution of the three rivers to selected embayments. Detailed NYHOPS model information, including construction and calibration/validation, can be found on their website.[3]

[3] http://hudson.dl.stevens-tech.edu/maritimeforecast/.

Methods

Methods used to conduct the hydrodynamic analysis are described in this section. Note that Tetra Tech's quality assurance process is described in the EPA-approved Quality Assurance Project Plan, which is available online.[4]

NYHOPS Model Download and Processing

Tetra Tech downloaded the NYHOPS hydrodynamic modeling output from the OPenDAP Server,[5] including flow velocity vectors and salinity for all vertical layers for each NYHOPS grid cell for the period 2004–2013 (Figure E-1). The model uses a sigma grid, so each lateral cell has the same number of vertical layers (11), regardless of depth. More detail on the grid structure is available in the NYHOPS model documentation.[6] Grid sizes were not adjusted. Data were later clipped to just the LIS region.

The NYHOPS model provides varied lateral grid cell densities across embayments, largely as a function of the size and shape of each embayment. As a result, some embayments contained more model grid cells than others (e.g., more cells in the Northport-Centerport Harbor Complex, NY, than in Niantic Bay, CT) (Figure E-2). The density of grid cells within each embayment will influence the resolution of salinity estimates for the embayment and, thus, estimates of mixing. Without embayment-specific hydrodynamic modeling, these are the constraints imposed by the available models and the best possible estimates of mixing will be made using these data.

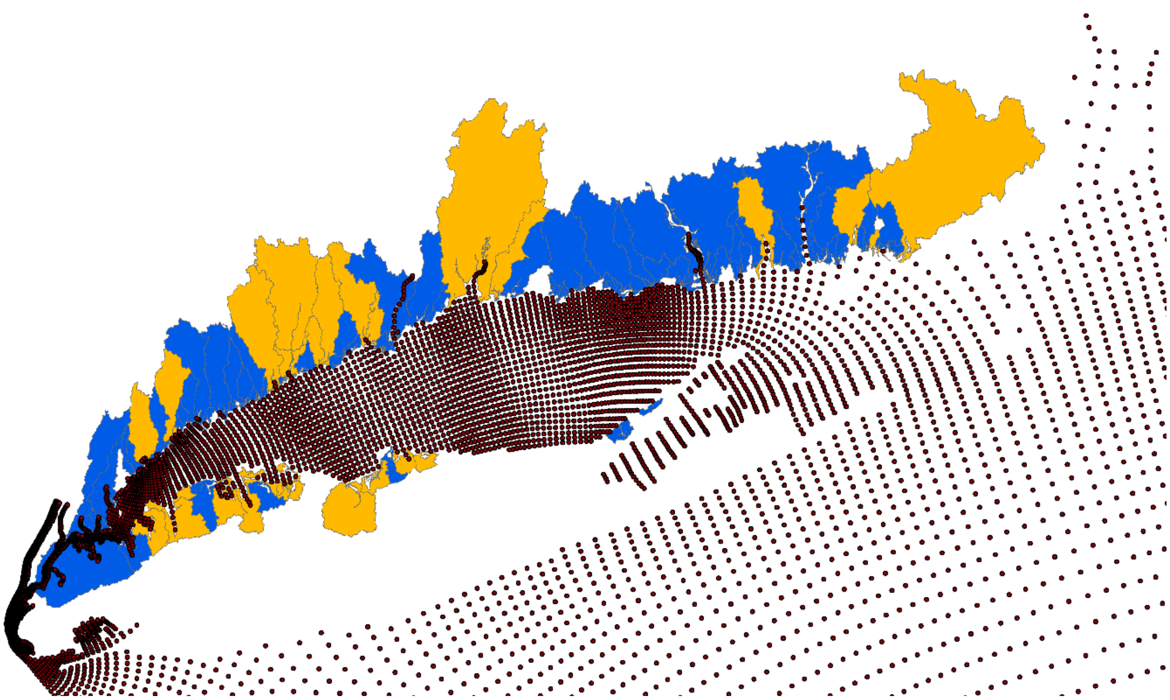

Figure E-1. NYHOPS Grid Domain along with LIS Embayments (Points Represent the Center of Grid Cells; Selected Watersheds are In Yellow)

[4] http://longislandsoundstudy.net/wp-content/uploads/2016/02/January-11-2017_TO-23-QAPP_LIS-N-Thresholds-and-Allowable-Loads.pdf.

[5] http://colossus.dl.stevens-tech.edu/thredds/dodsC/LISS/Hindcast/all_nb_mon_81.nc.html.

[6] Available at http://hudson.dl.stevens-tech.edu/maritimeforecast/.

