Niantic River Estuary Ecosystem Model (NREEM) Report

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Second Interim report for the TAC
Project: Data Synthesis and Modeling of Nitrogen Effects on Niantic River Estuary
## Contents

1. Executive Summary .................................................................................................................. 4
2. General Approach to Model Development .............................................................................. 5
  2.1 Define Model Purpose .......................................................................................................... 6
  2.2 Specification of the Modeling Context: scope and resources .............................................. 6
  2.3 Conceptualization of the system, specification of data and prior knowledge ..................... 7
  2.4 Model Features and Family .................................................................................................. 8
  2.5 Choice of How Model Structure and Parameter Values are to be Found ......................... 9
  2.6 Choice of Performance Criteria and Technique ................................................................. 9
  2.7 Identification of Model Structure and Parameter Values (Calibration) .............................. 9
  2.8 Conditional Verification of Model Output ............................................................................ 9
  2.9 Quantification of Uncertainty ............................................................................................. 10
  2.10 Model Evaluation (Skill Analysis) ..................................................................................... 10
3. Model Choice Justification ......................................................................................................... 10
  3.1 Watershed Models .............................................................................................................. 10
  3.2 Review of In-Estuary Models .............................................................................................. 11
  3.3 Summary of Model Choice Justification ............................................................................ 16
4. Hydrodynamic Model Development .......................................................................................... 16
  4.1 Officer Box Model Approach .............................................................................................. 17
  4.2 Simplified Mixing Approach ............................................................................................... 19
5. Biogeochemical Model Development ....................................................................................... 22
  5.1 Constants and Coefficients Related to Primary Producers ............................................... 24
  5.2 Constants and Coefficients - Summary ............................................................................. 31
  5.3 Description of Model Formulations .................................................................................... 33
  5.4 Forcing Functions .............................................................................................................. 48
  5.5 Boundary Conditions ......................................................................................................... 50
6. Hydrodynamic Model Results .................................................................................................. 66
  6.1 Comparison to Other Estimates of Residence Time ......................................................... 66
7. Biogeochemical Model Results ................................................................................................ 66
  7.1 Skill Assessment .................................................................................................................. 66
  7.2 Scenarios ............................................................................................................................ 66
8. Works Cited ................................................................................................................................. 67
9. Appendix A – Salinity Data ........................................................................................................ 70
  9.1 Estimating Niantic Bay Salinity Beyond NYHOPS End Date ............................................ 74
This report is provided as a Microsoft Word document to allow for easy commenting and editing. This interim report will eventually become part of the final technical report. Feedback is appreciated; please forward comments to jamie.vaudrey@uconn.edu.


This report is a review of the modeling portion of the project. This report addresses Task 2: Model Development: Utilize existing data to develop an ecosystem model (biogeochemical model coupled to a physical mixing model). Two models will be evaluated, including Vaudrey’s work modeling Narragansett Bay (Brush 2002; Brush and Nixon 2010; Kremer et al. 2010; Vaudrey 2014) and the Massachusetts Estuary Project model (Howes et al. 2001).
1 Executive Summary
2 General Approach to Model Development

The development of any model incorporates a series of steps moving from defining the purpose through the final stages of model testing. In recognition of the broad audience with interests in this model, a brief summary of these steps are provided below with reference to sections of the report where these steps are discussed in detail. Most readers will be familiar with the steps involved with hypothesis driven experimental science. Modeling also follows a series of steps, though some readers may be less familiar with the process. Jakeman and colleagues (2006) provide a review of model development, detailing the ten major steps in the modeling process. The steps employed in model development are presented in a diagram (Figure 1) and followed by a brief description of the steps as they apply to the development of the Niantic River Estuary Ecosystem Model (NREEM). The goal of this section is to introduce the general approach to model development and testing employed in this project. The details of each step are provided later in this report.

Figure 1: Overview of Basic Modeling - 10 Steps

The numbers in the boxes refer to the Section in the text where the step as it pertains to this model is covered. Based on process described by Jakeman et al. (2006).
2.1 Define Model Purpose

The primary objective of this model is to inform management decisions supportive of good water quality in NRE. The synthesis of existing data will be used to understand the dynamics of the system in relation to climate and nutrient loads. An analysis of the potential impact of nutrient mitigation strategies will guide prioritization of activities in the watershed, with the Niantic River Watershed Commission evaluating our suggestions and assessment of feasibility.

A number of secondary objectives have been identified.

- The model will be used to predict the level of nutrient loads supportive of eelgrass and shellfish (as indicators of good water quality) under a warming climatic regime.
- Identify gaps in the data which, if filled, will improve our understanding of shallow water habitat characteristics and improve the ability of the model to predict ecosystem state variables as indicators of response to nutrient loads and temperature increases.
- Determine if the ecosystem model is robust for cross-system comparison, i.e. it does not require locally specific modification of parameters when moving to a new site.

2.2 Specification of the Modeling Context: scope and resources

The Niantic River Estuary Ecosystem Model is specifically developed for the Long Island Sound embayment, Niantic River. While the model framework and formulations are transferrable to other locations, the ranges of parameters may vary if estuarine conditions are considerably different from Niantic River. The model may also be reconfigured to include the contribution and predict conditions for other species (e.g., oysters), provided that the other species are most influenced by the same forcing factors as are included in the model (light availability, temperature, nutrient load).

The model output consists of daily estimates of state variables and rates associated with these changes. The state variables are: salinity, dissolved oxygen, phytoplankton biomass, seagrass biomass, macroalgae biomass, water column nitrogen, water column phosphorus, and benthic carbon. The model domain includes three boxes within the Niantic River and a large box representing Niantic Bay. The boxes are assumed to be vertically well-mixed, though predictions of surface-bottom differences in some parameters are estimated (e.g., oxygen, chlorophyll) using a mass-balance approach and an estimate of vertical dispersion through a well-mixed water column. Freshwater inflow is determined from the USGS gaging station of Latimer Brook and extrapolated to the other freshwater inputs (other tributaries, groundwater).

Temporally, the model is representative of daily averaged conditions. The diel changes in parameters (oxygen, chlorophyll, etc.) are not assessed by the model.
2.3 Conceptualization of the system, specification of data and prior knowledge

The success of eelgrass within the system is known to be linked to a number of forcing factors. Light, temperature, water quality, and the amount of other primary producers have all been identified as affecting eelgrass. Criteria for eelgrass success in Long Island Sound have been identified for these parameters (Table 2-1, page 7).

Development of the model proceeded under certain assumptions:

- The physical mixing in the estuary is adequately represented by a simple dilution model approach to estimating hydrodynamic exchange.
- The NYHOPS model salinity output accurately represents the salinity structure of Niantic River and Niantic Bay.
- Extrapolation of the river flow from Latimer Brook’s USGS gage data to other streams and groundwater inflow is reasonable.
- River flow data are available for Latimer Brook from 9/17/08 to 9/30/2015. Model output from NYHOPS is available for 1/1/1981 to 12/31/16. River flow data for the missing period can be extrapolated from other gaged streams in Connecticut.
- The primary producers compete for resources (light, nutrients) and this competition is well-represented by Michaelis-Menten-type dynamics.

<table>
<thead>
<tr>
<th>Suggested Guidelines for LIS</th>
<th>Guideline Type</th>
<th>Analysis Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Light Requirement at the leaf surface (%)</td>
<td>&gt; 15 (CB)</td>
<td>primary requirement (must estimate epiphyte biomass)</td>
</tr>
<tr>
<td>Water Column Light Requirement (%)</td>
<td>&lt; 22 (CB)</td>
<td>substitute for Min. Light Requirement at the Leaf Surface</td>
</tr>
<tr>
<td>Kd (1/m)</td>
<td>&lt; 0.7</td>
<td>provided for reference, use minimum light as the standard</td>
</tr>
<tr>
<td>Chlorophyll-a (µg / L)</td>
<td>&lt; 5.5</td>
<td>secondary requirement (diagnostic tool)</td>
</tr>
<tr>
<td>Dissolved Inorganic Nitrogen (mg/L)</td>
<td>&lt; 0.03</td>
<td>secondary requirement (diagnostic tool)</td>
</tr>
<tr>
<td>Dissolved Inorganic Phosphorus (mg/L)</td>
<td>&lt; 0.02 (CB and LIS)</td>
<td>secondary requirement (diagnostic tool)</td>
</tr>
<tr>
<td>Total Suspended Solids (mg/L)</td>
<td>&lt; 15 (CB) &lt; 30 (LIS)</td>
<td>secondary requirement (diagnostic tool)</td>
</tr>
<tr>
<td>Sediment Organics (%)</td>
<td>&lt; 10</td>
<td>habitat constraint</td>
</tr>
<tr>
<td>Vertical Distribution (m)</td>
<td>Zmax = 1m + Zmin</td>
<td>habitat constraint</td>
</tr>
<tr>
<td>Sediment Grain Size</td>
<td>&lt; 20% silt and clay</td>
<td>habitat constraint</td>
</tr>
<tr>
<td>Sediment Sulfide Concentration (µM)</td>
<td>&lt; 400</td>
<td>habitat constraint</td>
</tr>
<tr>
<td>Current Velocity (cm/s)</td>
<td>5 &lt; X &lt; 100</td>
<td>habitat constraint</td>
</tr>
</tbody>
</table>

Table 2-1: Recommended habitat requirements for established eelgrass beds in Long Island Sound. Copied from Vaudrey (2008a), based on work discussed in Vaudrey (2008a, 2008b) and Yarish et al. (2006).
2.4 Model Features and Family

The physical mixing in the estuary is driven by a simple dilution model approach to estimating hydrodynamic exchange (Section 4, page 16).

The ecological model family (Section 5, page 22) is best characterized as a “black box” model, meaning that empirical data are used to define relationships of forcing factors (light, temperature, freshwater input, wind) to model output (state variable) without specifying the exact biological processes involved (e.g. consumption of phytoplankton classes by zooplankton). Instead of focusing on the mechanistic processes, a statistical relationship between the forcing factors and model output is employed. The model is deterministic; in other words, the same inputs will always yield the same outputs.

The model consists of relatively few processes and coefficients, and is thus termed a mid-level or intermediate complexity model. Formulations are based on empirically derived relationships from the literature. A general overview of the model is provided in Figure 2. Eight state variables are modeled: salt, phytoplankton biomass, macroalgae biomass, eelgrass biomass, nitrogen, phosphorus, benthic carbon, and oxygen. Differential equations define the rate of change in each state variable. The change due to mixing is not included in the differential equations of the ecological portion of the model, the mixing is handled in a separate part of the model. A full description of the processes included and justifications for constants and coefficients forms the bulk of this report.

Figure 2: Overview of Model Processes

Processes within the model are indicated by the blue arrows with the basis for the formulation shown in black italicized text. The state variables are nitrogen, phosphorus, sediment organic carbon, phytoplankton, macroalgae, eelgrass, and oxygen. Black arrows indicate transport of state variables across the boundary of the model domain. For example, N enters via river and groundwater input from the watershed and from atmospheric deposition to the surface of the embayment. N is exchanged with Niantic Bay / Long Island Sound via hydrodynamics and is lost to the atmosphere via denitrification. Note, the black arrows do not always point to the symbol for the state variable to which they are contributing in order to keep the graphical display uncluttered, but their contribution is assigned to those pools. C is carbon, N is nitrogen, P is phosphorus, O$_2$ is oxygen, T is temperature, OM is organic matter or biomass. The “≡” symbol indicates equivalency, that the N and P are calculated stoichiometrically from C.
2.5 Choice of How Model Structure and Parameter Values are to be Found

The Occam’s Razor principle of parsimony was employed when deciding upon the parameters to include (Jakeman et al. 2006). This refers to choosing the lowest number of parameters that yield accurate results. In modeling, the inclusion of additional parameters past a certain point increases uncertainty without a substantial increase in accuracy. This is due to estimation of parameters or processes, each having an error associated with the estimate which reflects temporal and spatial variability, sparseness of data, and error associated with interpolating between sample points and extrapolating into other areas where no data are present. As each new parameter is added to a model, the error of the model estimate increases. Eventually, the increased accuracy due to additional parameters is not detectable within the error associated with the model.

This model begins with the fewest possible parameters and coefficients. If necessary, addition of other processes may be included.

2.6 Choice of Performance Criteria and Technique

The performance criteria require a good match between model output for the state variables and rates to field data. The model should capture the correct range of data. The model output is unlikely to capture the short term variability in state variables as we will usually be comparing the box-wide daily average provided by the model to field data which represent a specific location at a specific time. Part of model assessment will include averaging field data to better match the spatial and temporal scale of model output.

2.7 Identification of Model Structure and Parameter Values (Calibration)

The acceptable ranges for constants and coefficients were defined by literature values coupled with local knowledge of typical ranges in Long Island Sound.

The structure of the model refers to formulations describing the processes included in the model (Figure 2, page 8). The model will be run many times, allowing parameters to randomly vary within their ranges; this will yield a family of predictions, providing an estimate of the range in predictions provided by the model – this is termed “stochastic simulations” (Kremer 1983).

2.8 Conditional Verification of Model Output

Conditional verification of the model was conducted at every step where model output was generated. This process involves examining the output to verify data values relative to what is known about the system.
2.9 Quantification of Uncertainty

Uncertainty in models can have many sources, including an incomplete understanding of the system and sparse data, the two sources most likely to affect this model. To quantify the degree of these uncertainties, model outputs are compared to the field data available. From this assessment, estimates of the fraction of model predictions which will accurately predict eelgrass success were determined.

2.10 Model Evaluation (Skill Analysis)

Evaluation of the model output relative to the available field data was used to assess the skill of the model. The accuracy of the model was determined by examining the model output relative to the location and mass of existing naturally occurring eelgrass beds and macroalgae. State variables are compared to water quality data available for Niantic River. A number of skill metrics appropriate to this model are employed. These are presented in Sections 6 (page 66) and 7 (page 66).

