Establishing Nitrogen Target Concentrations 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:

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Region 1 and Long Island Sound Office

Submitted by:

Tetra Tech, Inc.

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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 Total Maximum Daily Load (TMDL), nor proposed water quality criteria, nor recommended criteria. The study is not a regulation, is not guidance, and cannot impose legally binding requirements on EPA, States, Tribes, or the regulated community. The technical study might not apply to a particular situation or circumstance, but it is intended as a source of relevant information to be used by water quality managers, at their discretion, in developing nitrogen reduction strategies.

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Contents

Introduction

The purpose of this subtask was to identify areas of Long Island Sound (LIS) where tributary nitrogen loads are likely to influence nutrient concentrations. To accomplish this, Tetra Tech calculated (1) how much water and nitrogen exchange occurs between the open sound and individual embayments and (2) the areas of influence of the Connecticut, Housatonic, and Thames rivers and how much water and nutrients those rivers contribute to selected embayments and throughout LIS. The resulting concentration of nitrogen loads delivered from the contributing local watershed to an embayment is influenced by mixing with lower-concentration water from the open sound and nitrogen loads delivered to the embayment from LIS major tributaries. Dilution of salinity within embayments provides a proxy for the mixing of nitrogen loads that enter the embayment from the local watershed or from the LIS. Particle tracking in tributaries provides a proxy for the contributing nitrogen loads from the Connecticut, Housatonic, and Thames rivers. Hydrodynamic modeling can be used to accomplish the salinity dilution and particle tracking analyses.

Subtask E supports subtasks F and G (developing estimated nitrogen target concentrations for each selected embayment that are protective of seagrass and that do not show adverse effects related to eutrophication to capture both phytoplankton and macroalgae) by defining the areas of influence of the three rivers—which essentially identify their “embayment” extent. This subtask also supports subtask H (calculating reductions) and subtask I (allocating reductions) by providing estimates of mixing or dilution of embayment water with LIS water and contribution of embayment water from different tributaries. States can use the estimated levels and contributions to calculate nitrogen reductions needed by various sources in the watershed.

The method used in this analysis uses simple dilution calculations that may not fully describe the detailed time history of total nitrogen (TN) concentrations in an embayment. A more sophisticated representation of nitrogen cycling in estuaries would consider the variety of local nitrogen transformations, exchanges with the sediment, and gaseous emissions to the atmosphere. Over longer time periods, however, TN within an embayment is assumed to be in approximate equilibrium with loads from the local watershed, atmospheric deposition, and exchanges with the open sound. Under those assumptions, simple dilution calculations are sufficient to obtain an estimate of the reduction in loading from the local watershed that would be required to achieve a target TN concentration within the embayment. This simple dilution approach implies that TN inputs from the watershed and exchanges with the sound are of larger magnitude than the net results of TN losses and gains within the embayment at the spatial and temporal scales being considered for the estimation of needed TN load reductions.

Dilution of TN due to exchanges with the open sound is estimated using the percent salinity dilution in an embayment as a proxy for the percent reductions in local nutrient concentrations (calculated from average TN concentrations) needed to achieve target concentrations for embayments. Salinity dilution percentage is estimated using the following equation:

$$Percent\ Reduction = \frac{(C_e - C_t)}{\left\{C_e - \left[C_{LIS} \times \left(\frac{S_e}{S_{LIS}}\right)\right]\right\}} \times 100 \quad (1)$$

where:

C_t = TN target concentration within the embayment

C_e = receiving embayment average TN concentration under current conditions

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

S_e = average embayment salinity

S_{LIS} = LIS boundary–seasonal average salinity outside the embayment mouth

The derivation of this equation and its application to individual embayments are provided in the memorandum for subtask H.

Equation 1 calculates reductions needed to attain target TN concentrations using estimates of the existing TN concentrations inside an embayment and at the LIS boundary (S_{LIS}). The total reduction (on a concentration basis) is $C_e - C_t$. The S_e/S_{LIS} component of the equation is the ratio of mixed salinity in an embayment relative to salinity in the open sound and is available from the hydrodynamic modeling. Using salinity as a tracer of conservative mixing, $C_e - [C_{LIS} \times S_e/S_{LIS}]$ represents the portion of the load within the embayment that is comes from local watershed sources and not derived from mixing with the LIS.

A hydrodynamic model of LIS also provides useful information to quantify 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. For this subtask, we identified the areas of influence for the three rivers for the purpose of setting TN target concentrations for those waters. Moreover, the Connecticut, Housatonic, and Thames rivers contribute TN load to other embayments that are also 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 to allocate reductions to those sources.

Hydrodynamic Model Selection

Tetra Tech and the U.S. Environmental Protection Agency (EPA) evaluated existing hydrodynamic models of LIS, in particular those with salinity models already completed on an appropriate timescale (ideally hourly or daily during the critical summer season). Local universities and groups continue to model LIS and individual embayments. In the future, such evolving models might improve model-estimated areas of influence and estimates of embayment dilution once more site-specific data have been gathered and more analyses have been conducted. This could add further clarity to the analysis, as existing models do not fully characterize the smaller embayments and outputs from the applied models are not publicly available. More information about the research Tetra Tech conducted and used to select a final model is provided 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 mixing of that salinity as a reasonable surrogate for nitrogen dilution and nitrogen mixing 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.

Tetra Tech and EPA identified several candidate existing hydrodynamic models for potential use for subtask E, including the New York Harbor Observing and Prediction System (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 the modeling 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.[1] • Immediately available are hindcast hydrodynamics for 1979–2013 on a daily time step for a standard grid (varied horizontal spatial resolution; 11 sigma levels) from Delaware Bay to Cape Cod, including LIS. More recent output is also available on a Thematic Real-time Environmental Distributed Data Services (THREDDS) data server (TDS) at Stevens Institute of Technology. • Available output includes daily and monthly average: wave height, horizontal currents, water level, temperature, salinity, and wind. • All data are freely available via the TDS. Access can be automated. • Finer temporal resolution output could be obtained through use of finer scale, nested models for embayments, which are not currently available. • Small embayments may not be fully resolved on the given NYHOPS 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.

[1] Georgas, N., L. Yin, Y. Jiang, Y. Wang, P. Howell, V. Saba, J. Schulte, P. Orton, and B. Wen. 2016. An open-access, multi-decadal, three-dimensional, hydrodynamic hindcast dataset for the Long Island Sound and New York/New Jersey Harbor Estuaries. *Journal of Marine Science and Engineering* 4(3):48.

Model	Summary
ROMS	• Model framework calibrated and validated for LIS by Michael Whitney. • Spatial resolution similar to NYHOPS model resolution. • Small embayments may not be resolved well 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 those constraints.
ECOM	• Model developed by Hydroqual for original LIS total maximum daily load; model output managed for LIS by Jim O'Donnell and Grant McCardell. • ECOM is the hydrodynamic model for System Wide Eutrophication Model (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 similar to ROMS and NYHOPS. • Small embayments might not be resolved well 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 that has unstructured triangular grids and is easily adaptable to provide finer resolution in near-shore areas and embayments. • FVCOM has a more flexible grid structure but the LIS FVCOM model is still principally an open water model; some nested models could be used for smaller embayments, but only a few have currently been developed for LIS. • Freshwater inputs from major tributaries are represented in models. • Temporal extent for FVCOM output: 2014. • FVCOM output is in NetCDF format (easy to use) and could be made publicly available in the future. • 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 TDS.

After meeting with each modeling 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 available at the inception of subtask E to accomplish the task. The NYHOPS hydrodynamic model simulates water exchanges and resulting salinities in LIS and its embayments. The NYHOPS model is fully documented and has been calibrated and validated for salinity. This model and the rationale for its selection by EPA are described in further detail below. 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 contributions of the three rivers to selected embayments. Detailed NYHOPS model information, including construction and calibration/validation, can be found on the team's website.[2]

Methods

This section describes methods used to conduct the hydrodynamic analysis. Note that Tetra Tech's quality assurance process is described in the EPA-approved Quality Assurance Project Plan, which is available online.[3]

NYHOPS Model Download and Processing

Tetra Tech downloaded the NYHOPS hydrodynamic modeling output from the OPenDAP Server,[4] 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.[5] Grid sizes were not adjusted. Data were later clipped to only the LIS region. The NYHOPS model provided daily average outputs for lateral velocity and salinity in each vertical sigma layer, but it did not provide any vertical velocity outputs. The vertical exchange between layers could not be incorporated into the calculation and was assumed to be zero for particle tracking. We tested the impact of this assumption by calculating implied vertical velocities based on the continuity equation (flow into a cell is equal to flow out plus change in storage) and found that the vertical velocities were, on average, about three orders of magnitude smaller than the horizontal velocities. The omission of the vertical velocities is thus expected to have at most a small impact on particle tracking.

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., the Northport-Centerport Harbor Complex, NY, embayment contained more cells than Niantic Bay, CT, embayment) (Figure E-2). The density of grid cells within each embayment determines the resolution of salinity estimates for the embayment and, thus, affects estimates of mixing.

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

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

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

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

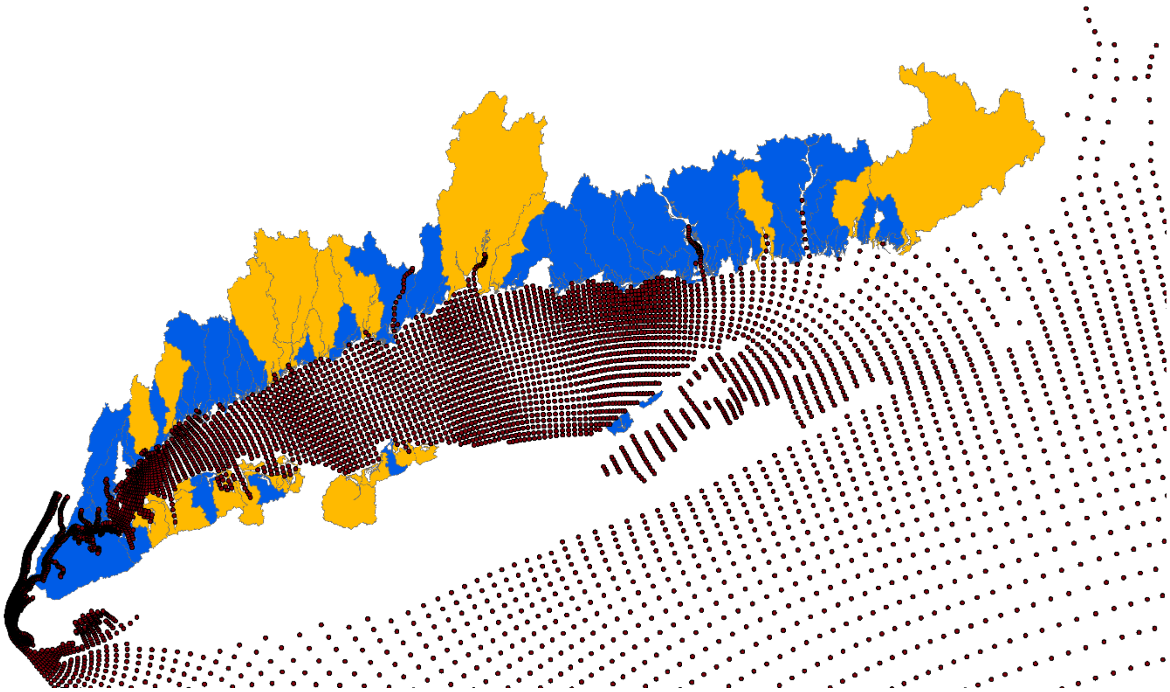

Figure E-1. NYHOPS Grid Domain along with LIS Embayments (Points Represent the Center of Grid Cells; Selected Watersheds are in Yellow; Watersheds Not Analyzed are in Blue)

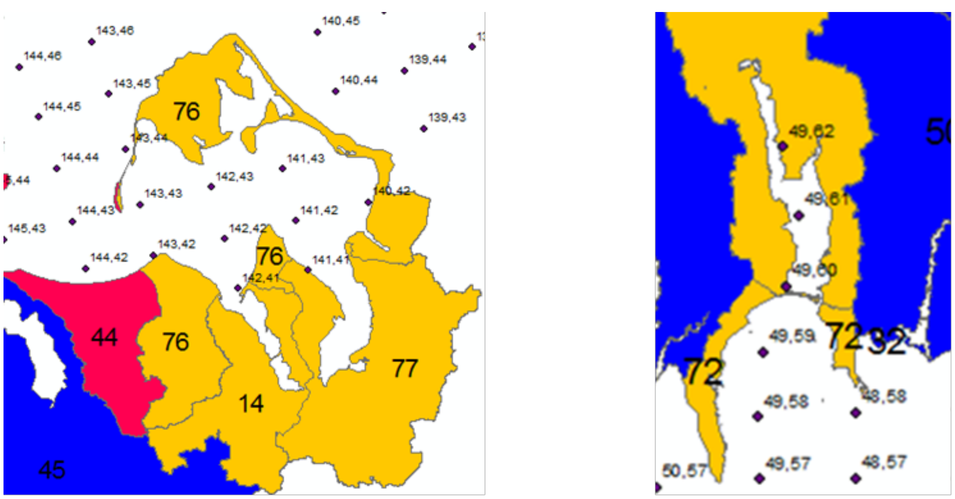

Figure E-2. Close-Up Images of Northport-Centerport Harbor Complex, NY, Embayment (*Left*) and Niantic Bay, CT, Embayment (*Right*)

Salinity Modeling

Model salinity prediction output (run sub-daily but summarized daily) provided a simple and direct route to resolving 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 landward. This observation enabled a direct estimate of the average degree of dilution of landward nutrient inputs via equation 1 and derived in the subtask H memorandum.