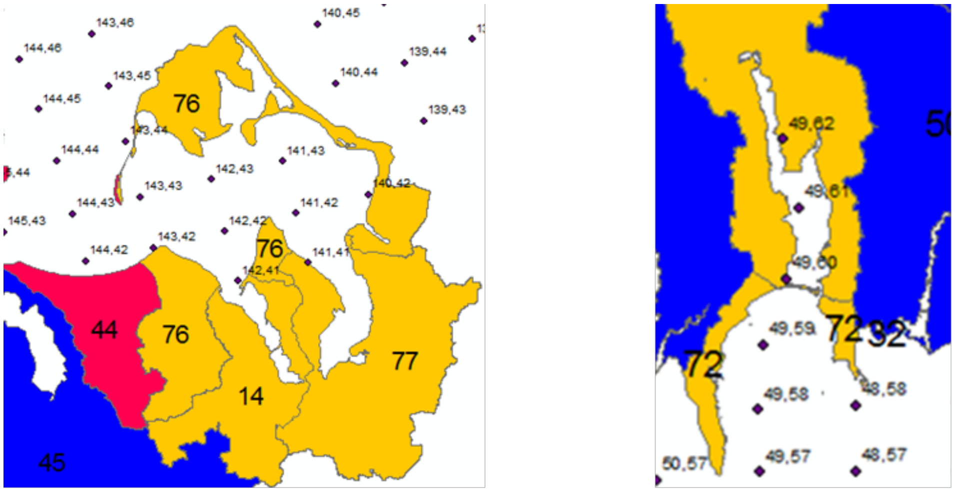

Figure E-2. Close-up Images of Northport-Centerport Harbor Complex, NY (Left) and Niantic Bay, CT (Right) Embayments

Salinity Modeling

The archived NYHOPS output provided daily average salinity data for each vertical layer for each grid cell (although the model itself runs on a shorter time step), and thus does not resolve sub-daily tidal excursions, which would require hourly archived output. Model salinity prediction output (run sub-daily, but summarized daily) provided a simple and direct route to resolve calculations of embayment dilution. In essence, the predicted average salinity within an embayment at a weekly or monthly scale is a mixture of the salinity within the adjacent part of LIS and a freshwater concentration that is near zero on the land side. This observation enabled a direct estimate of the average degree of dilution of landside nutrient inputs:

In general, concentration of a constituent in an embayment, C_e, can be represented as

$$C_e = \frac{(C_0Q_0 + C_{LIS}Q_{LIS})}{(Q_0 + Q_{LIS})} \qquad \text{(equation 2)}$$

where C is concentration and Q is net volumetric contribution and the subscripts 0 and LIS represent conditions from the freshwater inflow to the embayment and tidal mixing from LIS, respectively. For salinity we can assume that C_0 is insignificant relative to C_{LIS} (at the daily step, C_0 ~ 0 is appropriate because it represents net inflow from the land).[7] With that assumption,

$$Ce \approx \frac{(C_{LIS}Q_{LIS})}{(Q_o + Q_{LIS})} = C_{LIS} \times D \qquad \text{(equation 3)}$$

where:

$$D = \frac{(Q_{LIS})}{(Q_0 + Q_{LIS})} \qquad \text{(equation 4)}$$

[7] Refer to Appendix 1 in Anning, D.W, and M.E. Flynn. 2014. *Dissolved-Solids Sources, Loads, Yields, and Concentrations in Streams of the Conterminous United States*. U.S. Geological Survey Scientific Investigations Report 2014-5012, 101 p. http://dx.doi.org/10.3133/sir20145012.

and is a dilution factor relative to water in the Sound. D is also by definition equal to C_e/C_{LIS}, which may be obtained from the salinity results (S_e/S_{LIS}). Q_0 and Q_{LIS} are then related by

$$Q_0 = Q_{LIS}\left(\frac{1}{D} - 1\right) \quad \text{(equation 5)}$$

One can then estimate the concentration of any other conservative constituent for which C_0 is nonzero using the mixing and dilution information deduced from salinity by substituting the definition of Q_0 (equation 5) into the general equation for C (equation 2), such that

$$C_e = \frac{\left(C_0\left(\frac{1}{D}-1\right)+C_{LIS}\right)}{\left(\frac{1}{D}\right)} \quad \text{(equation 6)}$$

or

$$\frac{C_e}{C_0} = \left(\frac{C_{LIS}}{C_0} - 1\right)D + 1 \quad \text{(equation 7)}$$

NYHOPS daily salinity estimates were averaged over the summer growing season (July–September) to estimate long-term dilution rates in each selected embayment using the approach above. Average dilution over this critical summer growing season was considered most relevant to the eutrophication response because nutrient retention is likely the highest during this time. Tetra Tech also evaluated dilution rates over a longer growing season. Extending the evaluation for hydrodynamics from April to September decreases residence time (increases flushing) and reduces concentrations of constituents derived from the land. As there was a desire to model the more stressful condition, we focused on the July–September results. The 10-year average (2004–2013) of the mean annual July–September salinity concentrations in the top five vertical layers was used to calculate the dilution ratio ($D = S_e/S_{LIS}$) for each embayment. The annual growing season mean was used to dampen the influence of anomalies associated with large storm events on the results.

Particle Tracking

To estimate the area of influence of the Connecticut, Housatonic, and Thames rivers and the contribution of the river water to each of the selected embayments, Tetra Tech conducted a particle-tracking routine using the NYHOPS flow vector output and releasing "particles" into the model grid at the mouths of the three rivers.

