VI. WATER QUALITY MODELING

VI.1 DATA SOURCES FOR THE MODEL

Several different data types and calculations are required to support the water quality modeling effort. These include the output from the hydrodynamics model, calculations of external nitrogen loads from the watersheds, measurements of internal nitrogen loads from the sediment (benthic flux), and measurements of nitrogen in the water column.

VI.1.1 Hydrodynamics and Tidal Flushing in the Embayments

Extensive field measurements and hydrodynamic modeling of the embayments were an essential preparatory step to the development of the water quality model. The result of this work, among other things, was a set of five files of calibrated model output representing the transport of water within each of the five embayment systems. Files of node locations and node connectivity for the RMA-2V model grids were transferred to the RMA-4 water quality model; therefore, the computational grid for the hydrodynamic model also was the computational grid for the water quality model. The period of hydrodynamic output for the water quality model calibration was a 14-tidal cycle period in summer 2000 that included both the neap and spring cycles.

VI.1.2 Nitrogen Loading to the Embayments

Three primary nitrogen loads to the embayments are recognized in this modeling study: external loads from the watersheds, nitrogen load from direct rainfall on the embayment surface, and internal loads from the sediments. Additionally, there is a fourth load to the embayments, consisting of the background concentrations of total nitrogen in the waters entering from Nantucket Sound or Chatham Harbor. This load is represented as a constant concentration along the seaward boundary of each model grid.

VI.1.3 Measured Nitrogen Concentrations in the Embayments

In order to create a model that realistically simulates the total nitrogen concentrations in a system in response to the existing flushing conditions and loadings, it is necessary to calibrate the model to actual measurements of water column nitrogen concentrations. The Town of Chatham Water Quality Laboratory, in conjunction with the Chatham Water Watchers (citizen volunteers), initiated a water quality monitoring program in the Stage Harbor system in the fall of 1998, and continued it through the summer of 1999. In 2000, sampling stations were added in the Sulphur Springs, Taylors Pond, Muddy Creek and Bassing Harbor systems (Duncanson, 2000). The sampling continued during 2001 and 2002. The goals of this program were to monitor existing water quality conditions, to provide data on the extent to which water quality was meeting goals or criteria, to compare conditions in the different embayments and their watersheds for targeting remedial actions, to help focus future studies on areas perceived as degraded, and to provide a long term data set for monitoring the success of remediation activities (Duncanson, 2000). The data were reviewed and did meet quality control requirements under the MEP QAPP. The monitoring data were overseen by the Chatham Water Quality Laboratory and did have an approved QAPP. The refined and approved data for each system used in the water quality modeling effort are presented in Table VI-1A and Table VI-1B. The multi-year averages present the “best” comparison to the water quality model output, since factors of tide, temperature and rainfall may exert short-term influences on the individual sampling dates and even cause inter-annual differences. Three years of baseline field data is the minimum required to provide a baseline for MEP analysis.

Table VI-1a. Measured and modeled Nitrogen concentrations for Bassing Harbor and Muddy Creek, used in the model calibration plots of Figures VI-3 (Bassing Harbor total N),VI-4 (Bassing Harbor bio-active N), and VI-5 (Muddy Creek). All concentrations are given in mg/L N. "Data mean" values are calculated as the average of the separate yearly means.

System	Embayment	1999 mean	2000 mean	2001 mean	2002 mean	Overall mean	s.d.	N	model min	model average	model max
Bassing Harbor (TOTAL N)	Ryder Cove (inner)	-	0.465	0.634	0.653	0.569	0.183	46	0.556	0.564	0.573
	Ryder Cove (outer)	-	0.437	0.391	0.427	0.419	0.067	47	0.493	0.522	0.551
	Frost Fish Cr. (inner)	-	0.915	0.684	0.788	0.809	0.218	18	0.676	0.724	0.792
	Frost Fish Cr. (outer)	-	1.244	0.867	1.379	1.187	0.435	23	0.535	0.605	0.818
	Crows Pond	-	0.755	0.936	1.135	0.929	0.346	44	0.576	0.585	0.591
	Bassing Harbor	-	0.543	0.462	0.482	0.499	0.172	23	0.480	0.497	0.532
Bassing Harbor (Bio-Active N)	Ryder Cove (inner)	-	0.178	0.168	0.242	0.189	0.067	46	0.192	0.200	0.208
	Ryder Cove (outer)	-	0.167	0.139	0.191	0.163	0.036	47	0.129	0.158	0.187
	Frost Fish Cr. (inner)	-	-	0.364	0.409	0.387	0.065	10	0.312	0.360	0.428
	Frost Fish Cr. (outer)	-	0.391	0.307	0.290	0.338	0.173	23	0.171	0.241	0.454
	Crows Pond	-	0.220	0.200	0.232	0.218	0.095	44	0.212	0.221	0.227
	Bassing Harbor	-	0.156	0.108	0.131	0.133	0.037	23	0.116	0.133	0.168
Muddy Creek	Lower Muddy Cr.	-	0.569	0.591	0.622	0.586	0.092	21	0.557	0.597	0.658
	Upper Muddy Cr.	-	-	-	1.184	1.184	0.501	6	1.179	1.205	1.232

Table VI-1b. Measured and modeled Nitrogen concentrations for Stage Harbor, Sulphur Springs, and Taylors Pond, used in the model calibration plots of Figures VI-6 (Stage Harbor total N),VI-7 (Sulphur Springs), and VI-8 (Taylors Pond). All concentrations are given in mg/L N. "Data mean" values are calculated as the average of the separate yearly means.

System	Embayment	1999 mean	2000 mean	2001 mean	2002 mean	data mean	s.d.	N	model min	model average	model max
Stage Harbor*	Oyster Pond	0.597	0.786	0.708	0.604	0.667	0.252	63	0.671	0.678	0.687
	Lower Oyster Pond	-	-	0.552	0.498	0.505	0.083	8	0.371	0.547	0.658
	Oyster River	0.451	0.457	0.386	0.536	0.457	0.103	28	0.286	0.374	0.568
	Stage Harbor	0.425	0.664	0.632	0.677	0.597	0.182	58	0.288	0.339	0.427
	Upper Stage Harbor	0.418	0.457	0.503	0.548	0.474	0.116	62	0.382	0.401	0.423
	Mitchell River	-	-	0.429	0.487	0.451	0.092	13	0.403	0.432	0.467
	Mill Pond	0.471	0.503	0.418	0.507	0.463	0.102	70	0.466	0.473	0.485
	Little Mill Pond	0.792	0.690	0.742	0.741	0.733	0.226	60	0.696	0.711	0.723
Sulphur Springs	Mid Cockle Cove Cr.	-	1.492	2.043	1.613	1.685	0.698	18	0.704	1.378	2.493
	Cockle C. Cr. mouth	-	0.890	0.687	0.636	0.742	0.213	23	0.286	0.472	0.988
	Bucks Creek	-	0.401	0.479	0.576	0.473	0.139	20	0.285	0.337	0.508
	Sulphur Springs	-	0.360	0.453	0.584	0.451	0.123	23	0.288	0.369	0.498
Taylors Pond	Mill Creek	-	0.491	0.508	0.530	0.507	0.105	23	0.284	0.326	0.584
	Taylors Pond	-	0.509	0.487	0.530	0.508	0.122	48	0.424	0.467	0.517

* Stage Harbor also included the limited sampling data (N=4) from 1998.

VI.2 MODEL DESCRIPTION AND APPLICATION

A two-dimensional finite element water quality model, RMA-4 (King, 1990), was employed to study the effects of nitrogen loading in the five Chatham embayment systems. The RMA-4 model has the capability for the simulation of advection-diffusion processes in aquatic environments. It is the constituent transport model counterpart of the RMA-2 hydrodynamic model used to simulate the fluid dynamics of the Chatham embayments. Like RMA-2 numerical code, RMA-4 is a two-dimensional, depth averaged finite element model capable of simulating time-dependent constituent transport. The RMA-4 model was developed with support from the US Army Corps of Engineers (USACE) Waterways Experiment Station (WES), and is widely accepted and tested. Applied Coastal staff have utilized this model in water quality studies of other Cape Cod embayments, including West Falmouth Harbor and the Falmouth "finger" ponds (Ramsey et al., 2000).

The overall approach involves modeling total nitrogen as a non-conservative constituent, where bottom sediments act as a source or sink of nitrogen, based on local biochemical characteristics. This modeling represents summertime conditions, when algal growth is at its maximum. Total nitrogen modeling is based upon various data collection efforts and analyses presented in previous sections of this report. Nitrogen loading information was derived from the Cape Cod Commission watershed loading analysis (based on the revised USGS watersheds), as well as the measured bottom sediment nitrogen fluxes. Water column nitrogen measurements by the Chatham Water Watchers were utilized as model boundaries and as calibration data. Hydrodynamic model output (discussed in Section V) provided the remaining information (tides, currents, and bathymetry) needed to parameterize the water quality model.

VI.2.1 Model Formulation

The formulation of the model is for two-dimensional depth-averaged systems in which concentration in the vertical direction is assumed uniform. The governing equation of the RMA-4 constituent model can be most simply expressed as a form of the transport equation, in two dimensions:

$$\left(\frac{\partial c}{\partial t}+u\frac{\partial c}{\partial x}+v\frac{\partial c}{\partial y}\right)=\left(\frac{\partial}{\partial x}D_x\frac{\partial c}{\partial x}+\frac{\partial}{\partial y}D_y\frac{\partial c}{\partial y}+\sigma\right)$$

where c in the water quality constituent concentration; t is time; u and v are the velocities in the x and y directions, respectively; D_x and D_y are the model dispersion coefficients in the x and y directions; and σ is the constituent source/sink term. Since the model utilizes input from the RMA-2 model, a similar implicit solution technique is employed for the RMA-4 model.

The model is therefore used to compute spatially and temporally varying concentrations c of the modeled constituent (i.e., total nitrogen), based on model inputs of 1) water depth and velocity computed using the RMA-2 hydrodynamic model; 2) mass loading input of the modeled constituent; and 3) user selected values of the model dispersion coefficients. The dispersion coefficients used in the sub-embayments of each of the five modeled systems were developed during the calibration process. During the calibration procedure, the dispersion coefficients were incrementally changed until model concentration outputs matched measured data.

The depth-averaged assumption is justified since vertical mixing by wind and tidal processes prevent significant stratification in these systems, even in the relatively deep kettle sub-embayments that are part of some of the Chatham embayments. This lack of stratification is evident in the temperature and salinity profiles of three such estuarine kettle ponds in Chatham, shown in Figure VI-1 and VI-2.

