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 for the Pleasant Bay system. 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 calibrated hydrodynamic model representing the transport of water within the Pleasant Bay system. Files of node locations and node connectivity for the RMA-2 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 the 7 day period beginning November 13, 2004 1345 EST. This period corresponds to that used in the flushing analysis presented in Chapter V. Each modeled scenario (e.g., present conditions, build-out) required the model be run for a 28-day spin-up period thereby allowing the model to reach a dynamic “steady state” and ensure that model spin-up would not affect the final model output.

VI.1.2 Nitrogen Loading to the Embayments

Three primary nitrogen loads to sub-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 Pleasant Bay system’s sub-embayments, consisting of the background concentrations of total nitrogen in the waters entering from the open Atlantic Ocean. This load is represented as a constant concentration along the seaward boundary of the model grid.

VI.1.3 Measured Nitrogen Concentrations in the Embayments

In order to create a model that realistically simulates bioactive nitrogen (DIN+PON) 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 refined and approved data for each monitoring station used in the water quality modeling effort are presented in Table VI-1. Station locations are indicated in the area map presented in Figure VI-1. 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 are the minimum required to provide a baseline for MEP analysis. Typically, ten years of data (collected between 1995 and 2004) were available for stations monitored by in Pleasant Bay.

Table VI-1. Measured total (DIN+PON+DON) and bioactive nitrogen (DIN+PON) data and modeled bioactive nitrogen concentrations for the Pleasant Bay estuarine system used in the model calibration plots of Figures VI-2 and VI-3. All concentrations are given in mg/L N. "Data mean" values are calculated as the average of the separate yearly means. Data represented in this table were collected in the summers of 2000 through 2005. N represents sample size. The sentinel threshold stations are in bold print and depicted in Figure VI-1.

Bioactive Nitrogen	monitoring station	Total Nitrogen			Bioactive Nitrogen			model min (mg/L)	model max (mg/L)	model average (mg/L)
		data mean (mg/L)	s.d. all data (mg/L)	N	data mean (mg/L)	s.d. all data (mg/L)	N			
Meetinghouse Pond	PBA-16	0.724	0.218	83	0.407	0.351	90	0.351	0.401	0.380
Meetinghouse Pond	WMO-10	0.979	0.290	28	0.279	0.098	30	0.210	0.322	0.261
The River - upper	WMO-09	0.862	0.235	29	0.252	0.072	29	0.203	0.286	0.239
The River – mid	WMO-08	0.846	0.248	23	0.222	0.060	23	0.187	0.235	0.211
Lonnies Pond (Kescayo Ganset Pond)	PBA-15	0.777	0.188	80	0.281	0.103	86	0.241	0.260	0.250
Areys Pond	PBA-14	0.731	0.109	83	0.304	0.092	91	0.282	0.314	0.297
Namequoit River - upper	WMO-6	0.829	0.206	21	0.300	0.101	23	0.203	0.272	0.239
Namequoit River - lower	WMO-7	0.728	0.168	20	0.241	0.087	22	0.185	0.245	0.216
The River - lower	PBA-13	0.561	0.102	72	0.175	0.060	78	0.166	0.220	0.195
Pochet – upper	WMO-05	0.838	0.266	27	0.283	0.106	28	0.211	0.309	0.269
Pochet - lower	WMO-04	0.777	0.210	24	0.241	0.076	24	0.175	0.257	0.209
Pochet – mouth	WMO-03	0.716	0.239	39	0.180	0.063	39	0.163	0.202	0.183
Little Pleasant Bay - head	**PBA-12**	0.773	0.280	83	0.183	0.093	84	0.145	0.203	0.178
Little Pleasant Bay - main basin	PBA-21	0.565	0.174	51	0.135	0.038	52	0.133	0.187	0.162
Paw Wah Pond	PBA-11	0.707	0.216	75	0.268	0.160	79	0.231	0.286	0.257
Little Quanset Pond	WMO-12	0.599	0.116	22	0.205	0.071	24	0.220	0.240	0.229
Quanset Pond	WMO-01	0.562	0.149	79	0.189	0.063	87	0.176	0.208	0.191
Round Cove	PBA-09	0.707	0.230	83	0.246	0.097	84	0.222	0.266	0.241
Muddy Creek - upper	PBA-05a	1.257	0.368	25	0.700	0.411	27	0.660	0.690	0.674
Muddy Creek - lower	PBA-05	0.574	0.097	40	0.243	0.094	46	0.260	0.308	0.286
Pleasant Bay - head	PBA-08	0.439	0.099	83	0.162	0.063	86	0.132	0.162	0.149
Pleasant Bay - off Quanset Pond	WMO-02	0.555	0.144	34	0.174	0.049	38	0.153	0.166	0.160
Pleasant Bay- upper Strong Island	PBA-19	0.728	0.237	39	0.169	0.113	42	0.094	0.148	0.117
Pleasant Bay - mid west basin	PBA-07	0.434	0.118	79	0.161	0.054	84	0.163	0.174	0.168
Pleasant Bay - off Muddy Creek	PBA-06	0.489	0.117	67	0.188	0.057	70	0.187	0.199	0.192
Pleasant Bay - Strong Island channel	PBA-20	0.566	0.222	44	0.141	0.044	47	0.094	0.155	0.124
Ryders Cove - upper	**PBA-03**	0.718	0.255	97	0.254	0.114	100	0.234	0.260	0.250
Ryders Cove - lower	**CM-13**	0.417	0.071	86	0.159	0.044	92	0.117	0.196	0.158
Frost Fish - lower	CM-14	1.158	0.395	44	0.349	0.296	45	0.155	0.434	0.243
Crows Pond	PBA-04	0.838	0.325	96	0.208	0.093	97	0.158	0.165	0.162
Bassing Harbor	PBA-02	0.489	0.161	37	0.121	0.035	38	0.097	0.158	0.127
Pleasant Bay - lower	PBA-18	0.463	0.168	47	0.123	0.040	47	0.094	0.148	0.116
Chatham Harbor - upper	PBA-01	0.433	0.198	87	0.105	0.036	90	0.094	0.132	0.104
Chatham Harbor – lower (by CH buoy)	PBA-17	0.349	0.134	2	0.100	0.010	2	0.094	0.121	0.099
Chatham Harbor – lower (Flood Tide)	PBA-17a	0.232	0.044	17	0.094	0.020	18	-	-	-

Figure VI-1. Estuarine water quality monitoring station locations in the Pleasant Bay estuary system. Station labels correspond to those provided in Table VI-1.

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 Pleasant Bay estuarine system. 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 Pleasant Bay. 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 systems in Falmouth (Howes *et al*., 2005); Mashpee, MA (Howes *et al*., 2004), Barnstable (Howes *et al*., 2005) and Chatham, MA (Howes *et al*., 2003).

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 USGS watersheds), as well as the measured bottom sediment nitrogen fluxes. Water column nitrogen measurements 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 of the Pleasant Bay system.

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 depth-averaged assumption is justified since vertical mixing by wind and tidal processes prevent significant stratification in the modeled sub-embayments. 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 is 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. Dispersion coefficients used for each system sub-embayment were developed during the calibration process. During the calibration procedure, the dispersion coefficients were incrementally changed until model concentration outputs matched measured data.