Salinity estimates for each embayment (inside and outside) were calculated based on selected NYHOPS grid cells. The grid cells were selected based on the available NYHOPS grid and best professional judgement in order to accurately represent the embayments. 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. The 10-year average (2004–2013) of annual mean July–September salinity in the top six vertical layers was used to calculate the dilution ratio ($D = S_e/S_{LIS}$) for each embayment. All selected grid cells within each embayment were averaged to calculate salinity. The annual growing season mean was used to dampen the influence of anomalies associated with large storm events on the results. That approach does not account for the effects of any systematic trends in salinity across the growing season, such as those described by Hagy et al. (2000).[6]

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 chosen release point. The particle-tracking exercises were run for five different periods for each of the rivers. The scenarios were run to capture various flow regimes throughout the year. This helps in differentiating the temporal variations in relative concentrations. The different scenarios that were run are as follows:

- Scenario 1: Particles released for full year
- Scenario 2: Particles released from March through October
- Scenario 3: Particles released from July through September
- Scenario 4: Particles released from March through May
- Scenario 5: Particles released from March through May and monitored through October

Tetra Tech chose the furthest upstream NYHOPS grid cell as a consistent release point for each of the three rivers. We selected the top six layers because only those layers had significant net lateral particle movement in the model; they also incorporate the photic zone where algal and macrophyte growth is likely to occur. Selecting the 4-hour intervals allowed for higher resolution of particle movement estimates (compared to a single daily release). The particles moved according to the NYHOPS flow vectors for the nearest cell center, and each particle's motion was tracked. The sum of particles present in each grid cell over the entire simulation duration was tracked (with particles leaving LIS no longer being 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 concentration. This relative concentration estimates the dilution of the water in that grid cell compared to the Connecticut, Housatonic, and Thames rivers. The deterministic tracking algorithm ignores the

[6] Hagy, J.D., L.P. Sanford, and W.R. Boynton. 2000. Estimation of net physical transport and hydraulic residence times for a coastal plain estuary using box models. *Estuaries* 23:328–340.

effects of sub-daily tidal and wind mixing and is thus likely to produce an estimated area of influence that is more compact than actually exists, particularly along the edges. To correct for the lack of vertical exchange, particles were released equally in the top six 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.

To display the area of influence of each river, Tetra Tech used the particle-tracking algorithm output on the relative concentration of particles from each river to each grid cell to construct heat maps of relative concentrations of particles (0 to 1) in ArcGIS. Tetra Tech used these maps to identify the downstream extent of each riverine area of influence. More information about the area of influence is provided in the Results section.

Results

Salinity Model

Tetra Tech used the output from the salinity model, which consisted of 10-year average salinities inside and outside the selected embayments (Figure E-3) 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, the 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 to this project. The one exception was New Haven Harbor, CT, with 77 percent dilution. These dilution ratios are included in the calculation of reductions in subtask H.

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

Selected Embayments		Salinity Inside (ppt)	Salinity Outside (ppt)	D (S_e/S_{LIS})
Pawcatuck River, RI and CT		30.13	30.27	0.9952
Stonington Harbor, CT		28.94	29.97	0.9656
Saugatuck Estuary, CT	Saugatuck River, CT	25.57	26.88	0.9511
	Saugatuck River, North, CT	26.40	27.07	0.9753
Norwalk Harbor, CT		25.87	27.03	0.9572
Mystic Harbor, CT		29.83	29.93	0.9968
Niantic Bay, CT	Niantic River, CT	27.47	29.22	0.9402
	Niantic Bay, CT	28.52	29.22	0.9759
Farm River, CT		27.11	27.61	0.9820
Southport Harbor/Sasco Brook, CT		26.57	27.07	0.9818
Northport-Centerport Harbor Complex, NY	Centerport Harbor, NY	26.41	26.91	0.9815
	Northport Bay, NY	26.61	26.91	0.9890
	Northport Harbor, NY	26.27	26.91	0.9764
Port Jefferson Harbor, NY		26.91	27.32	0.9852
Nissequogue River, NY		26.65	26.96	0.9886
Stony Brook Harbor, NY		26.82	27.05	0.9915
Mt. Sinai Harbor, NY		27.04	27.26	0.9920
Mamaroneck River, NY		24.25	26.71	0.9081
Hempstead Harbor, NY		26.14	26.54	0.9848
Areas Adjacent to Northport-Centerport Harbor Complex	Huntington Bay, NY	26.75	27.01	0.9906
	Huntington Harbor	26.69	26.94	0.9906
	Lloyd Harbor, NY	26.69	27.01	0.9881
Oyster Bay/Cold Spring Harbor Complex, NY	Oyster Bay, NY	25.94	26.89	0.9645
	Cold Spring Harbor Complex, NY	26.32	26.90	0.9785
Manhasset Bay, NY		26.02	26.48	0.9827
Pequonnock River, CT		26.34	27.41	0.9612
Byram River, CT and NY		26.24	26.79	0.9795
New Haven Harbor, CT		21.21	27.66	0.7669
Little Narragansett Bay, CT		29.27	29.90	0.9791

Note: ppt = parts per thousand.

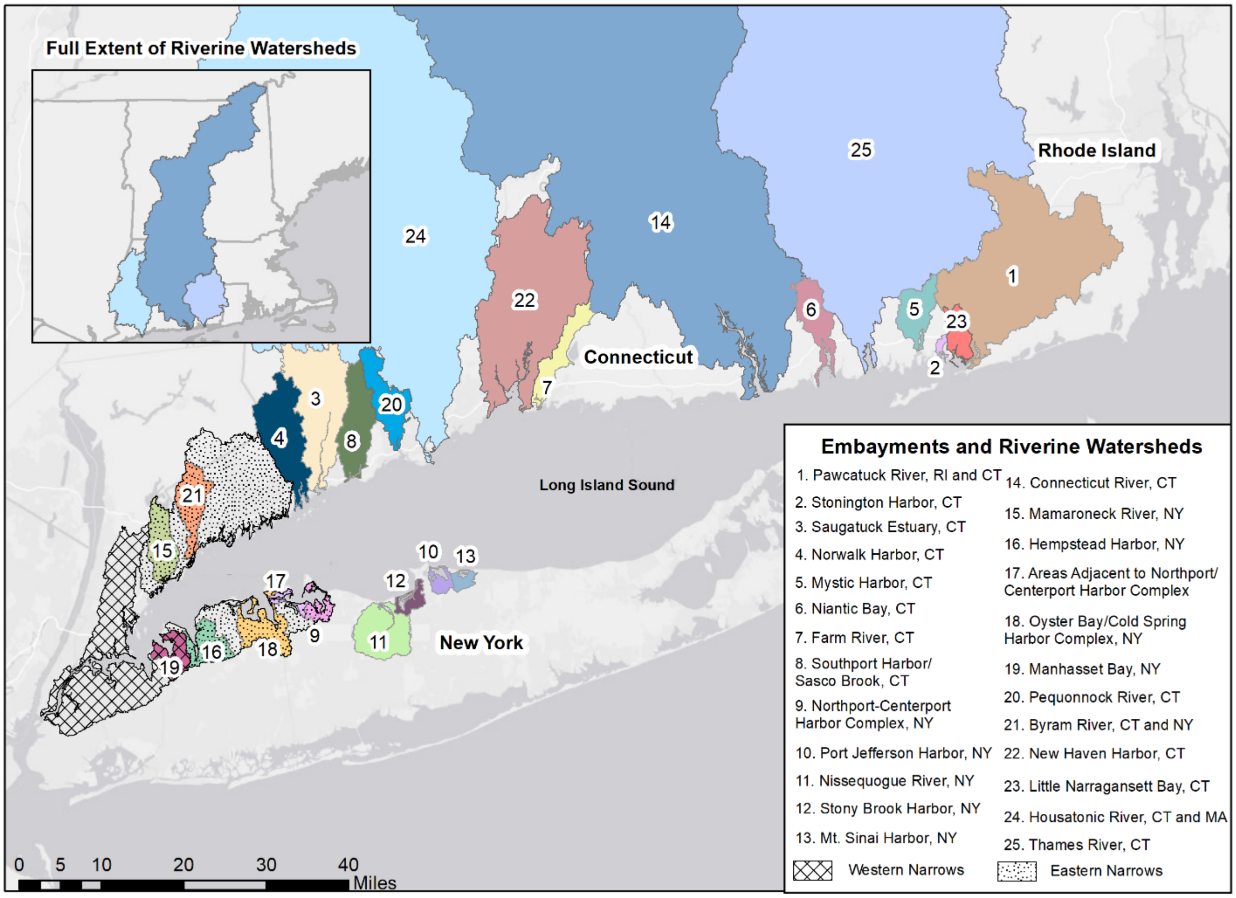

Figure E-3. Map of Study Area Indicating LIS Watersheds Evaluated

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 heat maps of relative concentrations that showed the percent dilution of water from the Connecticut, Housatonic, and Thames rivers to coastal water. The results of the analysis spatially represent the amount of dilution moving away from the release point of each of the rivers. Higher values of relative concentrations indicate a higher influence than lower values. Areas with different percent dilutions can be identified with the help of heat maps. The results from all the scenarios are presented in Figure E-4 through Figure E-18.

