VI. WATER QUALITY MODELING

The water quality modeling analysis approach that has been typically used for other systems that have been studied as part of the Massachusetts Estuaries Project was slightly modified for Sesachacha Pond.

This system differs from all other systems modeled up to this point in time mainly because it does not have inlet that is open at all times to the ocean. Water quality in the Pond is managed presently by opening an inlet bi-annually, once in the spring and once in autumn. The period of time that the inlet remains open after it is breached varies between 1 and 25 days, based on reports of openings made from 1997 through 2004 (Curley, 2004). On average, the pond is open 12 days total a year, which means it is closed off from the ocean more than 96% of the time.

Because Sesachacha Pond is actively managed in such a fashion, the water quality analysis has to include methods for determining conditions in the Pond at times when it is both open and closed to tidal exchange with the ocean. During times when the Pond inlet is breached, the RMA-4 model was used to model water quality constituent dispersion throughout the Pond basin. During the long periods when the breach is closed, a simple mass balance model was developed. As used together in this analysis, these two modeling techniques accurately simulate conditions in the Pond throughout the critical summer months, and provide a method of investigating alternatives to manage pond health.

VI.1 DATA SOURCES FOR THE MODEL

Several different data types and calculations are required to support the water quality modeling effort for the Sesachacha Pond 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 salinity and nitrogen in the water column.

VI.1.1 Hydrodynamics and Tidal Flushing in the Embayments

Field measurements and hydrodynamic modeling of the embayment provide essential preparatory input to the water quality model development effort. The pond breach simulation discussed in Chapter V is an important tool for determining the water quality dynamics that are in effect presently, and also for investigating how possibly the pond could be managed differently in the future to further improve water quality conditions. 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. For each of the modeling scenarios presented in this chapter, the breach model was run for an extended 30-day period, based on the tide data record from Nantucket Harbor, beginning on March 29, 2005. These tide data were input into the analytical breach model to develop the boundary condition used to force the RMA-2 model of Sesachacha Pond. The hydrodynamics of the breach model are not strongly dependent upon the small inter-monthly variations of the astronomical tide; therefore, the selected 30-day period is considered representative of typical tidal conditions year-round.

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 Sesachacha Pond, consisting of the background concentrations of total nitrogen (TN) in the waters entering from the Atlantic Ocean during the brief periods when the inlet is open. This load is represented as a constant concentration along the seaward boundary of the RMA-4 model grid during the pond breach simulation period.

VI.1.3 Measured Nitrogen Concentrations in the Embayments

In order to create a model that realistically simulates salinity and total nitrogen concentrations in Sesachacha Pond in response to the existing flushing conditions and loadings, it was necessary to calibrate the model to actual measurements. The refined and approved data for the 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. For Sesachacha Pond, 11 years of salinity data are available between 1992 and 2005, and six years of TN measurements are available between 2000 and 2005.

Table VI-1. Measured nitrogen concentrations and salinities for the Sesachacha Pond estuarine. "Data mean" values are calculated as the average of the separate yearly means. Data represented in this table were collected in 1992 through 2005 in Sesachacha Pond and the summer of 2005 in the Atlantic Ocean (offshore Pleasant Bay Inlet).

Sampling Station Location	total nitrogen			salinity		
	data mean (mg/L)	s.d. all data (mg/L)	N	data mean (ppt)	s.d. all data (ppt)	N
Sesachacha Pond	1.197	0.078	48	19.0	6.1	322
Atlantic Ocean	0.232	0.044	17	32.3	0.6	5

VI.2 MODEL DESCRIPTION AND APPLICATION

The overall approach used in the analysis of Sesachacha Pond involves first developing a salinity model of the Pond. Salinity is a conservative water quality constituent, meaning that is has no active sources or sinks other than tidal exchange with the ocean. Because salinity data are conservative, they are excellent calibration data for systems such as Sesachacha. In such simple systems it is an easy task to compute water recharge and rainfall rates based on the observed salinity record.

The Sesachacha Pond analysis requires that both periods when the inlet is open and closed be considered, so a two-part approach was developed. The initial period (when the Pond inlet is breached in the spring and there is tidal exchange with the ocean) is modeled using the RMA-4 dispersion model. The following period when the inlet is closed, and the Pond behaves like a simple reservoir, is simulated using a simple mass balance model which considers fresh water inputs and constituent mass flux into the Pond (which is 0 for the salinity simulation) throughout the simulation period.