The RMA-4 model can be utilized to predict both spatial and temporal variations in total for a given embayment system. 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 10-minute time intervals throughout the grid system. For this application, the RMA-4 model was used to predict tidally averaged bioactive nitrogen concentrations throughout the sub-embayments of the Pleasant Bay system.

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 Pleasant Bay also were used for the water quality constituent modeling portion of this study.

For each model, an initial total N concentration equal to the average concentration in the Bay was applied to the entire model domain. The model was then run for a simulated month-long (28 day) spin-up period. At the end of the spin-up period, the model was run for an additional 5 tidal-day (125 hour) period. Model results were recorded only after the initial spin-up period. The time step used for the water quality computations was 10 minutes, which corresponds to the time step of the hydrodynamics input for the Pleasant Bay hydrodynamic model.

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 watershed loads for Meetinghouse Pond were evenly distributed at grid cells that formed the perimeter of the sub-embayment. Combined benthic regeneration and direct atmospheric deposition loads were evenly distributed among another sub-set of grid cells which form in the interior portion of each basin.

The loadings used to model present conditions in the Pleasant Bay system are given in Table VI-2. 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 Table VI-2). Due to the highly variable nature of bottom sediments and other estuarine characteristics of coastal embayments in general, the measured benthic flux for existing conditions also is variable. For some areas of Pleasant Bay (i.e., Pleasant Bay/ Chatham Harbor channel and Chatham Harbor), the benthic flux is negative indicating a net uptake of nitrogen in the bottom sediments.

In addition to mass loading boundary conditions set within the model domain, concentrations along the model open boundary were specified. The model uses concentrations at the open boundary during the flooding tide periods of the model simulations. TN concentrations of the incoming water are set at the value designated for the open boundary. The boundary concentration Atlantic Ocean region offshore Pleasant Bay was set at 0.094 mg/L (bioactive N), based on Chatham data collected in the summer of 2005 and analyzed by SMAST.

Table VI-2. Sub-embayment and surface water loads used for total nitrogen modeling of the Pleasant Bay system, with total watershed N loads, atmospheric N loads, and benthic flux. These loads represent **present loading conditions** for the listed sub-embayments.

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Meetinghouse Pond	6.197	0.584	14.365
The River – upper	2.773	0.288	6.263
The River – lower	3.879	2.241	10.480
Lonnies Pond	2.441	0.225	1.591
Areys Pond	1.304	0.181	5.996
Namequoit River	2.737	0.523	14.570
Paw Wah Pond	1.860	0.082	3.630
Pochet Neck	8.422	1.767	-0.791
Little Pleasant Bay	7.496	24.023	37.226
Quanset Pond	1.781	0.170	5.988
Tar Kiln Stream	6.123	0.066	-
Round Cove	4.225	0.170	8.416
The Horseshoe	0.638	0.063	-
Muddy Creek - upper	9.981	0.162	4.560
Muddy Creek - lower	8.477	0.205	-1.226
Pleasant Bay	23.159	19.153	149.013
Pleasant Bay/Chatham Harbor Channel	-	17.786	-40.192
Bassing Harbor - Ryder Cove	9.819	1.296	9.356
Bassing Harbor - Frost Fish Creek	2.904	0.096	-0.154
Bassing Harbor - Crows Pond	4.219	1.389	0.612
Bassing Harbor	1.668	1.071	-4.976
Chatham Harbor	17.099	14.153	-40.208
TOTAL - Pleasant Bay System	**127.203**	**85.693**	**184.519**

VI.2.4 Model Calibration

Calibration of the bioactive nitrogen model of Pleasant Bay 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 system 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 (from tides or atmospheric forcing). Generally, the relatively quiescent main basin of Pleasant Bay and its tributary sub-embayment systems required values of *E* that are lower compared to the riverine estuary systems evaluated by Fischer, *et al.*, (1979). 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 system are presented in Table VI-3. These values were used to develop the “best-fit” total nitrogen model calibration. For the case of bioactive N 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.

A contour plot of calibrated model output is shown in Figure VI-2. In this figure, color contours indicate nitrogen concentrations throughout the model domain. The output in these figures show average bioactive nitrogen concentrations, computed using the full 5-tidal-day model simulation output period.

Comparisons between calibrated model output and measured nitrogen concentrations are shown in plots presented in Figures VI-3 and VI-4. In these plots, means of the water column data and a range of two standard deviations of the annual means 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 quality monitoring stations shown in Figure VI-1.

For model calibration, the mid-point between maximum modeled bioactive N and average modeled bioactive N was compared to mean measured bioactive N data values, at each water-quality monitoring station. The calibration target would fall between the modeled mean and maximum bioactive N because the monitoring data are collected, as a rule, during mid ebb tide.

Also presented in this figure are unity plot comparisons of measured data verses modeled target values for each system. The R2 correlation between the model output and measured data is greater than 0.96 and the computed root mean squared (rms) error is 0.021 mg/L, which demonstrates the exceptional fit of the model for this system.

Table VI-3. Values of longitudinal dispersion coefficient, E, used in calibrated RMA4 model runs of salinity and nitrogen concentration for the Pleasant Bay estuary system.

Embayment Division	E m^2/sec
Pleasant Bay Inlet	100.0
Lower Chatham Harbor	100.0
upper Chatham Harbor	100.0
Pleasant Bay - east basin	70.0
Pleasant Bay - West Basin	10.0
Little Pleasant Bay	20.0
Bassing Harbor - Main Basin	15.0
Crows Pond	0.5
Ryder Cove	0.8
Lower Frost Fish Creek	1.5
Upper Frost Fish Creek	5.0
Frost Fish Creek Culvert	10.0
Lower Muddy Creek	50.0
Upper Muddy Creek	10.0
Muddy Creek Culvert	50.0
Round Cove	2.5
Quonset Pond	0.5
Paw Wah Pond	1.0
The River -lower	60.0
The River - upper	30.0
Namequoit River	20.0
Areys Pond	10.0
Lonnies Pond (Kescayo Ganset) Creek	0.5
Kescayo Ganset (Lonnies) Pond	0.5
Meetinghouse Pond	0.5
Pochet Neck	1.0