In three separate exercises, Tetra Tech used the daily flow vector output from the NYHOPS model and released particles every 4 hours from the top six sigma layers of grid cells from a release point located near the mouth of each of the rivers during the growing season (July–September) for each year of simulation (2004–2013). The top six layers were selected because only those layers had significant net lateral particle movement in the model. The selection of 4 hours allows for more resolution of particle movement estimates (against only a single daily release), and the model was limited to using the NYHOPS average daily flow vectors; finer resolution would not, therefore, resolve more of the sub-daily movement but would increase the computational burden. These particles moved according to the deterministic NYHOPS flow vectors, and each particle's motion was tracked. Particles leaving LIS were no longer tracked. The sum of particles present in each grid cell over all days within the entire growing season for all years was tracked. This sum was divided by the volume of each grid cell to calculate particle concentration. Relative concentration was calculated by dividing each grid cell's concentration by the release point cell concentration. The average percent of released particles across sigma layers within a grid cell gave the percent dilution of water from the three rivers to each grid cell and each depth. These values were averaged across grid cells and depths to estimate the dilution of water from the Connecticut, Housatonic, and Thames rivers to each grid cell.

The deterministic tracking algorithm ignores the effects of dispersion and sub-daily tidal and wind mixing and is thus likely to produce an estimated zone of influence that is more compact than actually occurs, particularly at the edges. More specifically, tracking is done on daily average net movement, thus it does not fully represent sub-daily mixing. The resulting zone of influence was more concentrated than it should be, which is more conservative near the source and less conservative further away. Future efforts could resolve more of the sub-daily hydrology, but this effort is a defensible approximation of average daily movement over the time scale of interest. Note that the vertical (Z) flow components were not available from the model output, meaning the exchange of particles between depths could not be calculated. This was addressed by releasing particles equally in all vertical layers at the mouth of each river. This model is on a sigma grid, with an equal number of layers everywhere, so this correction should not significantly affect the estimated long-term average concentrations for the entire water column. Again, only the top six vertical layers were averaged for the analysis because only those layers had significant net lateral particle movement in the model. Again, the NYHOPS model lacked advection and mixing between layers; we did not have sufficient information on the bottom five layers to include them in the analysis. The modeling team recognizes these limitations and encourages improvement in the model in the future; but these limitations are the result of the constraints of using the available hydrodynamic model and represent a reasonable and defensible approximation under these conditions.

To display the area of influence of each river, Tetra Tech used the particle-tracking algorithm output on the percent dilution of particles from each river to each grid cell to construct contour maps in ArcGIS. Tetra Tech used these maps to identify the downstream extent of each riverine area of influence (areas where the relative dilution of river water was less than 60 percent, or more than 40 percent river water). Areas upstream of the release point were assumed to represent more than 40 percent river water. More information about the rationale for selecting 40 percent is provided in the results section below.

Results

Salinity Model

The output from the salinity model consisted of long-term (10-year) average salinities inside and outside the selected embayments, as well as the ratio of those salinities to estimate dilution of loads from the watershed contributing flows and loads to the embayment (Table E-3). With one exception, these embayments expressed high dilution (more than 90 percent) and appeared dominated by tidal flushing and mixing with LIS, at least at the scale resolved by the application of NYHOPS for this project. The one exception was New Haven Harbor, CT with 76 percent dilution. Note that these are daily average results and are most applicable to slack flood (high tide) conditions. These dilution ratios are included in the calculation of reductions (Subtask H) using the equations described above.

Table E-3. Salinity Dilution Analysis for Critical July–September 2004–2013 Period for Selected Embayments (see Figure E-3 for Selected Embayments)

Selected Embayments (Component Embayments)		Salinity Inside (ppt)	Salinity Outside (ppt)	D
Pawcatuck River, RI and CT		30.14	30.26	0.9961
Stonington Harbor, CT		28.92	29.98	0.9646
Saugatuck Estuary, CT	Saugatuck River, CT	25.56	26.88	0.9507
	Saugatuck River, North, CT	26.39	27.04	0.9759
Norwalk Harbor, CT		25.84	27.03	0.9561
Mystic Harbor, CT		29.90	29.93	0.9987
Niantic Bay, CT	Niantic River, CT	27.50	29.23	0.9408
	Niantic Bay, CT	28.50	29.23	0.9750
Farm River, CT		27.10	27.59	0.9823
Southport Harbor/Sasco Brook, CT		26.57	27.04	0.9824
Northport-Centerport Harbor Complex, NY	Centerport Harbor, NY	26.41	26.92	0.9811
	Northport Bay, NY	26.62	26.92	0.9890
	Northport Harbor, NY	26.27	26.92	0.9760
Port Jefferson Harbor, NY		26.93	27.30	0.9865
Nissequogue River, NY		26.66	26.98	0.9883
Stony Brook Harbor, NY		26.83	27.09	0.9902
Mt. Sinai Harbor, NY		27.05	27.30	0.9909
Mamaroneck River, NY		24.30	26.71	0.9094
Hempstead Harbor, NY		26.14	26.59	0.9831
Huntington Bay, NY		26.77	27.00	0.9915
Outer Hempstead Harbor, NY		26.46	26.61	0.9942
Lloyd Harbor, NY		26.69	27.00	0.9886
Oyster Bay/Cold Spring Harbor Complex, NY	Oyster Bay, NY	25.95	26.88	0.9653
	Cold Spring Harbor Complex, NY	26.34	26.89	0.9793
Manhasset Bay, NY		26.03	26.48	0.9832
Pequonnock River, CT		26.34	27.39	0.9616
Byram River, CT and NY		26.23	26.79	0.9789
New Haven Harbor, CT		21.20	27.64	0.7664
Bridgeport Harbor, CT		26.34	26.99	0.9757