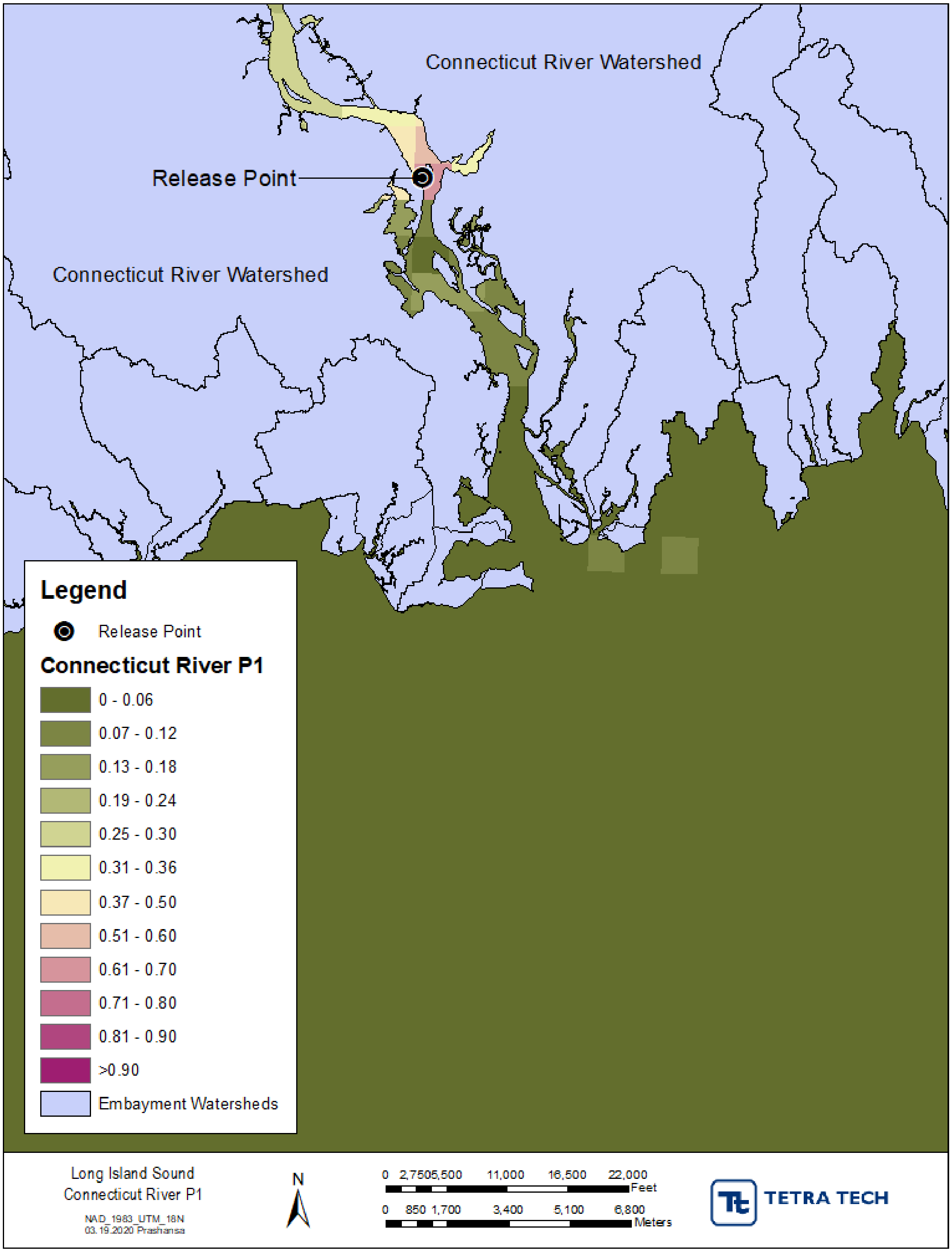

Figure E-4. Relative Contribution of Connecticut River Water in LIS (Scenario 1: Particles Released for Full Year)

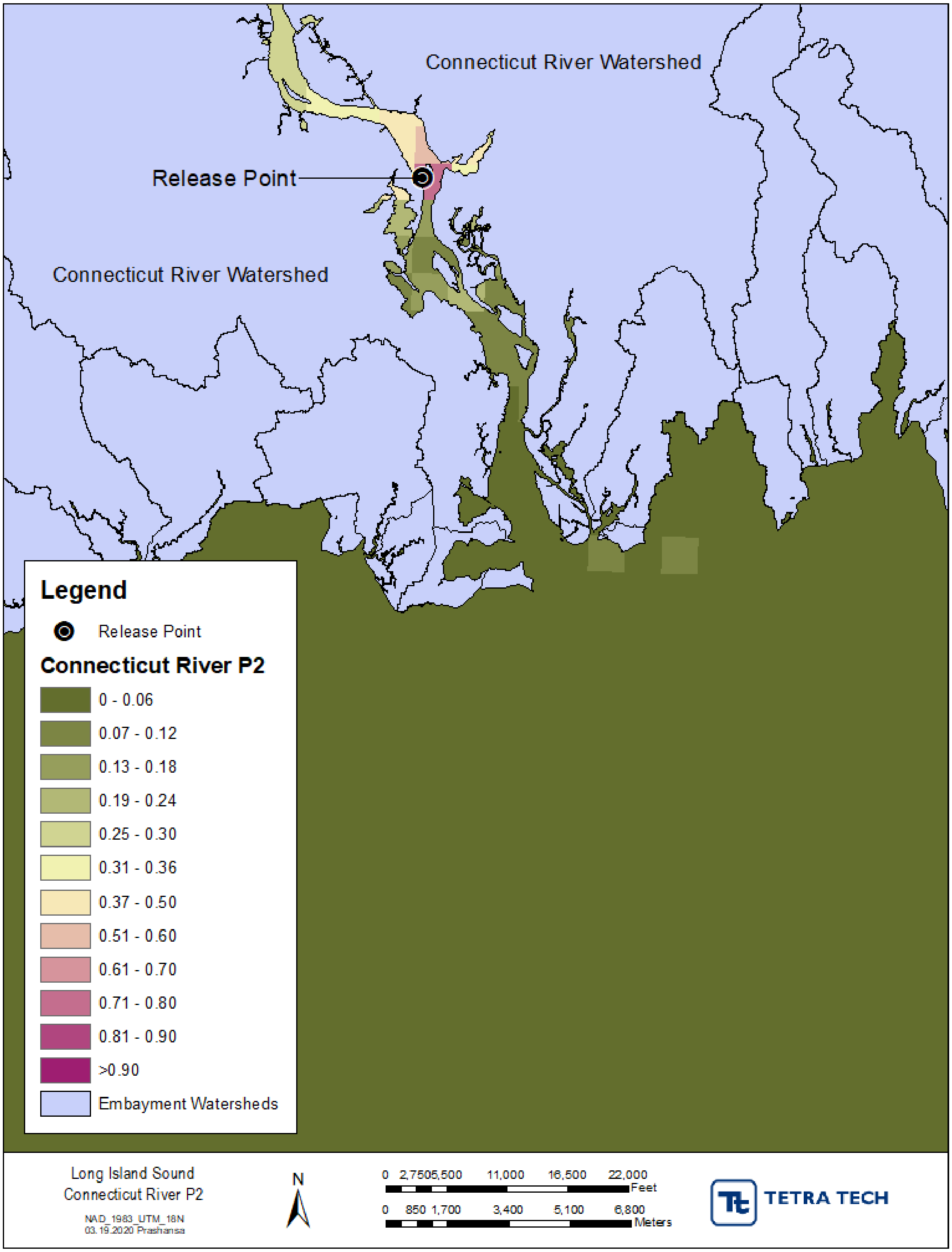

Figure E-5. Relative Contribution of Connecticut River Water in LIS (Scenario 2: Particles Released from March through October)

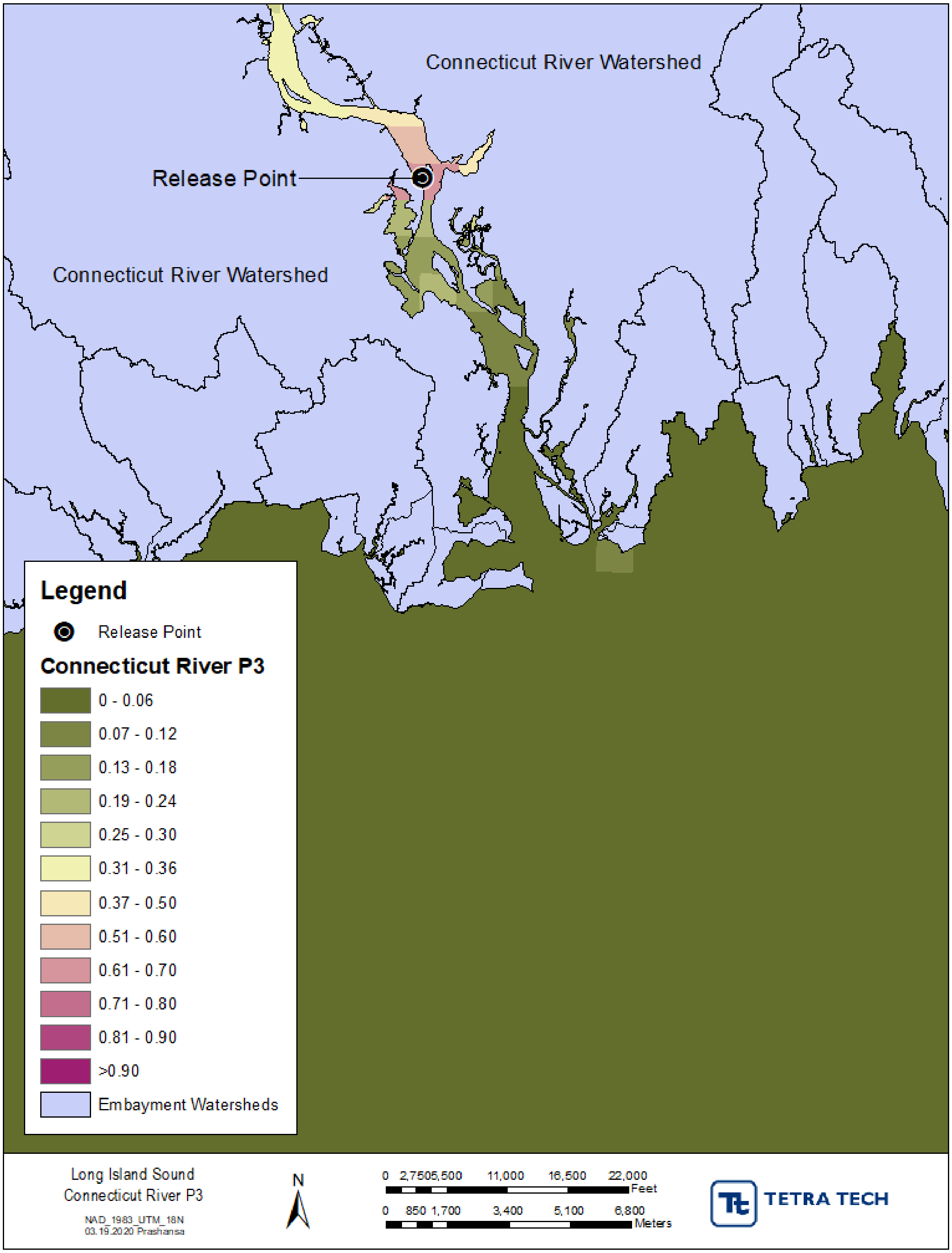

Figure E-6. Relative Contribution of Connecticut River Water in LIS (Scenario 3: Particles Released from July through September)