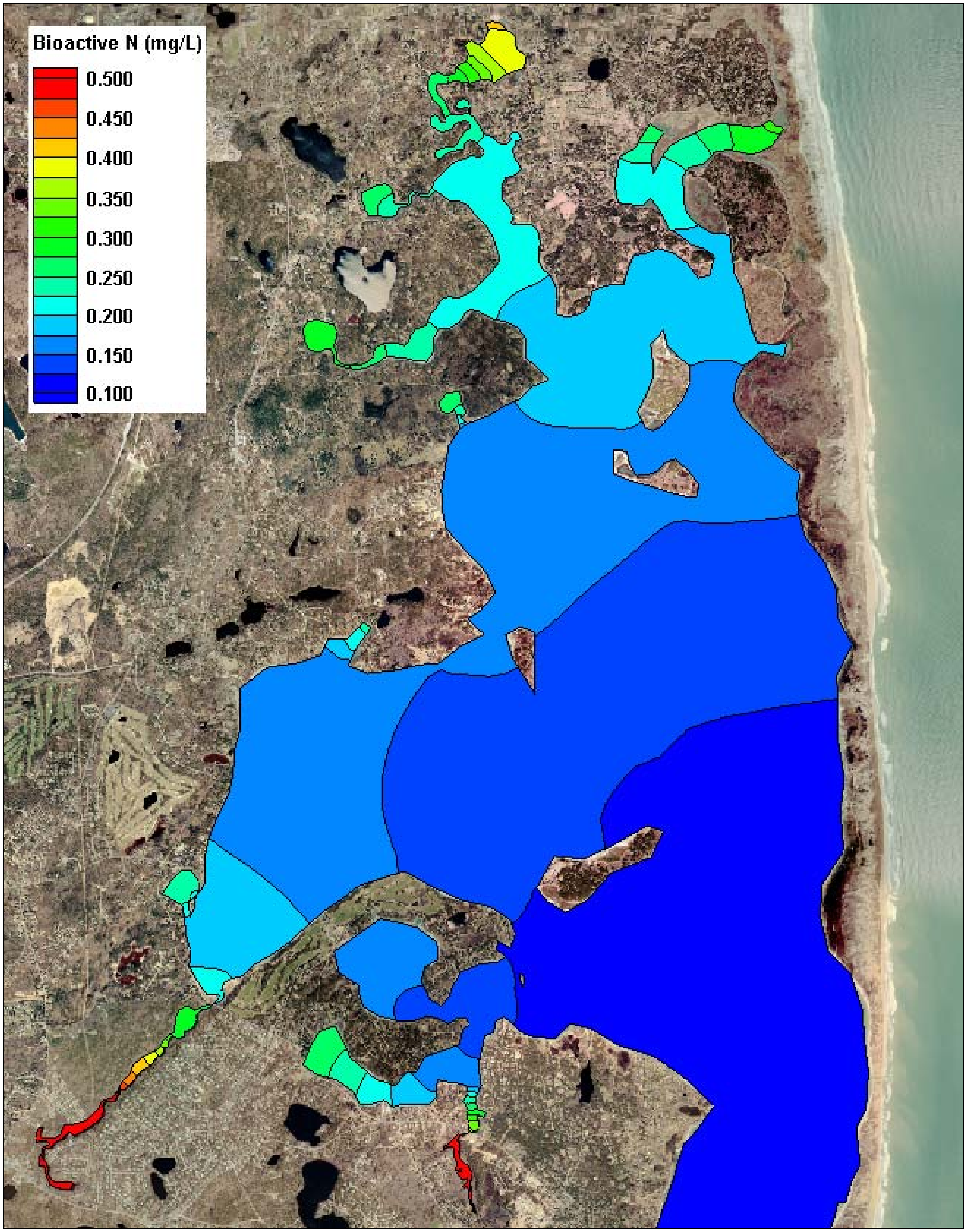

Figure VI-2. Contour plot of average bioactive (DIN+PON) nitrogen concentrations from results of the present conditions loading scenario, for the Pleasant Bay system.

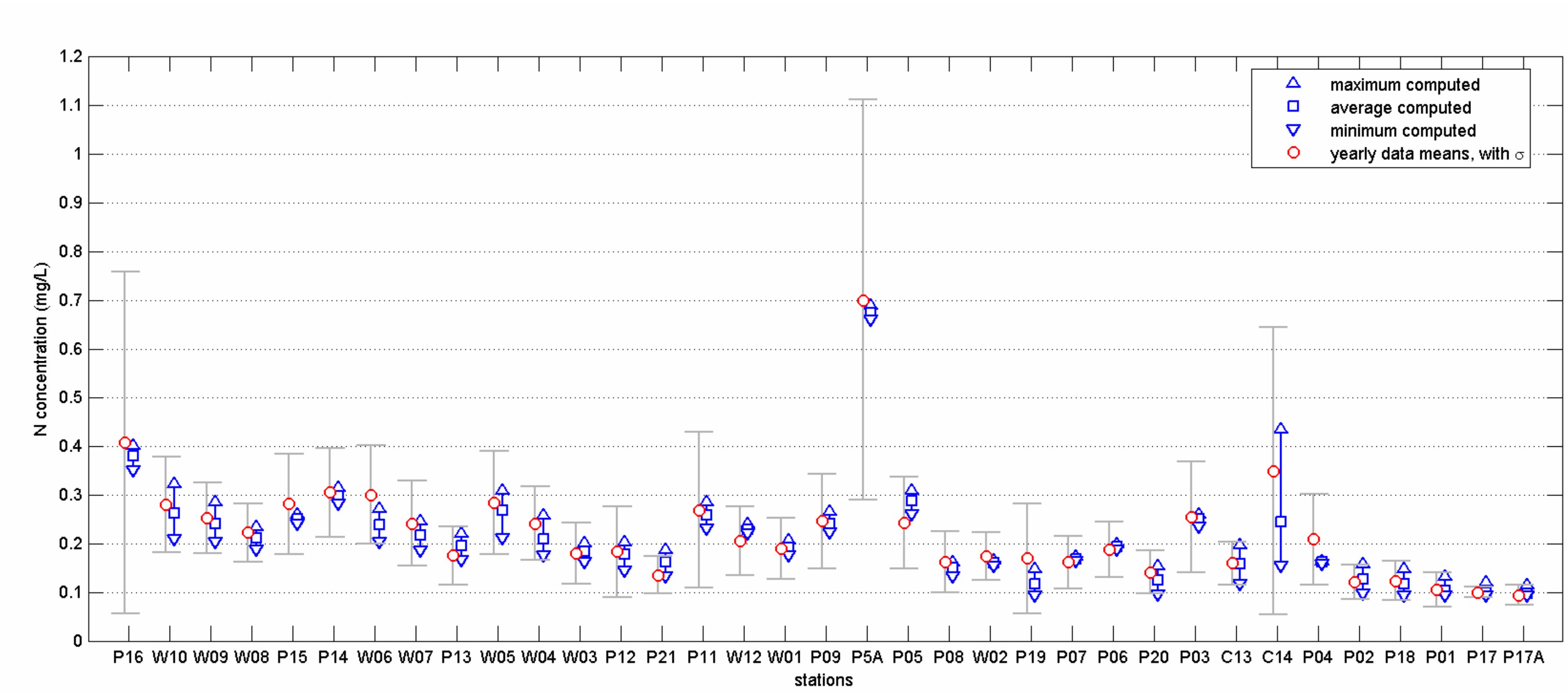

Figure VI-3. Comparison of measured bioactive (DIN+PON) nitrogen concentrations and calibrated model output at stations in the Pleasant Bay system. Station labels correspond with those provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during the simulation period (triangle markers), along with the average computed concentration for the same period (square markers). Measured data are presented as the total yearly mean at each station (circle markers), together with ranges that indicate ± one standard deviation of the entire dataset

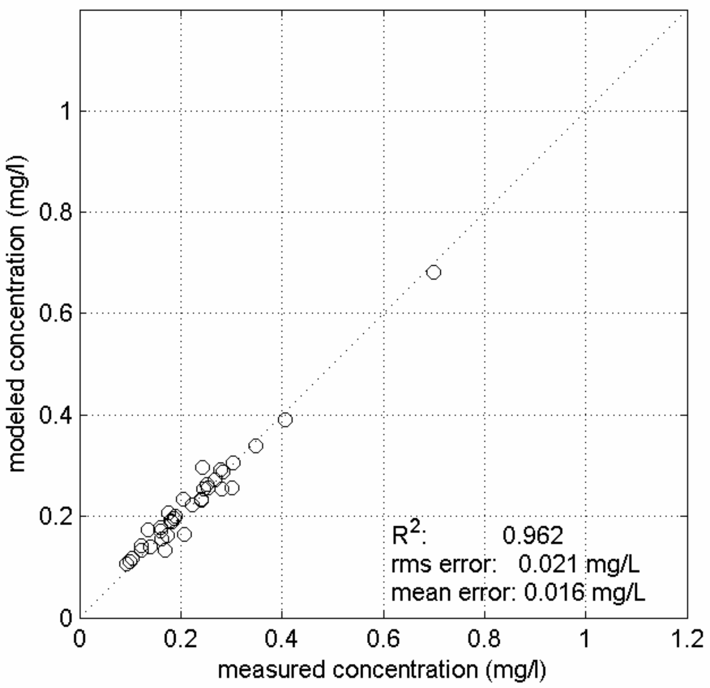

Figure VI-4. Model total nitrogen calibration target values are plotted against measured concentrations, together with the unity line. Computed correlation (R^2) and error (rms) for the model are also presented.