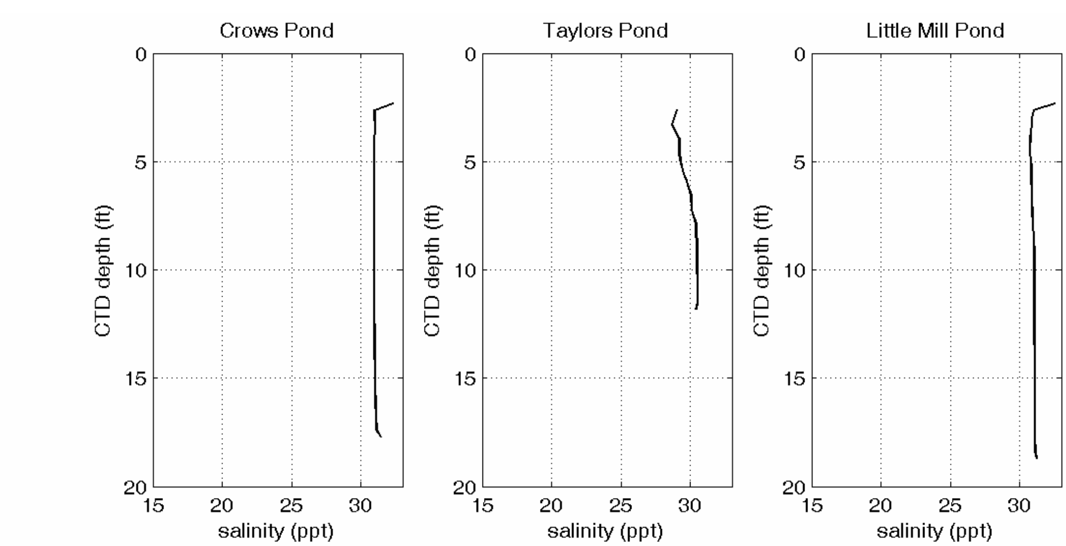

Figure VI-1. CTD cast salinity profiles for Crows Pond (Bassing Harbor), Taylors Pond, and Little Mill Pond (Stage Harbor). Cast data were recorded at 0.66 ft increments (0.2 m), during July 18 (Crows Pond), July 19 (Taylors Pond), and July 20 (Little Mill Pond) of 2000.

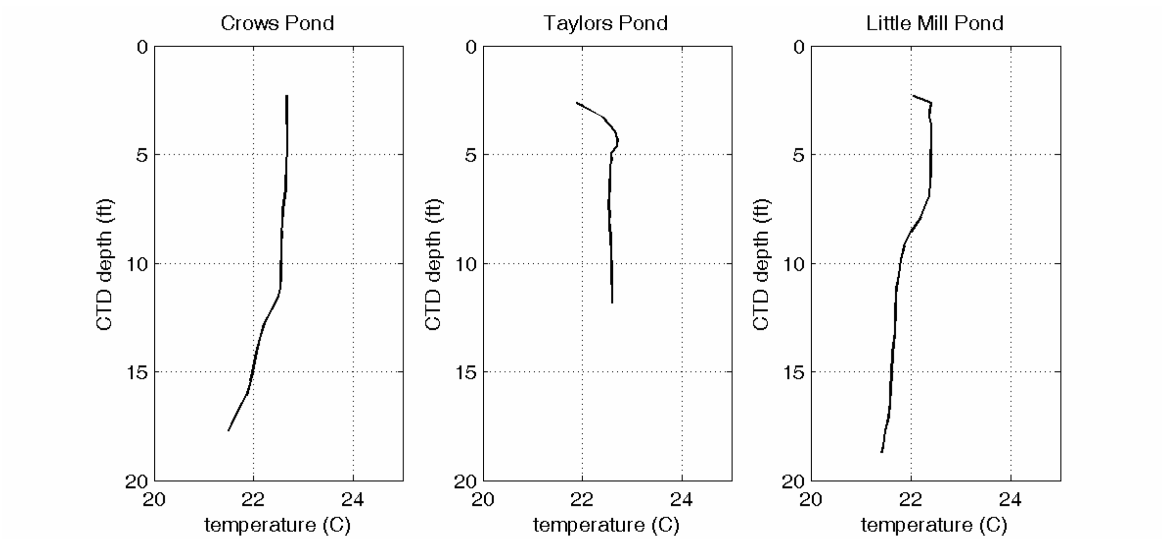

Figure VI-2. CTD cast temperature profiles for Crows Pond (Bassing Harbor), Taylors Pond, and Little Mill Pond (Stage Harbor). Cast data were recorded at 0.66 ft increments (0.2 m), during July 18 (Crows Pond), July 19 (Taylors Pond), and July 20 (Little Mill Pond) of 2000.

RMA-4 model can be utilized to predict both spatial and temporal variations in total At each time step the model computes constituent concentrations over the entire finite element grid and utilizes a continuity of mass equation to check these results. Similar to the hydrodynamic model, the water quality model evaluates model parameters at every element at 12-minute time intervals throughout the grid system. Therefore, the nitrogen concentrations within the coastal pond systems. For this application, the RMA-4 model was used to predict tidally averaged total nitrogen concentrations throughout the five estuarine systems in Chatham.

VI.2.2 Water Quality Model Setup

Required inputs to the RMA-4 model include a computational mesh, computed water elevations and velocities at all nodes of the mesh, constituent mass loading, and spatially varying values of the dispersion coefficient. Because the RMA-4 model is part of a suite of integrated computer models, the finite-element meshes and the resulting hydrodynamic simulations previously developed for the five Chatham sub-embayments also were used for the water quality constituent modeling portion of this study.

Based on updated groundwater recharge rates from the USGS, the Muddy Creek and Bassing Harbor hydrodynamic models were re-run. Muddy Creek and Frost Fish Creek (in the Bassing Harbor system) are the two sub-embayments where freshwater input is significant compared to the volume of water exchanged during a typical tide cycle. From the USGS, freshwater flux into Muddy Creek is 481,600 cubic feet/day, and 47,728 cubic feet/day for Frost Fish Creek. For Muddy Creek, the freshwater input during a single tide cycle (12.42 hours) is 25% of the tidal prism. In Frost Fish Creek, the freshwater recharge is 20% of the average tidal prism.

For each model, an initial total N concentration equal to the concentration at the open boundary was applied to the entire model domain. The model was then run for a simulated month-long (30 day) spin-up period. At the end of the spin-up period, the model was run for an additional 5 tidal-day (124 hour) period. Model results were recorded only after the initial spin-up. The time step used for the water quality computations was 12 minutes, which corresponds to the time step of the hydrodynamics input to each of the five Chatham systems.

VI.2.3 Boundary Condition Specification

Mass loading of nitrogen into each model included 1) sources developed from the results of the watershed analysis, 2) estimates of direct atmospheric deposition, and 3) summer benthic regeneration. Nitrogen loads from each separate sub-embayment watershed were distributed across the sub-embayment. For example, the loads from the Little Mill Pond watershed were evenly distributed at the grid cells that formed the perimeter of the pond. Similarly, benthic flux loads were distributed among grid cells in the central portions of each sub-embayment.

The loadings used to model present conditions in the five Chatham embayments are given in Table VI-2 for the South Coastal embayments and Stage Harbor, and Table VI-3 for the Pleasant Bay embayment systems. Watershed and depositional loads were taken from the results of the analysis of Section IV. Summertime benthic flux loads were computed based on the analysis of sediment cores in Section IV. The area rate (g/sec/m^2) of nitrogen flux from that analysis was applied to the surface area coverage computed for each sub-embayment (excluding marsh coverages, when present), resulting in a total flux for each embayment (as listed in Tables VI-2 and VI-3).

In addition to mass loading boundary conditions set within the model domain, concentrations along the model open boundaries were specified. The model uses concentrations at the open boundary during the flooding tide periods of the model simulations. Constituent concentrations of the incoming water are set at the value designated for the open boundary. For the south coast embayments (Taylors Pond and Sulphur Springs) and Stage Harbor, the boundary concentration in Nantucket Sound was set at 0.29 mg/L, based on Chatham Water Watchers data from the Sound (station CM-7). The open boundary condition for Bassing Harbor was set at 0.48 mg/L in Pleasant Bay (based on station PBA-20). For Muddy Creek, farther into Pleasant Bay, the boundary concentration was set at 0.50 mg/L (based on station PBA-6 and PBA-20). These total nitrogen concentration represent long-term average summer concentrations found within Nantucket Sound and appropriate regions of Pleasant Bay.

Table VI-2. Sub-embayment loads used for total nitrogen modeling of the Stage Harbor and South Coastal embayment systems, with total watershed N loads, atmospheric N loads, and benthic flux. These load represent present loading conditions for the listed sub-embayments.

sub-embayment	watershed load (kg/day)	atmospheric deposition (kg/day)	benthic flux (kg/day)
Stage Harbor			
Oyster Pond	13.03	0.29	26.8
Oyster River	11.47	1.05	0.7
Stage Harbor	2.76	3.25	12.8
Mitchell River	6.38	0.88	-3.4
Mill Pond	1.78	0.63	3.7
Little Mill Pond	1.64	0.12	2.0
Sulphur Springs			
Sulphur Springs	15.33	0.38	-3.6
Bucks Creek	4.08	0.13	2.9
Cockle Cove Creek	6.66	0.06	-0.9
Waste Water TF	3.03	-	-
Taylors Pond			
Mill Creek	6.22	0.17	-0.3
Taylors Pond	8.21	0.19	1.7

VI.2.4 Model Calibration

Calibration of each of the five Chatham embayment systems proceeded by changing model dispersion coefficients so that model output of nitrogen concentrations matched measured data. Generally, several model runs of each system were required to match the water column measurements. Dispersion coefficient (*E*) values were varied through the modeled systems by setting different values of *E* for each grid material type, as designated in Section V. Observed values of *E* (Fischer, *et al.*, 1979) vary between order 10 and order 1000 m^2/sec for riverine estuary systems characterized by relatively wide channels (compared to channel depth) with moderate currents. Coefficients in this range are appropriate for embayments with these characteristics, such as Oyster River (Stage Harbor) and Muddy Creek. Generally, the embayments of Chatham are small compared to the riverine estuary systems evaluated by Fischer, *et al.*, (1979); therefore the values of *E* also are relatively lower for Chatham. Smaller values of *E* occur in deeper and narrower, relatively quiescent sub-embayments, such as Taylors Pond and Crows Pond. Observed values of *E* in these calmer areas typically range between order 10 and order 0.001 m^2/sec (USACE, 2001). The final values of *E* used in each sub-embayment of the modeled systems are presented in Tables VI-4 and VI-5. These values were used to develop the “best-fit” total nitrogen model calibration. For the case of TN modeling, “best fit” can be defined as minimizing the error between the model and data at all sampling locations, utilizing reasonable ranges of dispersion coefficients within each sub-embayment.

Table VI-3. Sub-embayment loads used for total nitrogen modeling of the Bassing Harbor and Muddy Creek systems of Pleasant Bay, with total watershed N loads, atmospheric N loads, and benthic flux. These load represent present loading conditions for the listed sub-embayments.

sub-embayment	watershed load (kg/day)	atmospheric deposition (kg/day)	benthic flux (kg/day)
Bassing Harbor			
Crows Pond	5.79	1.39	3.5
Ryder Cove	12.35	1.30	7.4
Frost Fish Creek	3.59	0.10	-0.2
Bassing Harbor	2.66	1.08	-0.1
Muddy Creek			
Muddy Creek –lower	13.36	0.21	-1.9
Muddy Creek - upper	19.05	0.20	4.7

Table VI-4. Values of longitudinal dispersion coefficient, E, used in calibrated RMA4 model runs of salinity and nitrogen concentration for the South Coastal embayments and Stage Harbor.