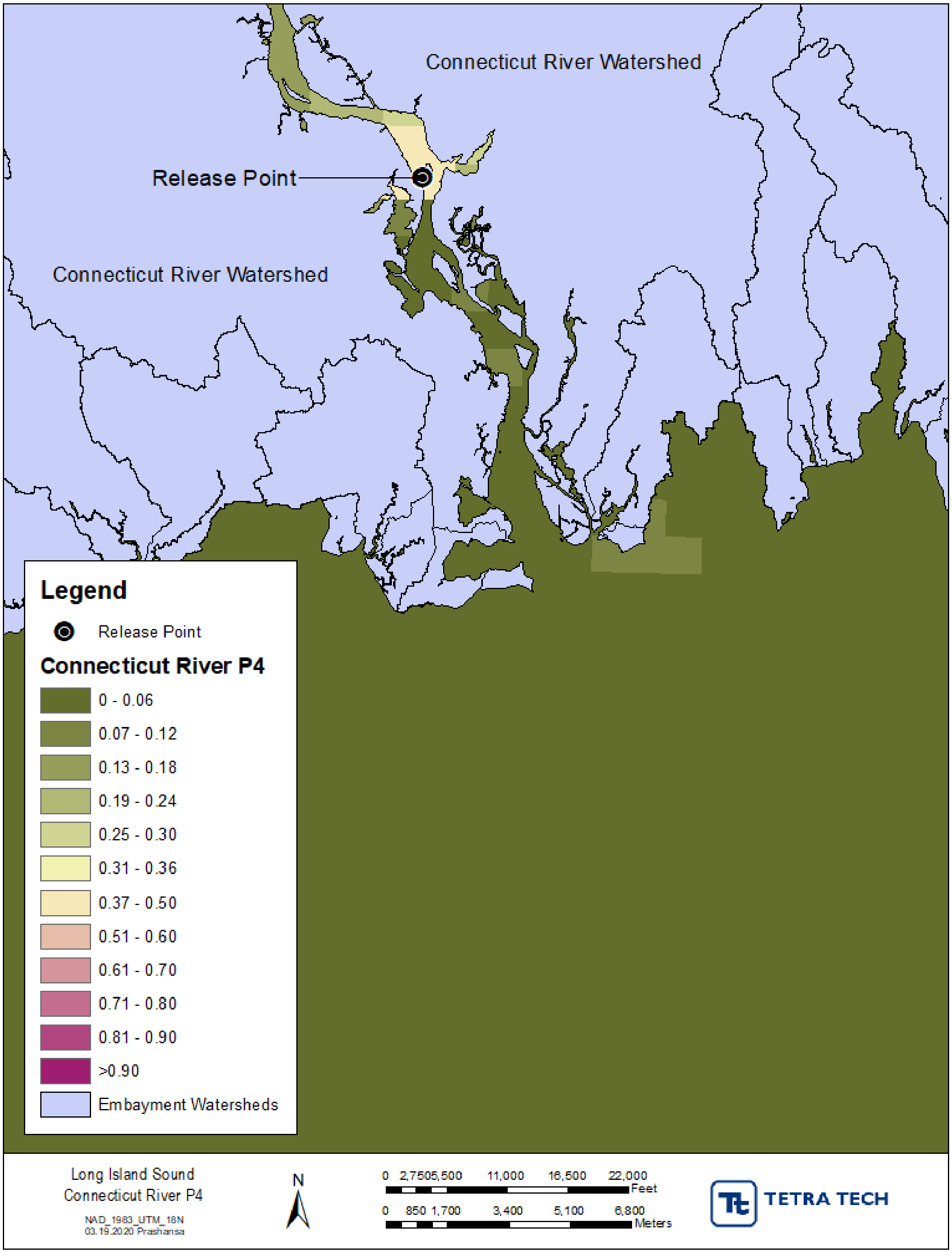

Figure E-7. Relative Contribution of Connecticut River Water in LIS (Scenario 4: Particles Released from March through May)

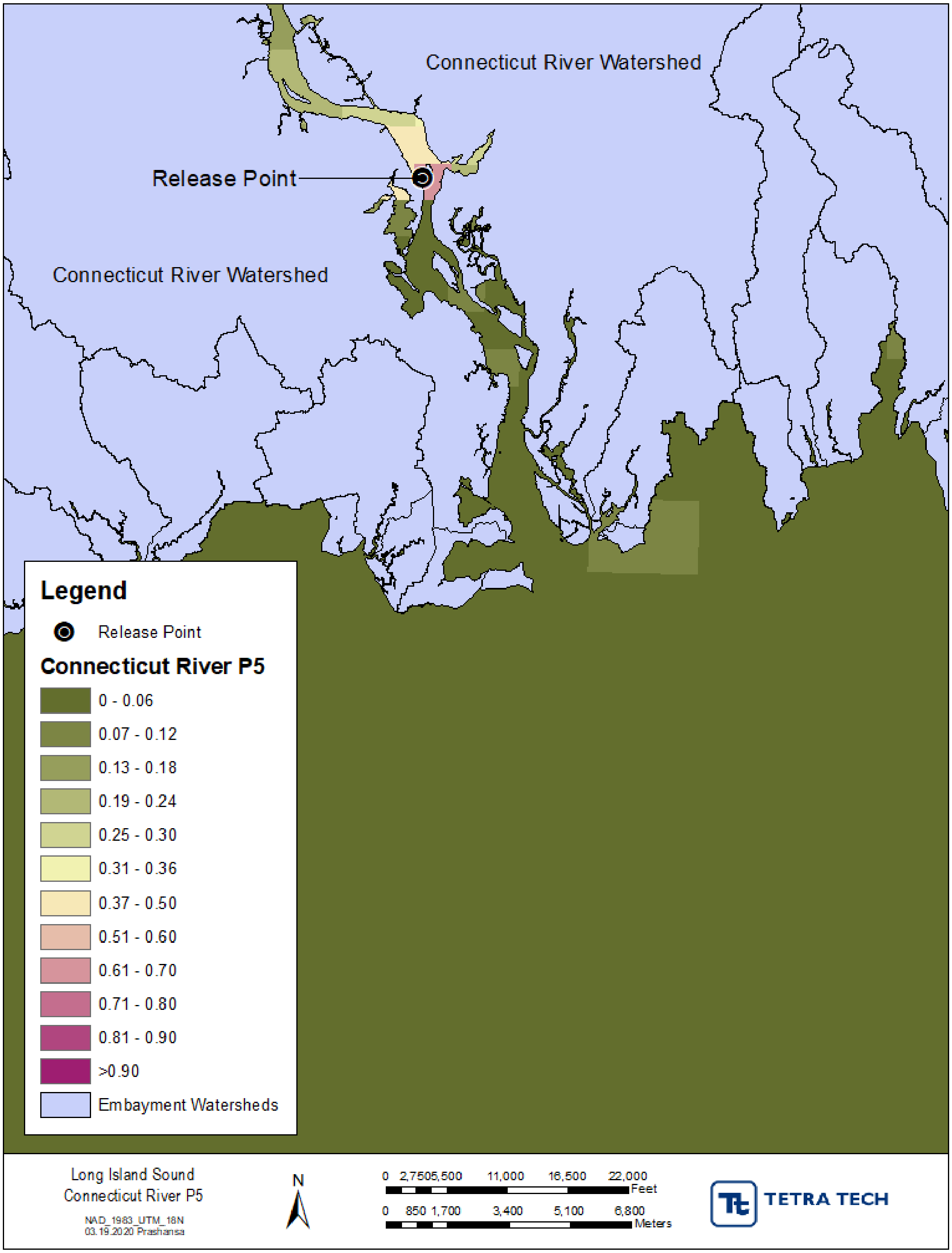

Figure E-8. Relative Contribution of Connecticut River Water in LIS (Scenario 5: Particles Released from March through May and Monitored through October)

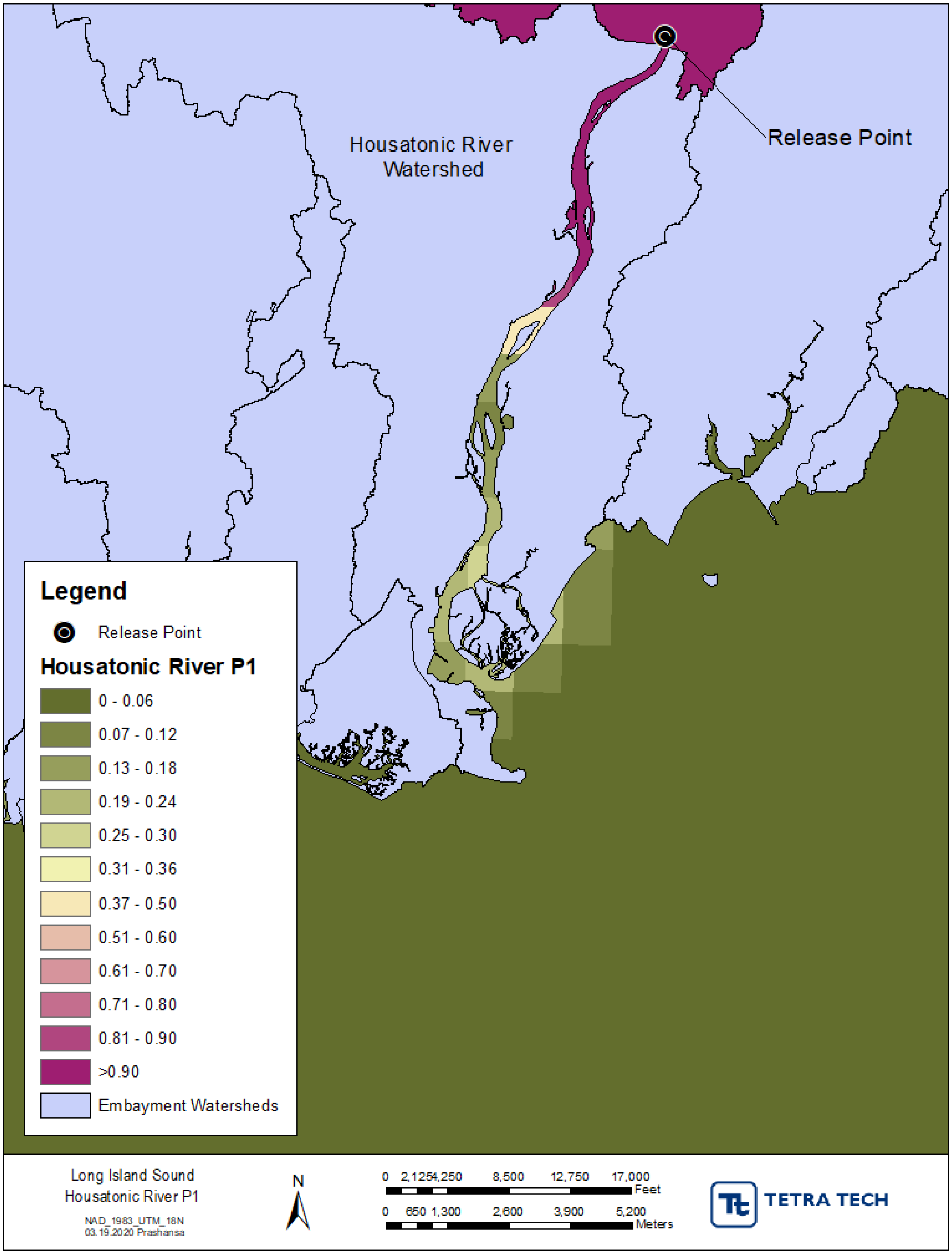

Figure E-9. Relative Contribution of Housatonic River Water in LIS (Scenario 1: Particles Released for Full Year)