VI.2.5 Model Salinity Verification

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 step was performed for the Pleasant Bay system using salinity data collected at the same stations as the nitrogen data. The only required inputs into the RMA4 salinity model of each system, in addition to the RMA2 hydrodynamic model output, were salinities at the model open boundary, at the freshwater stream discharges, and groundwater inputs. The open boundary salinity was set at 32.3 ppt, based on measurements taken at the inlet during flooding tides. For surface water steams and groundwater inputs salinities were set at 0 ppt. Surface water and groundwater inputs used for the model are listed in Table VI-4. Groundwater flows were distributed evenly in the model through the use of several 1-D element input points positioned along each model's land boundary. Rainfall to the estuary surface was also included as an additional freshwater input into the model. Based on an annual average rainfall of 27.25 inches, the freshwater input into the model from rain was computed to be 26.47 ft^3/sec.

Table VI-4. Freshwater inputs (groundwater and surface water) used as inputs to the salinity model of the Pleasant Bay estuary system.

System Division	flow ft^3/sec
Pochet Neck	2.76
Meetinghouse Pond	1.03
The River - upper	1.22
Lonnies Pond	1.32
Kescayo Ganset Stream	0.44
Lonnies Pond River	0.51
Areys Pond	1.34
Namequoit River	1.55
The River - lower	1.80
Paw Wah Pond	0.56
Quanset Pond	0.63
Tar Kiln Stream	1.02
Round Cove	1.02
The Horseshoe	0.42
Muddy Creek - upper	3.53
Muddy Creek - lower	2.71
Ryders Cove	3.05
Crows Pond	1.10
Bassing Harbor	0.76
Frost Fish Creek	0.72
Pleasant Bay/Little Pleasant Bay	13.85
Chatham Harbor	2.65

A contour plot of model output is shown in Figure VI-7, with comparisons of modeled and measured salinities presented in Figures VI-5 and VI-6. Though model dispersion coefficients were not changed from those values selected through the nitrogen model calibration process, the model skillfully represents salinity gradients throughout the Pleasant Bay estuary system. The rms error of the three models is 1.21 ppt, and correlation coefficient between the model and measured salinity data is 0.85. The salinity verification provides a further independent confirmation that model dispersion coefficients and represented freshwater inputs to the model correctly simulate the real physical system.

VI.2.6 Build-Out and No Anthropogenic Load Scenarios

To assess the influence of nitrogen loading on bioactive nitrogen concentrations within Pleasant Bay, 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 alternate watershed loading analyses are shown in Table VI-5. 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.

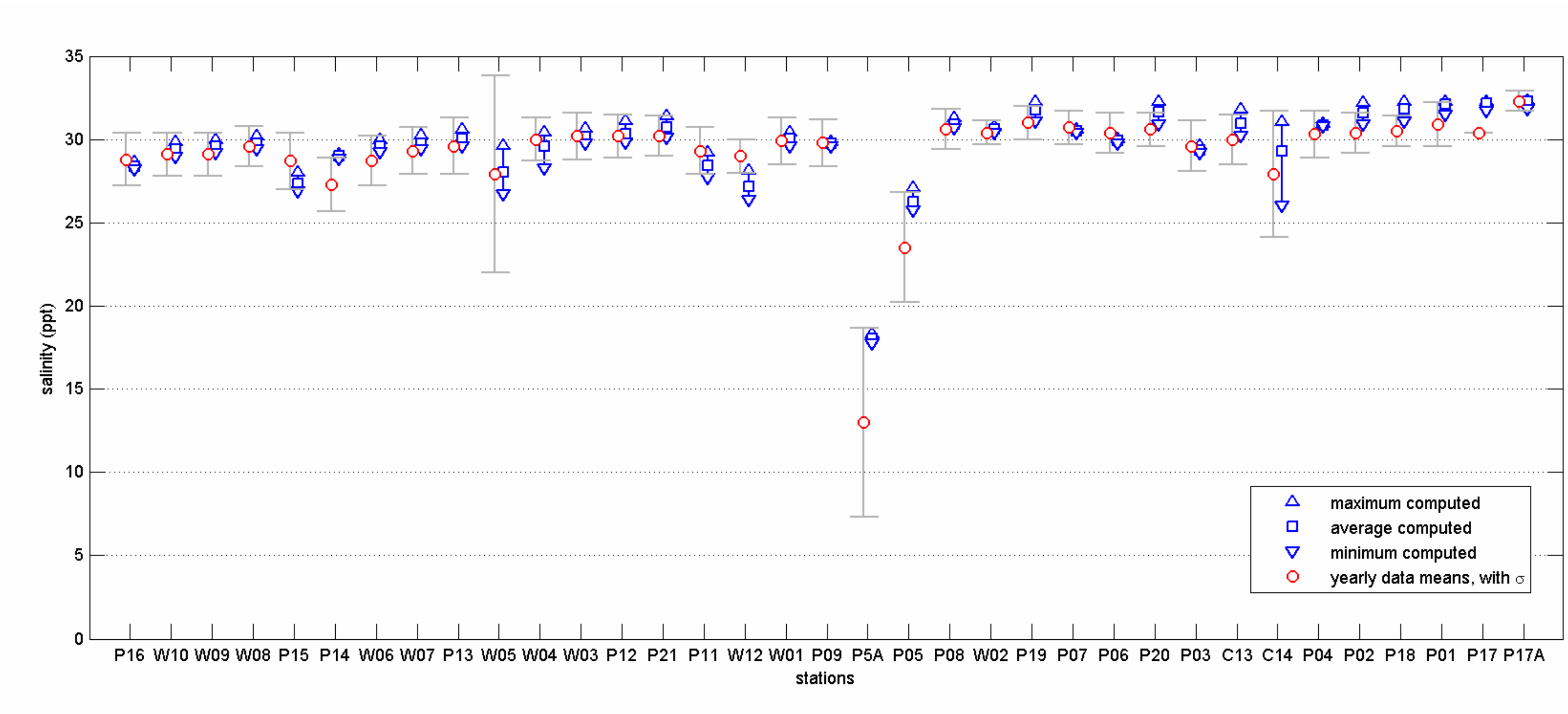

Figure VI-5. Comparison of measured and calibrated model output at stations in Pleasant Bay. Stations labels correspond with those provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during the simulation period (triangle markers), along with the average computed salinity for the same period (square markers). Measured data are presented as the total yearly mean at each station (circle markers), together with ranges that indicate ± one standard deviation of the entire dataset.