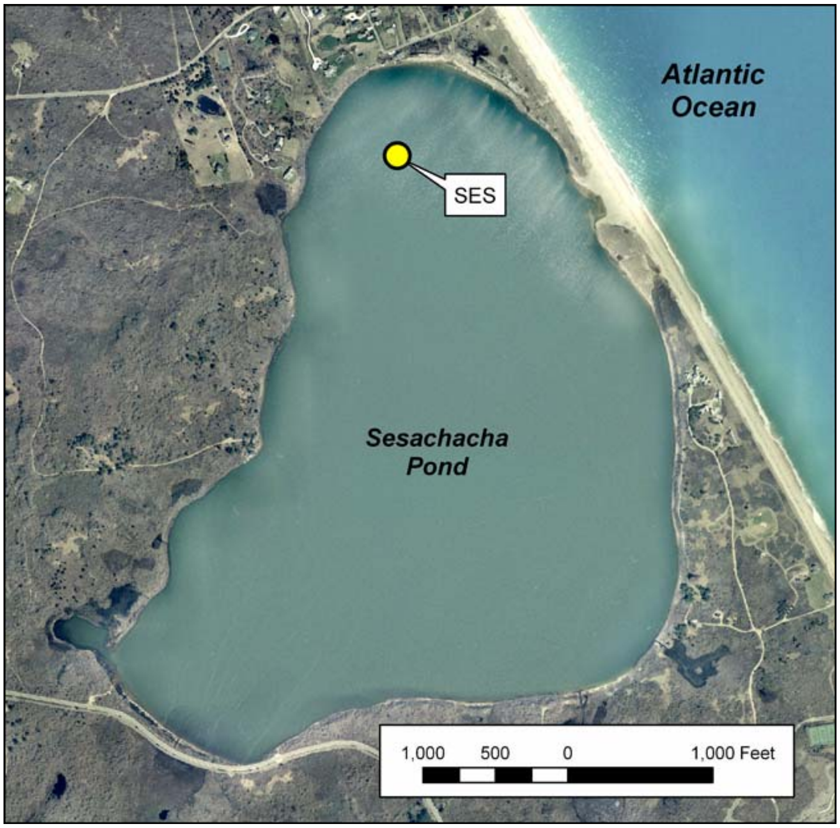

Figure VI-1. 2005 aerial photo showing monitoring station location in Sesachacha Pond that was used in the water quality analysis.

With a calibrated salinity model, a verification of the model is performed using total nitrogen, which is as a non-conservative constituent. For TN, bottom sediments act as a source or sink of nitrogen, based on local biochemical characteristics. The TN model considers summertime loading 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 (using watersheds delineated originally by the USGS and modified by WHOI), as well as the measured bottom sediment nitrogen fluxes. Water column nitrogen measurements were utilized as model boundaries and as calibration data.

VI.2.1 Model Formulation

VI.2.1.1 Dispersion Model

A two-dimensional finite element water quality model, RMA-4 (King, 1990), was employed to study the effects of water quality constituent dispersion in Sesachacha Pond during the periods when it is open to the ocean. 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 Pond. 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 other Massachusetts estuarine systems such as Pleasant Bay (Howes *et al*., 2006); Falmouth (Howes *et al*., 2005); and Mashpee, MA (Howes *et al*., 2004).

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* in the water quality constituent concentration; *t* is time; *u* and *v* are the velocities in the *x* and *y* directions, respectively; D_o and D_{ee} 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 time varying salinity and total nitrogen concentrations throughout Pond through the course of a month-long inlet opening.

VI.2.1.2 Mass Balance Model

During the extended periods when Sesachacha Pond is closed off from the Ocean, the system is modeled as a simple well mixed reservoir. The concentration *c* is a function of time *t*, and can be determined using the relationship

$$c(t)=\frac{m_o+t\,\frac{dm}{dt}}{V_o+t\,\frac{dV}{dt}},$$

Where *m* is the total mass of the modeled constituent, *V* is the volume of the Pond and the subscript *o* is used to designate the initial conditions. For the salinity model, the mass flux of salt (dm/dot) into the pond is zero. Using salinity data records from the summers of 1998, 2003, 2004 and 2005, a mass balance analysis of salt was performed to determine the rate of groundwater flow and salt flux through the barrier beach to the Ocean. This flow is the only possible sink for salinity in the Pond system. The four years used for this analysis were selected because in each of these years there was a successful springtime breaching of the pond. These breachings raised salinities in the Pond initially, and over the course of the summer, salinities slowly dropped as the Pond was diluted by ground water recharge and rainfall.