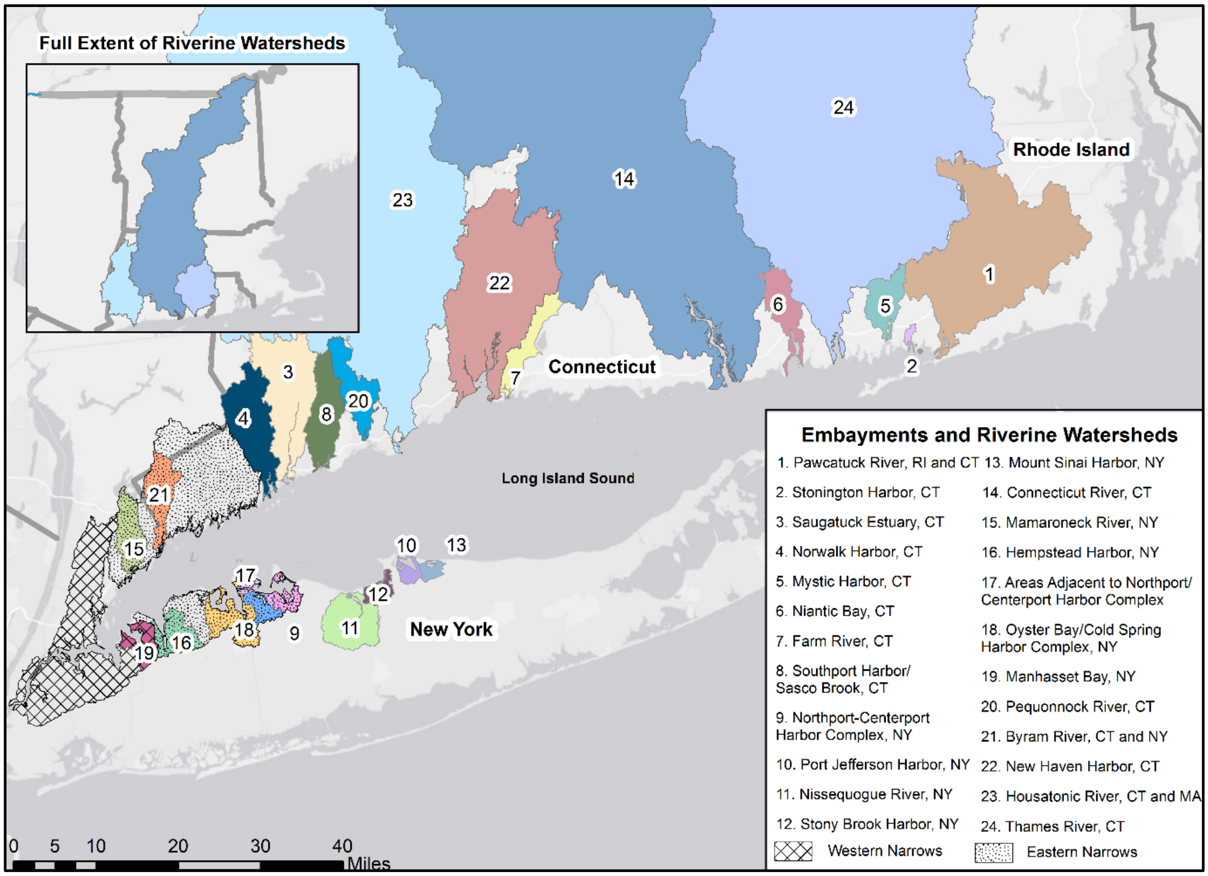

Figure E-3. Map of Study Area Indicating LIS Watersheds Evaluated

Particle-Tracking Model—Identification of Area of Influence

For the first part of the particle-tracking results, the area of influence was identified. This consisted of isopleths of the percent dilution of water from the Connecticut, Housatonic, and Thames rivers to coastal water (Figure E-4 through Figure E-6). The results of this analysis delineated a space from a 90 percent to a less than 10 percent contribution. A value of more than 40 percent dilution was used to define the area of influence because there is error around this value as a function of changes in flow. As such, 40 percent based on the growing season period would encompass an area more likely to include more than 50 percent dilution during higher flow periods (e.g., during spring runoff). The area with more than 40 percent dilution of each river was concentrated around the mouth. Tetra Tech constructed a polygon from this more than 40 percent isopleth, and the resulting area was used in setting nitrogen endpoints for the area of influence.