3 Model Choice Justification

3.1 Watershed Models

The watershed model used for this project is the Long Island Sound Nitrogen Loading Model (Vaudrey et al. 2013), which uses land use and population to estimate nitrogen load and applies attenuation factors for nitrogen removal as the groundwater travels through the watershed. The watershed portion of the model characterizes the nitrogen load reaching the edge of the estuary. This watershed model is used to run scenarios, changing the nitrogen contribution to the estuary as land use changes. It does this by providing a fractional modifier – comparing the load at baseline conditions to the load estimated via land-use changes. This process if further described in Section 7.2 (page 66).

In the in-estuary model, the nitrogen input from the watershed is characterized as the nitrogen concentration in incoming water multiplied by the volume of the incoming freshwater. The watershed model can be used to reduce or increase this input by comparing the changed nitrogen load to the default load and applying that fraction to the incoming freshwater’s nitrogen concentration. There is not a direct link between the watershed model and the in-estuary model – the user of the in-estuary model needs to specify by what fraction they want to change the nitrogen concentration.

Watershed models will not be reviewed further; we will use the LIS NLM because it is the only model which has already been applied to the Long Island Sound embayments. The comparison in Table 2 is provided to show the similarity among the coefficients used for the various watershed models. Three watershed models were reviewed by Howes et al. (2001) as part of the Massachusetts Estuary Project: Massachusetts Estuary Project Linked Model, Buzzards Bay Project Nitrogen Loading Methodology, Cape Cod Commission Nitrogen Loading/Critical Loads Methodology. Howes and colleagues reviewed the models by applying them to five embayments in Massachusetts. The Long Island Sound Nitrogen Loading Model (LIS NLM) is also presented in Table 3-1.
3.2 Review of In-Estuary Models

One of the project deliverables was a comparison of the in-estuary model chosen for this project (EcoGEM) and similar models. Each in-estuary model is reviewed for certain key characteristics. While each of these models includes subtle details not presented here, this comparison serves to highlight the differences among the models. Information on the Buzzards Bay and Cape Cod Commission models are summarized from the comparison presented in Howes et al. (2001). These two models essentially lack an in-estuary model. The models are presented side-by-side to facilitate comparison.

The Massachusetts Estuary Project uses the RMA-4 water quality module, coupled with the RMA-2 hydrodynamic model. The documentation on this model is vague in the online technical information and is not well described by Howes et al. (2001). Looking into the water quality modeling section of an embayment technical report provides more detail on the actual application of the model (e.g. Chp. 6 of Howes et al. 2006). Vaudrey and colleagues created EcoGEM, information is provided from personal experience and is documented in Vaudrey (2014).
Table 3-1: Review of key parameters in four watershed nitrogen load models.
The first three are taken from Table III-1 in Howes et al. (2001). The LIS NLM information is from Vaudrey. The MA Estuary Project Linked Model is also considered in Section 3.2, Review of In-Estuary Models (page 11).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Buzzards Bay Project Nitrogen Loading Methodology</th>
<th>Cape Cod Commission Nitrogen Loading Methodology</th>
<th>MA Estuary Project Linked Model</th>
<th>Long Island Sound Nitrogen Loading Model (LIS NLM)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LOADING FACTORS (as delivery to estuary, includes attenuation)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Septic Systems</td>
<td>2.67 kg N/person/yr</td>
<td>2.67 kg N/person/yr</td>
<td>1.80 kg N/person/yr</td>
<td>1.54 ± 0.5 kg N/person/yr&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Lawns</td>
<td>1.7 kg N/lawn/yr&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1.7 kg N/lawn/yr&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1.36 kg N/lawn/yr&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.8 ± 0.08 kg N/lawn/yr&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td>Precipitation to impervious surface that reaches groundwater</td>
<td>0.75 mg/L&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.75 mg/L&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.75 mg/L&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.81 mg/L</td>
</tr>
<tr>
<td>Precipitation to roadways that reaches groundwater</td>
<td>1.5 mg/L&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1.5 mg/L&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1.5 mg/L&lt;sup&gt;b&lt;/sup&gt;</td>
<td>0.81 mg/L</td>
</tr>
<tr>
<td><strong>ATTENUATION FACTORS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>attenuation in freshwater systems and surface water inflows</td>
<td>30%</td>
<td>0%</td>
<td>30 to 60%</td>
<td>50 to 70%</td>
</tr>
<tr>
<td>attenuation in groundwater</td>
<td>30%</td>
<td>0%</td>
<td>0%&lt;sup&gt;f&lt;/sup&gt;</td>
<td>0 to 88%&lt;sup&gt;f&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a</sup>Nitrogen added to residential lawns assumed to be 3 lb/1000 square feet, with lawn sizes assumed to be 5000 square feet. Leaching is assumed to be 20% in Linked Model, 25% on Buzzards Bay model, and 25% in Cape Cod Commission model.

<sup>b</sup>Only 90% of precipitation to surface reaches groundwater.

<sup>c</sup>A series of studies conducted in MA estuaries indicates attenuation in groundwater does not occur.

<sup>d</sup>Units of LIS NLM output have been converted to be consistent with results from Howes et al. (2001). The LIS NLM varies lawn size by watershed and zone within watershed. Fertilizer N applied is also varied with different regions within LIS, with Long Island and the Western Sound having higher application rates. The value shown includes all attenuation, the load to the estuary is shown; it is the average and standard error for all embayments. The value for Niantic River watershed is 0.74 ± 0.05 kg N/lawn.

<sup>e</sup>Units of LIS NLM output have been converted to be consistent with results from Howes et al. (2001). The LIS NLM identifies population on septic within each zone of the watershed and applies attenuation factors according to zone. The value shown includes all attenuation, the load to the estuary is shown.

<sup>f</sup>Attenuation depends upon land use category and location within the watershed.
3.2.1.1 Buzzards Bay Project Nitrogen Loading Methodology

3.2.1.1.1 Required Inputs
- estimates of nitrogen load from the watershed
- estimate of freshwater flushing time

3.2.1.1.2 Hydrodynamics
Not included. Freshwater flushing time is used to evaluate the residence time of nitrogen in the estuary.

3.2.1.1.3 Nutrient Inputs from Boundaries
Only includes the nutrient load as generated by the watershed loading model, which includes groundwater and surface water. Nutrient inputs are distributed to the whole system as a bulk number.

3.2.1.1.4 Time Frame
Annual estimate.

3.2.1.1.5 Calibration
None.

3.2.1.1.6 Verification
None.

3.2.1.1.7 Setting Nitrogen Thresholds
The thresholds are determined by allowing the estimated nitrogen load from the watershed to flush conservatively through the estuary. No in-estuary processes are included.

3.2.1.2 Cape Cod Commission Nitrogen Loading/Critical Loads Methodology

3.2.1.2.1 Required Inputs
- estimates of nitrogen load from the watershed
- estimate of freshwater flushing time

3.2.1.2.2 Hydrodynamics
Not included. Freshwater flushing time is used to evaluate the residence time of nitrogen in the estuary.

3.2.1.2.3 Nutrient Inputs from Boundaries
Only includes the nutrient load as generated by the watershed loading model, which includes groundwater and surface water. Nutrient inputs are distributed to the whole system as a bulk number.

3.2.1.2.4 Time Frame
Annual estimate.

3.2.1.2.5 Calibration
None.

3.2.1.2.6 Verification
None.

3.2.1.2.7 Setting Nitrogen Thresholds
The thresholds are determined by allowing the estimated nitrogen load from the watershed to flush conservatively though the estuary. No in-estuary processes are included.
3.2.1.3  Linked Model – used in Massachusetts Estuary Project

3.2.1.3.1  Required Inputs

- boundary conditions and dispersion coefficients output as a table from RMA-2
- estimates of nitrogen load from the watershed
- measurements of benthic flux of nitrogen during summer
- measurements of nitrogen in the water column during summer

3.2.1.3.2  Hydrodynamics

Uses a finely resolved, 2-D hydrodynamic model (RMA-2), which would include thousands of grid cells when applied to Niantic River. Each of these grid cells is equivalent to the coarsely resolved ecological model mentioned for the EcoGEM model.

3.2.1.3.3  Nutrient Inputs from Boundaries

Includes nutrients entering from freshwater surface flow, marine boundary (e.g. Long Island Sound for Niantic River), and groundwater. Nutrient inputs are distributed to each grid cell as appropriate. For example, groundwater enters throughout the spatial area of the embayment.

3.2.1.4  EcoGEM Box Model

3.2.1.4.1  Required Inputs

- boundary conditions and dispersion coefficients from the Officer Box Model approach to determining hydrodynamics
- light, wind, temperature
- estimates of nitrogen load from the watershed
- estimates of benthic flux of nitrogen
- measurements of state variables in the incoming water and within the estuary: salinity, chlorophyll, nitrogen, phosphorus, benthic carbon, dissolved oxygen

3.2.1.4.2  Hydrodynamics

Uses a coarsely resolved, 3-D box model approach to determining mixing within the embayment, with three boxes representing the NRE. This coarse resolution is more appropriate to the scale of ecological processes, allowing us to average over larger scales and verify model estimates with field data (Kremer et al. 2010). Ideally, a fine-scale hydrodynamic model would be used to estimate the mixing among the three boxes. NRE was well-mixed, both vertically and horizontally, thus the Officer box model approach which been used in many estuaries was not appropriate (Officer 1980; Officer and Kester 1991). The Officer approach could be applied to embayments with a greater range of salinity values along the embayment. For NRE, a simpler approach was used, employing a dilution scheme with an estimate of return flow (Plew et al. 2018).

3.2.1.4.3  Nutrient Inputs from Boundaries

Includes nutrients entering from freshwater surface flow, marine boundary (e.g. Long Island Sound for Niantic River), groundwater, and atmospheric deposition directly to the embayment surface. Nutrient inputs are distributed to each model box as appropriate. For
while surface flow enters at the location of streams and rivers.

3.2.1.3.4 Time Frame
The model has a spin-up of 28 days, followed by 7 days for the model run. The 28-day period allows the model domain to reach steady state, this period is not considered model output.

3.2.1.3.5 Calibration
Calibration of the model is in reference to the nitrogen concentrations measured in the water column. The dispersion coefficients are tuned until the model output matches the in-estuary concentration.

3.2.1.3.6 Verification
To verify the model is operating as expected, salinity output from the model are compared to salinity data from the estuary.

3.2.1.3.7 Setting Nitrogen Thresholds
Only nitrogen is modeled directly. Dissolved oxygen, eelgrass, and benthic infauna (when eelgrass was not present) are used to set targets for nitrogen loads, using actual data from the system. A site within the system is chosen as a sentinel site such that improvement in water quality in that location will restore habitat to the desired condition. For example, eelgrass may be desired at an inner station (landward). To set a nitrogen threshold, the nitrogen level at existing eelgrass beds in that system are used to set the target nitrogen concentration for the water column. The nitrogen load from the watershed is adjusted until the desired condition is achieved at the sentinel station.

example, groundwater enters throughout the spatial area of the embayment while surface flow enters at the location of streams and rivers.

3.2.1.4.4 Time Frame
The model will cover multiple years, and the model will be responsive to changes in temperature, light, and wind.

3.2.1.4.5 Calibration
Calibration of the model is in reference to the chlorophyll, nutrients, and dissolved oxygen measured in the water column. The respiratory coefficient of the water column and benthos are the only items tuned to achieve a goodness of fit.

3.2.1.4.6 Verification
To verify the model is operating as expected, salinity output from the model are compared to salinity data from the estuary.

3.2.1.4.7 Setting Nitrogen Thresholds
The model provides estimates of nutrients, chlorophyll, and dissolved oxygen. Macroalgae and seagrass will be added to the model. A result of the model is an estimate of the light attenuation coefficient in the water column. Estimates of the light reaching the bottom will predict success for eelgrass. Scenarios of changing nutrient loads (adjusting the nitrogen loads relative to the watershed model) in the context of increasing temperatures will provide estimates for nitrogen thresholds responsive to predicted water column warming.
3.3 Summary of Model Choice Justification

WATERSHED MODEL

- The Long Island Sound Nitrogen Loading Model (LIS NLM) will be used to determine the watershed loading rate for nitrogen for scenario runs. Changes in land use result in changes to the nitrogen load. The revised nitrogen input relative to the default is used as a fractional adjuster in the interface of the in-estuary model; the two models (watershed and in-estuary) are not dynamically linked. Further evaluation of the other three watershed models presented in Table 3-1 (page 12) is beyond the scope of this project. In addition, the LIS NLM model is the only one which has already been applied to the LIS embayment.

IN-ESTUARY MODEL

- The Buzzards Bay and Cape Cod Commission models essentially do not have an in-estuary model. We will have estimates of the flushing time of the embayment, and can thus apply these methods for setting criteria (basically, a flushing of the nitrogen through the system).

- The benefit of the Linked Model used in the MA Estuary Project is the application of a fine-scale hydrodynamic model. Application of that model is beyond the scope of this project in terms of both time and resources.

- The EcoGEM model, used in this project, operates over multiple years and can estimate the impacts of climate factors on water quality.

- We will compare estimates using a procedure similar to the Linked Model approach by substituting the mixing coefficients derived from the simplified hydrodynamic model approach used for EcoGEM.

4 Hydrodynamic Model Development

An overview of the hydrodynamic and biogeochemical models are provided in Section 2.4 (page 8).

Niantic River Estuary is divided into three boxes for both the hydrodynamic model and the biogeochemical model (Figure 3). The final choice for hydrodynamics in the model was a simple dilution scheme to drive mixing. This section reviews the attempt to use the more refined Officer box model equations and the justification for using a dilution scheme instead of the Officer box model equations.
Figure 3: Model domain and box delineations. Each colored area represents a box in the model domain. The red lines indicate boundaries between boxes, with the freshwater input at the north, and with Niantic Bay at the south.