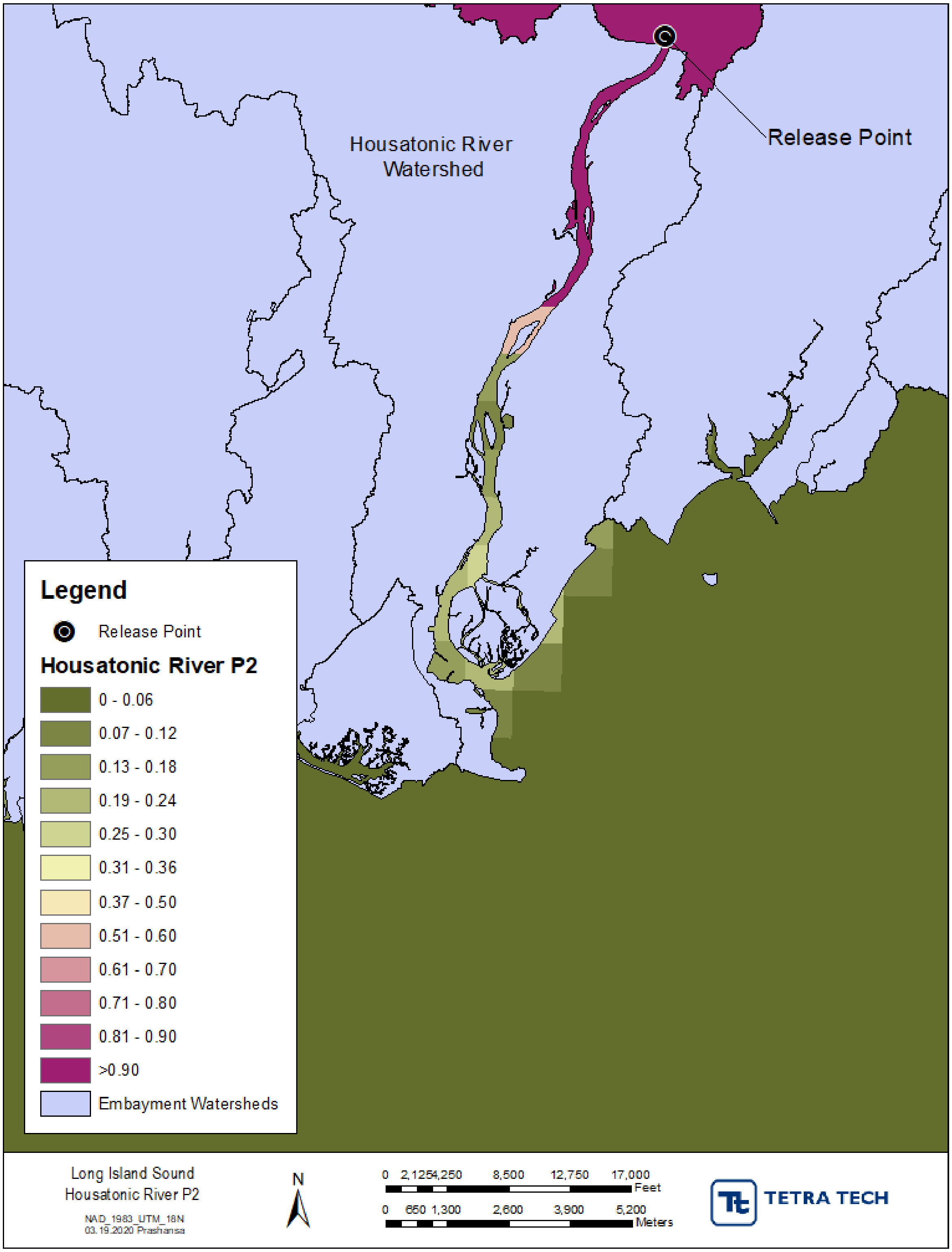

Figure E-10. Relative Contribution of Housatonic River Water in LIS (Scenario 2: Particles Released from March through October)

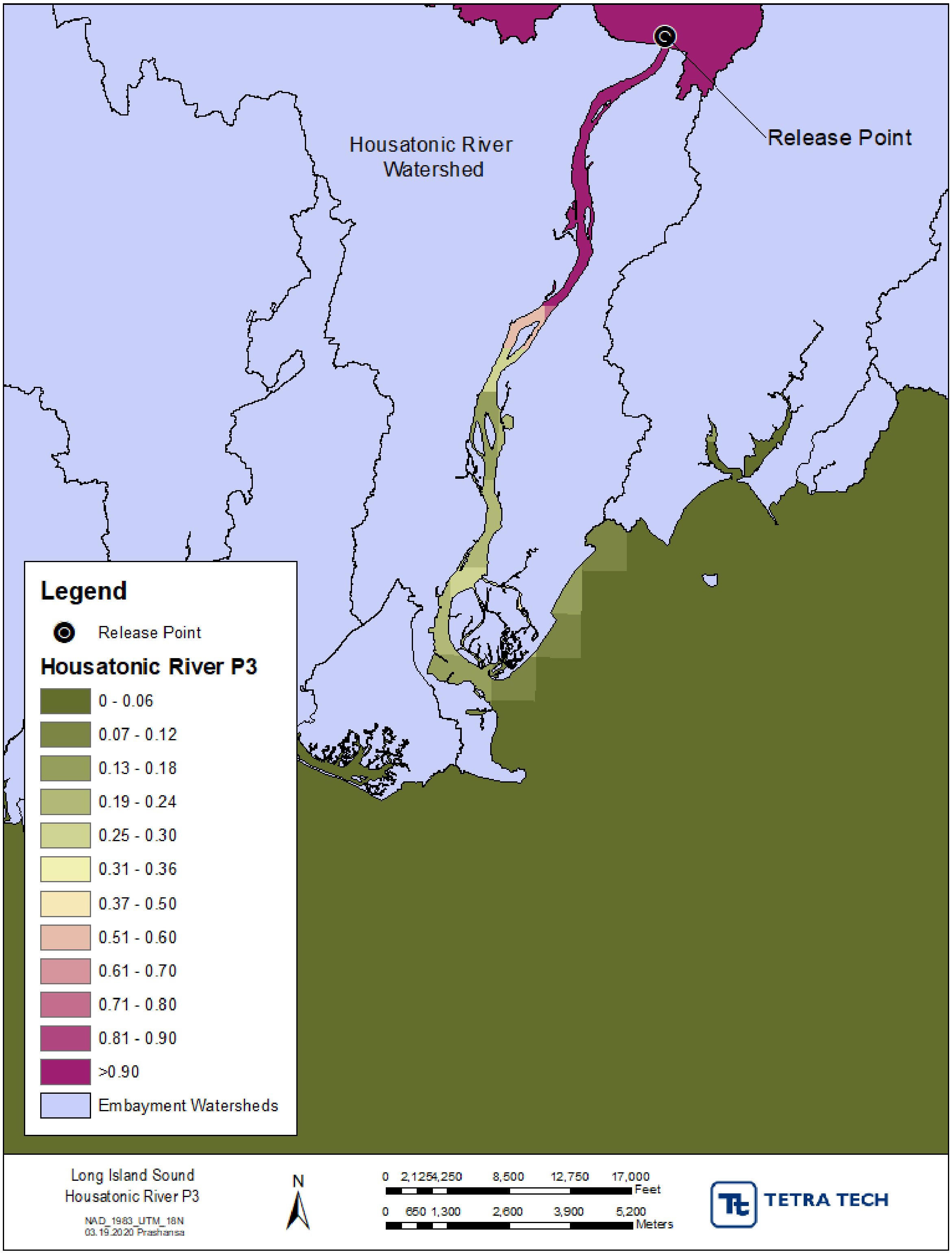

Figure E-11. Relative Contribution of Housatonic River Water in LIS (Scenario 3: Particles Released from July through September)

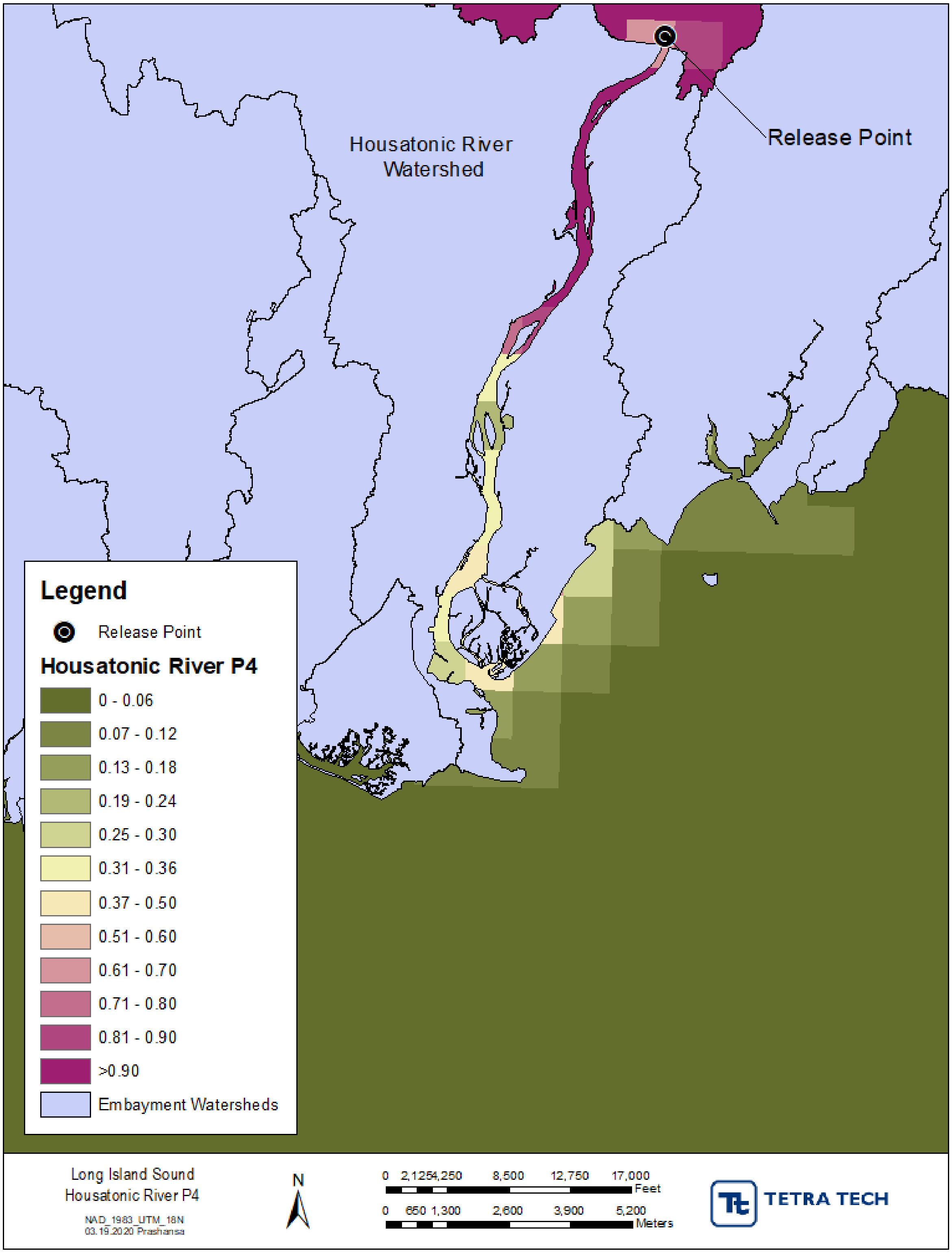

Figure E-12. Relative Contribution of Housatonic River Water in LIS (Scenario 4: Particles Released from March through May)

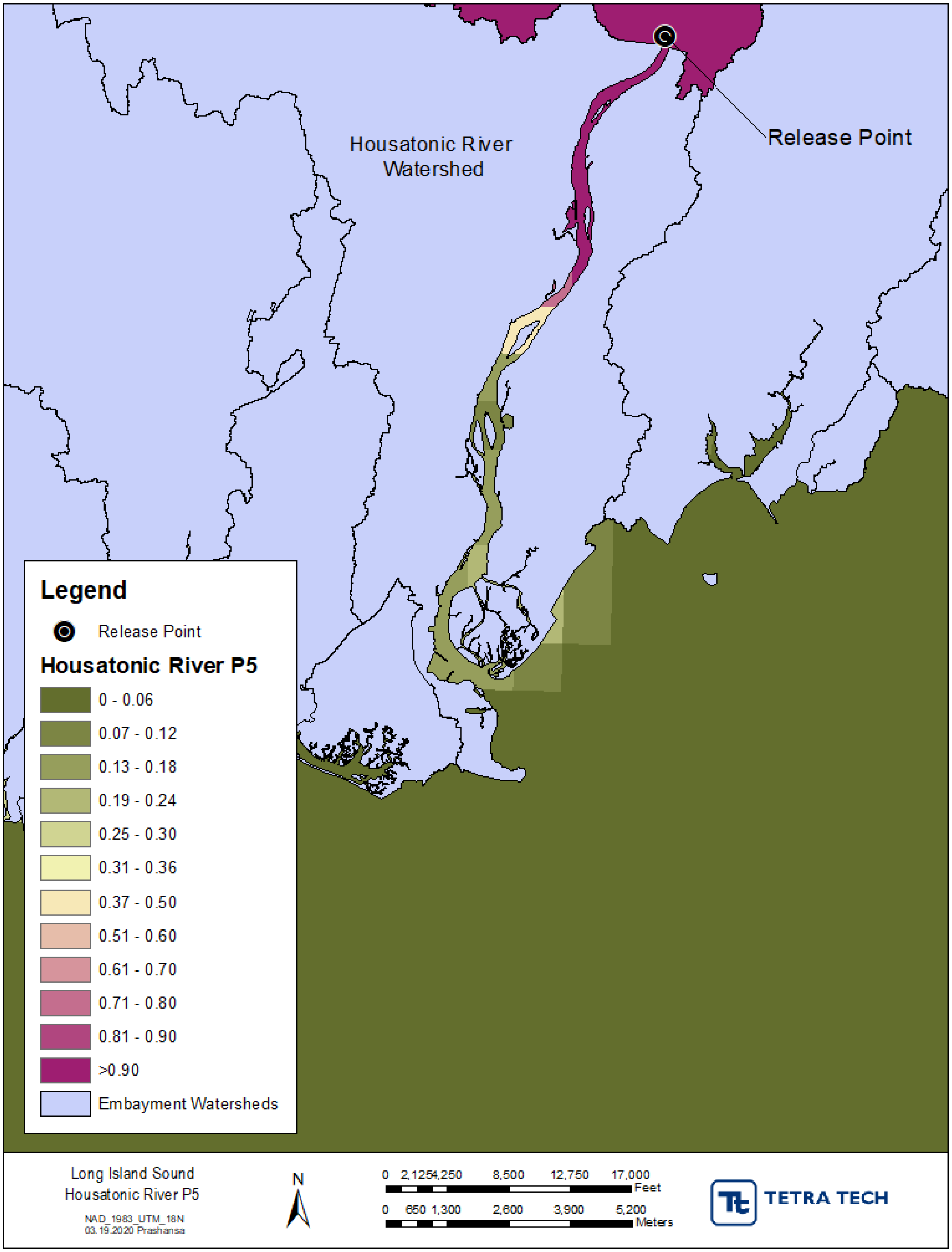

Figure E-13. Relative Contribution of Housatonic River Water in LIS (Scenario 5: Particles Released from March through May and Monitored through October)