By this analysis, the groundwater flow out of the Pond was determined to be less than 10 percent of the flow in from the Pond's watershed and direct rainfall. The salinity sink through the barrier beach was therefore assumed to be not significant. The net flux of salt is therefore zero, and the net volume flux of water is simply the recharge rate plus direct rainfall minus evaporation. For the TN model, the mass flux of nitrogen is set to the sum of the watershed, atmospheric, and benthic loads.

VI.2.2 Boundary Condition Specification

Mass loading of nitrogen into the 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 combined watershed and direct atmospheric deposition loads for Head of the Harbor were evenly distributed at grid cells that formed the perimeter of the sub-embayment. Benthic regeneration loads were distributed among another sub-set of grid cells which are in the interior portion of each basin.

The loadings used to model present conditions in Sesachacha Pond 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, resulting in a total flux for the system (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. The benthic flux presented in Table VI-2 represents the net flux for the entire pond. Sediments in deeper regions (>4.5 meters deep) of the Pond tend to have negative fluxes, which indicates that they are a nitrogen sink. The N production of the bottom sediment in shallower areas is greater than this sink, and as a result, the net flux from the whole pond is positive.

In addition to mass loading boundary conditions set within the model domain, concentrations along the model open boundary were specified for the dispersion model. The model uses concentrations at the open boundary during the flooding tide periods of the RMA-4 model simulations. TN concentrations of the incoming water are set at the value designated for the open boundary. The TN boundary concentration in the Atlantic Ocean region offshore the Pond was set at 0.232 mg/L, based on SMAST data collected offshore Pleasant Bay in the summer of 2005. For the salinity model, the offshore concentration was set at 32.3 ppt.

Table VI-2. Sub-embayment and surface water loads used for total nitrogen modeling of Sesachacha Pond, 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)
Sesachacha Pond	0.973	3.115	20.376

VI.2.3 Development of Present Conditions Model

To develop the water quality model of present conditions for Sesachacha Pond, the RMA-4 dispersion model and the mass balance model were used together to simulate salinities in the Pond during the period from April through November 2004. This time period was chosen because the Spring breach of the Pond lasted 25 days, which is longer than average, which resulted in a wider range of salinities in the Pond that year.

First, the breach was modeled using RMA-4 and the RMA-2 hydrodynamic model results for a simulated 30-day opening. Output from the dispersion model is presented in Figure VI-2. Initially, the Pond salinity is 16.7 ppt. Over 25 days and many tide cycles, the Pond salinity rises to 25.7 ppt. The model output compares exceptionally well with Pond measurements made after the breach closing (25.2 ppt).

For the six month period following the closing of the breach (May through November), the mass balance model was used. This model requires an initial salinity and pond volume, as well as net fresh water flux. The initial salinity (25.7 ppt) was taken from day 25 of the dispersion model run. The initial Pond volume was determined to be 106,700,000 ft^3, based on results from the hydrodynamic model. The net freshwater input to the Pond was determined to be 1.5 ft^3/sec, based on the salt balance analysis performed using the monthly data available from the spring to fall period of 2004. Though a breach was attempted in the fall of 2004, it is apparent from the salinity data record that there was no tidal exchange. The pond elevation would have dropped during the failed breach, and this reduction in volume in the fall was accounted for in the model. The effect on the modeled salinities from this failed breach is small.

The comparison of modeled verses measured salinities between April and November 2004 are presented in Figures VI-3 and VI-4. The comparison shows that the combined dispersion and mass balance models are able to simulate salinities will a high degree of skill, with an R^2 correlation of 0.75 and an rms error of 0.89 ppt. Also in Figure VI-3, the results of a model sensitivity analysis are shown. Model output for two additional cases, where the recharge rates were changed to be 4.1 (from the Cape Cod Commission) and 0 ft^3/sec, shows how the model behaves as the rate is varied. This shows that the model is very sensitive to the applied recharge rate, and further indication that the 1.5 ft^3/sec used to simulate this period in 2004 is close to the actual conditions of the pond during at this time.