4.1 Officer Box Model Approach

The physical mixing was first modelled using the Officer box model approach and available data for salinity and freshwater flow (Hagy et al. 2000; Officer 1980, eqns. 80-86; Officer and Kester 1991, Hansen-Rattray parameter). This approach estimates physical exchanges between adjacent elements using data on freshwater inputs to the estuary and the corresponding salinity within the estuary and at the ocean boundary.

This method did not work for NRE because the estuary is often vertically and horizontally well-mixed (Figure 4), though Niantic Bay shows more frequent stratification. As the salinity difference approaches zero, the Officer equations are not able to accurately estimate exchange. The end result in the ecological
model was that salt builds up in the estuary, achieving salinities over 100 ppt. The Officer box model approach is mentioned here because other embayments may have sufficient salinity differences to allow for the use of Officer’s approach.

The Officer box model approach requires daily salinity values in each box of the model domain and at the boundaries. For systems where the Officer box model approach is likely to work, a source of modeled salinity data for Long Island Sound is reviewed in Appendix A.

Figure 4: NYHOPS modeled salinity profiles. Salinity at the 11 depths modeled by the NYHOPS model; note, these are not in meters, but instead the water column is divided into 11 layers. Box 7 corresponds to Niantic Bay, 8 to the lower basin, 9 to the upper basin, and 10 to the arm (Figure 42). This series of was randomly chosen to illustrate the water column is often well-mixed.
4.2 Simplified Mixing Approach

A recent paper reviewed simple dilution models for use in water quality models and identified conditions under which more complex hydrodynamic models are required (Plew et al. 2018). In short, the criteria involve calculating an indicator ($I$) as:

$$I = \frac{Q_f \times T}{P} \quad \text{(eqn. 1)}$$

where $Q_f$ is the freshwater inflow (m$^3$ sec$^{-1}$), $T$ is the tidal period (sec), and $P$ is the volume of the tidal prism. For Niantic River, freshwater inflow from all three streams was calculated from USGS gage data, using an extrapolation from nearby gages (see the Data Synthesis section of the report for methods).

The tidal period is 12.42 hours, which equates to 44,712 seconds. The volume of the tidal prism was calculated from the average tidal range of 0.7 m and the area of NRE of 2.96 km, which equates to 2,069,256 m$^3$. For NRE, the value of the indicator, $I$, is 0.025. Less than 0.1 is well-mixed and less than 0.25 is reasonably well-mixed (Plew et al. 2018).

The simplified scheme balances volumes entering and leaving a box on a given day (Figure 5). The salt concentration in the sending box is multiplied by the volume to yield the amount of salt transported among boxes. Salinity in the box is calculated at the end of the day by balancing the salt inputs and outputs. Plew et al. (2018) provide a method for calculating return flow, which is the amount of water that leaves an estuary and immediately returns (Figure 6). They suggest this is more of a “tuning factor” than a known number.

---

**Figure 5: Simplified Mixing**

Colors of the arrows indicate the concentration of the state variable associated with the flow.
The change in salinity for each day (dy/dt) was calculated as follows for each box (Figure 5):

\[ dy_{\text{box1}} = \text{RivFlux} \times \text{RiverBoundaryConditions} - \text{RivFlux} \times Y_{\text{concbox1}} + \text{SurfArea}_{\text{box1}} \times TPfactor \times (1 - \text{ReturnFlowFrac}_{\text{box1}}) \times Y_{\text{concbox2}} - \text{SurfArea}_{\text{box1}} \times TPfactor \times (1 - \text{ReturnFlowFrac}_{\text{box1}}) \times Y_{\text{concbox1}} \]

\[ dy_{\text{box2}} = \text{RivFlux} \times Y_{\text{concbox1}} - \text{RivFlux} \times Y_{\text{concbox2}} + \text{SurfArea}_{\text{box2}} \times TPfactor \times (1 - \text{ReturnFlowFrac}_{\text{box2}}) \times Y_{\text{concbox3}} - \text{SurfArea}_{\text{box2}} \times TPfactor \times (1 - \text{ReturnFlowFrac}_{\text{box2}}) \times Y_{\text{concbox2}} + \text{SurfArea}_{\text{box1}} \times TPfactor \times (1 - \text{ReturnFlowFrac}_{\text{box1}}) \times Y_{\text{concbox1}} - \text{SurfArea}_{\text{box1}} \times TPfactor \times (1 - \text{ReturnFlowFrac}_{\text{box1}}) \times Y_{\text{concbox2}} \]

\[ dy_{\text{box3}} = \text{RivFlux} \times Y_{\text{concbox2}} - \text{RivFlux} \times Y_{\text{concbox3}} + \text{SurfArea}_{\text{box3}} \times TPfactor \times (1 - \text{ReturnFlowFrac}_{\text{box3}}) \times \text{OceanBoundaryConditions} - \text{SurfArea}_{\text{box3}} \times TPfactor \times (1 - \text{ReturnFlowFrac}_{\text{box3}}) \times Y_{\text{concbox3}} + \text{SurfArea}_{\text{box2}} \times TPfactor \times (1 - \text{ReturnFlowFrac}_{\text{box2}}) \times Y_{\text{concbox2}} - \text{SurfArea}_{\text{box2}} \times TPfactor \times (1 - \text{ReturnFlowFrac}_{\text{box2}}) \times Y_{\text{concbox3}} \]

Where:

- \( \text{RivFlux} (\text{m}^3) \) = the freshwater input from the three streams estimated from nearby USGS gages using a relationship developed using time periods when freshwater streams into Niantic River were gaged. This relationship is discussed in the Data Synthesis section of this report.
- \( Y_{\text{conc}} \) (ppt, kg m\(^{-3}\)) = the salinity value in each box at the end of the previous day.
- \( \text{RiverBoundaryConditions} = \) boundary conditions in the river; for salt, the salinity is 0 ppt.
- \( \text{OceanBoundaryConditions} = \) boundary conditions in Niantic Bay, salinity (ppt) is obtained from the NYHOPS model; this value is forced, not modeled.
- \( TPfactor (\text{m d}^{-1}) = 1.3527 \text{ m d}^{-1} = 0.7 \text{ m per tidal prism} \times 2 \text{ tidal prisms per day} \times (24 \text{ h/24.84 h}); \) Just under two tidal cycles per day, so adjusted for this.
- \( \text{ReturnFlowFrac} \) (unitless) = fraction of water leaving a box that returns to the box within that day, due to return flow associated with incoming tides. The base value was calculated using the formula for the return flow fraction ("b") provided in Plew et al. (2018), which results in a value which varies with freshwater flow into the system (Figure 6). A tuning factor was applied to the base value, as recommended by Plew et al. (2018). Because the mixing equations use “1 – return flow fraction” to indicate the amount leaving the box and not returning, a smaller tuning factor results in a larger return flow. The tuning factors were determined by minimizing the difference between the modeled salinity and the NYHOPS salinity output, keeping in mind that the NYHOPS salinity overestimates salinity in the arm (box 1) when compared to field data. The unitless tuning factors were: box 1 = 0.001, box 2 = 0.2, box 3 = 0.4; these factors were multiplied by the base value for the return flow fraction shown in Figure 6.
The return flow fraction for years with NYHOPS model output, 1981 to 2013, is shown in Figure 6. The values vary with freshwater input to Niantic River Estuary.

Return Flow Fraction by day for the year 2010 is shown in Figure 6 (right panel). Return Flow Fraction is calculated as $b = 0.949e^{-1.679x}$, where $x = QfT/P$, $Qf =$ freshwater inflow ($m^3 s^{-1}$), $T =$ tidal period ($12.42 h = 44,712 s$), and $P =$ the volume of the tidal prism ($m^3$).

The salinity output of EcoGEM, modeled using the equations shown above, were compared to the NYHOPS model salinity output (Figure 7). The NYHOPS model includes output for 1/1/1981 to 10/31/13, a total of 11,992 days. The NYHOPS model tends to overestimate the salinity in the Arm - box 1 (Appendix A, page 70), thus higher values of the difference between NYHOPS and EcoGEM salinity are preferred in box 1.

Figure 7: Difference in NYHOPS modeled salinity and EcoGEM salinity model output. Histograms of 11,992 days (1/1/81 to 10/31/13) of salinity modeling using the simple mixing model in EcoGEM relative to the NYHOPS model output. A boxplot of the same data is at the top of each panel. The box indicates the 25th percentile, median, and 75th percentile of data. The whiskers are at the 10th and 90th percentiles with the black dots indicating the 5th and 95th percentiles. The return flow fraction was optimized to minimize the error in EcoGEM relative to NYHOPS, taking into consideration that NYHOPS overestimates salinity in box 1 relative to field data (thus, skewing to the right in box 1 is preferred).
5 Biogeochemical Model Development

An overview of the hydrodynamic and biogeochemical models are provided in Section 2.4 (page 8).

The model is structured with three boxes in Niantic River Estuary (Figure 3, page 17). Material is input from the river source at the head (northern-most section) of the model and is exchanged across the southern boundary with Niantic Bay. Each box includes a single layer; original attempts included two layers, but the Niantic River Estuary is vertically well-mixed, so one layer was chosen as a better representation of the system.

Relatively few processes and coefficients constitute the model, thus the term intermediate-complexity model (Figure 8, page 23). Formulations are based on empirically derived relationships from the literature. Eight state variables are modeled: salt, phytoplankton biomass, macroalgae biomass, eelgrass biomass, labile nitrogen (inorganic and labile organic), labile phosphorus (inorganic, labile organic, and particulate), benthic carbon, and dissolved oxygen; these are defined below and described further in this section (Section 5). Differential equations define the daily rate of change in each state variable. The differential equation solver used in the model is MatLab’s ode45, which uses a Runge-Kutta 4th/5th order integration scheme. The change due to mixing is not included in the differential equations of the biogeochemical portion of the model, the mixing occurs once per day in accordance with the method used to create the GEM matrices of mixing coefficients. Constants and coefficients used in the model formulations are detailed in Section 5.2 (page 31).

OVERVIEW OF STATE VARIABLES

Salt is not modeled in the ecological portion of the model. Changes in salt are due solely to mixing.

Phytoplankton biomass (g C) is modeled as the gross primary production, minus the 24-hour phytoplankton community respiration, minus the heterotrophic respiration of phytoplankton. The heterotrophic respiration of the phytoplankton biomass is modeled using respiratory coefficients, versus modeling zooplankton grazing dynamics. The heterotrophic respiration is partitioned into the fraction of phytoplankton biomass respired in the water column (with nutrients regenerated to the water column) and the fraction delivered to the benthos (fueling benthic metabolism). Exchange of phytoplankton biomass across the open boundaries and among the elements is handled in the mixing routine.

Macroalgae biomass (g C) is modeled as the gross primary production, minus the 24-hour respiration, minus the heterotrophic respiration of macroalgae. The heterotrophic respiration is modeled using respiratory coefficients and includes consumption, death, and decay of the algae. Heterotrophic respiration is assumed to be occurring mostly at the sediment-water interface. Macroalgae are not allowed to exchange among boxes, they are assumed to be stationary on the bottom. Some fraction of macroalgae production will be sequestered in the estuarine sediments.
Figure 8: Overview of Model Processes

Processes within the model are indicated by the blue arrows with the basis for the formulation shown in black italicized text. The state variables are nitrogen, phosphorus, sediment organic carbon, phytoplankton, macroalgae, seagrass, and oxygen. Black arrows indicate transport of state variables across the boundary of the model domain. For example, N enters via river and groundwater input from the watershed and from atmospheric deposition to the surface of the embayment. N is exchanged with Niantic Bay / Long Island Sound via hydrodynamics and is lost to the atmosphere via denitrification. Note, the black arrows do not always point to the symbol for the state variable to which they are contributing in order to keep the graphical display uncluttered, but their contribution is assigned to those pools. C is carbon, N is nitrogen, P is phosphorus, O₂ is oxygen, T is temperature, OM is organic matter or biomass. The “≡” symbol indicates equivalency, that the N and P are calculated stoichiometrically from C.

Eelgrass biomass (g C) is modeled as the gross primary production, minus the 24-hour respiration, minus the heterotrophic respiration of eelgrass. The heterotrophic respiration is modeled using respiratory coefficients and includes consumption, death, and decay of the eelgrass. Heterotrophic respiration is assumed to be occurring mostly at the sediment-water interface. Eelgrass are not allowed to exchange among boxes, they are assumed to be stationary on the bottom. Some fraction of eelgrass production will be sequestered in the estuarine sediments.

Nitrogen (g N, dissolved inorganic) is modeled as N from atmospheric deposition, N mixed into or out of the element (from freshwater, Niantic Bay, or neighboring model elements), plus the N regenerated to the water column from the sediments as a result of benthic metabolism, plus the N regenerated to the water column from pelagic heterotrophy, plus the N regenerated to the water column due to phytoplankton community respiration, minus the N assimilated by phytoplankton production. A C : N ratio is used to convert these processes originally defined in terms of C to N. Exchange of N across the open boundaries and among the elements is handled in the mixing routine.

Phosphorus (g DIP, dissolved inorganic) is modeled as P mixed into or out of the element (from freshwater, Niantic Bay, or neighboring model elements), P regenerated to the water column from the sediments as a result of benthic metabolism, plus the P regenerated to the water column from
pelagic heterotrophy, plus the P regenerated to the water column due to phytoplankton community respiration, minus the P assimilated by phytoplankton production. A C : P ratio is used to convert these processes originally defined in terms of C to P. Exchange of P across the open boundaries and among the elements is handled in the mixing routine.

Benthic carbon (g C) is modeled as the C delivered to the benthos from the water column, minus the benthic metabolism. No physical mixing of benthic C is included in the model as benthic processes are not subject to mixing among elements.