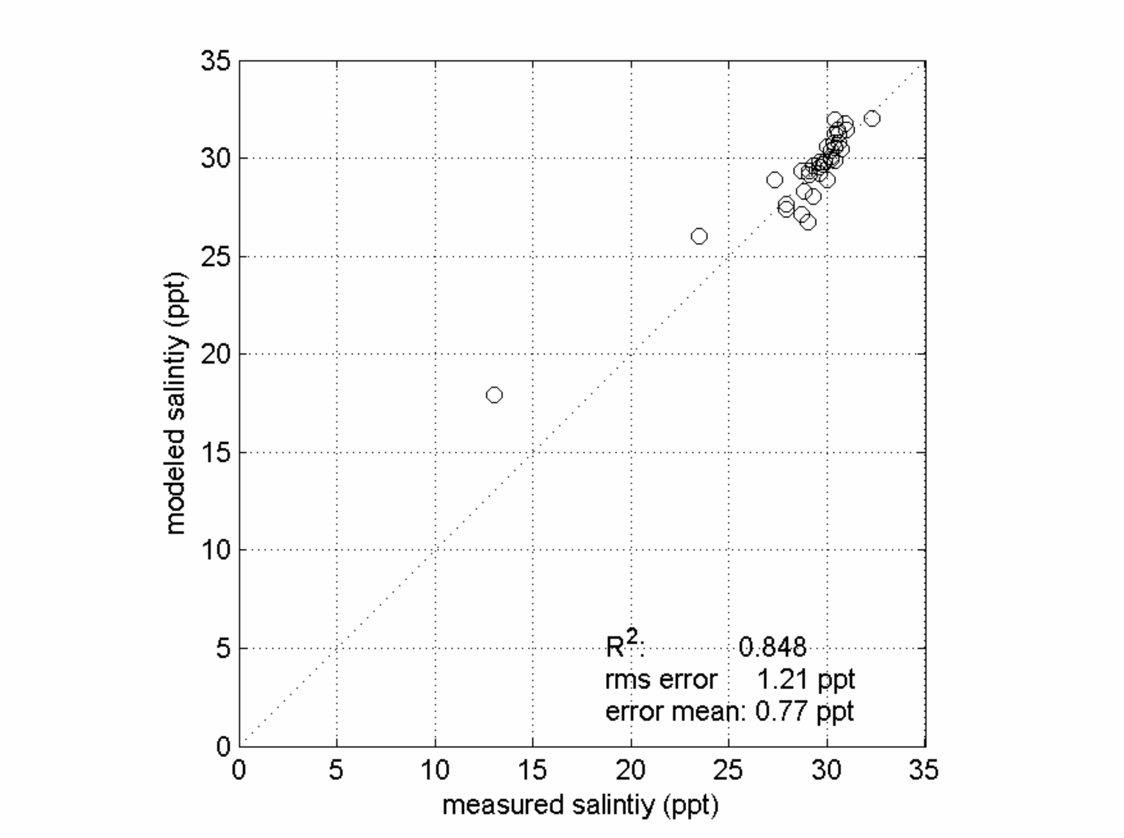

Figure VI-6. Model salinity target values are plotted against measured concentrations, together with the unity line. Computed correlation (R^2) and error (rms) for each model are also presented.

VI.2.6.1 Build-Out

In general, certain sub-embayments would be impacted more than others. For the build-out scenario, for the entire Pleasant Bay system the nitrogen load increases by more than 30%, or 38.273 kg/day. The smallest increase occurs in the Crows Pond watershed, where the nitrogen increases 10% due to potential future development. Other watershed areas would experience much greater load increases, for example the loads to the Little Pleasant Bay watershed would increase 61% from the present day loading levels. A maximum increase in watershed loading resulting from future development would occur in the lower watershed of The River, where the increase would be 2.768 kg/day, or 71% more than present conditions. 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 80%.

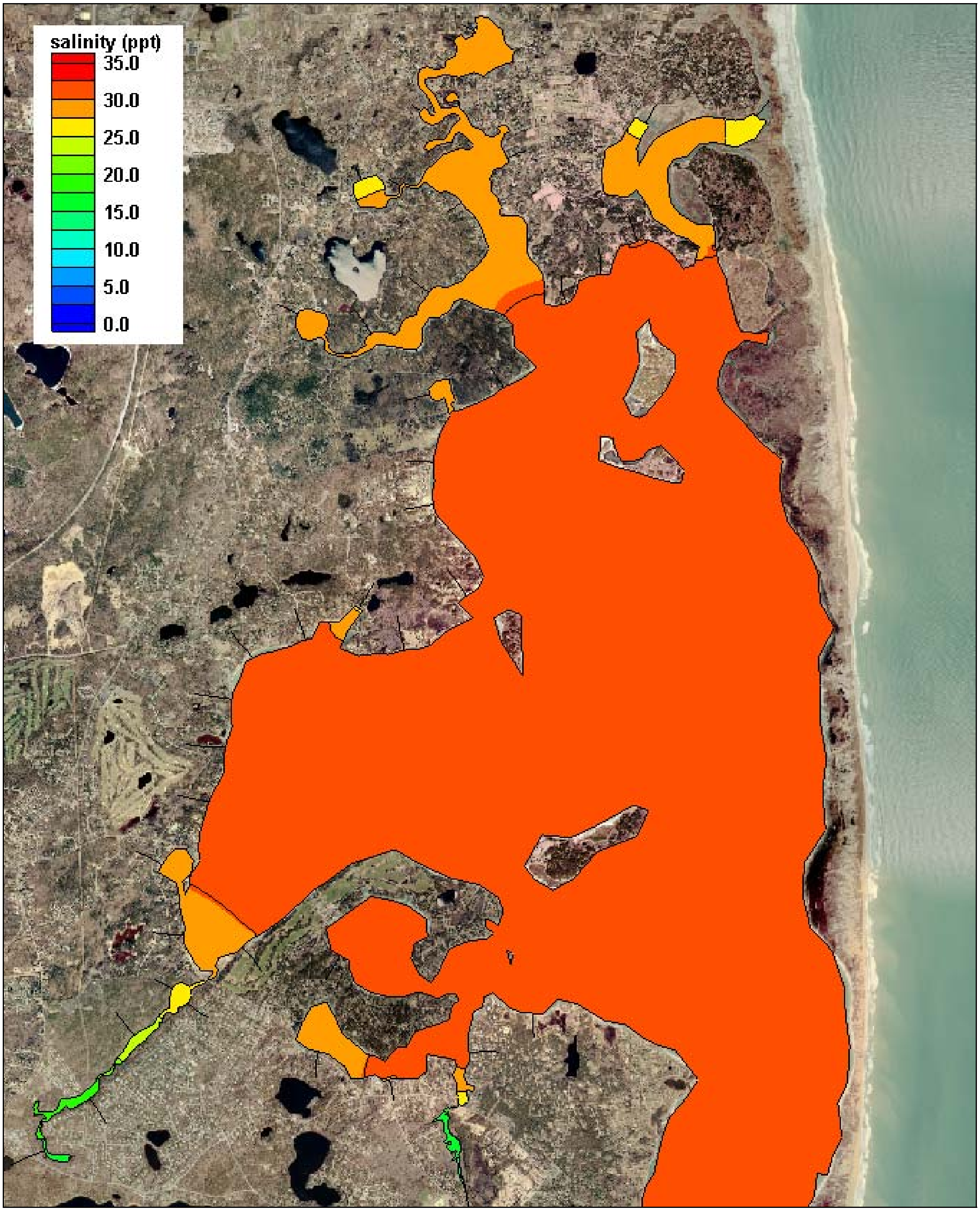

Figure VI-7. Contour Plot of modeled salinity (ppt) in the Pleasant Bay system.