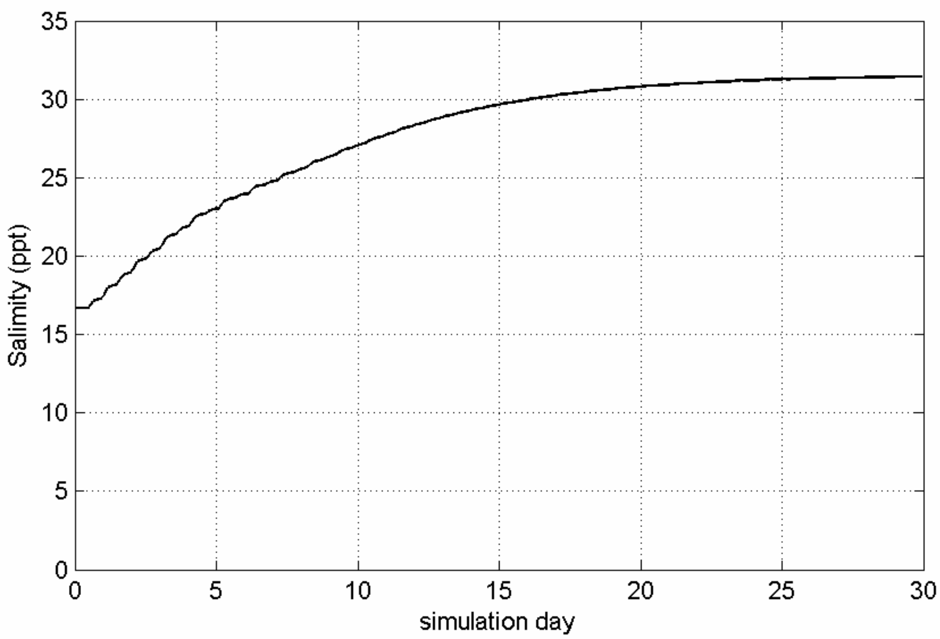

Figure VI-2. RMA-4 salinity dispersion model output for simulation of the spring 2004 opening of Sesachacha Pond. For this opening event, the inlet allowed tidal exchange with the Atlantic Ocean for 25 days before it closed again.

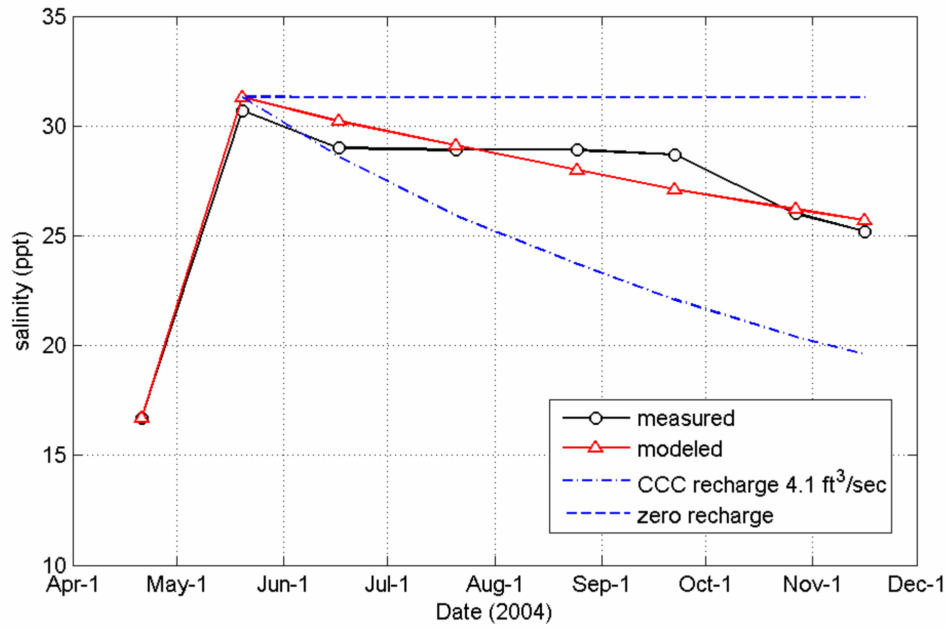

Figure VI-3. Comparison of measured (black circles) and modeled (red triangles) salinities through the summer of 2004, beginning with the spring breaching of an inlet to the Atlantic Ocean. The first two data points bracket the period of time that the inlet was open, and the Pond was tidally flushed. This breach period was simulated using the RMA-4 model of the Pond. Between May and November, the breach was closed, which prevented any tidal exchange. This period through the summer was simulated using the mass balance model. Results of the sensitivity analysis are also presented, showing model output using recharge rate determined by the Cape Cod Commission (CCC) and zero recharge.