Oxygen (g O₂) is modeled through stoichiometric relationships between metabolic processes listed above and O₂ production or consumption. Oxygen change is the sum of atmospheric exchange of oxygen across the air-sea interface, plus the O₂ produced through primary productivity by the phytoplankton and macrophytes, minus the O₂ demand by phytoplankton and macrophyte respiration, minus the O₂ demand by heterotrophic water column respiration of phytoplankton and macrophytes, minus the O₂ demand from benthic metabolism. Exchange of O₂ across the open boundaries and among the elements is handled in the mixing routine.

### 5.1 Constants and Coefficients Related to Primary Producers

Availability of light, temperature, and nitrogen limit the specific growth rate of the primary producers (μ). The specific growth rate (d⁻¹) during a time step is determined by calculating and comparing the specific growth rate based temperature, light and nitrogen. Only one of these factors is limiting to growth during any given time step, so the minimum specific growth rate from among the options (light, temperature, nitrogen) is used during a time step. Thus, the competition between the three groups of primary producers is driven by their physiological ability to take in N, grow at certain light levels, or grow at certain temperatures. This section describes how the competition for available nitrogen is handled in the model.

The Michaelis-Menten equation is an equation useful for describing enzymatic reaction rates. It has been applied to nutrient uptake by primary producers (Brush and Nixon 2010; Gurney and Nisbet 1998; Touchette and Burkholder 2000; Wang et al. 2014; Ward et al. 2012). This equation assumes that the substrate (nitrogen) reaches equilibrium on a much faster rate than biomass is formed. For primary producers, this is a valid assumption. The realized uptake rate, U (substrate per unit biomass), is calculated based on nitrogen (N):

\[
U = \frac{U_{\text{max}} \text{[substrate]}}{\left( k + \text{[substrate]} \right)}
\]

(eq. 2)

Where \(U_{\text{max}}\) is the maximum attainable uptake rate of the substrate (substrate per unit biomass), \(k\) is the half saturation constant for uptake, and \([\text{substrate}]\) is the concentration of the substrate (N). Please note, in most presentations of this relationship, \(U\) is denoted by the variable \(V\); in the NREEM model description, \(V\) refers to volume, so the letter \(U\) is used instead.

The same equation applies to all three groups of primary producers (\(P = \) phytoplankton, \(E = \) eelgrass, \(M = \) macroalgae):

- phytoplankton (\(U_{\text{Ph}}\)),
- eelgrass (\(U_{\text{El}}\)),
- macroalgae (\(U_{\text{Ma}}\)).

---

*Note: A similar relationship could be applied to phosphorus; to keep the model simple, we assume that P is not limiting and thus do not include it.*
Table 5.1: Michaelis-Menten equation coefficients.

Michaelis-Menten equation coefficients for the three groups of primary producers based on nitrogen concentration. The values shown in colored bold text are used in NREEM.

<table>
<thead>
<tr>
<th>MACROALGAE</th>
<th>Maximum Attainable Uptake Rate (U_{max}) of Nitrogen (μmol N g−DW−1 h−1)</th>
<th>Half Saturation Constant (k) for Nitrogen (mmol N m−3)</th>
<th>Information Necessary for Unit Conversion: g C / g DW</th>
<th>Maximum Attainable Uptake Rate (U_{max}) of nitrogen (gN uptake gCbiomass−1 d−1) (for sample calculation, see C)</th>
<th>Half Saturation Constant (k) for Nitrogen (gN m−3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ulva lactuca A</td>
<td>84.3</td>
<td>15</td>
<td>0.28</td>
<td>0.101</td>
<td>0.210</td>
</tr>
<tr>
<td>Ulva lactuca B</td>
<td>NH_{4}+: 450</td>
<td>NO_{3}−: 116</td>
<td>NH_{4}+: 85</td>
<td>NO_{3}−: 34</td>
<td>0.3</td>
</tr>
<tr>
<td>Ulva prolifera A</td>
<td>NH_{4}+: 285</td>
<td>NO_{3}−: 124</td>
<td>NH_{4}+: 25.1</td>
<td>NO_{3}−: 15.1</td>
<td>0.3</td>
</tr>
<tr>
<td>Ulva linza A</td>
<td>NH_{4}+: 250</td>
<td>NO_{3}−: 109</td>
<td>NH_{4}+: 37</td>
<td>NO_{3}−: 23</td>
<td>0.3</td>
</tr>
<tr>
<td>Ulva AVERAGE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.228</td>
</tr>
<tr>
<td>Ulva RANGE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.468</td>
</tr>
<tr>
<td>Ulva AVERAGE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.468</td>
</tr>
<tr>
<td>Ulva RANGE</td>
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<td></td>
<td></td>
<td></td>
<td>0.322</td>
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<tr>
<td>Gracilaria tikvahiae A</td>
<td>52.7</td>
<td>15</td>
<td>0.26</td>
<td>0.068</td>
<td>0.210</td>
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<tr>
<td>Gracilaria folifera A</td>
<td>NH_{4}+: 23.8</td>
<td>NO_{3}−: 9.7</td>
<td>NH_{4}+: 1.6</td>
<td>NO_{3}−: 2.5</td>
<td>0.22</td>
</tr>
<tr>
<td>Gracilaria pacifica A</td>
<td>NH_{4}+: 21.5</td>
<td>NO_{3}−: 6</td>
<td>NH_{4}+: 50.9</td>
<td>NO_{3}−: 26.8</td>
<td>0.22</td>
</tr>
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<td>Gracilaria gracilis A</td>
<td>NO_{3}−: 35</td>
<td>NH_{4}+: 5.6</td>
<td>0.22</td>
<td>0.053</td>
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<tr>
<td>Gracilaria tenunistipitata A</td>
<td>NO_{3}−: 37.2</td>
<td>NH_{4}+: 61.5</td>
<td>0.22</td>
<td>0.057</td>
<td>0.078</td>
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<tr>
<td>Gracilaria AVERAGE</td>
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<td>0.228</td>
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<tr>
<td>Gracilaria RANGE</td>
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<td></td>
<td></td>
<td></td>
<td>0.468</td>
</tr>
<tr>
<td>Cladophora AVERAGE</td>
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<td></td>
<td></td>
<td>0.083</td>
</tr>
<tr>
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<td></td>
<td></td>
<td>0.02-0.29</td>
</tr>
<tr>
<td>Zostera marina A</td>
<td>leaf, NH_{4}+: 20.5</td>
<td>root, NH_{4}+: 211</td>
<td>leaf, NH_{4}+: 9.2</td>
<td>root, NH_{4}+: 104</td>
<td>0.336</td>
</tr>
<tr>
<td>Ruppia maritima A</td>
<td>leaf, NH_{4}+: 243-270</td>
<td>root, NH_{4}+: 48-56</td>
<td>leaf, NH_{4}+: 9-0.17.7</td>
<td>root, NH_{4}+: 2.8-12.6</td>
<td>0.336</td>
</tr>
<tr>
<td>phytoplankton G</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.125</td>
</tr>
<tr>
<td>phytoplankton RANGE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.02-0.29</td>
</tr>
<tr>
<td>phytoplankton RANGE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.02-0.29</td>
</tr>
</tbody>
</table>

For modeling the growth of phytoplankton, macroalgae, and eelgrass, the Michaelis-Menten equation will be used to determine the rate of nutrient acquisition by each group (phytoplankton, macroalgae, and eelgrass).
eelgrass). A review of typical values for maximum attainable uptake rate and half saturation coefficient for nitrogen is provided in Table 5-1. This realized uptake rate will be translated into the fraction of the nutrient pool available to each group. However, the Michaelis-Menten equation will not be used to assess growth. Other equations which incorporate important controls on growth for each group will be employed.

As an illustration of the relationships among groups of primary producers and the impact on nitrogen demand by each group is plotted for a gradient of water column nitrogen concentrations typical of Niantic River Estuary (Figure 9). While phytoplankton have a faster realized nitrogen uptake rate than macroalgae and seagrass, once the biomass of the three groups is factored in, eelgrass and macroalgae can demand more of the available nitrogen because of their greater biomass. The eelgrass and macroalgae grow slowly compared to phytoplankton, but they also survive longer (lower death and decay rate) and remain in the estuary whereas phytoplankton is exchanged with Long Island Sound through mixing.

Figure 9: Michaelis-Menten relationships for primary producers versus nitrogen.

Left panel: Curves describe the impact of limiting factors on the maximum attainable uptake rate for each class of primary producers. Right panel: Nitrogen demand based on typical biomass levels found in NRE: 4.5 gC m⁻² algae; 24.5 gC m⁻² eelgrass; 0.168 gC m⁻² phytoplankton.

Modeling macroalgae and eelgrass growth require an understanding of typical carbon to nitrogen ratios (C:N, molar ratio). For estuarine macrophytes, we assume phosphorus is not limiting. Millstone Environmental Lab has collected macrophytes from their trawl station in Niantic River since July 2012,
with trawls conducted every two weeks throughout the year (Figure 10, page 27). Macroalgae is collected from one location, thus comparisons are not confounded by the potential impact of varying nutrient supply in different locations within Niantic River Estuary. Carbon content varies by species, but is generally stable throughout the year. Nitrogen content varies by season and thus drives the variability in the C:N molar ratio. Individual species typically show a similar range in values interannually (Figure 10, page 27), allowing for grouping of all samples by month (Figure 11, page 28).

**Figure 10: C : N molar ratio of macrophytes.**

Macrophytes are collected during Millstone Environmental Lab’s biweekly trawl survey in Niantic River. Analysis of macrophyte samples are ongoing, explaining the gaps in the data. Only species with 12 or more samples are included in the analysis for the model.
Examination of the C:N molar ratio by day of the year (ordinal date) illustrates the impact of growth rate on the internal deficiency of nitrogen in macrophytes (Figure 11, page 28). The winter months represent the ideal C:N ratio for macrophyte growth. During the spring, summer, and fall months, the increased amount of light and warmer temperatures allow for increased growth rates. Macrophytes are capable of luxury uptake of nitrogen (Brush and Nixon 2010); when nitrogen is plentiful, they take in excess nitrogen and store it internally. When nitrogen in the environment is lower, they can access these internal pools of nitrogen. The winter values represent the optimal (minimum) C:N molar ratio (Table 5-2, page 29). The maximum summer values represent the C:N molar ratio required by each species. The three highest C:N molar ratios for each species were used to calculate the maximum allowable C:N molar ratio (Table 5-2, page 29). Use of daily varying C:N and C:P ratios based on local field data accomplish the same end as modeling luxury uptake of nutrients.

*Adding luxury uptake and internal storage of nitrogen to the macroalgae pool increases the complexity of the model. These steps may be taken if necessary, following the methods of Brush and Nixon (2010). If luxury uptake is added, the C:N of the macrophytes will be modeled versus determined based on field data.*

Agardhiella subulata and Ulva sp., blade form are the dominant macroalgae species found throughout Niantic River, with Codium fragile also commonly found in the southern portions of the river (Vaudrey 2007; Vaudrey et al. 2019). The average C:N molar ratio was determined for each ordinal date by using a third order polynomial regression of C:N molar ratio on ordinal date for the period of 2/17 through 11/28 (Table 5-3, page 30; Figure 12, page 30). For the winter, C:N molar ratio was set to the minimum C:N molar ratio (Table 5-2, page 29).
**Zostera marina** in NRE exhibits a C:N of 18.6 in June (average of lowest three values) ranging to a high value (average of highest three values) of 51 in late July (Figure 11, page 28). The June value of 18.6 C:N coincides with a worldwide review of C:N ratios for seagrasses not experiencing nutrient limitation (Duarte 1990) of 16 C:N and the overall pattern of increasing C:N in late summer has been observed elsewhere in Long Island Sound eelgrass beds (Vaudrey et al. 2009). The average C:N molar ratio was determined for each ordinal date by using a third order polynomial regression of C:N molar ratio on ordinal date for the period of 2/17 through 11/28 (Table 5-3, page 30; Figure 13, page 31). For the winter, C:N molar ratio was set to the minimum C:N molar ratio (Table 5-2, page 29).

**Table 5-2: C:N molar ratios of macrophytes.**

All available samples from the winter were used in calculating the optimal C:N molar ratios. The highest three C:N molar ratios from the summer period were used for calculating the maximum C:N. The bold font identifies the species with greatest biomass in Niantic River Estuary. Samples were collected by Millstone Environmental Lab during biweekly trawl surveys at one location in Niantic River Estuary.