Embayment Division	E m^2/sec
Stage Harbor System	
Oyster Pond - upper	1.5
Oyster Pond - lower	2.5
Oyster River	25.0
Little Mill Pond	0.01
Mill Pond	1.0
Mitchell River	10.0
Stage Harbor - upper	4.0
Stage Harbor – main basin	2.0
Stage Harbor - inlet	5.0
Sulphur Springs System	
Cockle Cove Creek – marsh	1.0
Cockle Cove Creek – channel	1.0
Sulphur Springs – basin	0.75
Sulphur Springs – marsh	2.0
Bucks Creek – marsh	2.0
Bucks Creek – channel	2.0
Bucks Creek – inlet to Nantucket Sound	1.0
Taylors Pond System	
Taylors Pond – basin	0.15
Mill Creek – upper channel	0.2
Mill Creek – lower channel	0.5
Mill Creek – marsh	0.05
Mill Creek – inlet to Nantucket Sound	1.0

Table VI-5. Values of longitudinal dispersion coefficient, E, used in calibrated RMA4 model runs of salinity and nitrogen concentration for Bassing Harbor and Muddy Creek.

Embayment Division	E m^2/sec
Bassing Harbor System	
Ryder Cove - inner	10.0
Ryder Cove – outer	10.0
Crows Pond	0.1
Frost Fish Creek – upper (above culverts)	25.0
Frost Fish Creek - lower	10.0
Bassing Harbor – main basin	10.0
Bassing Harbor – Pleasant B. entrance	10.0
Muddy Creek System	
Muddy Creek – upper	10.0
Muddy Creek – mid	15.0
Muddy Creek – lower	90.0
Route 28 culvert	150.0
Entrance to Pleasant Bay	100.0

Comparisons between model output and measured nitrogen concentrations are shown in Figures VI-3 through VI-8 for each of the five modeled embayment systems. In each plot, annual means of the Water Watcher data, and the mean value of all the data at each individual station are plotted against the modeled maximum, mean, and minimum concentrations output from the model at locations which corresponds to the Water Watcher stations. Because the water samples are taken during ebbing tides, calibration targets in each sub-embayment were set such that the means of the measured data would fall within the range between the modeled maximum and modeled mean concentration, for stations where there is a wide range of modeled concentrations. This is demonstrated in plots of results from Frost Fish Creek (Figure VI-3) and Oyster River (Figure VI-6). At other locations (e.g., Ryder Cove and Muddy Creek), where the model exhibited less variability than the measured data, a calibration target near the mean of the Chatham Water Watcher data was selected.

For Bassing Harbor, an alternate calibration technique was employed (Figure VI-3) due to difficulties calibrating the model based on total N concentrations. Bio-active N (DIN+PON, without DON) concentrations were used for calibration due to elevated DON concentrations (relative to other sub-embayments in Bassing Harbor and in the other Chatham system) that exist in outer Frost Fish Creek and Crows Pond. The elevated DON concentrations in these sub-embayments are due to N fluxes not included in the N loading analysis from sources within the water column and from fresh water aquatic plants (more important for Frost Fish Creek). The water column DON pool is refractory, and therefore does not contribute significantly to phytoplankton production. Further discussion of the reasoning for using bio-active N concentrations for Bassing Harbor is given in Section VIII.

Calibrated model output is shown in Figures VI-9 through VI-13 for Stage Harbor, Sulphur Springs/Cockle Cove Creek, Taylors Pond/Mill Creek, Bassing Harbor, and Muddy Creek. In these figures, color contours indicate nitrogen concentrations throughout the model domain. The output in these figures show average total nitrogen concentrations, computed using the full

5-tidal-day model simulation output period. The range of the color scale used to indicate total N concentrations is the same for all five of these figures, to show conditions that exist in each system relative to the complete range of nitrogen concentrations observed in Chatham's embayments.

In addition to the model calibration based on nitrogen loading and water column measurements, numerical water quality model performance is typically verified by modeling salinity. This additional modeling step was not feasible in the modeled Chatham embayment systems because measured salinity data show only a slight gradient through to the uppermost reaches of each system (<1 ppt). The only exceptions are in Muddy Creek, Frost Fish Creek, and Cockle Cove Creek, which are brackish to fresh in their upper portions. Salinity modeling was not performed for these systems, however, because the existing salinity data does not provide enough information for adequate model verification. Also, modeling salinity requires extensive knowledge of freshwater inflow to the estuary. For systems where freshwater inflow is dominated by surface flows (e.g., rivers), direct measurement of the inflow is possible and salinity measurements can be utilized to assess dispersion of the freshwater into the estuary. Since Muddy Creek and Frost Fish Creek freshwater inputs are dominated by groundwater flow, no direct measurement of freshwater flow is available. Instead, the groundwater flow rate is assumed to be the long-term average and the freshwater input is evenly distributed around the shoreline. These simplifying, but necessary, assumptions prohibit use of salinity data to evaluate dispersion coefficients.

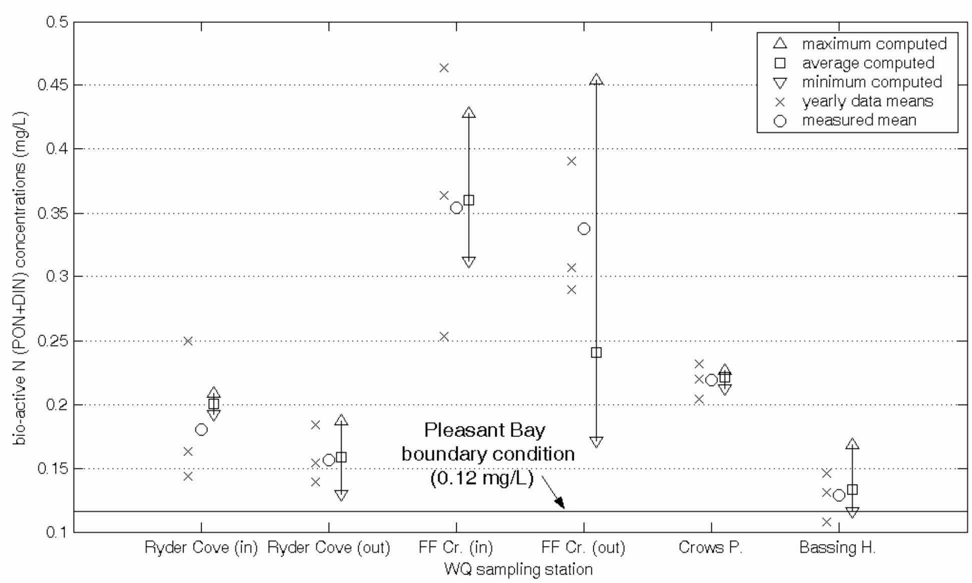

Figure VI-3. Comparison of measured bio-active nitrogen (PON+DIN) concentrations (means for individual years and means of all data together) and calibrated model output at stations in the Bassing Harbor system (with Frost Fish Creek, FF Cr.). Model output is presented as a range of values from minimum to maximum values computed during the simulation period (triangle markers), along with the average computed concentration for the same period (square markers). The background concentration (0.12 mg/L) in Pleasant Bay is indicated using a solid line.

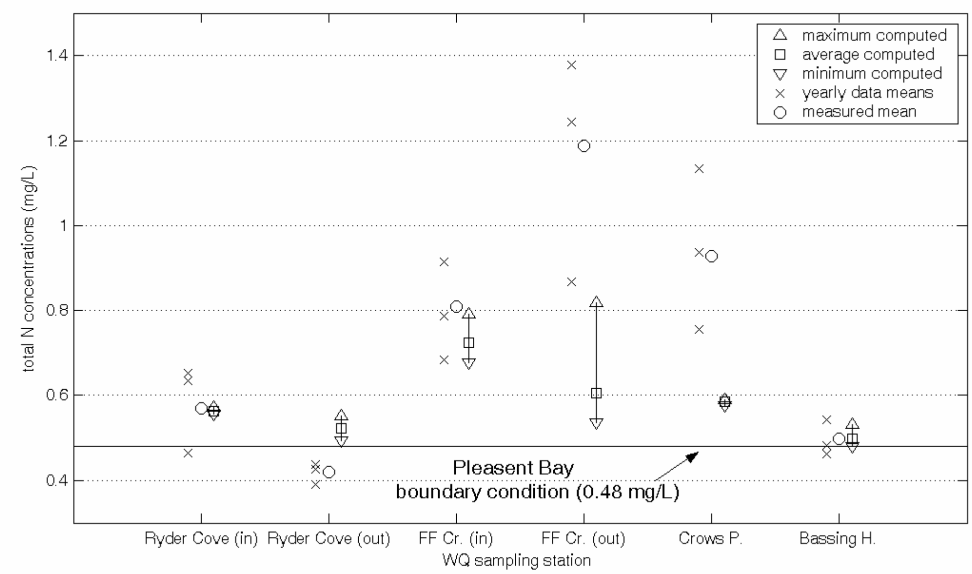

Figure VI-4. Comparison of measured total nitrogen (PON+DIN+DON) concentrations (means for individual years and means of all data together) and calibrated model output at stations in the Bassing Harbor system. Model output is presented as a range of values from minimum to maximum values computed during the simulation period (triangle markers), along with the average computed concentration for the same period (square markers). The background concentration (0.48 mg/L) in Pleasant Bay is indicated using a solid line.

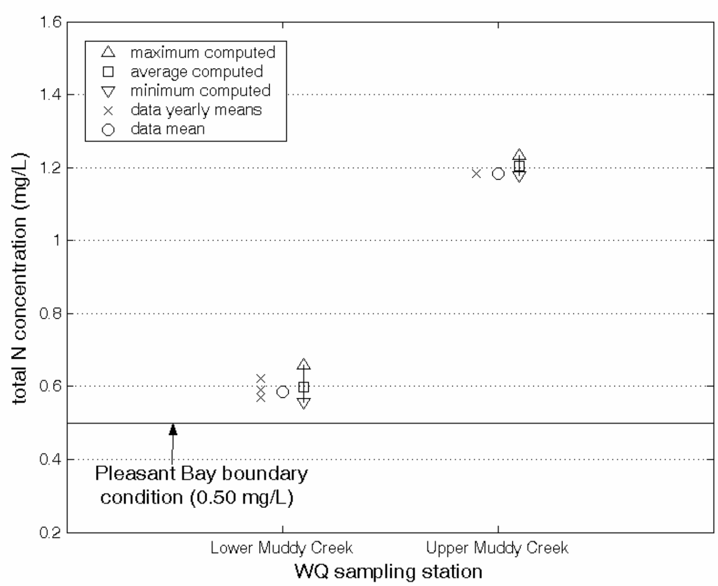

Figure VI-5. Comparison of measured total nitrogen concentrations (means for individual years and means of all data together) and calibrated model output at stations in the Muddy Creek system. Model output is presented as a range of values from minimum to maximum values computed during the simulation period (triangle markers), along with the average computed concentration for the same period (square markers). The background concentration (0.50 mg/L) in Pleasant Bay is indicated using a solid line.