Table VI-5. Comparison of sub-embayment watershed loads used for modeling of present, build-out, and no-anthropogenic ("no-load") loading scenarios of the Pleasant Bay system. 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
Meetinghouse Pond	6.197	8.263	+33.3%	0.69	-88.8%
The River – upper	2.773	3.978	+43.5%	0.53	-81.0%
The River – lower	3.879	6.647	+71.3%	0.76	-80.5%
Lonnies Pond	2.441	3.556	+45.7%	0.68	-72.1%
Areys Pond	1.304	2.044	+56.7%	0.47	-64.1%
Namequoit River	2.737	4.052	+48.0%	0.56	-79.5%
Paw Wah Pond	1.860	2.808	+51.0%	0.23	-87.5%
Pochet Neck	8.422	11.893	+41.2%	1.23	-85.4%
Little Pleasant Bay	7.496	12.036	+60.6%	1.53	-79.6%
Quanset Pond	1.781	2.395	+34.5%	0.30	-83.4%
Tar Kiln Stream	6.123	6.992	+14.2%	0.32	-94.9%
Round Cove	4.225	5.178	+22.6%	0.60	-85.7%
The Horseshoe	0.638	0.992	+55.4%	0.13	-79.4%
Muddy Creek - upper	9.981	13.540	+35.7%	1.95	-80.5%
Muddy Creek - lower	8.477	10.189	+20.2%	1.47	-82.6%
Pleasant Bay	23.159	30.792	+33.0%	3.49	-84.9%
Pleasant Bay/Chatham Harbor Channel	-	-	-	-	-
Bassing Harbor - Ryder Cove	9.819	11.137	+13.4%	2.00	-79.6%
Bassing Harbor - Frost Fish Creek	2.904	3.318	+14.2%	0.40	-86.2%
Bassing Harbor - Crows Pond	4.219	4.647	+10.1%	0.53	-87.3%
Bassing Harbor	1.668	1.967	+17.9%	0.23	-86.0%
Chatham Harbor	17.099	19.055	+11.4%	1.84	-89.2%
TOTAL - Pleasant Bay System	**127.203**	**165.477**	**+30.1%**	**19.951**	**-84.3%**

For the build-out scenario, a breakdown of the nitrogen load entering each sub-embayment is shown in Table VI-6. The benthic flux for the build-out scenarios is assumed to vary proportional to the watershed load, where an increase in watershed load will result in an increase in benthic flux (i.e., a positive change in the absolute value of the flux), and *vise versa*.

Projected benthic fluxes (for both the build-out and no load scenarios) are based upon projected PON concentrations and watershed loads, determined as:

$$(\mathit{Projected\ N\ flux}) = (\mathit{Present\ N\ flux}) * [PON_{projected}]/[PON_{present}]$$

where the projected PON concentration is calculated by,

$$[PON_{projected}] = R_{load} * \Delta PON + [PON_{(present\ offshore)}],$$

using the watershed load ratio,

$$R_{load} = (\mathit{Projected\ N\ load}) / (\mathit{Present\ N\ load}),$$

and the present PON concentration above background,

$$\Delta PON = [PON_{(present\ flux\ core)}] - [PON_{(present\ offshore)}].$$

Table VI-6. **Build-out** sub-embayment and surface water loads used for total nitrogen modeling of the Pleasant Bay system, with total watershed N loads, atmospheric N loads, and benthic flux.

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Meetinghouse Pond	8.263	0.584	16.976
The River – upper	3.978	0.288	7.408
The River – lower	6.647	2.241	12.086
Lonnies Pond	3.556	0.225	1.982
Areys Pond	2.044	0.181	8.036
Namequoit River	4.052	0.523	16.652
Paw Wah Pond	2.808	0.082	4.865
Pochet Neck	11.893	1.767	-0.904
Little Pleasant Bay	12.036	24.023	39.552
Quanset Pond	2.395	0.170	7.040
Tar Kiln Stream	6.992	0.066	-
Round Cove	5.178	0.170	9.680
The Horseshoe	0.992	0.063	-
Muddy Creek - upper	13.540	0.162	5.793
Muddy Creek - lower	10.189	0.205	-1.383
Pleasant Bay	30.792	19.153	163.977
Pleasant Bay/Chatham Harbor Channel	-	17.786	-42.317
Bassing Harbor - Ryder Cove	11.137	1.296	10.334
Bassing Harbor - Frost Fish Creek	3.318	0.096	-0.166
Bassing Harbor - Crows Pond	4.647	1.389	0.636
Bassing Harbor	1.967	1.071	-5.178
Chatham Harbor	19.055	14.153	-42.173
TOTAL - Pleasant Bay System	**165.477**	**85.693**	**212.895**

Following development of the nitrogen loading estimates for the build-out scenario, the water quality models of each system were run to determine nitrogen concentrations within each sub-embayment (Table VI-7). Total nitrogen concentrations in the receiving waters (i.e., the Atlantic Ocean) remained identical to the existing conditions modeling scenarios. Total N concentrations increased the most in the upper portions of the system, with the largest change at a station in upper muddy Creek (+25.4% at PBA-05a), with the least change occurring in Chatham Harbor (+0.8% at PBA-17) near the system's inlet to the open ocean. Color contours of model output for the build-out scenario are present in Figure VI-8. The range of nitrogen concentrations shown are the same as for the plot of present conditions in Figure VI-2, which allows direct comparison of nitrogen concentrations between loading scenarios.

Table VI-7. Comparison of model average bioactive N (DIN+PON) concentrations from present loading and the build-out scenario, with percent change, for the Pleasant Bay system. The sentinel threshold stations are in bold print and depicted in Figure VI-1.