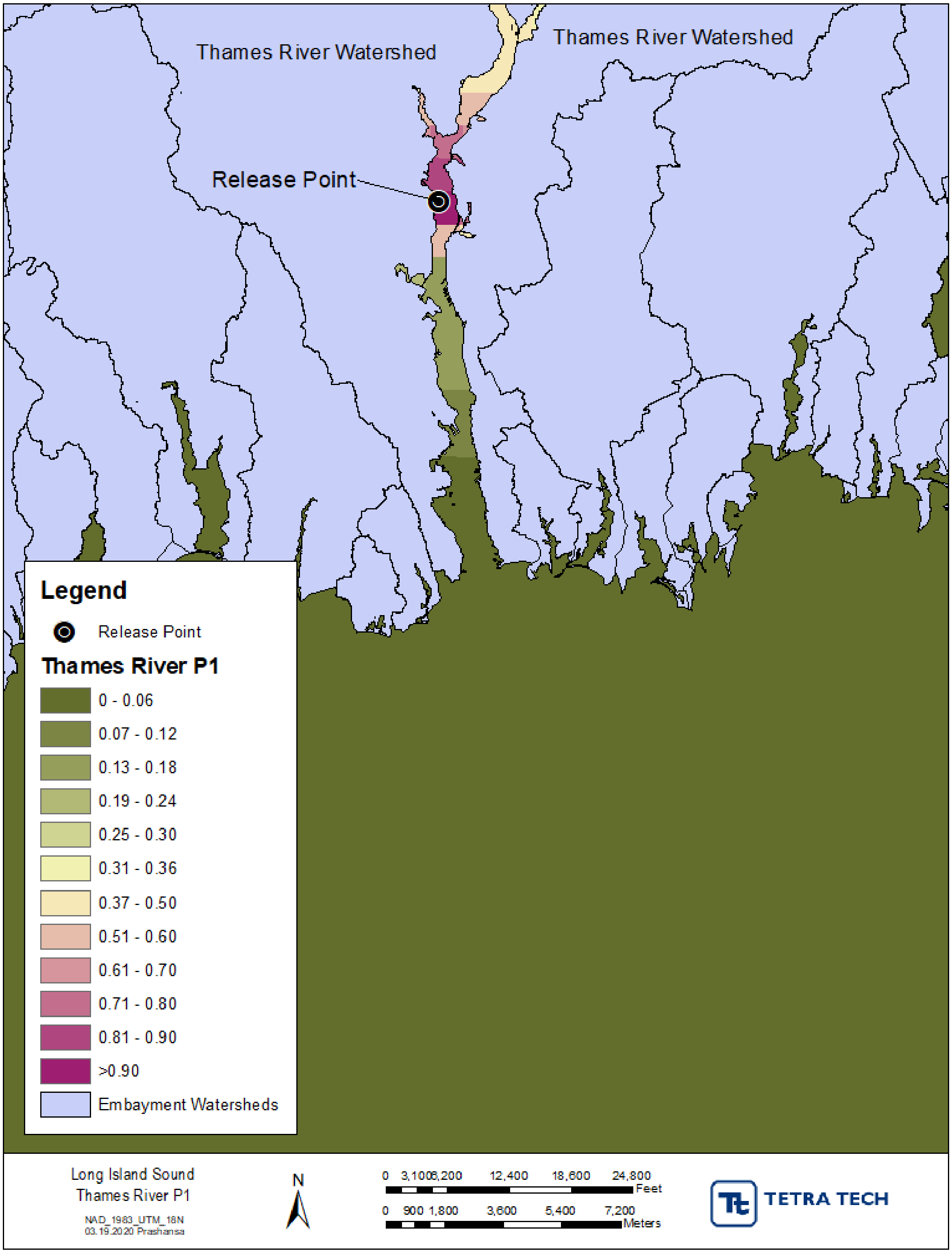

Figure E-14. Relative Contribution of Thames River Water in LIS (Scenario 1: Particles Released for Full Year)

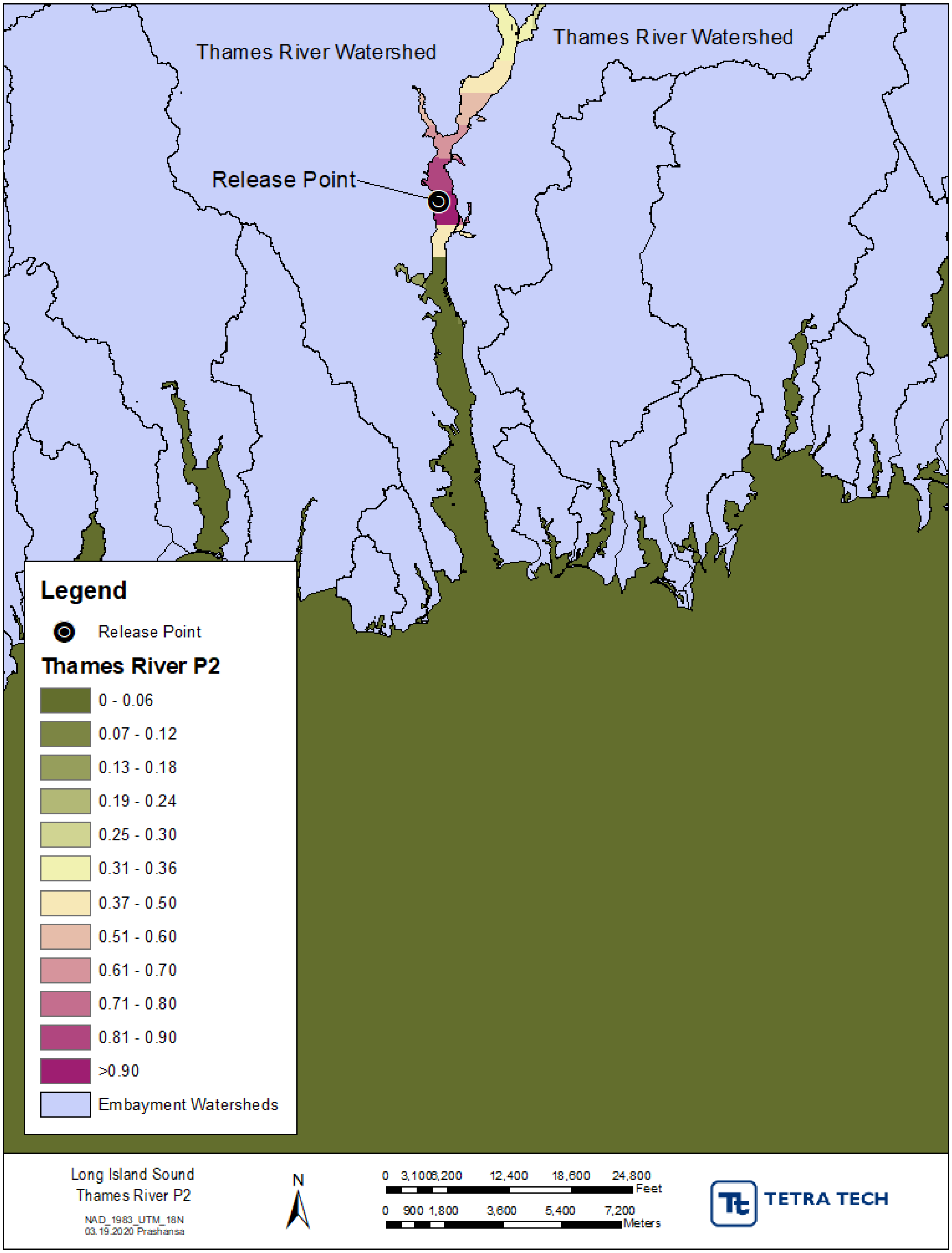

Figure E-15. Relative Contribution of Thames River Water in LIS (Scenario 2: Particles Released from March through October)

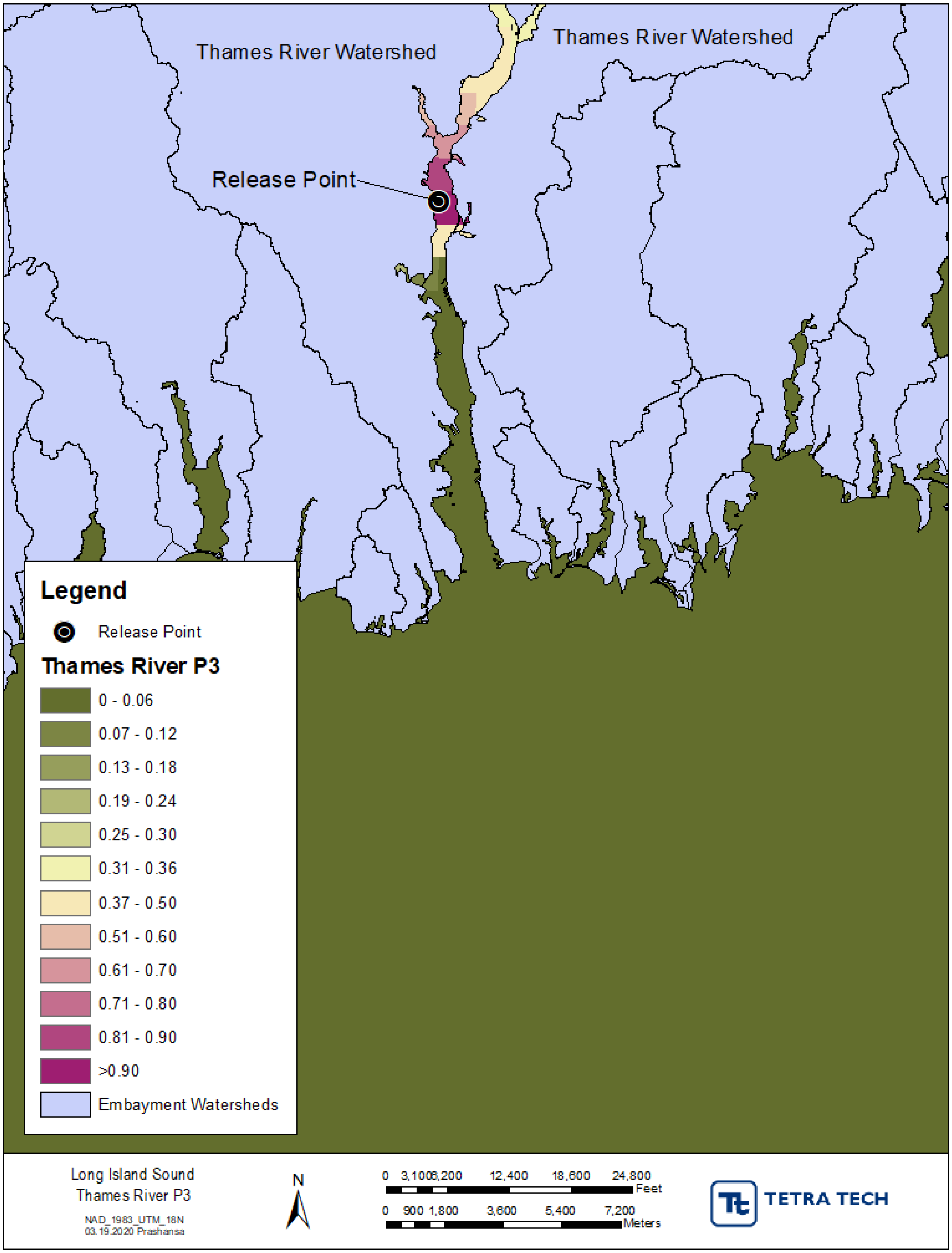

Figure E-16. Relative Contribution of Thames River Water in LIS (Scenario 3: Particles Released from July through September)