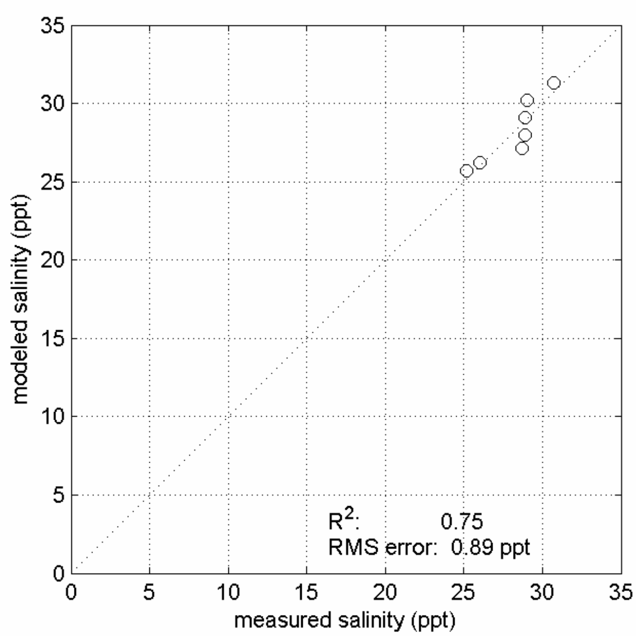

Figure VI-4. Model salinity target values are plotted against measured concentrations, together with the unity line, for the simulation period from May through November 2004. RMS error for this model verification run is 0.89 ppt and the R^2 correlation coefficient is 0.75.

VI.2.4 Total Nitrogen Model Verification

With the completion of the salinity model, it was possible to verify the model calibration by modeling total nitrogen, which is a water quality constituent that is completely independent of salinity.

The dispersion model was again run to simulate TN concentrations through the 25-day breach period starting in late April 2004. An open ocean TN concentration of .232 mg/L was used together with the nitrogen mass loading rates presented in Table VI-2 for Sesachacha Pond. As the Pond tidally flushed through the breach, TN concentrations dropped from the initial 1.1 mg/L to 0.29 mg/L at 25 days, as can be seen in Figure VI-5. This result compares very well again to measurements. The observed TN concentration measured soon after the breach closed was 0.28 mg/L, which is only 0.01 mg/L less that the modeled concentration.

Following the dispersion model, the mass balance model was used to simulate the period following the breach closure in May. This model used the same N mass loading rates as the dispersion model and included the same 1.5 ft^3/sec freshwater input used in the modeling of salinity.

Model output is compared to measurements for the entire spring to fall 2004 period in Figure VI-6 and VI-7. Similar to the results of the salinity model of Sesachacha Pond, the comparison demonstrates a high degree of modeling skill, with an R^2 correlation of 0.89 and an rms error of 0.17 mg/L. Model sensitivity to the applied recharge rate is indicated also in Figure VI-6. Rates were varied between the CCC estimate of the rate (4.1 ft^3/sec) and zero. Like the salinity analysis, the results show that the model is very sensitive to the applied recharge rate, and indicate that the 1.5 ft^3/sec used to simulate this period in 2004 is close to actual conditions.