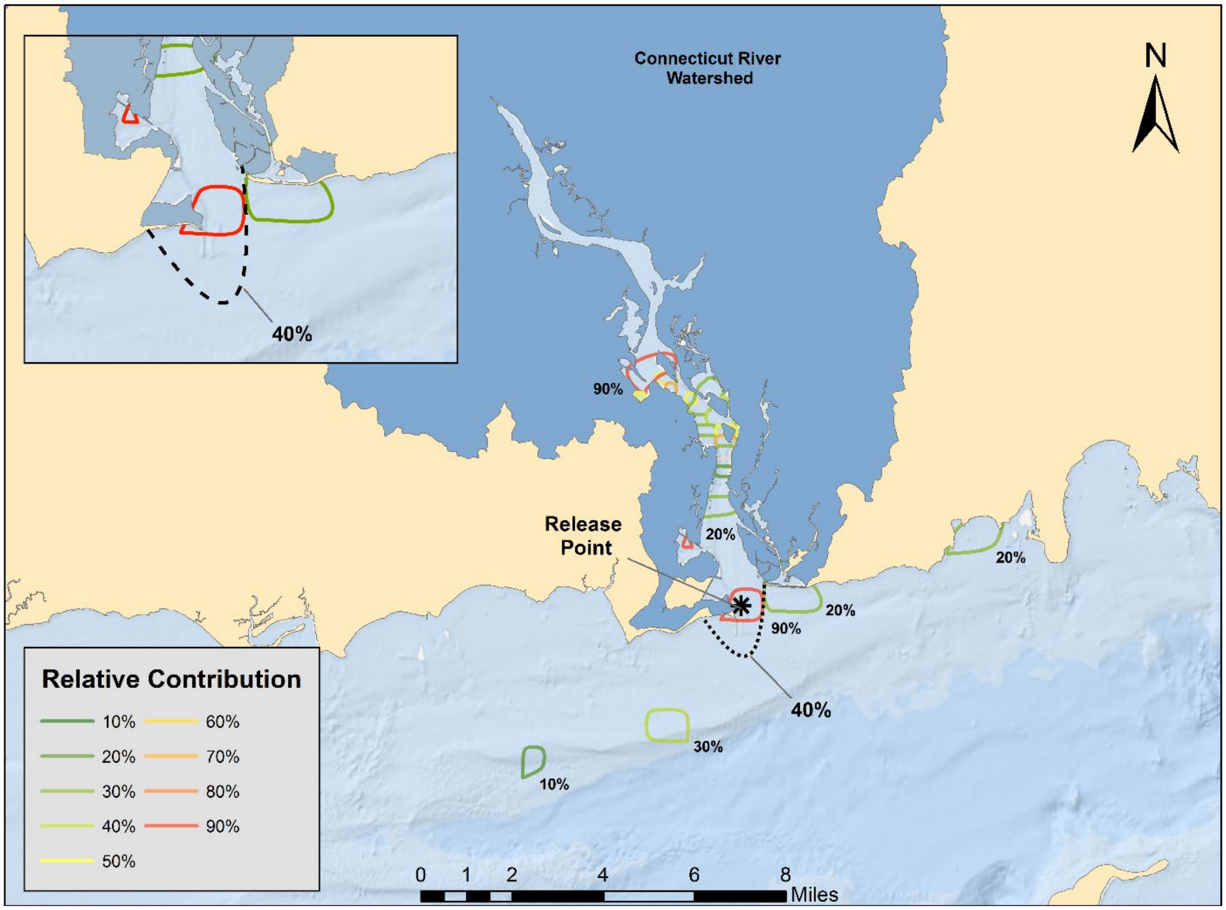

Figure E-4. Percent Dilution of Connecticut River Water in LIS

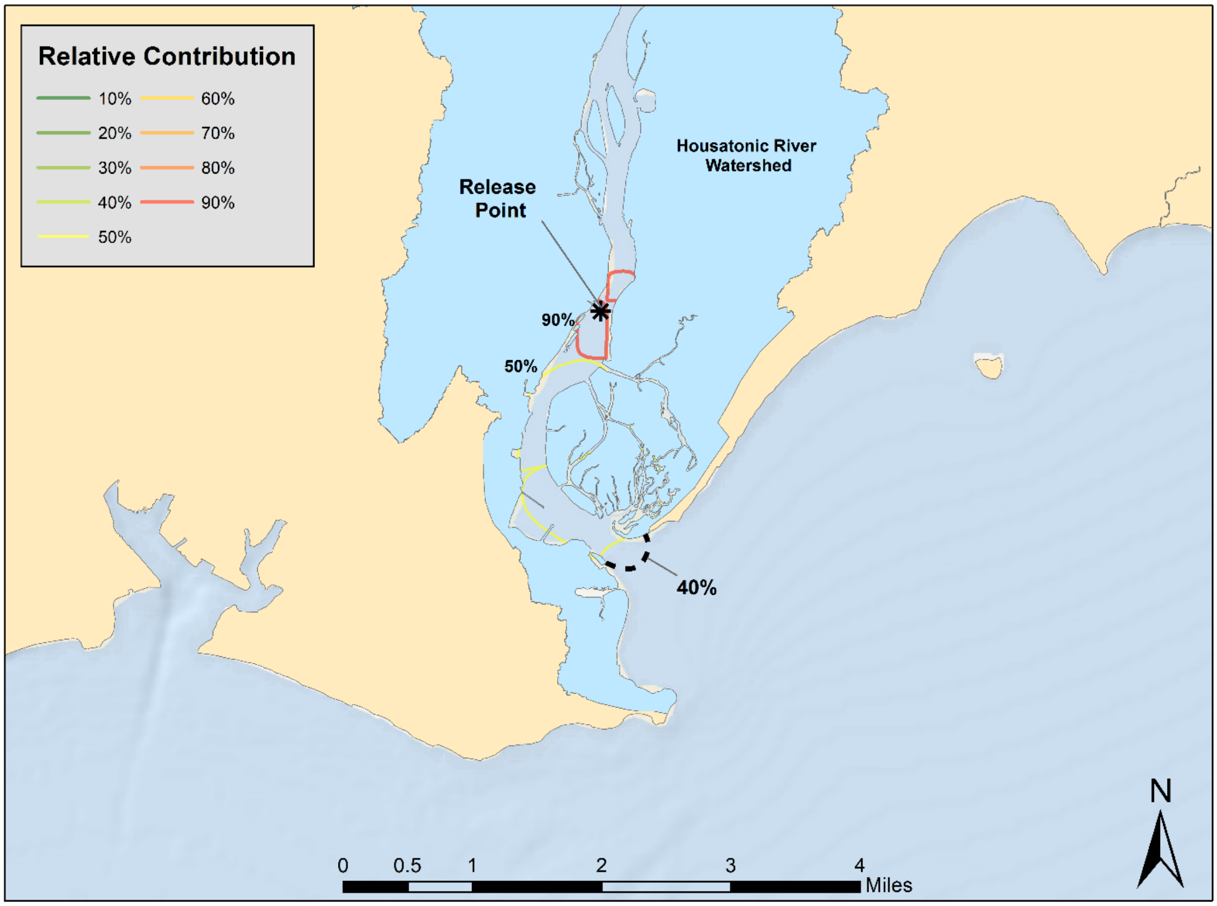

Figure E-5. Percent Dilution of Housatonic River Water in LIS

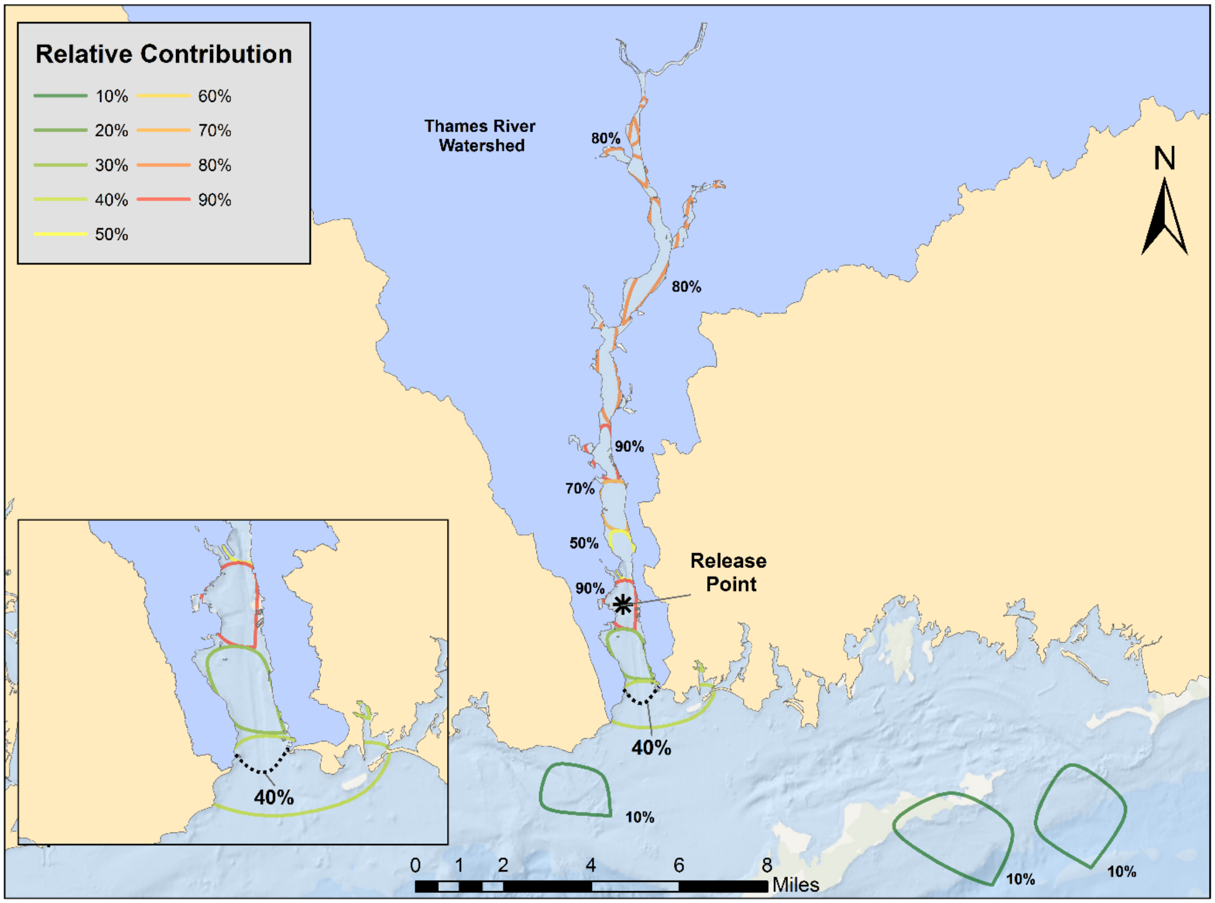

Figure E-6. Percent Dilution of Thames River Water in LIS

Particle-Tracking Model—Dilution of River Water to Each Embayment

The purpose of the second analytical output from particle tracking was to calculate the dilution of water from the Connecticut, Housatonic, and Thames rivers to each selected embayment for eventual allocation, as needed. A certain portion of river nitrogen loads will contribute to nitrogen loads and concentrations in some embayments. Tetra Tech calculated the dilution of water from the three rivers using the particle-tracking model. The output consists of a multiplicative factor for the Connecticut, Housatonic, and Thames rivers generated as an average dilution of particles from the three rivers to each embayment (Table E-4, Table E-5, and Table E-6). The multiplicative factor depends on both locations and distance in Euclidean space, as well as the relative rate of exchange with the different plumes from the three rivers in LIS. This factor can be used in concert with concentration data for the rivers and other sources to estimate the percent contribution of rivers to embayment TN concentrations.