Sub-Embayment	monitoring station	present (mg/L)	build-out (mg/L)	% change
Meetinghouse Pond	PBA-16	0.380	0.441	+16.1%
Meetinghouse Pond	WMO-10	0.261	0.296	+13.4%
The River - upper	WMO-09	0.239	0.269	+12.5%
The River – mid	WMO-08	0.211	0.235	+11.1%
Lonnies Pond (Kescayo Ganset Pond)	PBA-15	0.250	0.286	+14.5%
Areys Pond	PBA-14	0.297	0.345	+16.1%
Namequoit River - upper	WMO-6	0.239	0.269	+12.7%
Namequoit River - lower	WMO-7	0.216	0.240	+11.3%
The River - lower	PBA-13	0.195	0.214	+10.0%
Pochet – upper	WMO-05	0.269	0.316	+17.8%
Pochet - lower	WMO-04	0.209	0.234	+11.9%
Pochet – mouth	WMO-03	0.183	0.199	+8.8%
Little Pleasant Bay - head	**PBA-12**	**0.178**	**0.193**	**+8.6%**
Little Pleasant Bay - main basin	PBA-21	0.162	0.173	+7.4%
Paw Wah Pond	PBA-11	0.257	0.304	+18.4%
Little Quanset Pond	WMO-12	0.229	0.260	+13.3%
Quanset Pond	WMO-01	0.191	0.209	+9.3%
Round Cove	PBA-09	0.241	0.267	+10.8%
Muddy Creek - upper	PBA-05a	0.674	0.845	+25.4%
Muddy Creek - lower	PBA-05	0.286	0.331	+15.4%
Pleasant Bay - head	PBA-08	0.149	0.158	+6.0%
Pleasant Bay - off Quanset Pond	WMO-02	0.160	0.171	+6.8%
Pleasant Bay- upper Strong Island	PBA-19	0.117	0.121	+3.2%
Pleasant Bay - mid west basin	PBA-07	0.168	0.181	+7.4%
Pleasant Bay - off Muddy Creek	PBA-06	0.192	0.210	+9.0%
Pleasant Bay - Strong Island channel	PBA-20	0.124	0.129	+3.9%
Ryders Cove - upper	**PBA-03**	**0.250**	**0.270**	**+8.0%**
Ryders Cove - lower	**CM-13**	**0.158**	**0.168**	**+5.7%**
Frost Fish - lower	CM-14	0.243	0.265	+8.8%
Crows Pond	PBA-04	0.162	0.171	+5.5%
Bassing Harbor	PBA-02	0.127	0.132	+4.0%
Pleasant Bay - lower	PBA-18	0.116	0.120	+3.0%
Chatham Harbor - upper	PBA-01	0.104	0.105	+1.4%
Chatham Harbor - lower	PBA-17	0.099	0.100	+0.8%

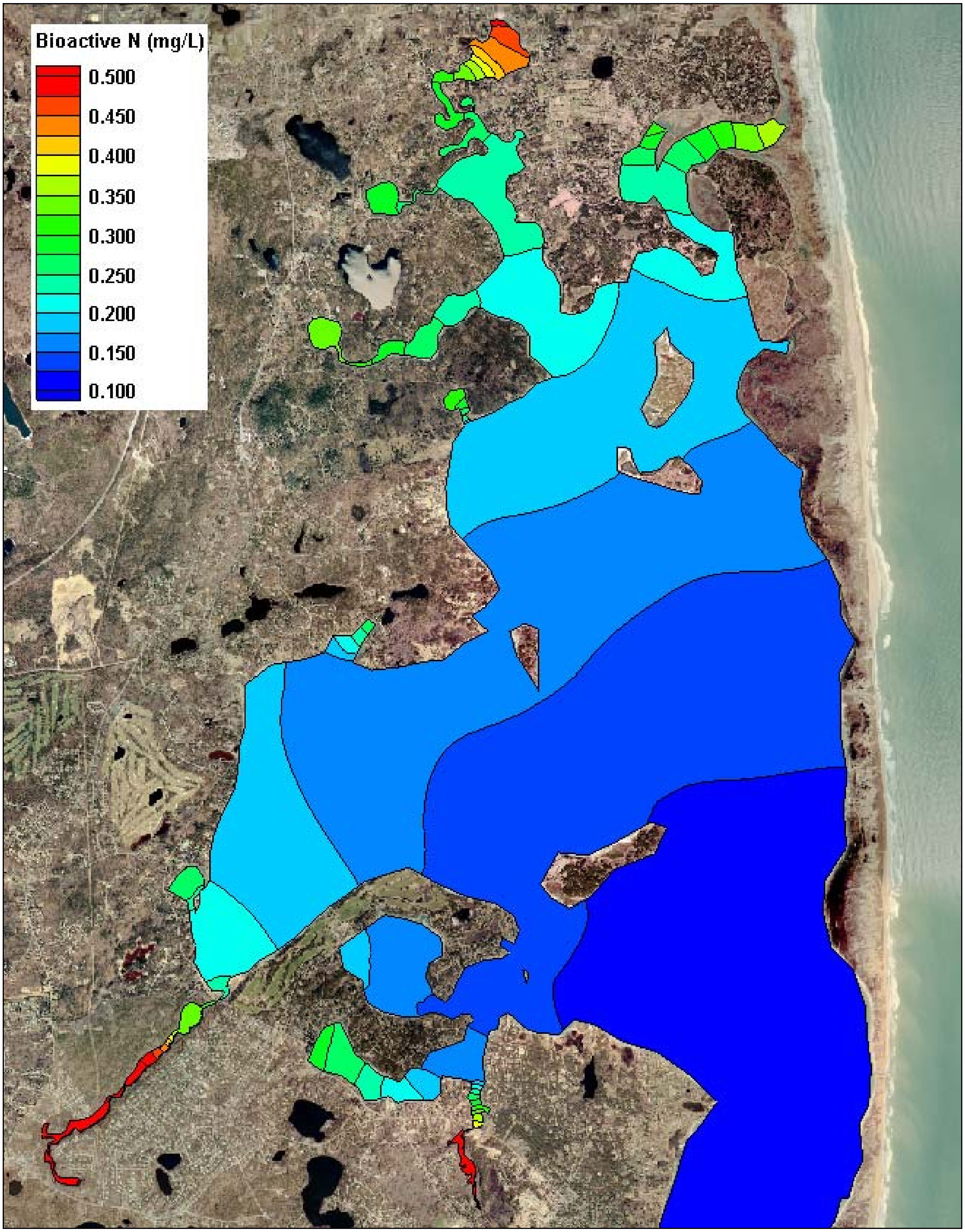

Figure VI-8. Contour plot of modeled total nitrogen concentrations (mg/L) in the Pleasant Bay system, for projected build-out loading conditions.

VI.2.6.2 No Anthropogenic Load

A breakdown of the total nitrogen load entering each sub-embayment for the no anthropogenic load ("no load") scenarios is shown in Table VI-8. The benthic flux input to each embayment was reduced (toward zero) based on the reduction in the watershed load (as discussed in §VI.2.6.1). Compared to the modeled present conditions and build-out scenario, 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.

Table VI-8. "**No anthropogenic loading**" ("no load") sub-embayment and surface water loads used for total nitrogen modeling of the Pleasant Bay system, with watershed N loads, atmospheric N loads, and benthic flux

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Meetinghouse Pond	0.69	0.58	7.40
The River – upper	0.53	0.29	3.55
The River – lower	0.76	2.24	7.35
Lonnies Pond	0.68	0.22	0.97
Areys Pond	0.47	0.18	3.70
Namequoit River	0.56	0.52	9.52
Paw Wah Pond	0.23	0.08	2.24
Pochet Neck	1.23	1.77	-0.51
Little Pleasant Bay	1.53	24.02	32.57
Quanset Pond	0.30	0.17	3.45
Tar Kiln Stream	0.32	0.07	-
Round Cove	0.60	0.17	3.61
The Horseshoe	0.13	0.06	-
Muddy Creek - upper	1.95	0.16	1.78
Muddy Creek - lower	1.47	0.21	-0.56
Pleasant Bay	3.49	19.15	114.57
Pleasant Bay/Chatham Harbor Channel	-	17.79	-35.14
Bassing Harbor - Ryder Cove	2.00	1.30	5.49
Bassing Harbor - Frost Fish Creek	0.40	0.10	-0.08
Bassing Harbor - Crows Pond	0.53	1.39	0.43
Bassing Harbor	0.23	1.07	-3.92
Chatham Harbor	1.84	14.15	-36.00
TOTAL - Pleasant Bay System	**19.951**	**85.693**	**120.417**

Following development of the 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 (i.e., the Atlantic Ocean) remained identical to the existing conditions modeling scenarios. The relative change in total nitrogen concentrations resulting from "no load" was significant as shown in Table VI-9, with reductions greater than 35% (at PBA-16 and PBA-05a) occurring the upper portions of the system. Results for each system are shown pictorially in Figure VI-9.