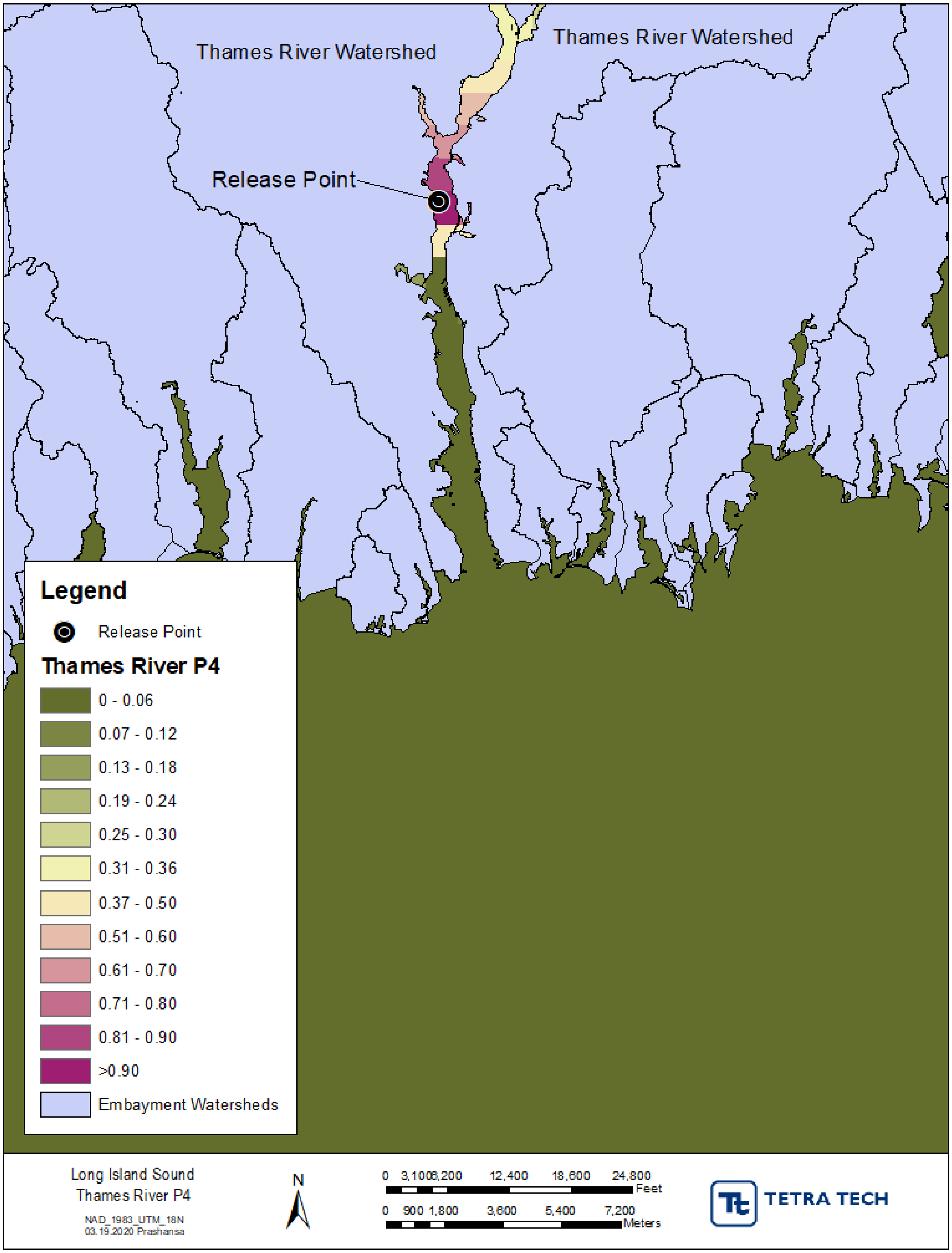

Figure E-17. Relative Contribution of Thames River Water in LIS (Scenario 4: Particles Released from March through May)

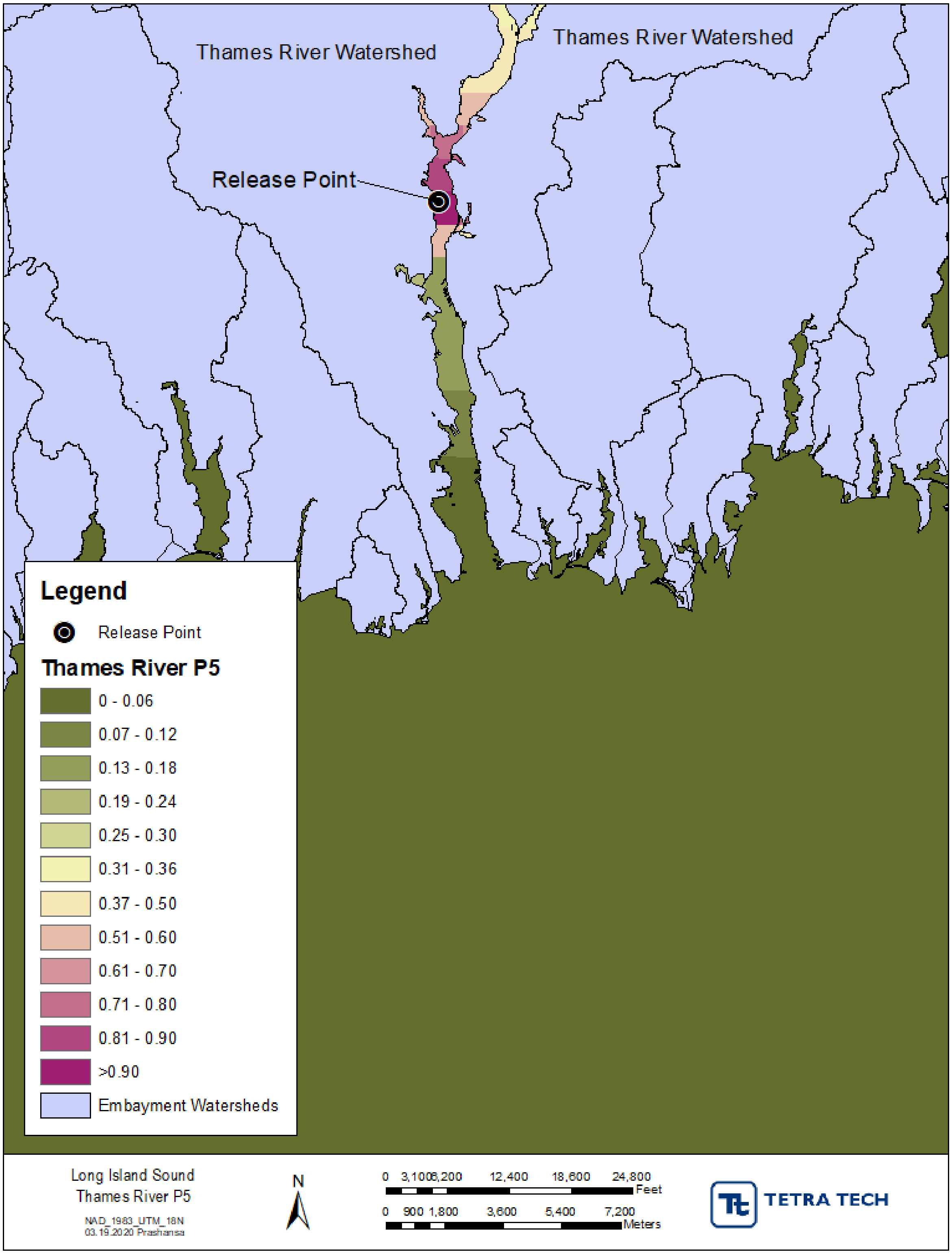

Figure E-18. Relative Contribution of Thames River Water in LIS (Scenario 5: Particles Released from March through May and Monitored through October)

Figure E-4 through Figure E-18 show that the riverine influence in each case decreases within a short distance downstream from the release point and reflects the influence of LIS. The Housatonic River exhibited the greatest riverine influence downstream of the release point. It also was observed that the area of influence was similar across the different scenarios run for each river. The shorter time periods of scenario 3 (particles released July–September) and scenario 4 (particles released March–May) exhibit a smaller area of influence than the longer time periods exhibit.

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

The purpose of the second analytical output from particle tracking was to calculate the contribution 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 contribution of water from the three rivers using the particle-tracking model. The output consists of a multiplicative contribution factor for the Connecticut, Housatonic, and Thames rivers generated as an average dilution of particles from the three rivers to each embayment. 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 combination with concentration data for the rivers and other sources to estimate the percent contribution of rivers to embayment TN concentrations.

The contribution factors for the respective river are used as a fractional coefficient on the river's nutrient concentration to calculate its effect on TN concentration for each embayment (see Table E-4 through Table E-6). For example, if the TN concentration in the Connecticut River discharge is 3.5 milligrams per liter (mg/L), using information from Table E-5, the contribution factor for the Connecticut River to the Saugatuck River North, CT, embayment is 0.00735 for scenario 1 (particles released full year). Therefore, the fraction contributed by the Connecticut River to concentrations in the Saugatuck River North, CT, would be 0.00735*3.5= 0.025725 mg/L, based on assumptions that mass loads from each source are additive. 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.

Table E-4. Thames River Contribution Factors by Selected Embayment (Average All Years, Top 6 Layers)