Table E-4. Connecticut River Dilution Factors by Selected Embayment

Selected Embayments (Component Embayments)		Connecticut River Dilution Factor Average All Years, Top 6 Layers—Summer Critical Period
Connecticut River		1.00000
Pawcatuck River, RI and CT		<0.00001
Stonington Harbor, CT		0.00001
Saugatuck Estuary, CT	Saugatuck River, CT	0.00007
	Saugatuck River, North, CT	0.00066
Norwalk Harbor, CT		0.00043
Mystic River, CT		0.00004
Niantic Bay, CT	Niantic River, CT	0.00064
	Niantic Bay, CT	0.00072
Farm River, CT		0.00010
Southport Harbor/Sasco Brook, CT		0.00066
Northport-Centerport Harbor Complex, NY	Centerport Harbor, NY	<0.00001
	Northport Bay, NY	<0.00001
	Northport Harbor, NY	<0.00001
Port Jefferson Harbor, NY		0.00031
Nissequogue River, NY		<0.00001
Stony Brook Harbor, NY		0.00004
Mt. Sinai Harbor, NY		0.00125
Mamaroneck River, NY		<0.00001
Hempstead Harbor, NY		<0.00001
Huntington Bay, NY		<0.00001
Outer Hempstead Harbor, NY		<0.00001
Lloyd Harbor, NY		<0.00001
Oyster Bay/Cold Spring Harbor Complex, NY	Oyster Bay, NY	0.00003
	Cold Spring Harbor Complex, NY	<0.00001
Manhasset Bay, NY		<0.00001
Pequonnock River, CT		0.00071
Byram River, CT and NY		<0.00001