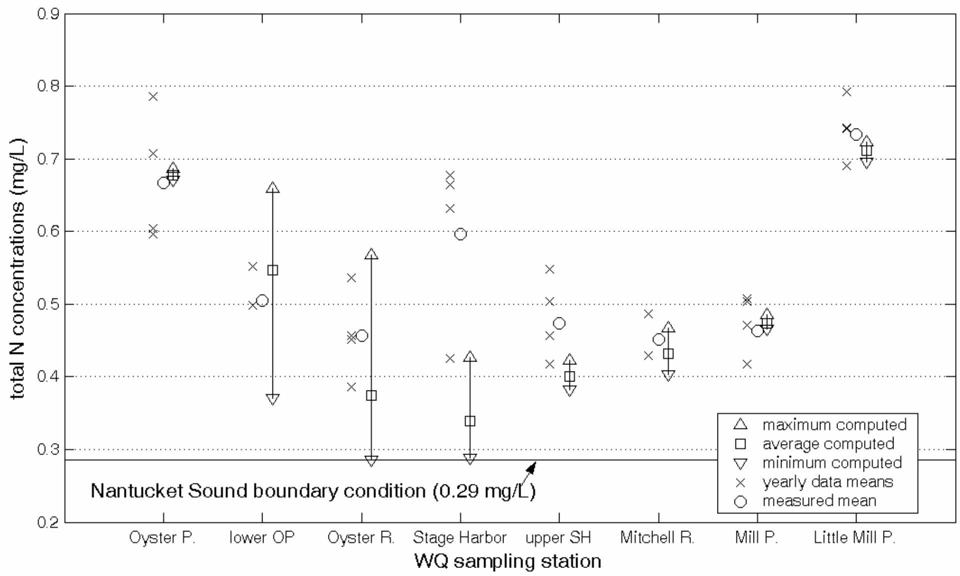

Figure VI-6. Comparison of measured total nitrogen concentrations (means for individual years and means of all data together) and calibrated model output at stations in the Stage Harbor system. Model output is presented as a range of values from minimum to maximum values computed during the simulation period (triangle markers), along with the average computed concentration for the same period (square markers). The background concentration (0.29 mg/L) in Nantucket Sound is indicated using a solid line.

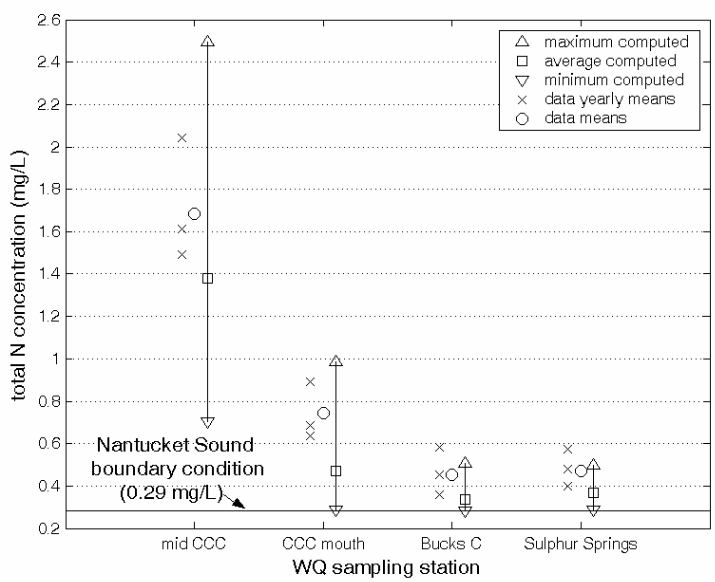

Figure VI-7. Comparison of measured total nitrogen concentrations (means for individual years and means of all data together) and calibrated model output at stations in the Sulphur Springs system, with Cockle Cove Creek (CCC). Model output is presented as a range of values from minimum to maximum values computed during the simulation period (triangle markers), along with the average computed concentration for the same period (square markers). The background concentration (0.29 mg/L) in Nantucket Sound is indicated using a solid line.

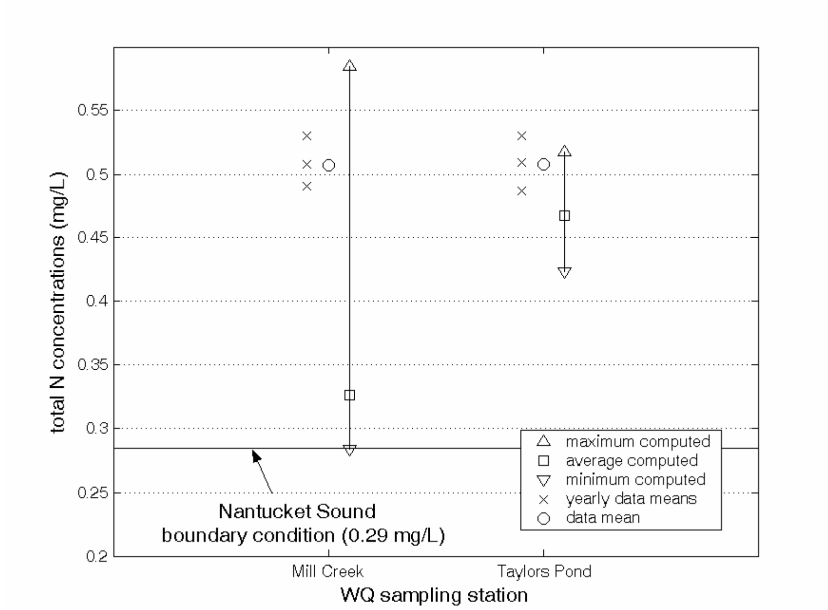

Figure VI-8. Comparison of measured total nitrogen concentrations (means for individual years and means of all data together) and calibrated model output at stations in the Taylors Pond system, with Mill Creek. Model output is presented as a range of values from minimum to maximum values computed during the simulation period (triangle markers), along with the average computed concentration for the same period (square markers). The background concentration (0.29 mg/L) in Nantucket Sound is indicated using a solid line.

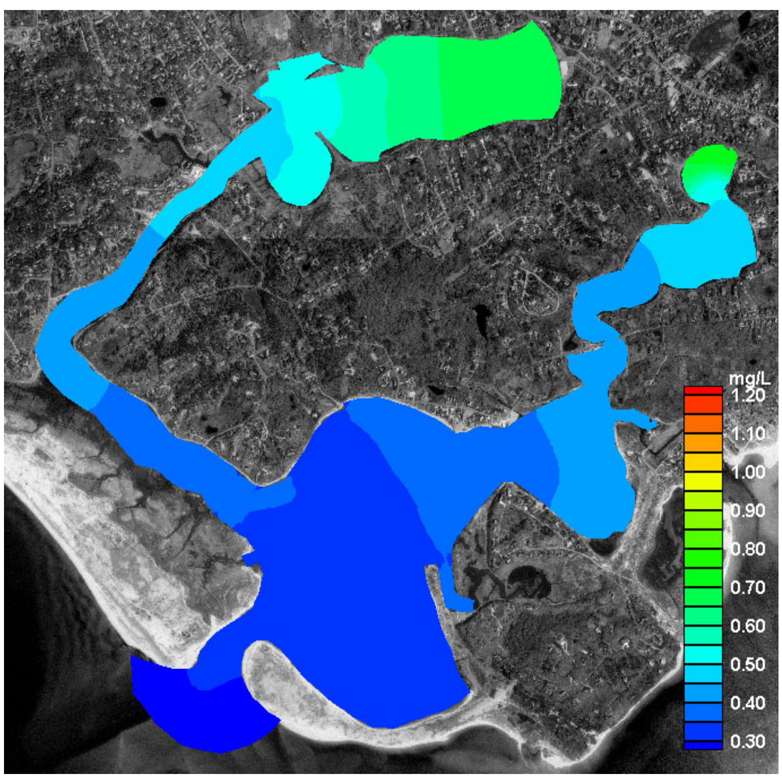

Figure VI-9. Contour plot of average total nitrogen concentrations from results of the present conditions loading scenario, for the Stage Harbor system.

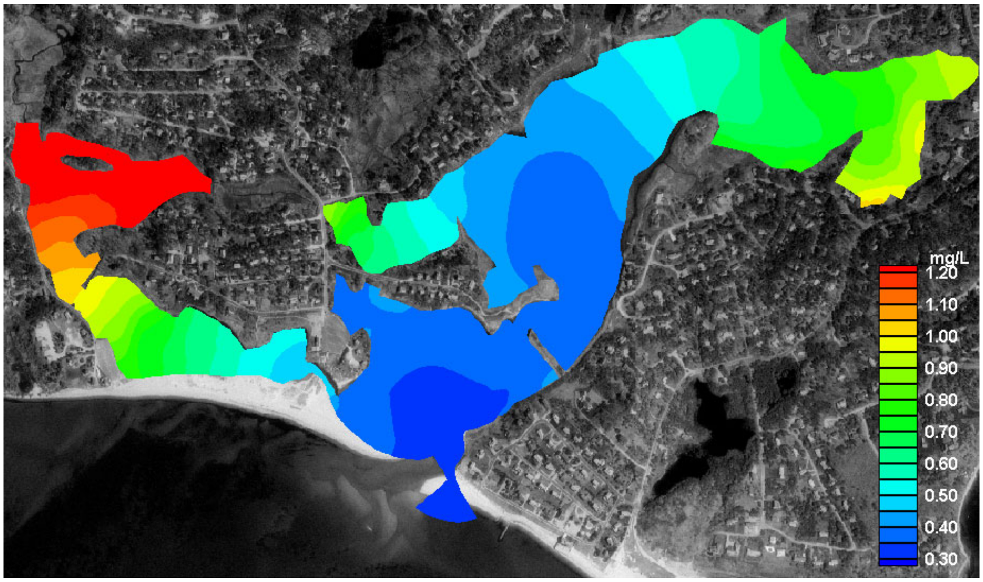

Figure VI-10. Contour Plot of modeled total nitrogen concentrations (mg/L) in the Sulphur Springs/Cockle Cove Creek system, for present loading conditions.

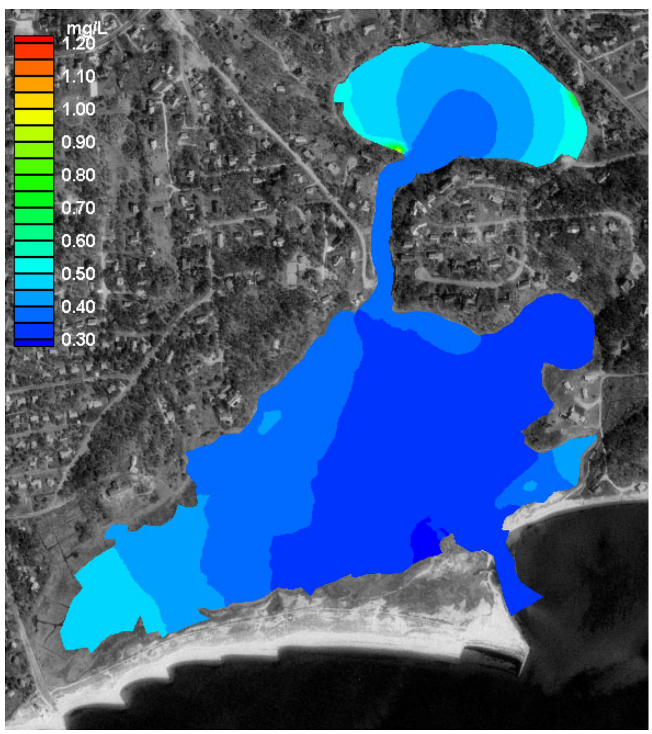

Figure VI-11. Contour Plot of modeled total nitrogen concentrations (mg/L) in the Taylors Pond/Mill Creek system, for present loading conditions.