<table>
<thead>
<tr>
<th></th>
<th>Average C:N  (molar ratio)</th>
<th>Standard Deviation of C:N (molar ratio)</th>
<th>Standard Error of C:N (molar ratio)</th>
<th>Number of Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>WINTER</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Agardhiella subulata (red)</td>
<td>8.3</td>
<td>1.0</td>
<td>0.3</td>
<td>12</td>
</tr>
<tr>
<td>Ulva sp., blade form (green)</td>
<td>8.6</td>
<td>0.6</td>
<td>0.1</td>
<td>44</td>
</tr>
<tr>
<td>Codium fragile (green)</td>
<td>10.0</td>
<td>0.8</td>
<td>0.1</td>
<td>32</td>
</tr>
<tr>
<td>Heterosiphonia japonica (red)</td>
<td>7.3</td>
<td>0.5</td>
<td>0.1</td>
<td>19</td>
</tr>
<tr>
<td>Grateloupia turuturu (red)</td>
<td>9.3</td>
<td>1.2</td>
<td>0.3</td>
<td>15</td>
</tr>
<tr>
<td>Saccharina latissima (brown)</td>
<td>12.2</td>
<td>2.7</td>
<td>1.0</td>
<td>7</td>
</tr>
<tr>
<td><strong>SUMMER</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Agardhiella subulata (red)</td>
<td>15.3</td>
<td>0.7</td>
<td>0.4</td>
<td>3</td>
</tr>
<tr>
<td>Codium fragile (green)</td>
<td>19.4</td>
<td>1.0</td>
<td>0.6</td>
<td>3</td>
</tr>
<tr>
<td>Ulva sp., blade form (green)</td>
<td>43.2</td>
<td>3.1</td>
<td>1.8</td>
<td>3</td>
</tr>
<tr>
<td>Zostera marina (vascular) - max</td>
<td>50.7</td>
<td>3.5</td>
<td>2.0</td>
<td>3</td>
</tr>
<tr>
<td>Zostera marina (vascular) - min</td>
<td>18.6</td>
<td>1.0</td>
<td>0.6</td>
<td>3</td>
</tr>
<tr>
<td>Grateloupia turuturu (red)</td>
<td>21.1</td>
<td>4.6</td>
<td>2.6</td>
<td>3</td>
</tr>
<tr>
<td>Heterosiphonia japonica (red)</td>
<td>10.5</td>
<td>1.6</td>
<td>0.9</td>
<td>3</td>
</tr>
<tr>
<td>Laminaria saccharina (brown)</td>
<td>54.8</td>
<td>4.2</td>
<td>2.4</td>
<td>3</td>
</tr>
<tr>
<td>Punctaria sp. (brown)</td>
<td>35.2</td>
<td>0.7</td>
<td>0.4</td>
<td>3</td>
</tr>
<tr>
<td>Saccharina latissima (brown)</td>
<td>59.2</td>
<td>5.9</td>
<td>3.4</td>
<td>3</td>
</tr>
<tr>
<td>Sargassum filipendula (brown)</td>
<td>30.8</td>
<td>2.8</td>
<td>1.6</td>
<td>3</td>
</tr>
</tbody>
</table>
Table 5-3: Results of Polynomial Regression of C:N on ordinal date.

Non-winter data for C:N molar ratios were regressed on ordinal date. Statistical results are fully reported in Sections 12.1 (page 94), 12.2 (page 95), and 12.3 (page 96).

The format of the regression equation is $f = y_0 + a(x) + b(x^2) + c(x^3)$.

<table>
<thead>
<tr>
<th></th>
<th>Aghardhiella subulata</th>
<th>Ulva sp., blade form</th>
</tr>
</thead>
<tbody>
<tr>
<td>coefficient</td>
<td>std. error</td>
<td>t</td>
</tr>
<tr>
<td>$y_0$</td>
<td>2.1855</td>
<td>6.3945</td>
</tr>
<tr>
<td>$a$</td>
<td>0.0575</td>
<td>0.1069</td>
</tr>
<tr>
<td>$b$</td>
<td>3.22 x 10^{-1}</td>
<td>0.0005</td>
</tr>
<tr>
<td>$c$</td>
<td>-1.6 x 10^{-5}</td>
<td>5.66 x 10^{-7}</td>
</tr>
</tbody>
</table>

Adjusted $R^2$ 0.30 0.24

Standard Error of the Estimate 1.78 6.64

F-statistic 10.59 17.48

P <0.0001 <0.0001

Zostera marina

<table>
<thead>
<tr>
<th></th>
<th>coefficient</th>
<th>std. error</th>
<th>t</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>$y_0$</td>
<td>-440.2775</td>
<td>129.848</td>
<td>-3.391</td>
<td>0.0030</td>
</tr>
<tr>
<td>$a$</td>
<td>5.643</td>
<td>1.800</td>
<td>3.135</td>
<td>0.0023</td>
</tr>
<tr>
<td>$b$</td>
<td>-0.0214</td>
<td>0.0082</td>
<td>-2.6162</td>
<td>0.0104</td>
</tr>
<tr>
<td>$c$</td>
<td>2.56 x 10^{-5}</td>
<td>1.22 x 10^{-5}</td>
<td>2.106</td>
<td>0.0380</td>
</tr>
</tbody>
</table>

Adjusted $R^2$ 0.47

Standard Error of the Estimate 5.90

F-statistic 29.62

P <0.0001

Figure 12: C:N molar ratio for seaweeds, modeled versus field data.

Winter field data were set to the minimum average C:N molar ratio. For each ordinal date, a C:N molar ratio was calculated using a third order polynomial regression (Table 5-3, page 30), indicated by the black lines. The C:N molar ratio for each date is presented in Section 11.1, (page 85).
5.2 Constants and Coefficients - Summary

Constants and coefficients used in the model are presented in Table 31 (page 31). References and descriptions in the Table explain the derivation of these values. A longer description is available in Vaudrey (2016).

<table>
<thead>
<tr>
<th>variable name</th>
<th>typical value</th>
<th>units</th>
<th>description</th>
<th>reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_{B\text{-phyto}}$</td>
<td>42 (30 to 60)</td>
<td>g C : g Chl</td>
<td>carbon to chlorophyll, for phytoplankton</td>
<td>Valiela (1995), Cloern et al. (1995), Brush et al. (2002)</td>
</tr>
<tr>
<td>$c_{N\text{-phyto}}$</td>
<td>6.625</td>
<td>moles C : moles N</td>
<td>conversion of C to N, for phytoplankton</td>
<td>Redfield Ratio; Kremer and Nixon (1978)</td>
</tr>
<tr>
<td>$c_{P\text{-phyto}}$</td>
<td>106</td>
<td>moles C : moles P</td>
<td>conversion of C to P, for phytoplankton</td>
<td>Redfield Ratio; Kremer and Nixon (1978)</td>
</tr>
<tr>
<td>$c_{N\text{-eelg}}$</td>
<td>changes daily (18 to 40)</td>
<td>moles C : moles N</td>
<td>conversion of C to N, for eelgrass</td>
<td>see Section 5.1 (page 24) and Appendix C (page 85)</td>
</tr>
<tr>
<td>$c_{P\text{-eelg}}$</td>
<td>435 (200 to 800)</td>
<td>moles C : moles P</td>
<td>conversion of C to P, for eelgrass</td>
<td>Duarte (1992)</td>
</tr>
<tr>
<td>$c_{N\text{-algae}}$</td>
<td>changes daily (8 to 28)</td>
<td>moles C : moles N</td>
<td>conversion of C to N, for macroalgae</td>
<td>see Section 5.1 (page 24) and Appendix C (page 85)</td>
</tr>
<tr>
<td>$c_{P\text{-algae}}$</td>
<td>800 (300 to 1000)</td>
<td>moles C : moles P</td>
<td>conversion of C to P, for macroalgae</td>
<td>Duarte (1992)</td>
</tr>
<tr>
<td>$r_P$</td>
<td>0.52 (0.02 to 1.2)</td>
<td>d$^{-1}$</td>
<td>phytoplankton autotrophic respiration as a fraction of phytoplankton stock</td>
<td>Oviatt and Smith field data (pers. comm.), corresponds to Falkowski and Woodhead (1992)</td>
</tr>
<tr>
<td>$r_{MD}$</td>
<td>$7.875 \times 10^{-4}$</td>
<td>d$^{-1}$</td>
<td>macroalgae autotrophic respiration rate at 0°C</td>
<td></td>
</tr>
</tbody>
</table>

Figure 13: C:N molar ratio for eelgrass, modeled versus field data. Winter field data were set to the minimum average C:N molar ratio. For each ordinal date, a C:N molar ratio was calculated using a third order polynomial regression (Table 5-3, page 30), indicated by the black line. The C:N molar ratio for each date is presented in Section 11.1, (page 85).
<table>
<thead>
<tr>
<th>variable name</th>
<th>typical value</th>
<th>units</th>
<th>description</th>
<th>reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_{MQ}$</td>
<td>0.15</td>
<td>°C⁻¹</td>
<td>macroalgae autotrophic thermal respiratory quotient ($Q_{10}$ for respiration)</td>
<td></td>
</tr>
<tr>
<td>$g_0$</td>
<td>0.047</td>
<td>d⁻¹</td>
<td>water column phytoplankton grazing rate at 0°C</td>
<td>optimized value</td>
</tr>
<tr>
<td>$g_Q$</td>
<td>0.095</td>
<td>°C⁻¹</td>
<td>water column phytoplankton grazing thermal respiratory quotient ($Q_{10}$ for respiration)</td>
<td>Brush's (2002) Greenwich Bay model, from Sampou &amp; Kemp (1994)</td>
</tr>
<tr>
<td>$g_{MQ}$</td>
<td>0.01</td>
<td>d⁻¹</td>
<td>grazing rate on macroalgae at 0°C</td>
<td>Brush and Nixon (2010)</td>
</tr>
<tr>
<td>$g_{MQ}$</td>
<td>0.122</td>
<td>°C⁻¹</td>
<td>macroalgae grazing thermal respiratory quotient ($Q_{10}$ for respiration)</td>
<td>Brush and Nixon (2010)</td>
</tr>
<tr>
<td>$\varphi$</td>
<td>0.238</td>
<td>(0.23 to 0.25)</td>
<td>fraction of phytoplankton NPP24 delivered to the benthos</td>
<td>Nixon (1981) = 0.238 NPP24, Brush (2002) = 0.25 NPP24, Kemp et al (2005) = 0.24 phyt_bio</td>
</tr>
<tr>
<td>$b_0$</td>
<td>0.00489</td>
<td>(0.001 to 0.2)</td>
<td>optimized value</td>
<td></td>
</tr>
<tr>
<td>$b_Q$</td>
<td>0.14</td>
<td>d⁻¹</td>
<td>benthic thermal respiratory quotient ($Q_{10}$ for respiration)</td>
<td>Brush (2002) based Greenwich Bay model value.</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>0.4</td>
<td>unitless</td>
<td>fraction of the sediment N denitrified</td>
<td>Kremer used a straight fraction of 0.5 in the CLUE model</td>
</tr>
<tr>
<td>$\omega$</td>
<td>1.3</td>
<td>(1 to 1.4)</td>
<td>moles O₂ : moles C</td>
<td>photosynthetic quotient for phytoplankton, O₂ produced : C assimilated</td>
</tr>
<tr>
<td>$\omega_p$</td>
<td>0.89</td>
<td>(narrowly constrained)</td>
<td>moles C : moles O₂</td>
<td>respiratory quotient for phytoplankton, Org C respired : O₂ consumed</td>
</tr>
<tr>
<td>$\omega_g$</td>
<td>0.97</td>
<td>(0.78 to 1.16)</td>
<td>moles C : moles O₂</td>
<td>respiratory quotient for phytoplankton grazing, Org C respired : O₂ consumed</td>
</tr>
<tr>
<td>$\omega_s$</td>
<td>1 : 30.5</td>
<td>(1:14.8 to 1:46.2)</td>
<td>moles N : moles O₂</td>
<td>respiratory quotient for sediment, N regenerated : O₂ consumed</td>
</tr>
<tr>
<td>$K_{phyto}$</td>
<td>0.017</td>
<td>(0.015 to 0.019)</td>
<td>m⁻¹ (μg/L)⁻¹</td>
<td>diffuse attenuation coeff. due to phytoplankton</td>
</tr>
<tr>
<td>$K_0$</td>
<td>0.527</td>
<td>(0.512 to 0.542)</td>
<td>m⁻¹</td>
<td>diffuse attenuation coefficient due to water</td>
</tr>
<tr>
<td>$d_{dry}$</td>
<td>6</td>
<td>Kg N ha⁻¹ y⁻¹</td>
<td>dry deposition</td>
<td>Clark and Kremer (2005)</td>
</tr>
<tr>
<td>$d_{wet}$</td>
<td>30 (9 - 200)</td>
<td>μM N</td>
<td>nitrogen concentration in wet precipitation</td>
<td>Clark and Kremer (2005), Nat'l. Atm. Deposition Program</td>
</tr>
</tbody>
</table>
5.3 Description of Model Formulations

5.3.1 Light Available at Depth

The productivity of phytoplankton, macroalgae, and eelgrass form the basis of many of the formulations in the ecological model. Light is an important forcing factor as it is one of the primary factors affecting primary production. The light attenuation factor ($K, \text{m}^{-1}$) is calculated as the sum of the contribution from the water ($K_0$) and the phytoplankton ($K_p$), which are defined in Table 5-4 (page 31). Field data from Narragansett Bay, RI were used to validate the choice of model for calculating $K$ and for the decision of the intercept term ($K_0$) which describes the light attenuation due to non-phytoplankton related properties of the water (Vaudrey 2016). This data set from Narragansett Bay included 202 profiles of light in the water column gathered with a Li-Cor LI193SA Spherical Underwater Quantum Sensor coupled with a Li-Cor Quantum deck sensor. While some data are available for local Long Island Sound embayments, no data set matches the number of profiles and consistency with which these Narragansett Bay data were collected. The CTDEEP cruises have a similar dataset collected over a long time frame, but those collections are in deeper, more open waters. The field data were used to estimate an average and range of values for $K_0$ and $K_p$ (Table 5-4, page 31) and indicated a linear model was the best choice:

$$K = K_0 + \frac{1000K_pBP}{c BV}$$ (eqn. 3)

where $B_P$ is the phytoplankton biomass in each element (gC element$^{-1}$), $V$ is the volume of each element (m$^3$), and $c_B$ is the carbon to chlorophyll mass ratio (unitless). The $K$ is calculated for both surface and bottom elements, using the light available at the surface of the element.

5.3.1.1 Correction to Photic Zone Depth in Shallow Systems

The depth of the photic zone was calculated using the Lambert-Beer equation,

$$I_z = I_0 e^{-Kz}$$ (eqn. 4)

where $z$ is depth (m), $K$ is the diffuse attenuation coefficient (m$^{-1}$, eqn. 3), $I_0$ is the light at the surface, and $I_z$ is the light at depth $z$. The depth of the photic zone was defined as the depth receiving 1% of the incident irradiance at the surface of the water column.

The polynomial regressions in Table 5-5 (page 34) are used to correct the photic zone depth in cases where light reaches the bottom of the element. Light decays in the water in an exponential fashion with depth. Thus, taking a fraction of the photic zone attributed to the depth of a layer would yield an incorrect estimate of the total light received integrated over the water column depth of the element.
Table 5-5: Table 1 from Brush and Brawley (2009).