New Haven Harbor, CT		0.00115
Bridgeport Harbor, CT		0.00108

Table E-5. Housatonic River Dilution Factors by Selected Embayment

Selected Embayments (Component Embayments)		Housatonic River Dilution Factor Average All Years, Top 6 Layers—Summer Critical Period
Housatonic River		1.00000
Pawcatuck River, RI and CT		<0.00001
Stonington Harbor, CT		<0.00001
Saugatuck Estuary, CT	Saugatuck River, CT	0.00025
	Saugatuck River, North, CT	0.00040
Norwalk Harbor, CT		0.00040
Mystic River, CT		<0.00001
Niantic Bay, CT	Niantic River, CT	<0.00001
	Niantic Bay, CT	<0.00001
Farm River, CT		0.00005
Southport Harbor/Sasco Brook, CT		0.00049
Northport-Centerport Harbor Complex, NY	Centerport Harbor, NY	0.00004
	Northport Bay, NY	0.00014
	Northport Harbor, NY	0.00004
Port Jefferson Harbor, NY		0.00021
Nissequogue River, NY		0.00003
Stony Brook Harbor, NY		0.00013
Mt. Sinai Harbor, NY		0.00020
Mamaroneck River, NY		0.00034
Hempstead Harbor, NY		<0.00001
Huntington Bay, NY		<0.00001
Outer Hempstead Harbor, NY		0.00003
Lloyd Harbor, NY		<0.00001
Oyster Bay/Cold Spring Harbor Complex, NY	Oyster Bay, NY	0.00002
	Cold Spring Harbor Complex, NY	0.00009
Manhasset Bay, NY		<0.00001
Pequonnock River, CT		0.00081
Byram River, CT and NY		0.00006
New Haven Harbor, CT		0.00132
Bridgeport Harbor, CT		0.00054