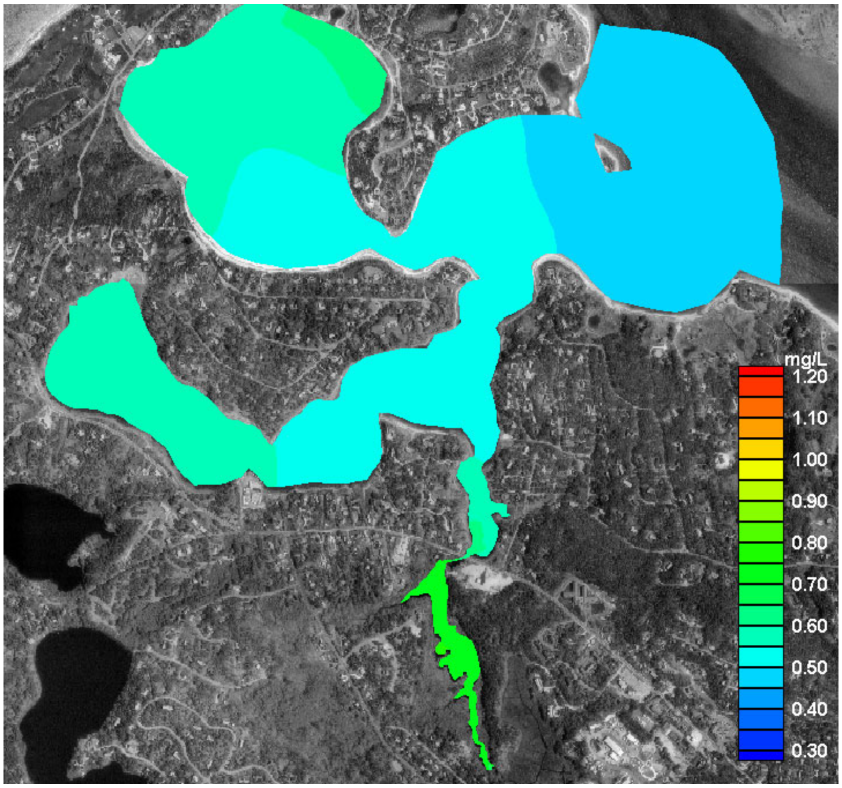

Figure VI-12. Contour Plot of modeled total nitrogen concentrations (mg/L) in the Bassing Harbor system, for present loading conditions, and present background N concentration at the entrance to Pleasant Bay (0.48 mg/L).

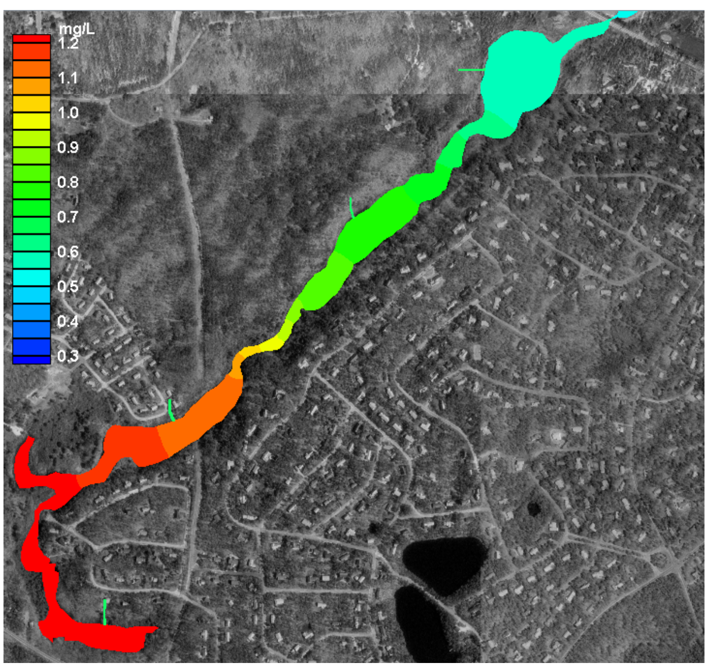

Figure VI-13. Contour plot of modeled total nitrogen concentrations in Muddy Creek, for present loading conditions, and present total nitrogen concentration in Pleasant Bay (0.50 mg/L).

VI.2.5 Build-Out and No Anthropogenic Load Scenarios

To assess the influence of nitrogen loading on total nitrogen concentrations within each of the embayment systems, two standard water quality modeling scenarios were run: a “build-out” scenario based on potential development (described in more detail in Section IV) and a “no anthropogenic load” or “no load” scenario assuming only atmospheric deposition on the watershed and sub-embayment, as well as a natural forest within each watershed. Comparisons of the watershed loading analyses are shown in Tables VI-6 and VI-7. Loads are presented in kilograms per day (kg/day) in this Section, since it is inappropriate to show benthic flux loads in kilograms per year due to seasonal variability. In general, the build-out scenario indicates that there would be less than a 20% increase in watershed nitrogen load as a result of potential future development. However, certain sub-embayments would be impacted more than others. A maximum increase in watershed loading resulting from future development would occur in the Taylors Pond watershed, where the increase would be 32.4%. For the no load scenarios, almost all of the load entering the watershed is removed; therefore, the load is generally lower than existing conditions by over 95%.

Table VI-6. Comparison of sub-embayment watershed loads used for modeling of present, build out, and no-anthropogenic (“no-load”) loading scenarios of the Stage Harbor and South Coastal embayment systems. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.

sub-embayment	present load (kg/day)	build out (kg/day)	build out % change	no load (kg/day)	no load % change
Stage Harbor					
Oyster Pond	13.03	14.98	14.9%	0.64	-95.1%
Oyster River	11.47	12.74	11.1%	0.54	-95.3%
Stage Harbor	2.76	3.24	17.3%	0.16	-94.4%
Mitchell River	6.38	6.64	4.0%	0.16	-97.5%
Mill Pond	1.78	2.08	17.1%	0.06	-96.8%
Little Mill Pond	1.64	1.79	9.7%	0.04	-97.7%
Sulphur Springs					
Sulphur Springs	15.33	17.17	12.0%	0.45	-97.0%
Bucks Creek	4.08	4.83	18.4%	0.21	-95.0%
Cockle Cove Creek	6.66	7.98	19.8%	0.18	-97.3%
Waste Water TF	3.03	3.03	0.0%	0.00	-100.0%
Taylors Pond					
Mill Creek	6.22	7.17	15.2%	0.21	-96.6%
Taylors Pond	8.21	10.87	32.4%	0.27	-96.7%

For the build out scenario, a breakdown of the total nitrogen load entering each sub-embayment is shown in Tables VI-8 and VI-9. The benthic flux for the build-out scenarios is assumed to vary in a linear fashion, where an increase in watershed load will result in the same percentage increase (positive) in benthic flux. Due to the highly variable nature of bottom sediments and other estuarine characteristics of Chatham’s coastal embayments, the measured benthic flux for existing conditions also is variable. For build-out conditions, some sub-embayments have approximately twice the benthic flux as total watershed load (e.g. Oyster Pond and Mill Pond). For other sub-embayments, the benthic flux is relatively low or negative (indicating a net uptake of nitrogen in the bottom sediments).

Table VI-7. Comparison of sub-embayment watershed loads used for modeling of present, build out, and no-anthropogenic ("no-load") loading scenarios of the Pleasant Bay embayment systems. These loads do not include atmospheric deposition and benthic flux loading terms.

sub-embayment	present load (kg/day)	build out (kg/day)	build out % change	no load (kg/dy)	no load % change
Bassing Harbor					
Crows Pond	5.79	6.04	4.4%	0.14	-97.6%
Ryder Cove	12.35	14.06	13.9%	0.45	-95.2%
Frost Fish Creek	3.59	3.88	8.0%	0.08	-97.7%
Bassing Harbor	2.66	3.22	20.9%	0.10	-96.4%
Muddy Creek					
Muddy Creek -lower	13.36	14.24	6.6%	0.50	-96.3%
Muddy Creek - upper	19.05	22.69	19.1%	0.87	-95.5%

Table VI-8. Sub-embayment loads used for modeling of buildout out scenarios in the Bassing Harbor and Muddy Creek systems of Pleasant Bay, with total watershed N loads, atmospheric N loads, and benthic flux.

sub-embayment	watershed load (kg/day)	atmospheric deposition (kg/day)	benthic flux (kg/day)
Bassing Harbor			
Crows Pond	6.04	1.39	3.9
Ryder Cove	14.06	1.30	8.1
Frost Fish Creek	3.88	0.10	-0.2
Bassing Harbor	3.22	1.08	-0.1
Muddy Creek			
Muddy Creek –lower	14.24	0.21	-2.1
Muddy Creek - upper	22.69	0.20	5.3

Following development of the various nitrogen loading estimates for the build out scenario, the water quality model was run to determine nitrogen concentrations within each sub-embayment. Total nitrogen concentrations in the receiving waters (Nantucket Sound or Pleasant Bay) remained identical to the existing conditions modeling scenarios. The relative change in total nitrogen concentrations resulting from build out was relatively small as shown in Tables VI-10 and VI-11. These results are shown pictorially in Figures VI-14 to VI-18. Again, the range of nitrogen concentrations shown represent the complete range of total nitrogen values observed in Chatham's coastal embayments. This allows direct comparison of nitrogen concentrations between regional embayment systems.

Table VI-9. Sub-embayment loads used for modeling of build out scenarios of the Stage Harbor and South Coastal embayment systems, with total watershed N loads, atmospheric N loads, and benthic flux.

sub-embayment	watershed load (kg/day)	atmospheric deposition (kg/day)	benthic flux (kg/day)
Stage Harbor			
Oyster Pond	14.98	0.29	29.3
Oyster River	12.74	1.05	0.7
Stage Harbor	3.24	3.25	14.0
Mitchell River	6.64	0.88	-3.8
Mill Pond	2.08	0.63	4.0
Little Mill Pond	1.79	0.12	2.2
Sulphur Springs			
Sulphur Springs	17.17	0.38	-4.1
Bucks Creek	4.83	0.13	3.3
Cockle Cove Creek	7.98	0.06	-1.0
Waste Water TF	3.03	-	-
Taylors Pond			
Mill Creek	7.17	0.17	-0.4
Taylors Pond	10.87	0.19	2.2

Table VI-10. Comparison of model average total N concentrations from present loading and build out scenario, with percent change, for South Coastal embayments and Stage Harbor.

sub-embayment	present (mg/L)	build out (mg/L)	% change
Stage Harbor			
Oyster Pond –upper	0.68	0.72	6.4%
Oyster Pond – lower	0.55	0.58	5.2%
Oyster River	0.37	0.38	2.5%
Stage Harbor – main	0.34	0.34	1.6%
Stage Harbor – upper	0.40	0.41	2.7%
Mitchell River	0.43	0.45	3.2%
Mill Pond	0.47	0.49	3.8%
Little Mill Pond	0.71	0.75	5.6%
Sulphur Springs			
Cockle Cove Cr. – mid	1.38	1.49	8.3%
Cockle Cove Cr. – low	0.47	0.50	5.1%
Bucks Creek	0.34	0.34	2.0%
Sulphur Springs	0.37	0.38	2.7%
Taylors Pond			
Mill Creek	0.33	0.33	2.3%
Taylors Pond	0.47	0.52	11.6%

Table VI-11. Comparison of model average total N concentrations from present loading and build out scenario, with percent change, for Pleasant Bay embayment systems.

sub-embayment	present (mg/L)	build out (mg/L)	% change
Bassing Harbor			
Ryder Cove – inner	0.56	0.57	1.6%
Ryder Cove – outer	0.52	0.53	0.8%
Frost Fish Creek - out	0.72	0.74	2.8%
Frost Fish Creek – in	0.60	0.62	2.0%
Crows Pond	0.59	0.59	1.2%
Bassing Harbor	0.50	0.50	0.3%
Muddy Creek			
Muddy Creek –lower	0.60	0.61	2.4%
Muddy Creek - upper	1.21	1.32	9.9%