Io in the table is equal to Io in NREEM. %Pt in the table is equal to Zcorr in NREEM. “Polynomial regressions of BZpIo‐predicted daily production (%Pt) occurring in various fractions of the theoretical photic depth (%Zp). aEb is shorthand for a * 10b. All equations had r² > 0.99.” (quoted from table 1 caption, Brush and Brawley (2009))

<table>
<thead>
<tr>
<th>L, (E m⁻² d⁻¹)</th>
<th>Regression</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 10</td>
<td>%gIₓ = -1.20E⁻⁹(8zₓ)⁻¹ + 4.25E⁻⁶(8zₓ)⁻¹ - 5.85E⁻³(8zₓ)⁻¹ + 3.80(8zₓ)⁻¹</td>
</tr>
<tr>
<td>11 - 20</td>
<td>%gIₓ = -9.66E⁻⁹(8zₓ)⁻¹ - 8.85E⁻⁶(8zₓ)⁻¹ - 1.66E⁻²(8zₓ)⁻¹ + 2.64(8zₓ)⁻¹</td>
</tr>
<tr>
<td>21 - 30</td>
<td>%gIₓ = -1.50E⁻⁸(8zₓ)⁻¹ - 2.25E⁻⁵(8zₓ)⁻¹ - 1.45E⁻¹(8zₓ)⁻¹ + 2.10(8zₓ)⁻¹</td>
</tr>
<tr>
<td>21 - 40</td>
<td>%gIₓ = -1.15E⁻⁸(8zₓ)⁻¹ - 2.30E⁻⁵(8zₓ)⁻¹ - 3.28E⁻¹(8zₓ)⁻¹ + 1.82(8zₓ)⁻¹</td>
</tr>
<tr>
<td>41 - 50</td>
<td>%gIₓ = -6.96E⁻⁸(8zₓ)⁻¹ - 1.99E⁻⁴(8zₓ)⁻¹ + 4.22E⁻¹(8zₓ)⁻¹ + 1.67(8zₓ)⁻¹</td>
</tr>
<tr>
<td>51 - 60</td>
<td>%gIₓ = -6.84E⁻⁸(8zₓ)⁻¹ + 1.16E⁻⁴(8zₓ)⁻¹ + 3.99E⁻¹(8zₓ)⁻¹ + 1.59(8zₓ)⁻¹</td>
</tr>
<tr>
<td>61 - 70</td>
<td>%gIₓ = -3.80E⁻⁸(8zₓ)⁻¹ - 1.34E⁻⁴(8zₓ)⁻¹ + 3.31E⁻¹(8zₓ)⁻¹ + 1.53(8zₓ)⁻¹</td>
</tr>
<tr>
<td>71 - 80</td>
<td>%gIₓ = 3.13E⁻⁸(8zₓ)⁻¹ - 1.06E⁻⁴(8zₓ)⁻¹ + 2.58E⁻¹(8zₓ)⁻¹ + 1.04(8zₓ)⁻¹</td>
</tr>
<tr>
<td>81 - 90</td>
<td>%gIₓ = -1.75E⁻⁸(8zₓ)⁻¹ - 8.64E⁻⁵(8zₓ)⁻¹ - 1.75E⁻¹(8zₓ)⁻¹ + 1.45(8zₓ)⁻¹</td>
</tr>
<tr>
<td>91 - 100</td>
<td>%gIₓ = -7.80E⁻⁹(8zₓ)⁻¹ - 6.21E⁻⁵(8zₓ)⁻¹ + 1.12E⁻¹(8zₓ)⁻¹ + 1.43(8zₓ)⁻¹</td>
</tr>
</tbody>
</table>

5.3.2 Balancing Production Among the Three Groups of Primary Producers

Checks in the model prevent the primary producers (phytoplankton, macroalgae, eelgrass) from growing beyond the availability of the limiting nutrient in the water column, nitrogen or phosphorus. The available stock of each nutrient is checked at each time step. The C : N and C : P ratios are used to confirm that N and P are sufficient to support the predicted growth. If a nutrient is limiting, growth is limited to that which is supported by the available stock.

The competition for nitrogen among the three primary producers takes into account the biomass of each group in the box model as well as the nitrogen stock in the water column. When nitrogen stock is low, phytoplankton will have a competitive edge due to their higher realized uptake rate at low concentrations. But at higher nitrogen stocks, eelgrass and macroalgae will get a higher fraction of the available nitrogen due to slightly increased uptake rates, though their affinity for nitrogen is still low compared to phytoplankton. The fraction of N available to each group is calculated as:

\[ U_{I} = B_{I} \cdot U_{max, \text{substrate}} \left( \frac{\text{substrate}}{V + \text{substrate}} \right) \]  

(eqn. 5)

Where \( U_{I} \) (g N element⁻¹ d⁻¹) is the realized uptake rate based on the Michaelis-Menten coefficients for the group (Table 5-1; \( U_{max, \text{gN}} \) gCgNmax⁻¹ d⁻¹; \( k_{i} \) gN gCbiomass⁻¹), \( V \) is the volume of the element (m³), and substrate is the stock of nitrogen in the element (gN element⁻¹).

Seagrass is able to access nutrients stored in the sediment. At present, the seagrass growth is modeled using only the water column nutrients. If necessary, a separate state variable for benthic nitrogen could be added to allow seagrass access to this source.
The fraction assigned to each group of primary producers is determined by:

\[
\text{fraction of } N_i = \frac{u_i}{(u_P + u_M + u_E)} 
\]

(eqn. 6)

5.3.3 Phytoplankton Gross Primary Production and Autotrophic Respiration

Phytoplankton growth is modeled using a BZI (biomass-photic zone depth-incident irradiance) relationship which has been applied in many estuarine ecosystems (see reviews in: Brawley et al. 2003; Brush and Brawley 2009; Brush et al. 2002). The temperature range in Niantic River Estuary should not limit growth of phytoplankton and is not included in the assessment of production, though it is included in respiration. The empirical BZI (biomass-photic zone depth-incident irradiance) model predicts estuarine phytoplankton daytime net primary production (\( \beta \), as mg C m\(^{-2}\) d\(^{-1}\)) from the existing standing stock of phytoplankton (\( B_P \), as chl \( a \), mg m\(^{-3}\)), depth of the photic zone (\( Z \), m), and surface irradiance (\( I_0 \), E m\(^{-2}\) d\(^{-1}\)) (Brawley et al. 2003; Brush et al. 2002).

\[
\beta = 200 + 0.76B_PZI_0
\]

(eqn. 7)

If the depth of the model element is less than the photic zone depth, a correction (eqn. 8) is applied to equation 7. The correction factor, \( Z_{corr} \) (fraction), is calculated using polynomial regression equations predicting net primary production occurring in various fractions of the photic depth, as presented in Brush and Brawley (2009) and detailed in Section 5.3.1.1, (page 33).

\[
\beta_{corr} = \beta Z_{corr}
\]

(eqn. 8)

The daytime net primary production (\( \beta_{corr} \), mg C m\(^{-2}\) d\(^{-1}\)) is converted to units appropriate to the model (\( \beta_{day} \), g C element\(^{-1}\) d\(^{-1}\)) separately for each element, where \( V \) is the volume of the element (m\(^3\)), and \( T \) is the thickness or depth of the element (m):

\[
\beta_{day} = \frac{\beta_{corr} V}{1000T}
\]

(eqn. 9)

To calculate the 24-hour net primary production (\( \beta_{day} \)), the phytoplankton respiration during the nighttime must be estimated. Phytoplankton respiration is calculated using a constant fraction (\( r_P \), d\(^{-1}\)) of the phytoplankton stock (\( B_P \), g C element\(^{-1}\)), where the length of night (\( \Theta \)) is expressed as a fraction of the 24-hour day.

\[
\beta_{24} = \beta_{day} - r_P B_P \Theta
\]

(eqn. 10)

The 24-hour phytoplankton respiration (g C element\(^{-1}\)) is calculated as:

\[
R_P = r_P B_P
\]

(eqn. 11)

If the sum of the oxygen demand by all primary producers is greater than the oxygen available in the water column dissolved oxygen pool, primary producers will die. The amount of death in each class of primary producer will be determined by first looking at the net oxygen production by each class (\( G_i - R_i \)); if it is positive, that class of primary producers does not sustain any oxygen-related death. If the net oxygen production by a class of primary producers is negative, the negative net production may potentially be converted into a loss term, to bring the system back to a 0 mg/L level of oxygen. Multiple
demands are placed on the oxygen pool: autotrophic respiration, heterotrophic respiration, and benthic
respiration. These demands will be balanced, apportioning death or reduction in function to each
process proportional to the demand and the deficit in oxygen – all processes will compete on equal
footing for oxygen.

The theoretical gross primary production \((g \text{ C element}^{-1} \text{ d}^{-1})\) of phytoplankton \((GP_t)\) is calculated from \(\beta_{day}\)
by adding an estimate of the phytoplankton autotrophic respiration during the day, where length of day
\((1-\Theta)\) is expressed as a fraction of the 24-hour day:

\[
GP_t = \beta_{day} + R_p(1 - \Theta) \quad \text{(eqn. 12)}
\]

The actual gross primary production \((g \text{ C element}^{-1} \text{ d}^{-1})\) of phytoplankton \((GP)\) will be the minimum value
of \(GP_t\) and the maximum attainable growth based on the nitrogen available to the phytoplankton.

\[
GP = \min \left( GP_t \left( \frac{U_p}{U_p + U_A + U_M} \cdot N \cdot c_{N\text{-phyto}} \cdot \frac{12 gC}{1 \text{ mole C}} \cdot \frac{1 \text{ mole N}}{14 gN} \right) \right) \quad \text{(eqn. 13)}
\]

where \(U_p, U_A,\) and \(U_M\) are the nitrogen utilization of each class of primary producers (equation 2, page
24); \(N\) is the nitrogen in the element \((gN \text{ element}^{-1})\); and \(c_{N\text{-phyto}}\) is the C:N molar ratio for phytoplankton.

5.3.4 Macroalgae Gross Primary Production and Autotrophic Respiration

The model for macroalgae production will follow the methods of Brush and Nixon (2010) with a number
of simplifications. Brush and Nixon (2010) modeled the thick mats of macroalgae \((Ulva\ sp.\ and\ Gracilaria\ sp.)\)
in Greenwich Bay, RI, dividing the mats into 11 vertical
layers and modeling attenuation of light as you progress down
through the mat. Niantic River does not currently host thick
mats of algae, except possibly in the depths of the channel in
the lower basin. While \(Aghardiella\ subulata\) covers much of the
northern most portion of the estuary, in the shallow regions, it
is not especially thick. Loss of light within the depth of the
macroalgae mat will not be modeled. Brush and Nixon (2010)
modeled algae by using the maximum uptake rate coupled
with substrate availability and competition among primary
producers. The production is further controlled by
temperature. They included luxury uptake and storage of
nutrients within the macroalgae; in the NREEM, use of daily
varying C:N and C:P ratios based on local field data accomplish
the same end as modeling luxury uptake of nutrients. For
simplicity, only \(Ulva\ sp.\) is modeled in the NREEM; alternate
equations for \(Aghardiella\ sp.\) could be added in at a later time,
using Brush and Nixon’s (2010) equations for \(Gracilaria.\)

Additional modifications to the macroalgae model could include
modeling Ulva and Aghardiella species as two separate pools
with separate uptake rates, adding light limitation in thick
mats of macroalgae, and adding
in luxury uptake of nutrients
(which would mean that C:N is
modeled, not specified based on
field data). To keep the model
simple, these processes are not
currently included.
For macroalgae, the growth rate will be determined as the minimum specific growth rate among light (µM-I) and nutrient availability (µM-N) (Equation 2, page 24; Table 5-1, page 25) and the impact of temperature on growth rate (presented below).

5.3.4.1 Gross Primary Production of Macroalgae

Temperature impacts both the gross primary production (GPP) and respiration (R) rates of the macroalgae. The maximum attainable GPP (GPP$_{max}$) is an exponential temperature-dependent function up to an optimum value above which the GPP$_{max}$ declines rapidly to zero; the equation follows that used for Ulva by Brush and Nixon (2010). Brush and Nixon’s (2010) equations for GPP were in units of mg O$_2$ versus mg C used in the NREEM.

The max attainable biomass specific GPP based on temperature (GPP$_T$, mg O$_2$ gD.W.$^{-1}$ h$^{-1}$) becomes:

\[ GPP_T = 0.51 e^{(0.195 - 0.000007 e^{0.364})} e \]

(eqon. 14)

where $e$ is temperature (°C). The rate is initially calculated in hours as the intensity of the sunlight impacts the rate of productivity, calculated as the daily total insolation divided by the number of hours of light on a given day.