Table E-6. Thames River Dilution Factors by Selected Embayment

Selected Embayments (Component Embayments)		Thames River Dilution Factor Average All Years, Top 6 Layers—Summer Critical Period
Thames River		1.00000
Pawcatuck River, RI and CT		<0.00001
Stonington Harbor, CT		0.00003
Saugatuck Estuary, CT	Saugatuck River, CT	<0.00001
	Saugatuck River, North, CT	<0.00001
Norwalk Harbor, CT		<0.00001
Mystic River, CT		0.00004
Niantic Bay, CT	Niantic River, CT	0.00003
	Niantic Bay, CT	0.00092
Farm River, CT		<0.00001
Southport Harbor/Sasco Brook, CT		<0.00001
Northport-Centerport Harbor Complex, NY	Centerport Harbor, NY	<0.00001
	Northport Bay, NY	<0.00001
	Northport Harbor, NY	<0.00001
Port Jefferson Harbor, NY		<0.00001
Nissequogue River, NY		<0.00001
Stony Brook Harbor, NY		<0.00001
Mt. Sinai Harbor, NY		<0.00001
Mamaroneck River, NY		<0.00001
Hempstead Harbor, NY		<0.00001
Huntington Bay, NY		<0.00001
Outer Hempstead Harbor, NY		<0.00001
Lloyd Harbor, NY		<0.00001
Oyster Bay/Cold Spring Harbor Complex, NY	Oyster Bay, NY	<0.00001
	Cold Spring Harbor Complex, NY	<0.00001
Manhasset Bay, NY		<0.00001
Pequonnock River, CT		<0.00001
Byram River, CT and NY		<0.00001
New Haven Harbor, CT		<0.00001
Bridgeport Harbor, CT		<0.00001

The multiplicative factors are relative dilution concentration multipliers on the river discharge for each embayment. As mentioned, they can be used in combination with concentration information to estimate percent contributions. For example, if the TN concentration in the Connecticut River discharge is 3.5 mg/L, using information from Table E-4 the additive contribution of the Connecticut River to concentrations in Saugatuck River North, CT would be 0.00066*3.5 = 0.00231 mg/L based on assumptions that concentrations are conserved and superposable. The analysis is based on particle transport with NYHOPS daily flow vectors for the 2004–2013 period. The results are averages for all NYHOPS grid cells that intersect a defined embayment of interest. Although the NYHOPS grid resolution is too coarse to resolve details within embayments, NYHOPS remains the best model based on available data, resources, and deadlines. Should resources become available to develop individual temporal and spatial hydrodynamic models, that would resolve more detail within embayments.

Conclusion

The goal of this Subtask was to calculate (1) the area of influence of the Connecticut, Housatonic, and Thames rivers and their contributions of nitrogen to selected embayments and throughout LIS and (2) the relative mixing between LIS open water and individual embayments. Both analyses provided preliminary information on the linkage between nitrogen loading sources and ambient concentrations in the embayments. Resources were insufficient to develop *de novo* highly resolved, temporally extensive hydrodynamic models for LIS, including for every embayment. Therefore, the project team identified available defensible hydrodynamic model output, with the expert input of three existing LIS hydrodynamic modeling teams from Stevens Institute and the University of Connecticut. After consultation with and input from these experts, it was determined that the NYHOPS model provided the best combination of readily available output at the spatial and temporal resolution needed, given the constraints of the project schedule and resources. The modeling team recognized that the readily available output of the model had constraints (e.g., did not provide sub-daily flow vectors or mixing between sigma layers), but that it still provided defensible and comparable approximations of flow and salinity across the widest area of LIS for the purpose of this project.

The NYHOPS model data were used to estimate dilution of LIS water within the selected embayments to be applied in calculating nitrogen endpoints in Subtasks F and G. The model data were also used to track water movement in LIS to evaluate the dilution of water from the Connecticut, Housatonic, and Thames rivers during the summer to each grid cell in LIS, allowing the team to both estimate areas of influence of the three rivers for the purpose of informing N targets for each waterbody and calculate the contribution of water, and ultimately nitrogen, from the three rivers to selected embayments during the summer growing season.

The limited resolution of the NYHOPS grid did not include the entirety of each embayment and likely overestimated dilution of the landward, freshwater ends of embayment waters. This limitation could be improved in the future by constructing more resolved hydrodynamic models or collecting data to make more refined empirical estimates of dilution for each embayment. Since the temporal scale of interest is average dilution, the lack of sub-daily hydrodynamics was likely not as influential on dilution estimates.

The available NYHOPS data did not provide vertical flow vectors, although the salinity predictions incorporated those flows. The lack of vertical mixing and diffusive exchange among grid cells affected the estimates of river water movement through LIS. Because the deterministic tracking algorithm ignored the effects of dispersion and sub-daily tidal and wind mixing, it is likely to produce an estimated zone of influence that is more compact, particularly at the edges, than actually occurs in LIS. Future efforts, again, could help resolve this limitation.

The temporal scale of modeling (July–September) was intentionally focused on a critical time period most stressful in terms of nutrient effects on responses in LIS embayments. Flow and material contributions from all tributaries, including the three rivers, are greater at other times, especially in the spring and during storms, and mixing and exchange likely vary. Because of significant tidal flushing of water, nutrient loads from winter are likely retained only into the late summer primarily through storage in sediment and biota (dissolved nutrients will be flushed out). Without the resources to model the fate of such temporal inputs in each embayment, however, their influence on critical period exposure concentrations is unknown. Future efforts should consider how to improve on these estimates.