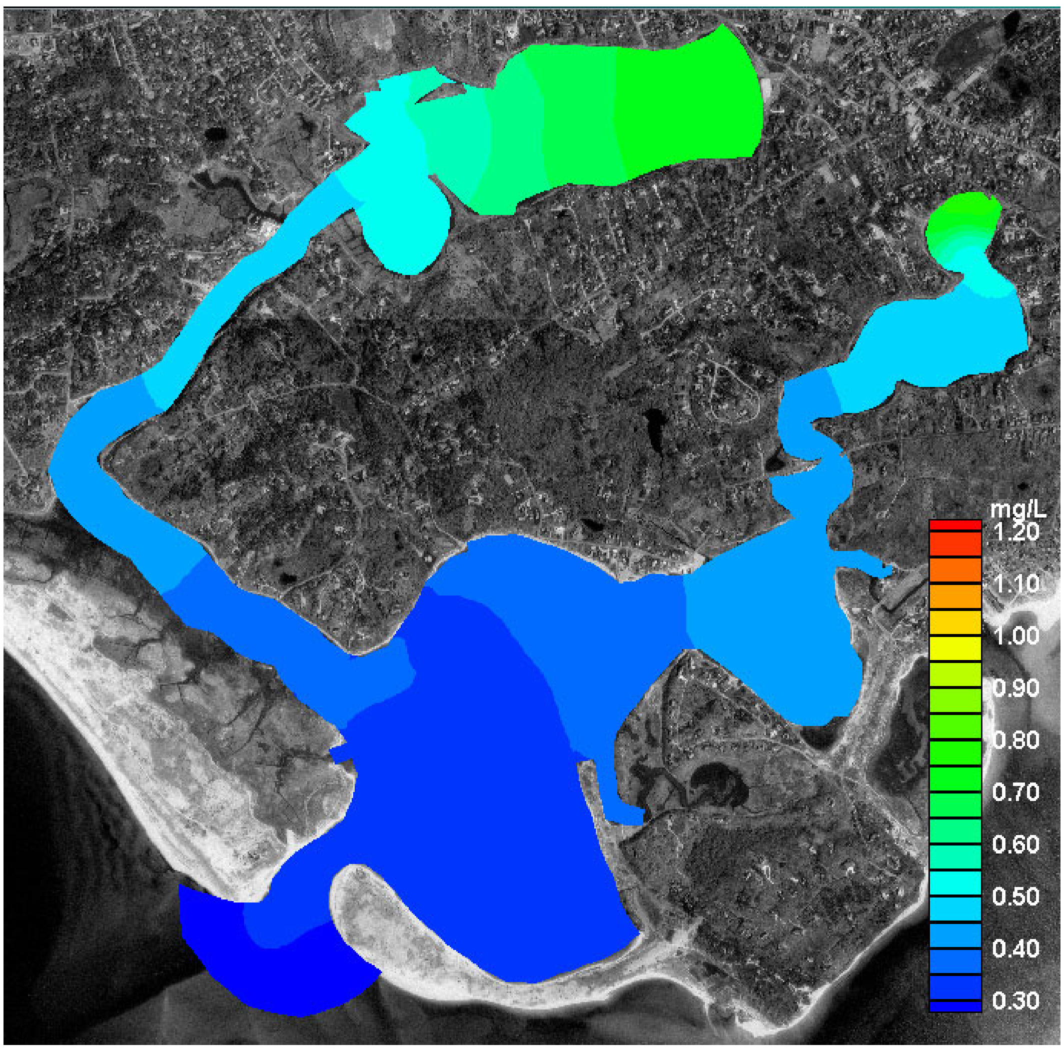

Figure VI-14. Contour Plot of modeled total nitrogen concentrations (mg/L) in the Stage Harbor system, for projected build out loading conditions.

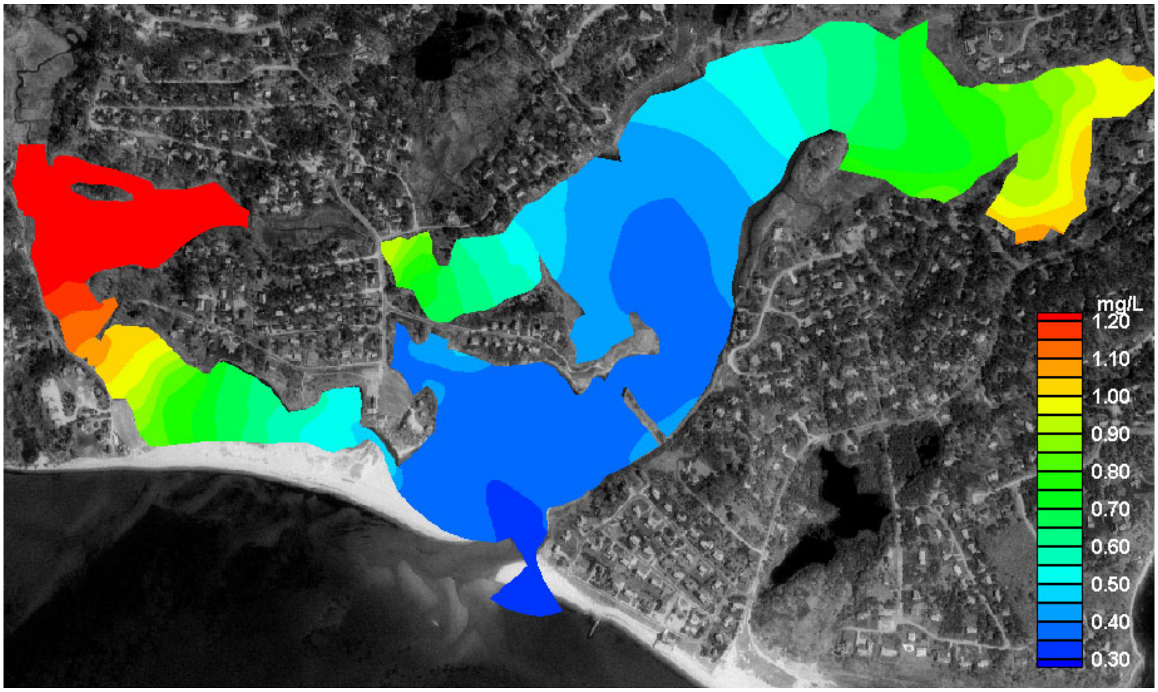

Figure VI-15. Contour Plot of modeled total nitrogen concentrations (mg/L) in the Sulphur Springs/Cockle Cove Creek system, for projected build out loading conditions

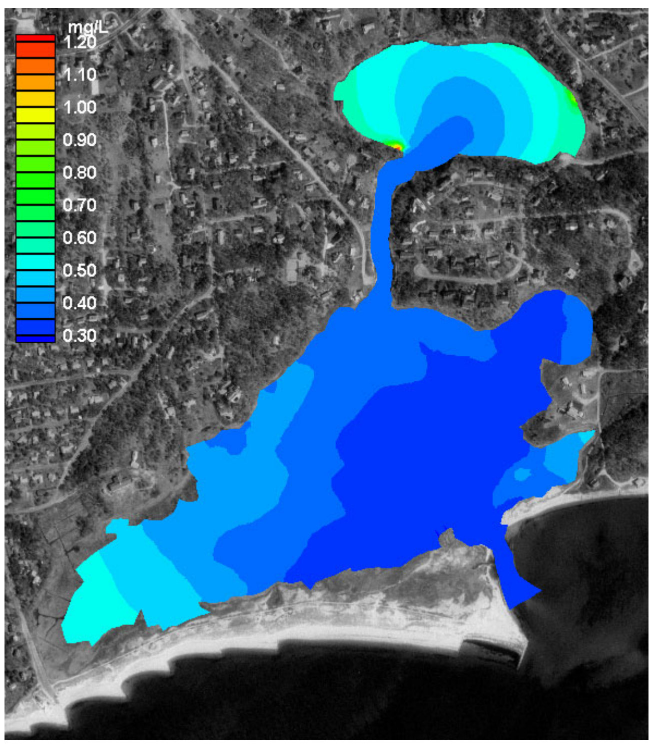

Figure VI-16. Contour Plot of modeled total nitrogen concentrations (mg/L) in the Taylors Pond/Mill Creek system, for projected build out loading conditions.

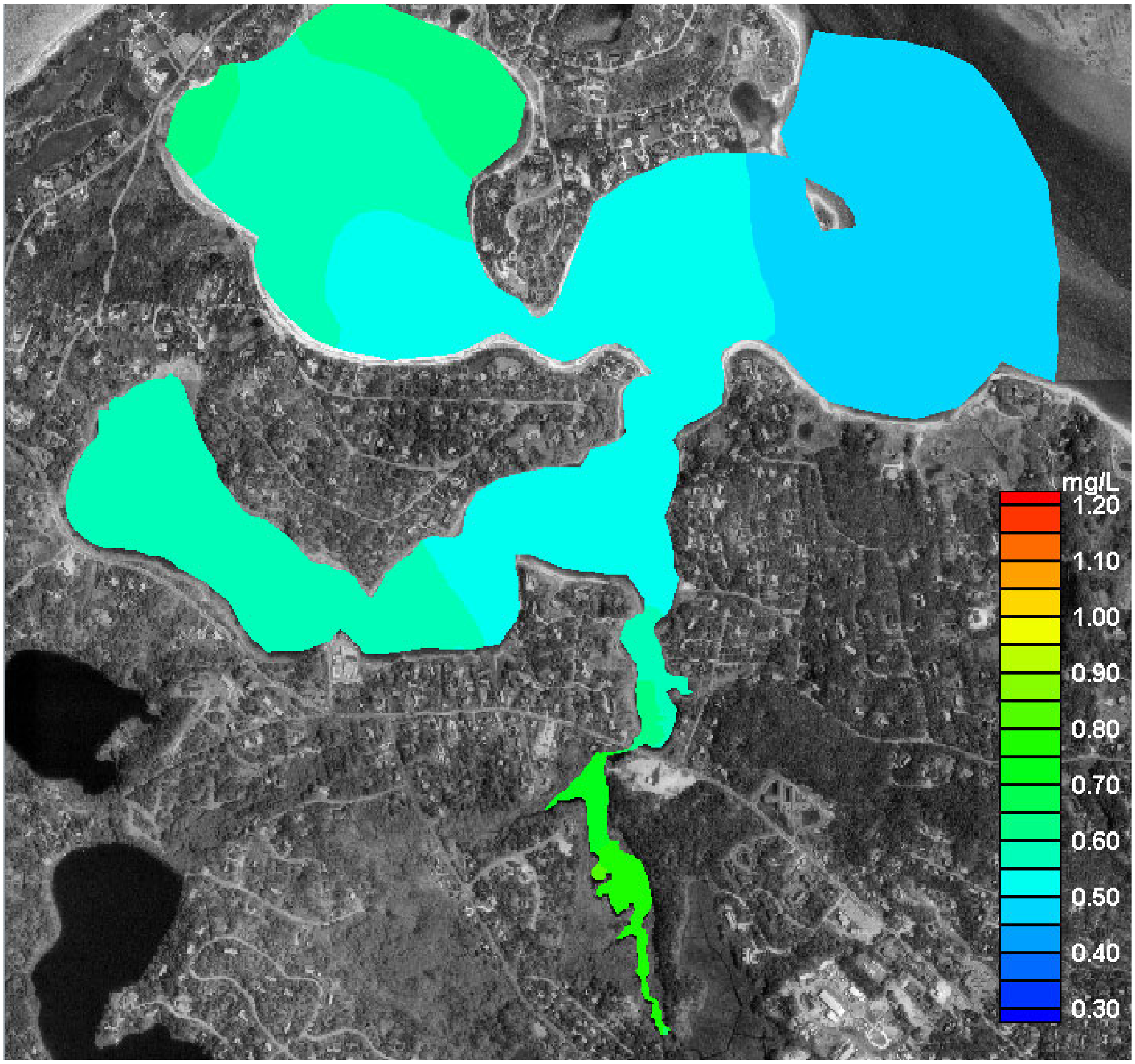

Figure VI-17. Contour Plot of modeled total nitrogen concentrations (mg/L) in the Bassing Harbor system, for projected build out loading conditions, and present background N concentration at the entrance to Pleasant Bay (0.48 mg/L).