Selected Embayments*		D (S_e/S_{LIS})	Scenario 1: Particles Released Full Year	Scenario 2: Particles Released Mar–Oct	Scenario 3: Particles released Jul–Sep	Scenario 4: Particles Released Mar–May	Scenario 5: Particles Released Mar–May and Monitored Through Oct
Pawcatuck River, RI and CT		0.9952	<0.00001	<0.00001	0.00002	0.00002	<0.00001
Little Narragansett Bay, CT		0.9791	0.00014	0.00014	0.00018	0.00030	0.00010
Stonington Harbor, CT		0.9656	0.00010	0.00010	0.00014	0.00020	0.00007
Mystic Harbor, CT		0.9968	0.00016	0.00015	0.00019	0.00038	0.00013
Thames River, CT			1.00000	1.00000	1.00000	1.00000	1.00000
Niantic Bay, CT	Niantic River, CT	0.9402	0.00051	0.00057	0.00090	0.00045	0.00016
	Niantic Bay, CT	0.9759	0.00017	0.00016	0.00024	0.00026	0.00009
Farm River, CT		0.9820	0.00001	0.00001	<0.00001	0.00002	0.00002
New Haven Harbor, CT		0.7669	0.00002	0.00001	<0.00001	0.00001	0.00002
Pequonnock River, CT		0.9612	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001
Southport Harbor/Sasco Brook, CT		0.9818	0.00001	0.00001	<0.00001	<0.00001	0.00002
Saugatuck Estuary, CT	Saugatuck River, CT	0.9511	0.00009	0.00008	<0.00001	<0.00001	0.00012
	Saugatuck River, North, CT	0.9753	0.00001	0.00001	<0.00001	<0.00001	0.00002
Norwalk Harbor, CT		0.9572	0.00005	0.00005	<0.00001	<0.00001	0.00007
Byram River, CT and NY		0.9795	0.00006	0.00006	<0.00001	<0.00001	0.00011
Mamaroneck River, NY		0.9081	0.00023	0.00030	<0.00001	0.00003	0.00054
Manhasset Bay, NY		0.9827	0.00002	0.00002	<0.00001	<0.00001	0.00004
Hempstead Harbor, NY		0.9848	0.00716	0.00648	0.00023	0.00588	0.01078
Oyster Bay/Cold Spring Harbor Complex, NY	Oyster Bay, NY	0.9645	0.00043	0.00049	<0.00001	0.00062	0.00086
	Cold Spring Harbor Complex, NY	0.9785	0.00077	0.00075	0.00014	0.00069	0.00118
Northport-Centerport Harbor Complex, NY	Centerport Harbor, NY	0.9815	0.00137	0.00136	0.00019	0.00053	0.00218
	Northport Bay, NY	0.9890	0.00027	0.00028	0.00003	0.00009	0.00044
	Northport Harbor, NY	0.9764	0.00059	0.00069	0.00011	0.00016	0.00110
Areas Adjacent to Northport-Centerport Harbor Complex	Huntington Bay, NY	0.9906	0.00005	0.00007	0.00003	0.00006	0.00009
	Huntington Harbor	0.9906	0.00049	0.00059	0.00009	0.00019	0.00097
	Lloyd Harbor, NY	0.9881	0.00042	0.00051	0.00008	0.00017	0.00083
Nissequogue River, NY		0.9886	0.00021	0.00021	0.00002	0.00023	0.00033
Stony Brook Harbor, NY		0.9915	0.00023	0.00022	0.00003	0.00020	0.00033
Port Jefferson Harbor, NY		0.9852	0.00121	0.00109	0.00015	0.00059	0.00175
Mt. Sinai Harbor, NY		0.9920	0.00011	0.00015	0.00003	0.00007	0.00024

*Ordered from East to West Starting with the North Shore and then West to East along the South Shore.

Table E-5. Connecticut River Contribution Factors by Selected Embayment (Average All Years, Top 6 Layers)

Selected Embayments*		D (S_e/S_{LIS})	Scenario 1: Particles Released Full Year	Scenario 2: Particles Released Mar–Oct	Scenario 3: Particles Released Jul–Sep	Scenario 4: Particles Released Mar–May	Scenario 5: Particles Released Mar–May and Monitored Through Oct
Pawcatuck River, RI and CT		0.9952	0.00023	0.00017	0.00007	0.00010	0.00028
Little Narragansett Bay, CT		0.9791	0.00548	0.00318	0.00066	0.00261	0.00569
Stonington Harbor, CT		0.9656	0.00485	0.00263	0.00053	0.00213	0.00488
Mystic Harbor, CT		0.9968	0.00283	0.00190	0.00064	0.00227	0.00362
Niantic Bay, CT	Niantic River, CT	0.9402	0.40759	0.21836	0.06592	0.09822	0.45807
	Niantic Bay, CT	0.9759	0.02028	0.01322	0.00452	0.01068	0.02639
Connecticut River, CT			1.00000	1.00000	1.00000	1.00000	1.00000
Farm River, CT		0.9820	0.01407	0.00908	0.00291	0.00903	0.02168
New Haven Harbor, CT		0.7669	0.10076	0.04187	0.00607	0.02237	0.13061
Pequonnock River, CT		0.9612	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001
Southport Harbor/Sasco Brook, CT		0.9818	0.00677	0.00596	0.00106	0.00182	0.01516
Saugatuck Estuary, CT	Saugatuck River, CT	0.9511	0.14081	0.09975	0.00613	0.00834	0.31271
	Saugatuck River, North, CT	0.9753	0.00735	0.00646	0.00104	0.00179	0.01687
Norwalk Harbor, CT		0.9572	0.03428	0.03084	0.00261	0.00364	0.09202
Byram River, CT and NY		0.9795	0.03671	0.03385	0.00113	0.00118	0.10535
Mamaroneck River, NY		0.9081	0.12460	0.06727	0.00120	0.00246	0.21567
Manhasset Bay, NY		0.9827	0.00322	0.00208	0.00004	0.00025	0.00611
Hempstead Harbor, NY		0.9848	0.26505	0.12463	0.00135	0.04762	0.46096
Oyster Bay/Cold Spring Harbor Complex, NY	Oyster Bay, NY	0.9645	0.02061	0.01296	0.00012	0.00717	0.04651
	Cold Spring Harbor Complex, NY	0.9785	0.06809	0.03598	0.00097	0.00792	0.11688
Northport-Centerport Harbor Complex, NY	Centerport Harbor, NY	0.9815	0.05012	0.03597	0.00069	0.00600	0.12529
	Northport Bay, NY	0.9890	0.02322	0.01874	0.00058	0.00195	0.06364
	Northport Harbor, NY	0.9764	0.07221	0.05448	0.00033	0.00356	0.20162
Areas Adjacent to Northport-Centerport Harbor Complex	Huntington Bay, NY	0.9906	0.00238	0.00209	0.00025	0.00097	0.00635
	Huntington Harbor	0.9906	0.04773	0.03033	0.00139	0.00307	0.09100
	Lloyd Harbor, NY	0.9881	0.04047	0.02562	0.00118	0.00259	0.07703
Nissequogue River, NY		0.9886	0.02622	0.02016	0.00158	0.00369	0.05984
Stony Brook Harbor, NY		0.9915	0.02302	0.01598	0.00170	0.00388	0.04403
Port Jefferson Harbor, NY		0.9852	0.13423	0.08835	0.00737	0.01531	0.26455
Mt. Sinai Harbor, NY		0.9920	0.01394	0.01389	0.00240	0.00546	0.03777

*Ordered from East to West Starting with the North Shore and then West to East along the South Shore.

Table E-6. Housatonic River Contribution Factors by Selected Embayment (Average All Years, Top 6 Layers)

Selected Embayments*		D (S_e/S_{LIS})	Scenario 1: Particles Released Full Year	Scenario 2: Particles Released Mar–Oct	Scenario 3: Particles Released Jul–Sep	Scenario 4: Particles Released Mar–May	Scenario 5: Particles Released Mar–May and Monitored Through Oct
Pawcatuck River, RI and CT		0.9952	0.00003	0.00002	<0.00001	<0.00001	0.00002
Little Narragansett Bay, CT		0.9791	0.00057	0.00023	0.00007	0.00019	0.00035
Stonington Harbor, CT		0.9656	0.00049	0.00018	0.00005	0.00014	0.00029
Mystic Harbor, CT		0.9968	0.00038	0.00018	0.00005	0.00022	0.00024
Niantic Bay, CT	Niantic River, CT	0.9402	0.00889	0.00243	0.00056	0.00170	0.00400
	Niantic Bay, CT	0.9759	0.00155	0.00068	0.00016	0.00062	0.00100
Farm River, CT		0.9820	0.01275	0.00833	0.00264	0.01420	0.00941
New Haven Harbor, CT		0.7669	0.12663	0.04937	0.00394	0.09596	0.09136
Housatonic River, MA and CT			1.00000	1.00000	1.00000	1.00000	1.00000
Pequonnock River, CT		0.9612	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001
Southport Harbor/Sasco Brook, CT		0.9818	0.00507	0.00538	0.00337	0.00573	0.00657
Saugatuck Estuary, CT	Saugatuck River, CT	0.9511	0.11521	0.07557	0.01799	0.04054	0.12796
	Saugatuck River, North, CT	0.9753	0.00549	0.00573	0.00338	0.00579	0.00727
Norwalk Harbor, CT		0.9572	0.02399	0.02423	0.00802	0.01672	0.03958
Byram River, CT and NY		0.9795	0.02332	0.02418	0.00410	0.00941	0.04236
Mamaroneck River, NY		0.9081	0.07285	0.05563	0.01936	0.02833	0.09186
Manhasset Bay, NY		0.9827	0.00261	0.00191	0.00015	0.00184	0.00302
Hempstead Harbor, NY		0.9848	0.10293	0.04741	0.00244	0.04465	0.08694
Oyster Bay/Cold Spring Harbor Complex, NY	Oyster Bay, NY	0.9645	0.01173	0.00790	0.00077	0.01186	0.01338
	Cold Spring Harbor Complex, NY	0.9785	0.03339	0.01610	0.00163	0.01039	0.02504
Northport-Centerport Harbor Complex, NY	Centerport Harbor, NY	0.9815	0.01512	0.00961	0.00116	0.00718	0.01789
	Northport Bay, NY	0.9890	0.01187	0.01023	0.00130	0.00423	0.01866
	Northport Harbor, NY	0.9764	0.02409	0.01542	0.00083	0.00304	0.03040
Areas Adjacent to Northport-Centerport Harbor Complex	Huntington Bay, NY	0.9906	0.00145	0.00122	0.00041	0.00178	0.00192
	Huntington Harbor	0.9906	0.02899	0.02030	0.00462	0.01045	0.02994
	Lloyd Harbor, NY	0.9881	0.02459	0.01720	0.00394	0.00902	0.02545
Nissequogue River, NY		0.9886	0.01448	0.00974	0.00296	0.00789	0.01325
Stony Brook Harbor, NY		0.9915	0.01573	0.01072	0.00420	0.00987	0.01372
Port Jefferson Harbor, NY		0.9852	0.07508	0.04444	0.01274	0.04122	0.06273
Mt. Sinai Harbor, NY		0.9920	0.00867	0.00862	0.00459	0.01479	0.01215

*Ordered from East to West Starting with the North Shore and then West to East along the South Shore.

Limitations

Several limitations to Tetra Tech's approach should be noted:

- The limited resolution of the NYHOPS grid did not fully resolve each embayment and likely overestimated dilution of the landward, freshwater ends of embayment waters. This limitation could be improved by constructing hydrodynamic models at a finer spatial resolution or collecting data to make better empirical estimates of dilution for each embayment. Since the temporal scale of interest is average dilution, the lack of sub-daily hydrodynamics was assumed to have minimal impact on dilution estimates.
- The available NYHOPS data did not provide vertical flow vectors, although the salinity predictions (and thus the dilution estimates) incorporated those flows. The lack of vertical fluxes, sub-daily tidal and wind 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 mixing and sub-daily tidal and wind mixing, it is likely to produce an estimated area of influence that is more compact, particularly at the edges, than occurs in LIS. Future efforts, again, could help overcome this limitation.
- The temporal scale of modeling was varied to capture seasonal changes in terms of nutrient effects on responses in LIS embayments. Flow and material contributions from all tributaries, including the three rivers, vary greatly, especially in the spring and during storms, and mixing and exchange likely vary also. 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). In the future, modeling the fate of such temporal inputs in each embayment could determine their influence on critical period exposure concentrations, which might result in the contribution of freshwater inputs to embayments being underestimated. Future efforts should consider how to improve on these estimates.

Summary

The goal of this subtask was to identify areas of LIS where tributary nitrogen loads are likely to influence nutrient concentrations. The analyses used hydrodynamic modeling to provide information to support evaluating the linkage between nitrogen-loading sources and ambient concentrations in the embayments. For this hydrodynamic analysis, EPA focused on identifying available defensible hydrodynamic model output, with the expert input of three existing LIS hydrodynamic modeling teams from Stevens Institute of Technology and the University of Connecticut. After consultation with and input from these experts, Tetra Tech determined that the NYHOPS model provided the best combination of readily available output at the spatial and temporal resolution needed. Tetra Tech and EPA recognized that the readily available output of the model had constraints (e.g., it did not provide sub-daily flow vectors or mixing between sigma layers), but that the NYHOPS model still provided defensible and comparable approximations of flow and salinity across the widest area of LIS for the purpose of this study.

The NYHOPS model data were used to estimate dilution of LIS water within the selected embayments to be applied in calculating nitrogen target concentrations 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. This allowed the team to both estimate areas of influence of the three rivers to inform nitrogen target concentrations for each waterbody and to calculate the contribution of water, and ultimately nitrogen, from the three rivers to selected embayments during the summer growing season.