Brush and Nixon (2010) calculate the GPP per layer of macroalgae, where a layer is 1 cm thick. For the NREEM, we assume that productivity is well-represented by a single layer. In embayments with thicker mats of macroalgae, the calculation by layer can be added in, which allows for light attenuation as you move down in the mat of algae. Gross primary production of macroalgae is driven by a photosynthesis-irradiance relationship, yielding an hourly value for GPP (GPP$_{hr}$, mg O$_2$ g D.W.$^{-1}$ h$^{-1}$):

\[ GPP_{hr} = GPP_T \left(1 - e^{-\left(\frac{\alpha I}{\alpha P_T}\right)}\right) \]

(eqon. 15)

where $GPP_T$ is the macroalgae temperature-dependent maximum attainable GPP (Equation 14, Figure 14) (mg O$_2$ gD.W.$^{-1}$ h$^{-1}$), $I$ is instantaneous incident irradiance at the bottom of the water column (µmol m$^{-2}$ s$^{-1}$), and $\alpha$ (mg O$_2$ gDW$^{-1}$ h$^{-1}$ (µmol m$^{-2}$ s$^{-1}$)$^{-1}$) is a coefficient set to 0.18 based on measurements in Ulva (Brush and Nixon 2010).
To convert GPPTI (mg O₂ gD.W.⁻¹ h⁻¹) to units of the rate of change for the state variable in the model (g C element⁻¹ d⁻¹), conversions are needed. To convert oxygen to carbon, a molar ratio of 1.7 O₂ : C was derived by balancing the following production/respiration equation using the average C : N ratio of 20 for macroalgae (1.6 O₂ : C is equivalent to an RQ of 0.59):

\[
640 \text{ CO}_2 + 1382 \text{ H}_2\text{O} + 32 \text{ NO}_3 + 2 \text{ PO}_4 = (\text{CH}_2\text{O})_{640}(\text{NH}_3)_{32}(\text{H}_3\text{PO}_4)_{2} + 1059 \text{ O}_2 \quad \text{(eqn. 16)}
\]

The fraction of carbon in seaweed dry weight was set at: 0.25 g C / 1 g dry weight. This value was based on the %C in Ulva sp. and Agardhiella subulata in NRE (Figure 10, page 27). Carbon content remains relatively steady across years and across seasons. Agardhiella subulata is typically around 20% C while Ulva is typically around 30% C. The value of 25% was chosen as representative of both species, with a range of 18% to 35%.

The theoretical gross primary production of macroalgae (\(G_{Mt}\), g C element⁻¹ d⁻¹) becomes:

\[
G_{Mt} = \frac{\text{GPPTI}}{0.25 \text{ g C}} \cdot \frac{1 \text{ mmole O}_2}{32 \text{ mg O}_2} \cdot \frac{1 \text{ mmole C}}{1.7 \text{ mmole O}_2} \cdot \frac{12 \text{ mg C}}{1 \text{ mmole C}} \cdot \frac{1 \text{ g C}}{1000 \text{ mg C}} \cdot \frac{24 \text{ h}}{d} \cdot (1 - \Theta) \cdot B_M \quad \text{(eqn. 17)}
\]

where GPPTI (mg O₂ gD.W.⁻¹ h⁻¹) is the gross primary production determined based on light and temperature (equation 15, page 37), where the length of day (1 - \(\Theta\)) is expressed as a fraction of the 24-hour day, and \(B_M\) is the biomass of macroalgae in the box (gC element⁻¹).

The actual gross primary production (g C element⁻¹ d⁻¹) of macroalgae (\(G_M\)) will be the minimum value of \(G_{Mt}\) and the maximum attainable growth based on the nitrogen available to the macroalgae.

\[
G_M = \min \left( G_{Mt}, \frac{\text{UM}}{\text{UM} + \text{U}_E} \cdot N \cdot \epsilon_{N-algae} \cdot \frac{12 \text{ g C}}{1 \text{ mole C}} \cdot \frac{1 \text{ mole N}}{14 \text{ g N}} \right) \quad \text{(eqn. 18)}
\]
where $U_U$, $U_L$, and $U_M$ are the nitrogen utilization of each class of primary producers calculated as the minimum based on available light and nitrogen (equation 2, page 24); $N$ is the nitrogen in the element (gN element$^{-1}$); and $C_{N:\text{algae}}$ is the C:N molar ratio for macroalgae (Table 5-4, page 31).

5.3.4.2 Autotrophic Respiration of Macroalgae

An exponential function of temperature was developed by Brush and Nixon (2010) to describe autotrophic respiration of macroalgae. Their equation for Ulva was based on a sparse data set and used a Q$_{10}$ of 0.15°C$^{-1}$ and a respiration rate at 0°C of 0.035 mg O$_2$ gD.W.$^{-1}$ h$^{-1}$. The following equation converts the respiration rate at 0°C ($r_{M0}$) to units consistent with the NREEM (d$^{-1}$):

$$r_{M0} = 7.412 \times 10^{-4} \frac{0.035 \text{ mg O}_2}{\text{gD.W. h}} \frac{gD.W.}{0.25 \text{ gC}} \frac{1 \text{ mmole O}_2}{12 \text{ mg C}} \frac{1 \text{ mmole C}}{1 \text{ mmole N}} \frac{1 \text{ gC}}{1000 \text{ mg C}} \frac{24 \text{ h}}{d} \quad (\text{eqn. 19})$$

The autotrophic respiration of macroalgae (gC element$^{-1}$ d$^{-1}$) is modeled as (Figure 15):

$$R_M = r_{M0} e^{(r_{M0} - \epsilon)} B_M \quad (\text{eqn. 20})$$

where $r_{M0}$ is the macroalgae autotrophic respiration rate at 0°C (d$^{-1}$, Table 5-4, page 31), $r_{M0}$ is the macroalgae autotrophic thermal respiratory quotient (Q$_{10}$ for respiration) (°C$^{-1}$, Table 5-4, page 31), $\epsilon$ is the temperature (°C), and $B_M$ is the biomass of macroalgae (gC element$^{-1}$).

Autotrophic respiration returns N and P to the water column, in stoichiometric balance with C.

If the sum of the oxygen demand of all primary producers is greater than the oxygen available in the water column dissolved oxygen pool, primary producers will die. The amount of death in each class of primary producer will be determined by first looking at the net oxygen production by each class ($G_i - R_i$); if it is positive, that class of primary producers does not sustain any oxygen-related death. If the net oxygen production by a class of primary producers is negative, the negative net production may potentially be converted into a loss term, to bring the system back to a 0 mg/L level of oxygen. Multiple demands are placed on the oxygen pool: autotrophic respiration, heterotrophic respiration, and benthic respiration. These demands will be balanced, apportioning death or reduction in function to each process proportional to the demand and the deficit in oxygen – all processes will compete on equal footing for oxygen.
5.3.5 Eelgrass Gross Primary Production and Autotrophic Respiration

For eelgrass, the growth rate of eelgrass will be determined as the minimum specific growth rate among light ($\mu_{E,l}$) and nitrogen ($\mu_{E,n}$) (Equation 2, page 24; Table 5-1, page 25) and the impact of temperature on growth rate (presented below).

5.3.5.1 Gross Primary Production of Eelgrass

In northern latitudes, a unimodal pattern of growth may be observed, if the warmest summer temperatures remain in the optimal range for growth, usually 15°C to 20°C (Lee et al. 2007). Above 20°C, eelgrass growth declines quickly with increases in temperature (Figure 16, page 41).

For eelgrass, the specific growth rate based on temperature ($\mu_{E,\epsilon}$, d$^{-1}$) through the upper limit of optimal temperature (20°C) for growth is modeled as:

$$\mu_{E,\epsilon} = \left( -7 \times 10^{-6} \right) \epsilon^3 + 0.002 \epsilon^2 - 0.003 \epsilon + (6 \times 10^{-6})$$

(eq. 21)

where $\epsilon$ is the water column temperature. This model for seagrass specific growth with temperature was calculated from a set of data provided by Zimmerman and colleagues (1989). For temperatures above 20°C, the specific growth rate is modeled as an exponential decay:

$$\mu_{E,\epsilon} = 17709 e^{-0.5 \epsilon}$$

(eq. 22)
The theoretical gross primary production of eelgrass ($G_{et}$, g C element$^{-1}$ d$^{-1}$) becomes:

$$G_{et} = \mu_{E-\epsilon} B_E$$  (eqn. 23)

where $\mu_{E-\epsilon}$ (d$^{-1}$) is the specific growth rate of eelgrass based on temperature and $B_E$ is the biomass of eelgrass in the element (gC element$^{-1}$).

The actual gross primary production (g C element$^{-1}$ d$^{-1}$) of eelgrass ($G_E$) will be the minimum value of $G_{et}$ and the maximum attainable growth based on the nitrogen and light available to the eelgrass:

$$G_E = \min \left( G_{et}, \min \left( \frac{G_{et} \cdot U_P \cdot U_E \cdot U_M}{D_P + D_E + D_M}, \frac{12 \text{ gC}}{1 \text{ mole C}}, \frac{1 \text{ mole N}}{14 \text{ gN}} \right) \right)$$  (eqn. 24)

where $U_P$, $U_E$, and $U_M$ are the nitrogen utilization of each class of primary producers based on available nitrogen (equation 2, page 24); $N$ is the nitrogen in the element (gN element$^{-1}$); and $c_{N-ee}g$ is the C:N molar ratio for eelgrass (Table 5-4, page 31).

5.3.5.2 Autotrophic Respiration of Eelgrass

A review by Duarte and Cebrián (1996) concluded that seagrass autotrophic respiration accounts for 57.1 ± 5.7% of gross primary production. This fraction will be used to estimate autotrophic respiration ($R_E$, gC element$^{-1}$ d$^{-1}$) for eelgrass:

$$R_E = 0.571 \, G_E$$  (eqn. 25)

where $G_E$ is the gross primary production of eelgrass (gC element$^{-1}$ d$^{-1}$).

Autotrophic respiration returns N and P to the water column, in stoichiometric balance with C.
If the sum of the oxygen demand of all primary producers is greater than the oxygen available in the water column dissolved oxygen pool, primary producers will die. The amount of death in each class of primary producer will be determined by first looking at the net oxygen production by each class ($G_i - R_i$); if it is positive, that class of primary producers does not sustain any oxygen-related death. If the net oxygen production by a class of primary producers is negative, the negative net production may potentially be converted into a loss term, to bring the system back to a 0 mg/L level of oxygen. Multiple demands are placed on the oxygen pool: autotrophic respiration, heterotrophic respiration, and benthic respiration. These demands will be balanced, apportioning death or reduction in function to each process proportional to the demand and the deficit in oxygen — all processes will compete on equal footing for oxygen.

5.3.6 Heterotrophic Processes

The primary producer biomass ($B_P$, $B_M$, $B_E$) is depleted through two external pathways: consumption by grazers ($B_{g-P}$, $B_{g-M}$, $B_{g-E}$) and delivery to the benthos ($B_{b-P}$, $B_{b-M}$, $B_{b-E}$). These pathways encompass the sum of heterotrophic processes acting on the primary producers. The resulting estimates of heterotrophic processes are compared to the total stock available, such that the heterotrophic processes do not exceed the available primary producer biomass. This check is necessary as the sum of the processes could be greater than the stock available, especially as the consumption by grazers is calculated using the running average of biomass stock. Nitrogen and phosphorus associated with the $B_{g-i}$ and $B_{b-i}$ are determined using the C : N : P molar ratio (Table 5-4, page 31). Nitrogen and phosphorus in the biomass respired through heterotrophic processes are assumed to be regenerated to the water column. In reality, some of the N and P will be in complex organic molecules with a lag time in the return of the nutrients to the inorganic pools. To maintain the simplicity of the model, this lag is assumed to be nonexistent.

If the sum of the oxygen demand of autotrophic respiration and heterotrophic processes from all primary producer is greater than the oxygen available in the water column dissolved oxygen pool, primary producers will die and heterotrophic processes will be reduced. Multiple demands are placed on the oxygen pool: autotrophic respiration, heterotrophic respiration, and benthic respiration. These demands will be balanced, apportioning death or reduction in function to each process proportional to the demand and the deficit in oxygen — all processes will compete on equal footing for oxygen.

5.3.6.1 Phytoplankton Heterotrophic Processes - Grazing

The grazing on the phytoplankton stock ($B_{p-P}$) is estimated using a multi-day running average of the phytoplankton stock ($B_P$) and a water column grazing coefficient developed using a Q10 relationship.

$$B_{g-P} = g_0 e^{(gQ \epsilon)} \frac{B_P}{B_{f-P}} \quad \text{(eqn. 26)}$$

where $\epsilon$ is the water column temperature, which is provided as output from the NYHOPS model; $g_0$ ($^\circ$C$^{-1}$) is the thermal respiratory quotient and $g_0$ ($^\circ$C$^{-1}$) is the water column grazing rate at 0$^\circ$C (Table 5-4, page 31).

Heterotrophic processes will be reduced if sufficient oxygen is not available in the water column pool to fuel all autotrophic respiration and heterotrophic processes.
5.3.6.2 Phytoplankton Heterotrophic Processes - Death / Delivery to the Benthos

The amount of phytoplankton delivered to the benthos \( B_{b} \) is based on an empirically derived statistical relationship between the primary production and benthic remineralization (Nixon 1981). Nixon’s (1981) formulation was presented in terms of the annual production and annual benthic remineralization, thus the intercept has been divided by the number of days in a year.

\[
B_{b-p} = \frac{15}{365} + 0.238 \beta_{24} \tag{eqn. 27}
\]

The \( B_{b-p} \) describes the amount of phytoplankton stock from an element that will be delivered to the benthos.

The NREEM does not currently include a surface and bottom element in each box. If two layers are added to this model, an adjustment of phytoplankton delivery to the bottom will be required. Some of the surface element phytoplankton biomass may be delivered to the benthos of the surface element and some may pass through the boundary between vertical elements and be delivered to the benthos of the bottom element. The fraction of the surface element \( B_{s} \) delivered to the surface element benthos versus the bottom element benthos is determined by comparing the area of the surface element relative to the area of the interface between the surface and bottom element.

Heterotrophic processes will be reduced if sufficient oxygen is not available in the water column pool to fuel all autotrophic respiration and heterotrophic processes.

5.3.6.3 Macroalgae Heterotrophic Processes - Grazing

Grazing rates on macroalgae are highly variable (Brush and Nixon, 2010). Brush and Nixon (2010) employed a temperature dependent model for grazing which they later modified to extend high grazing rates until later in the fall. As a first pass, grazing will be modeled using the temperature dependent grazing rate and adjusted as needed at a later time.