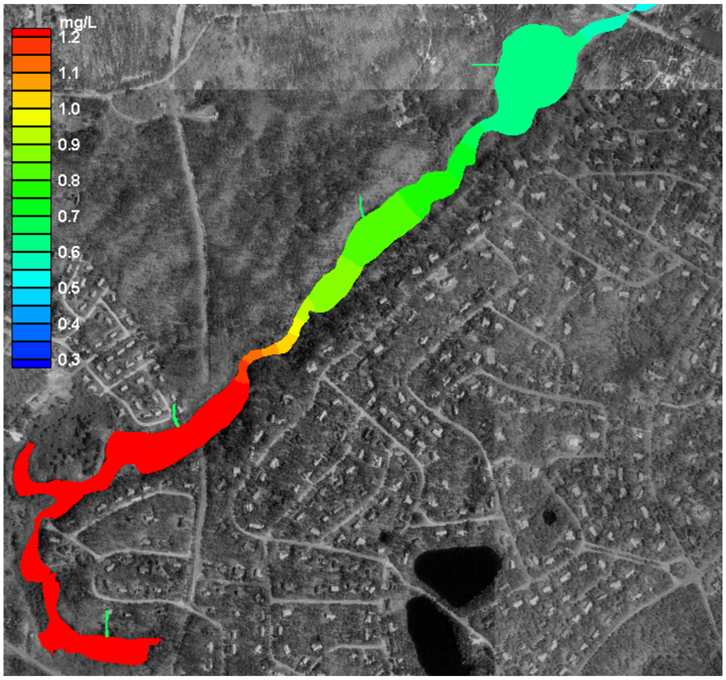

Figure VI-18. Contour plot of modeled total nitrogen concentrations in Muddy Creek, for projected build out loading conditions, and present total nitrogen concentration in Pleasant Bay (0.50 mg/L).

A breakdown of the total nitrogen load entering each sub-embayment for the no anthropogenic load scenarios is shown in Tables VI-12 and VI-13. The benthic flux for the "no load" scenarios is assumed to vary in a linear fashion, where a decrease in watershed load will result in the same percentage decrease in benthic flux. Due to the highly variable nature of bottom sediments and other estuarine characteristics of Chatham's coastal embayments, the measured benthic flux for existing conditions also is variable. For no load conditions, some sub-embayments have a benthic load that is significantly larger than the watershed load (e.g. Oyster Pond and Stage Harbor). Additionally, atmospheric deposition directly to each sub-embayment becomes a greater percentage of the total nitrogen load as the watershed load and related benthic flux decrease.

Following development of the various nitrogen loading estimates for the no load scenario, the water quality model was run to determine nitrogen concentrations within each sub-embayment. Again, total nitrogen concentrations in the receiving waters (Nantucket Sound or Pleasant Bay) remained identical to the existing conditions modeling scenarios. The relative change in total nitrogen concentrations resulting from "no load" was relatively significant as shown in Tables VI-14 and VI-15. These results are shown pictorially in Figures VI-19 to VI-23. Again, the range of nitrogen concentrations shown represent the complete range of total nitrogen values observed in Chatham's coastal embayments. This allows direct comparison of nitrogen concentrations between regional embayment systems. For the no load scenario, the sub-embayment concentrations are generally governed by the total nitrogen concentrations observed in the local receiving waters, where the concentrations in Stage Harbor, Sulphur Springs/Cockle Cove Creek, and Taylors Pond/Mill Creek are dictated by Nantucket Sound, and the concentrations in Bassing Harbor and Muddy Creek are dictated by Pleasant Bay. For the embayment systems serviced by Nantucket Sound waters, total nitrogen concentrations were below 0.35 mg/L..

Table VI-12. Sub-embayment loads used for modeling of no-anthropogenic loading scenarios of the Stage Harbor and South Coastal embayment systems, with total watershed N loads, atmospheric N loads, and benthic flux.

sub-embayment	watershed load (kg/day)	atmospheric deposition (kg/day)	benthic flux (kg/day)
Stage Harbor			
Oyster Pond	0.64	0.29	4.8
Oyster River	0.54	1.05	0.1
Stage Harbor	0.16	3.25	2.3
Mitchell River	0.16	0.88	-0.6
Mill Pond	0.06	0.63	0.7
Little Mill Pond	0.04	0.12	0.4
Sulphur Springs			
Sulphur Springs	0.45	0.38	-0.2
Bucks Creek	0.21	0.13	0.2
Cockle Cove Creek	0.18	0.06	-0.1
Waste Water TF	0.00	-	-
Taylors Pond			
Mill Creek	0.21	0.17	0.0
Taylors Pond	0.27	0.19	0.1

Table VI-13. Sub-embayment loads used for modeling of no-anthropogenic loading scenarios in the Bassing Harbor and Muddy Creek systems of Pleasant Bay, with total watershed N loads, atmospheric N loads, and benthic flux.

sub-embayment	watershed load (kg/day)	atmospheric deposition (kg/day)	benthic flux (kg/day)
Bassing Harbor			
Crows Pond	0.14	1.39	0.6
Ryder Cove	0.45	1.30	1.4
Frost Fish Creek	0.08	0.10	0.0
Bassing Harbor	0.10	1.08	0.0
Muddy Creek			
Muddy Creek –lower	0.50	0.21	-0.1
Muddy Creek - upper	0.87	0.20	0.3

Table VI-14. Comparison of model average total N concentrations from present loading and the no anthropogenic ("no load") scenario, with percent change, for South Coastal embayments and Stage Harbor. Loads are based on atmospheric deposition and a scaled N benthic flux (scaled from present conditions).

sub-embayment	present (mg/L)	no load (mg/L)	% change
Stage Harbor			
Oyster Pond –upper	0.68	0.34	-49.6%
Oyster Pond – lower	0.55	0.32	-40.9%
Oyster River	0.37	0.30	-20.3%
Stage Harbor – main	0.34	0.29	-13.2%
Stage Harbor – upper	0.40	0.31	-23.9%
Mitchell River	0.43	0.31	-28.0%
Mill Pond	0.47	0.32	-32.9%
Little Mill Pond	0.71	0.35	-51.2%
Sulphur Springs			
Cockle Cove Cr. – mid	1.38	0.30	-77.9%
Cockle Cove Cr. – low	0.47	0.29	-38.7%
Bucks Creek	0.34	0.29	-14.7%
Sulphur Springs	0.37	0.29	-21.6%
Taylors Pond			
Mill Creek	0.33	0.29	-11.9%
Taylors Pond	0.47	0.30	-36.8%

Table VI-15. Comparison of model average total N concentrations from present loading and the no anthropogenic ("no load") scenario, with percent change, for Pleasant Bay embayment systems. Loads are based on atmospheric deposition and a scaled N benthic flux (scaled from present conditions).

sub-embayment	present (mg/L)	no load (mg/L)	% change
Bassing Harbor			
Ryder Cove – inner	0.56	0.49	-12.7%
Ryder Cove – outer	0.52	0.49	-6.9%
Frost Fish Creek - out	0.72	0.50	-31.3%
Frost Fish Creek – in	0.60	0.49	-18.5%
Crows Pond	0.59	0.50	-14.5%
Bassing Harbor	0.50	0.48	-2.9%
Muddy Creek			
Muddy Creek –lower	0.60	0.50	-16.2%
Muddy Creek - upper	1.21	0.53	-55.7%

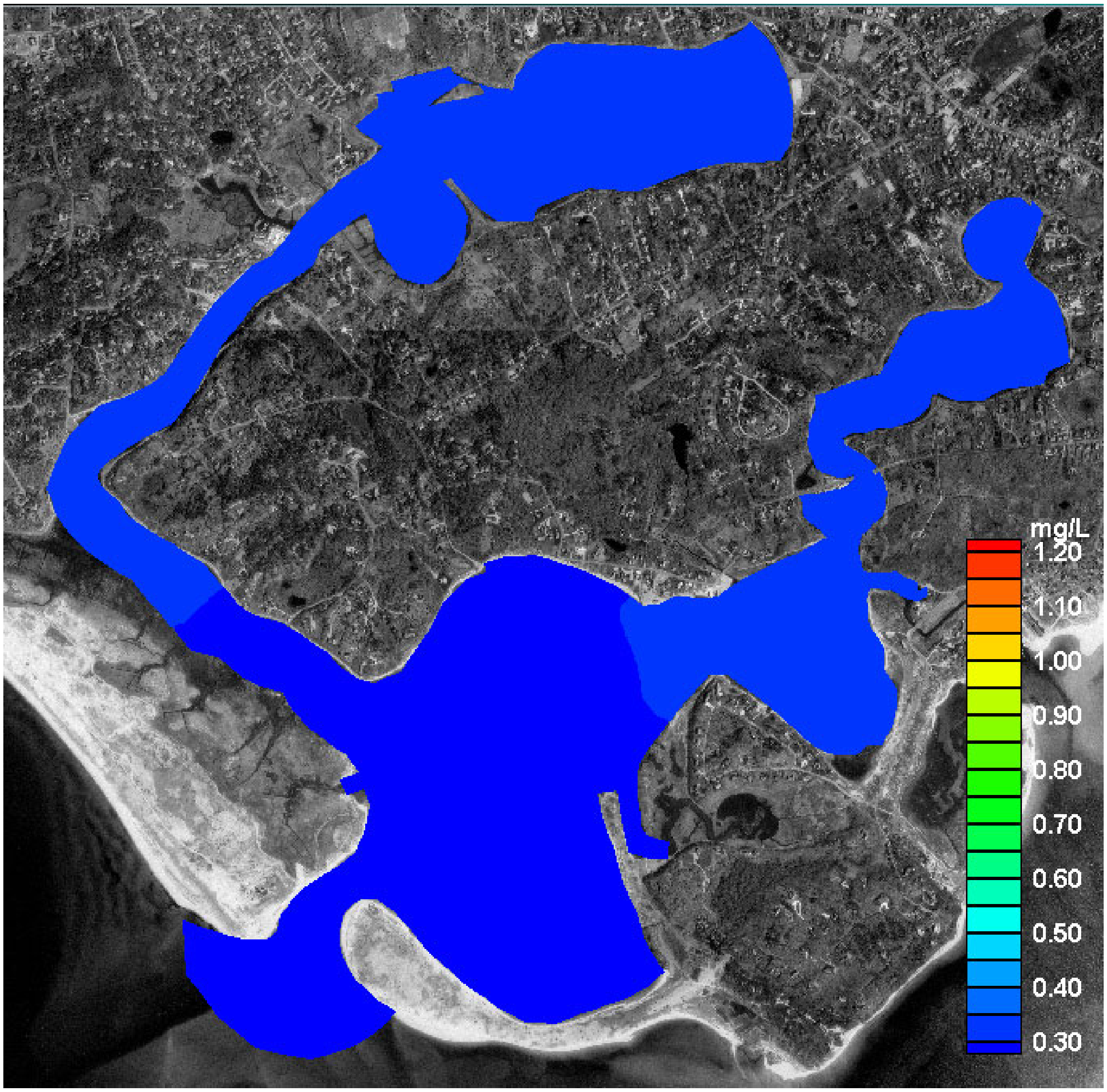

Figure VI-19. Contour Plot of modeled total nitrogen concentrations (mg/L) in the Stage Harbor system, for no anthropogenic loading conditions.