Table VI-9. Comparison of model average bioactive N (DIN+PON) concentrations from present loading and the no anthropogenic ("no load") scenario, with percent change, for the Pleasant Bay system. Loads are based on atmospheric deposition and a scaled N benthic flux (scaled from present conditions). The sentinel threshold stations are in bold print.

Sub-Embayment	monitoring station	present (mg/L)	no load (mg/L)	% change
Meetinghouse Pond	PBA-16	0.380	0.233	-38.7%
Meetinghouse Pond	WMO-10	0.261	0.184	-29.7%
The River - upper	WMO-09	0.239	0.174	-27.2%
The River – mid	WMO-08	0.211	0.162	-23.3%
Lonnies Pond (Kescayo Ganset Pond)	PBA-15	0.250	0.179	-28.4%
Areys Pond	PBA-14	0.297	0.214	-27.9%
Namequoit River - upper	WMO-6	0.239	0.180	-24.7%
Namequoit River - lower	WMO-7	0.216	0.166	-22.9%
The River - lower	PBA-13	0.195	0.154	-20.7%
Pochet – upper	WMO-05	0.269	0.170	-36.6%
Pochet - lower	WMO-04	0.209	0.157	-24.8%
Pochet – mouth	WMO-03	0.183	0.149	-18.7%
Little Pleasant Bay - head	**PBA-12**	**0.178**	**0.145**	**-18.3%**
Little Pleasant Bay - main basin	PBA-21	0.162	0.136	-16.1%
Paw Wah Pond	PBA-11	0.257	0.181	-29.6%
Little Quanset Pond	WMO-12	0.229	0.155	-32.5%
Quanset Pond	WMO-01	0.191	0.147	-23.0%
Round Cove	PBA-09	0.241	0.163	-32.3%
Muddy Creek - upper	PBA-05a	0.674	0.273	-59.5%
Muddy Creek - lower	PBA-05	0.286	0.169	-41.0%
Pleasant Bay - head	PBA-08	0.149	0.128	-14.5%
Pleasant Bay - off Quanset Pond	WMO-02	0.160	0.133	-16.9%
Pleasant Bay- upper Strong Island	PBA-19	0.117	0.108	-7.8%
Pleasant Bay - mid west basin	PBA-07	0.168	0.137	-18.8%
Pleasant Bay - off Muddy Creek	PBA-06	0.192	0.147	-23.5%
Pleasant Bay - Strong Island channel	PBA-20	0.124	0.112	-9.8%
Ryders Cove - upper	**PBA-03**	**0.250**	**0.159**	**-36.7%**
Ryders Cove - lower	**CM-13**	**0.158**	**0.125**	**-21.1%**
Frost Fish - lower	CM-14	0.243	0.148	-39.2%
Crows Pond	PBA-04	0.162	0.128	-21.1%
Bassing Harbor	PBA-02	0.127	0.112	-11.9%
Pleasant Bay - lower	PBA-18	0.116	0.107	-7.9%
Chatham Harbor - upper	PBA-01	0.104	0.100	-3.9%
Chatham Harbor - lower	PBA-17	0.099	0.097	-2.2%

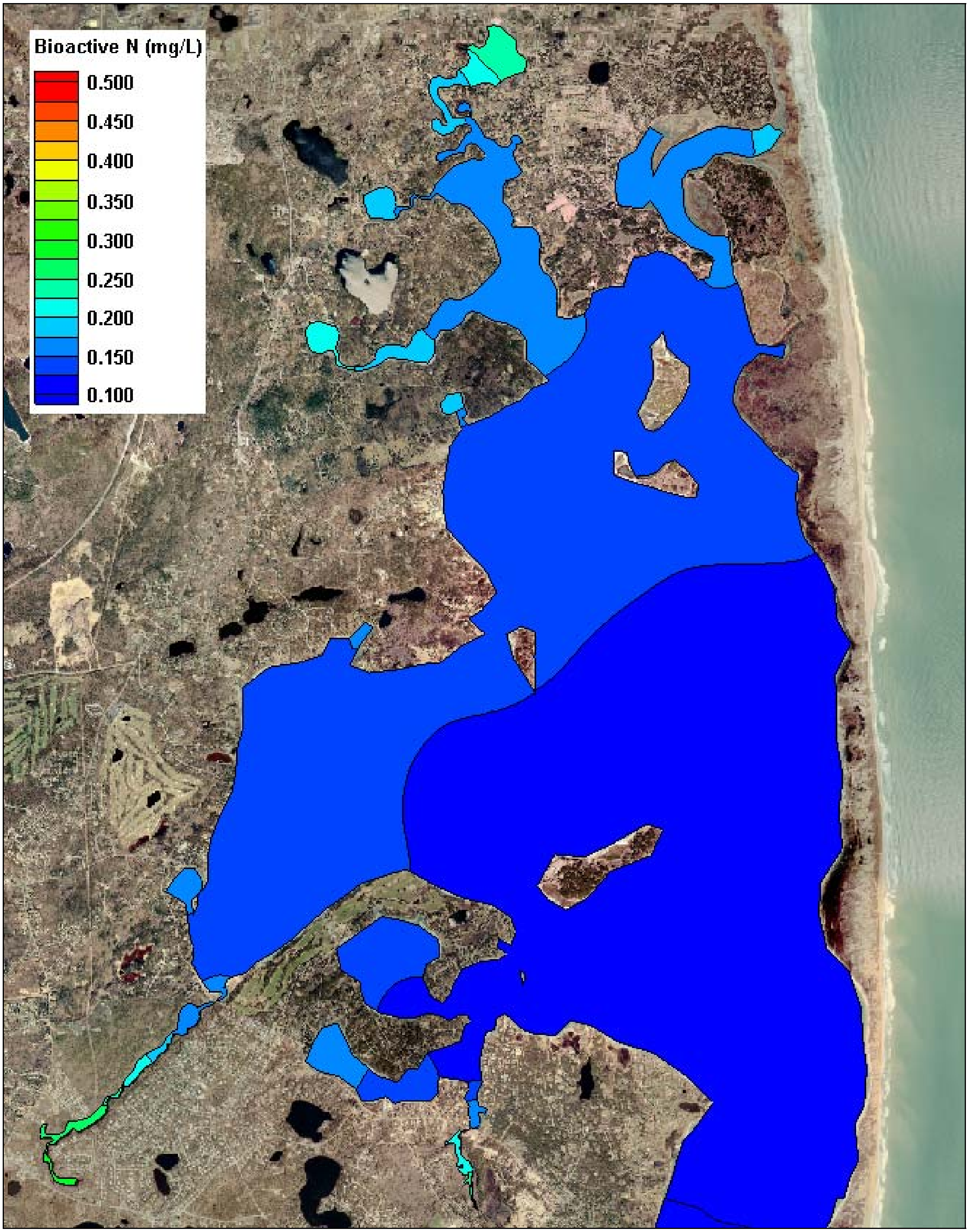

Figure VI-9. Contour plot of modeled total nitrogen concentrations (mg/L) in Pleasant Bay, for no anthropogenic loading conditions.