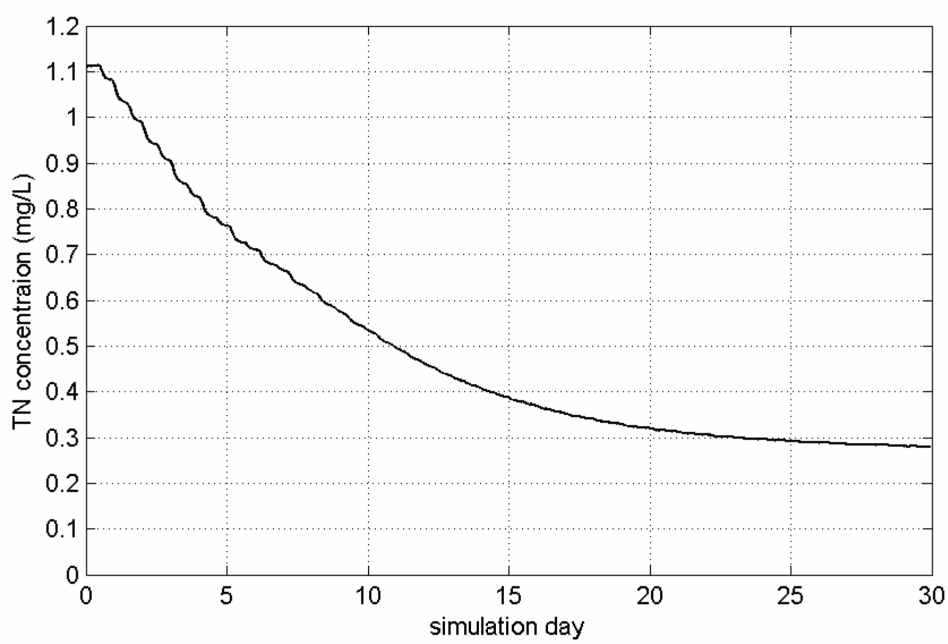

Figure VI-5. RMA-4 total nitrogen dispersion model output for simulation of the spring 2004 opening of Sesachacha Pond. For this opening event, the inlet allowed tidal exchange with the Atlantic Ocean for 25 days before it closed again.

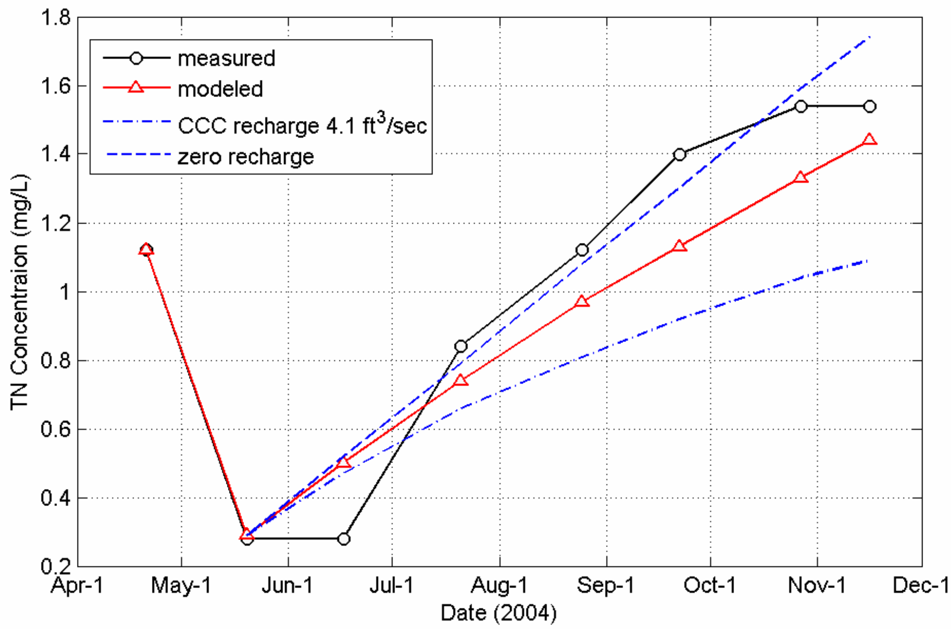

Figure VI-6. Comparison of measured (black circles) and modeled (red triangles) total nitrogen concentrations through the summer of 2004, beginning with the spring breaching of an inlet to the Atlantic Ocean. The first two data points bracket the period of time that the inlet was open, and the Pond was tidally flushed. Between May and November, the breach was closed, which prevented any tidal exchange. Results of the sensitivity analysis are also presented, showing model output using recharge rate determined by the Cape Cod Commission (CCC) and zero recharge.