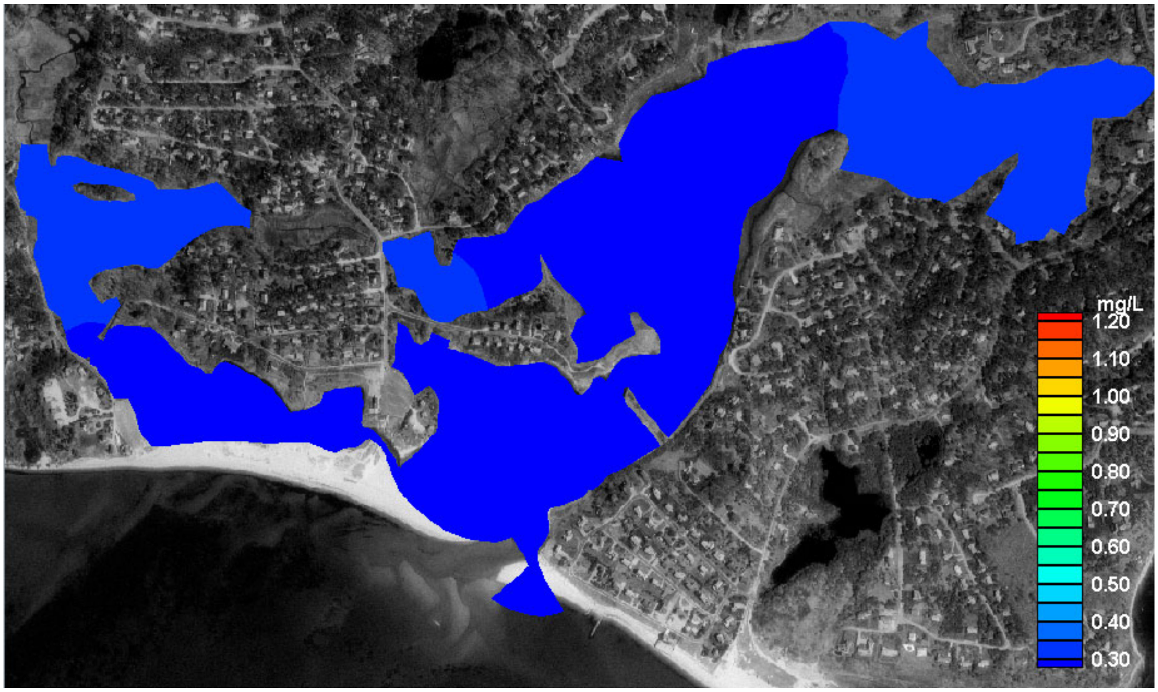

Figure VI-20. Contour Plot of modeled total nitrogen concentrations (mg/L) in the Sulphur Springs/Cockle Cove Creek system, for no anthropogenic loading conditions.

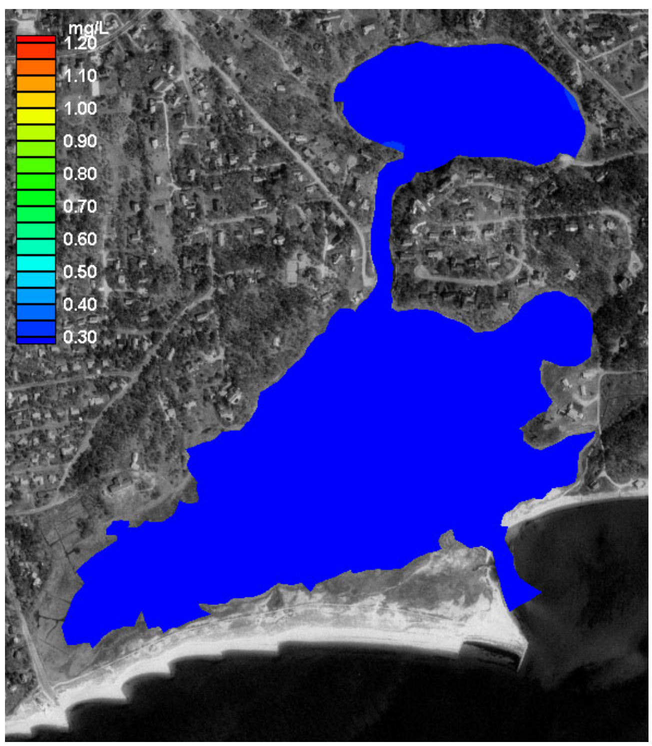

Figure VI-21. Contour Plot of modeled total nitrogen concentrations (mg/L) in the Taylors Pond/Mill Creek system, for no anthropogenic loading conditions.

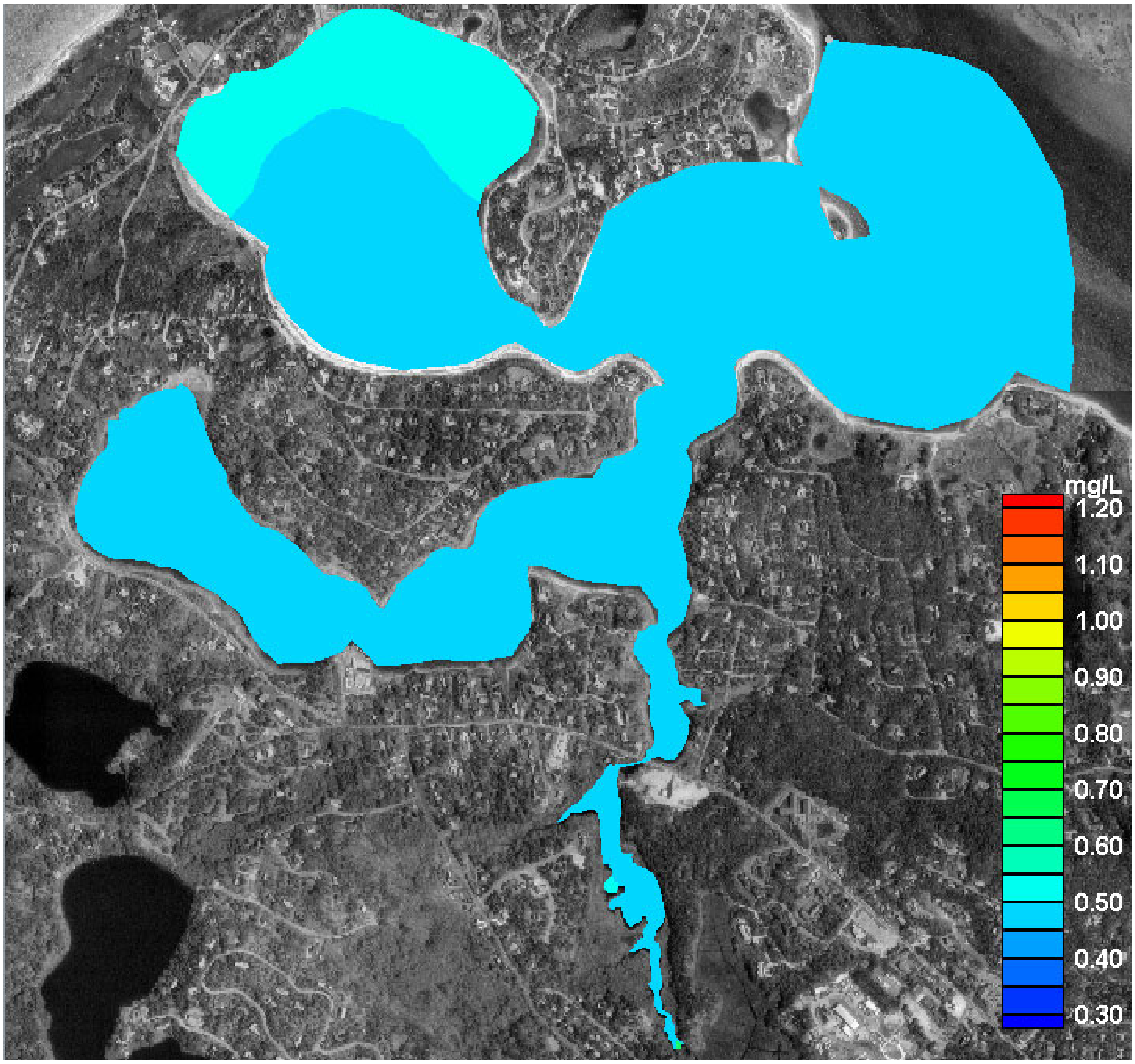

Figure VI-22. Contour Plot of modeled total nitrogen concentrations (mg/L) in the Bassing Harbor system, for no anthropogenic loading conditions, and present background N concentration at the entrance to Pleasant Bay (0.48 mg/L).

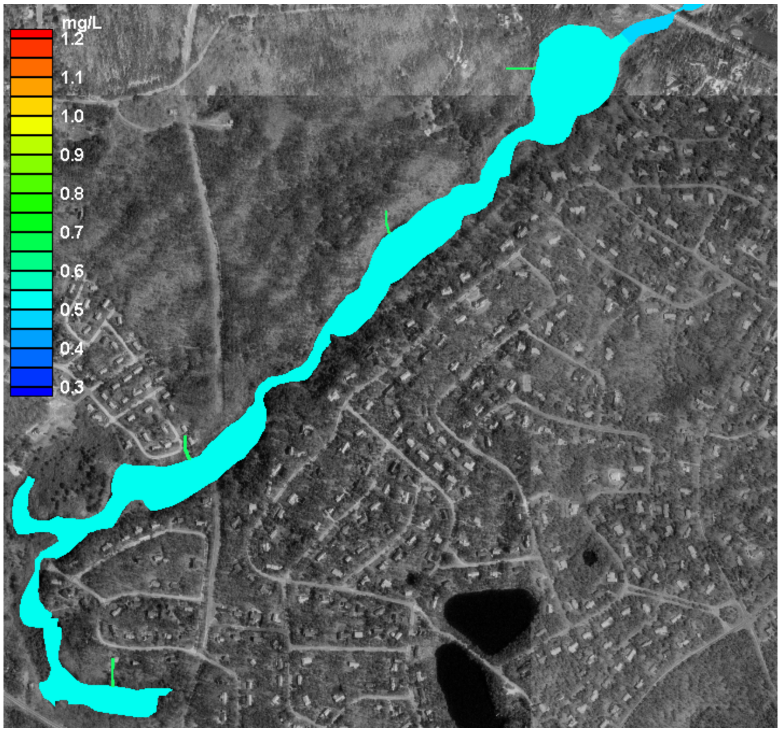

Figure VI-23. Contour plot of modeled total nitrogen concentrations in Muddy Creek, for no anthropogenic loading conditions, and present total nitrogen concentration in Pleasant Bay (0.50 mg/L).