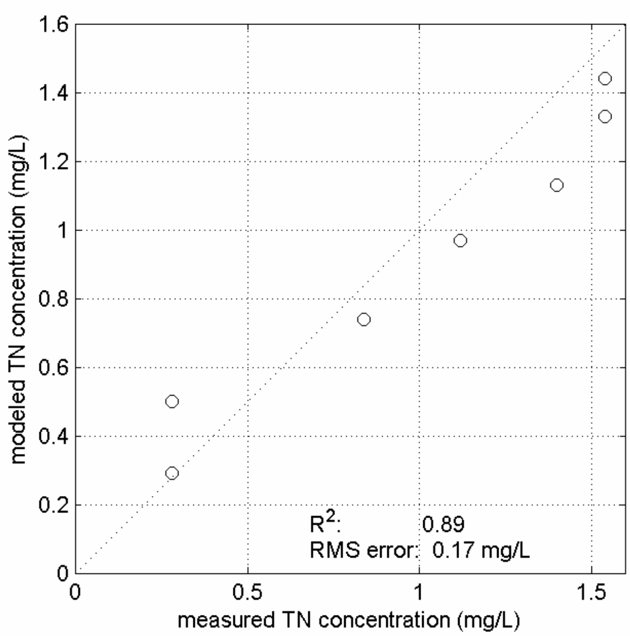

Figure VI-7. Model total nitrogen calibration target values are plotted against measured concentrations, together with the unity line, for the simulation period from May through November 2004.. Computed correlation (R^2) and error (rms) for the model are also presented.

Finally, Table VI-3 presents a comparison of modeled TN concentrations and salinities through the complete 30-day period simulated using the breach model hydrodynamics together with the dispersion model. For both modeled constituents, it is shown that concentrations do not change much after 20 days. The half-life of TN during the breach is approximately 9 days, for the modeled conditions.

Table VI-3. Model TN concentrations and salinities verses inlet days open. For modeled Spring though Fall 2004 conditions.

duration of opening	TN concentration	Salinity
days	mg/L	ppt
0	1.12	16.7
5	0.76	18.9
10	0.53	22.2
15	0.39	24.3
20	0.32	25.3
25	0.29	25.7
30	0.28	25.8

VI.2.5 Build-Out and No Anthropogenic Load Scenarios

To assess the influence of nitrogen loading on total nitrogen concentrations in Sesachacha Pond, the standard "build-out" and "no-load" water quality modeling scenarios were run. These runs included two "build-out" scenarios, 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-4. 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.

Table VI-4. Comparison of sub-embayment watershed loads used for modeling of present, build-out (scenarios "A" and "B"), and no-anthropogenic ("no-load") loading scenarios of Sesachacha Pond. 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
Sesachacha Pond	0.973	1.104	+11.9%	0.575	-69.2

VI.2.5.1 Build-Out

A breakdown of the total nitrogen load entering the Pond for the modeled Build-out scenario is shown in Table VI-5. 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:

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

where the projected PON concentration is calculated by,

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

using the watershed load ratio,

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

and the present PON concentration above background,

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

Table VI-5. **Build-out scenario** sub-embayment and surface water loads used for total nitrogen modeling of the Sesachacha Pond 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)
Sesachacha Pond	1.104	3.115	20.967

Following development of the nitrogen loading estimates for the build-out scenarios, the dispersion model was run to determine nitrogen concentrations within in the Pond (Table VI-6). Total nitrogen concentrations in the receiving waters (i.e., the Atlantic Ocean) remained identical to the existing conditions modeling scenario.

For the modeled build-out scenario, the increase in modeled TN concentrations is less than 1% through the entire breach simulation. Using the mass balance model to extend the build-out simulation to November 2004, the final concentration is computed to be 1.47 mg/L, or only 0.03 mg/L greater than for present conditions.

VI.2.5.2 No Anthropogenic Load

A breakdown of the total nitrogen load entering the Pond sub for the no anthropogenic load ("no load") scenarios is shown in Table VI-6. 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-6. "**No anthropogenic loading**" ("no load") sub-embayment and surface water loads used for total nitrogen modeling of the Sesachacha Pond 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)
Sesachacha Pond	0.575	3.115	18.583

Following development of the nitrogen loading estimates for the no load scenario, the water quality model was run to determine nitrogen concentrations in the Pond. Again, total nitrogen concentrations in the receiving waters (i.e., Atlantic Ocean) remained identical to the existing conditions modeling scenarios. The relative change in total nitrogen concentrations resulting from "no load" was small. Similar to build-out, modeled changes where small. The decrease in modeled TN concentrations is less than 1% through the entire breach simulation. Using the mass balance model to extend the build-out simulation to November 2004, the final concentration is computed to be 1.32 mg/L, or only 0.12 mg/L less than for present conditions.