The grazing rate on macroalgae biomass is modeled as \( B_{g-m} \) (g C element\(^{-1}\)) (Figure 17):

\[
B_{g-m} = g_{M0} e^{(g_{MQ} \epsilon)} B_{M} \tag{eqn. 28}
\]

where \( g_{M0} \) is the rate of grazing on macroalgae at 0°C (d\(^{-1}\), Table 5-4, page 31), \( g_{MQ} \) is the grazing on macroalgae thermal respiratory quotient (Q_{10} for respiration) (°C\(^{-1}\), Table 5-4, page 31), \( \epsilon \) is the temperature (°C), and \( B_{M} \) is the biomass of macroalgae (gC element\(^{-1}\)). The coefficients for this relationship \( (g_{M0}, g_{MQ}) \) were based on the work of Brush and Nixon (2010), but can be changed to better reflect NRE, if changing them improves model performance at predicting macroalgae biomass.

Heterotrophic processes will be reduced if sufficient oxygen is not available in the water column pool to fuel all autotrophic respiration and heterotrophic processes.
Grazing rate on macroalgae is a function of temperature. The panel on the right shows how grazing rate varies over the course of a year using a warm year (2012) and a cold year (1996).

5.3.6.4 Macroalgae Heterotrophic Processes - Death / Delivery to the Benthos

Macroalgae autotrophic respiration in excess of the oxygen available will produce death of the macroalgae sufficient to bring the water column oxygen pool into balance (not negative, but only going as low as 0 mg/L). See the section on oxygen for how this will be handled (Section 5.3.8, page 46). When autotrophic respiration is greater than the oxygen available, this loss term is included:

\[
B_{\text{p-M}} = R_M = \frac{(\text{net oxygen demand})}{(\text{total oxygen demand})} \times \left( \frac{12 \text{ g C}}{1.7 \text{ moles } O_2} \right) \left( \frac{32 \text{ g } O_2}{\text{ moles } O_2} \right)
\]  

(eqn. 29)

where \( R_M \) is the 24-hour respiration of macroalgae (gC element\(^{-1}\)).

Note, Brush and Nixon (2010) applied a similar scheme, but only included death when the respiration allowed by oxygen availability was 10% of the target respiration for five days. If macroalgae death is too high, this alteration could be applied. In an effort to maintain simplicity in the model, this caveat was not included.

As a simplification, no other death of macroalgae is currently included in the model. If greater complexity is needed to adequately simulate the situation in NRE, a temperature dependent loss of macroalgae will be considered following the methods of Brush and Nixon (2010) or Solidoro et al. (1997).

Commented [VJ9]: compare heterotrophic processes to ranges from Duarte 1995

need to check this equation
5.3.6.5  Eelgrass Heterotrophic Processes – Loss of Leaves (Death / Delivery to the Benthos)

Grazing on eelgrass is assumed to be zero. However, eelgrass does shed a leaf every five to twelve days during the growing season (plastochrone interval). This is a natural process of the plant, not a death of the plant.

The first iteration of the model includes a simplification: if we assume plants typically have six leaves, one sixth of the plant is shed every ten days. This equates to a loss of 0.016 d⁻¹. A second simplification, we will assume that the leaves stay within the embayment and decay and that no outside leaves are introduced to the embayment.

\[ B_{g-E} = 0.016 \, B_E \]  
(eqn. 30)

No additional death term is added to eelgrass. Under high temperatures, GPP is reduced or goes to zero. Under low light, the GPP is reduced or goes to zero. The shedding of leaves will account for the reduction in eelgrass biomass.

5.3.7  Benthic Processes

If the sum of the oxygen demand from autotrophic respiration and heterotrophic processes by all primary producer is greater than the oxygen available in the water column dissolved oxygen pool, primary producers will die and heterotrophic processes will be reduced. Multiple demands are placed on the oxygen pool: autotrophic respiration, heterotrophic respiration, and benthic respiration. These demands will be balanced, apportioning death or reduction in function to each process proportional to the demand and the deficit in oxygen – all processes will compete on equal footing for oxygen.

The benthic metabolism \((S_M)\) is estimated using the accumulated benthic stock of carbon \((S)\) and a benthic respiratory coefficient developed using a \(Q_{10}\) relationship:

\[ S_M = b_0 \, e^{(b_2 \, \epsilon)} \, S \]  
(eqn. 31)

where \(\epsilon\) is the water column temperature, which is provided as output from the ROMS model or modeled based on ordinal date, \(b_0 \, (°C^{-1})\) is the benthic thermal respiratory quotient and \(b_0 \, (d^{-1})\) is the benthic respiratory rate at 0°C (Table 5-4, page 31).

Benthic metabolism is considered in terms of carbon, with respiration of nitrogen and phosphorus related to carbon metabolism through a C : N \((c_0)\) and C : P \((c_0)\) molar ratio (Table 5-4, page 31) converted to a mass ratio. These C : N and C : P molar ratios within the sediment are weighted to reflect the source of the delivery to the benthos (phytoplankton, macroalgae, eelgrass) taking into account the amount of material that remains in the benthos. We assume bacterial respire organic matter with a ratio of 106 : 16 : 1 for C : N : P. If N or P are not sufficient, benthic metabolism is reduced and carbon-rich organic matter builds up in the sediment.

A fraction of the benthic nitrogen is removed from the model domain through denitrification.

Denitrification is modeled as a constant fraction of the carbon metabolism \((\sigma\, Table 5-4, page 31)\).
metabolized nitrogen not lost through denitrification is assumed to be regenerated to the water column

$N_s = \frac{s_N (1-\sigma)}{c_N}$

(eqn. 32)

5.3.8 Oxygen

Oxygen is coupled to all processes through stoichiometric relationships of C : O$_2$. This relationship is termed a respiratory quotient (RQ) for C : O$_2$ and a photosynthetic quotient (PQ) for O$_2$: C.

In the NREEM, when oxygen stocks are low in the water column, primary producers may die and heterotrophic processes may cease, to keep oxygen levels from going negative. If the oxygen levels approach zero, the model triggers a routine that compares the oxygen demand from each source as a fraction of the total oxygen demand. Each oxygen demand receives that fraction of the available oxygen.

Specifically, for autotrophic respiration, the respiration demand for each class of primary producers is first compared to the oxygen produced by the primary producer for that day. If the demand is less than what the primary producer produced, it may take that oxygen from the pool and the available oxygen in the pool is recalculated for the other demands.

Autotrophic respiration demands in excess of what the primary producer generated that day are then compared to all other oxygen demands. Each demand is awarded the oxygen equivalent to the fraction of the demand out of the total demands (recalculated after autotrophic respiration has been handled as described in the previous paragraph).

Atmospheric exchange and boundary conditions occur at the end of the day; they are not included in the daily iteration of changes to state variables.

Contributors:

- atmosphere
- boundary conditions
- gross primary production

Detractors:

- atmosphere
- boundary conditions
- autotrophic respiration
- grazing
- death / delivery to benthos
- benthic processes (decay)
5.3.9 Atmospheric Deposition as a Source of Nitrogen

Atmospheric deposition \((N_A)\) contributes nitrogen to the estuary in the form of wet and dry deposition to the surface elements. Wet deposition is estimated as the product of the precipitation \((\rho, \text{ m d}^{-1})\) and the average concentration of dissolved inorganic nitrogen in rain water \((d_{wet}, \text{ gN m}^{-3}, \text{ Table 5-4, page 31})\).

Dry deposition is based on an annual average flux \((d_{dry}, \text{ gN m}^{-2} \text{ d}^{-1}, \text{ Table 5-4, page 31})\), based on the work of Clark and Kremer (2005). Given the degree in uncertainty in atmospheric deposition nitrogen concentrations, the uncertainty in the final results due to N deposition were assessed by running the model using three concentrations: 30 μM, 50 μM, and 100 μM. The effect on model output was negligible, and for most parameters, insignificant. A slight difference was seen in the nitrogen concentration, but this did not translate into higher productivity or greater oxygen demand.

\[
N_A = (\rho d_{wet} + d_{dry})a
\]

(eqn. 33)

where \(N_A\) is the nitrogen delivered from atmospheric deposition \((\text{gN element}^{-1} \text{ d}^{-1})\), \(\rho\) is precipitation \((\text{m d}^{-1})\), \(d_{wet}\) is nitrogen concentration in wet deposition \((\text{gN m}^{-3})\), \(d_{dry}\) is the average dry deposition \((\text{gN m}^{-2} \text{ d}^{-1})\), and \(a\) is the surface area of the upper element \((\text{m}^2)\).

5.3.10 Differential Equations

Eight differential equations are solved for each model day to estimate the daily change in stocks. The variables indicated in the differential equations were defined in equations 9 through 33; constants and coefficients were defined in Table 5-4 (page 31).

\[
\frac{dP}{dt} = G_P - R_P - B_{g-P} - B_{b-P}
\]

(eqn. 34) **phytoplankton**

\[
\frac{dM}{dt} = G_M - R_M - B_{g-M} - B_{b-M}
\]

(eqn. 35) **macroalgae**

\[
\frac{dE}{dt} = G_E - R_E - B_{g-E} - B_{b-E}
\]

(eqn. 36) **eelgrass**

\[
\frac{db}{dt} = B_b - S_M
\]

(eqn. 37) **benthic carbon**

\[
\frac{dn}{dt} = N_k + N_A + \frac{B_{g-P+E}+R_{P-E}}{C_{N-phyto}} + \frac{B_{g-M+E}+R_{M-E}}{C_{N-algae}} + \frac{B_{g-E+E}+R_{E-E}}{C_{N-eelg}}
\]

(eqn. 38) **nitrogen**

\[
\frac{dp}{dt} = \frac{S_p n}{C_p} + \frac{B_{g-P+E}+R_{P-E}}{C_p} + \frac{B_{g-M+E}+R_{M-E}}{C_p} + \frac{B_{g-E+E}+R_{E-E}}{C_p}
\]

(eqn. 39) **phosphorus**

The oxygen dynamics are modeled through stoichiometric relationships based on the production and respiration terms in the model converted from molar units to mass \((\dot{\omega}, \omega_p, \omega_r, \omega_o; \text{ Table 5-4, page 31})\). In addition, oxygen exchanges between the surface layer and the atmosphere \((O_{atm})\) are modeled following the equations of Garcia and Gordon (1992).

\[
\frac{do}{dt} = O_{atm} + G \dot{\omega} - \frac{R}{\omega_p} - \frac{R}{\omega_r} - \frac{N_k}{\omega_o}
\]

(eqn. 40) **oxygen**

Commented [VJ11]: need to revise
Field data in the rivers and ocean boundaries were used to determine concentration of state variables entering the model domain. The volume of river and ocean water entering the domain were determined as part of the hydrodynamic modeling component. The user interface allows for nutrient inputs to be increased or decreased overall or for a specific component such as nutrients from fertilizers. This flexibility allows for hindcasting and forecasting scenarios related to changes in nutrient loads.

5.4 Forcing Functions

Data for the period of 1/1/81 to 12/31/16 are included for all forcing functions. When additional years were available, they were included in the MatLab file, to allow for expansion of the model time frame at a later point.

Temperature, light, and wind were taken from the Millstone meteorological dataset, discussed in the statistical portion of this project (Figures 18, 19, 20). Dates included span from 1/1/1976 to 12/31/16.

Light data must be in units of Einsteins per square meter per day (E m⁻² d⁻¹) for the productivity equation. This unit is equivalent to moles of photons per square meter per day (mol m⁻² d⁻¹).

Precipitation data (Figure 21) came from the NOAA National Centers for Environmental Information website, using the “Climate Data Online” order form to access the data (https://www.ncdc.noaa.gov/cdo-web/). Data from the Groton station were preferentially used (GROTON, CT US (GHCND:USC00063207)). Data from the Groton airport were used when data from the Groton station were unavailable (1491 days out of 11953 days = 12% of the time) (GROTON NEW LONDON AIRPORT, CT US (GHCND:USW00014707)). Data currently available in the model source files are 1/1/1981 to 1/16/18.

Data shown are from Millstone’s Meteorological dataset. Temperature is measured at the Plant intake. An offset is not currently applied to account for warmer temperatures in the Niantic River boxes; this may be included at a later time.

![Water Temperature](https://example.com/water_temperature.png)

Figure 18: Water Temperature

Data shown are from Millstone’s Meteorological dataset. Temperature is measured at the Plant intake. An offset is not currently applied to account for warmer temperatures in the Niantic River boxes; this may be included at a later time.
Figure 19: Light
Data shown are from Millstone’s Meteorological dataset. $E \text{ m}^{-2} \text{ d}^{-1} = \text{mol m}^{-2} \text{ d}^{-1}$

Figure 20: Wind Speed
Data shown are from Millstone’s Meteorological dataset.
Precipitation data are from NOAA data sources for Groton. The average precipitation over the record shown is 0.0034 m per day (= 0.34 cm per day = 0.13 inches per day).

### 5.5 Boundary Conditions

Boundary conditions refers to the state variables located outside of the model domain but contributing to the model. These conditions are forced using real data. The boundaries exist at the river, with freshwater input, and at the mouth, with input from the Niantic Bay area.

- Benthic carbon, macroalgae, and seagrass are not exchanged across the boundaries as these are benthic state variables – they do not move with the exchange of water.
- Salt is set to zero in the river and the NYHOPS model is used to set the salinity in Niantic Bay (Figure 22). NYHOPS provides salinity from 1/1/81 to 10/31/13. Salinity from 10/31/13 to 12/22/18 was estimated from a linear regression of salinity on river flow (Appendix A, page 70).
- Oxygen is assumed to be at 100% saturation in the freshwater inputs and Niantic Bay; details are provided below on how this quantity is estimated (Section 5.5.1, page 52).
- Phytoplankton is set to zero in the river because freshwater phytoplankton should not survive in the estuary. Data collected by CTDEEP are used to estimate phytoplankton in Niantic Bay; details are provided below on how this quantity is estimated (Section 5.5.2, page 53).
- Nutrients (nitrogen and phosphorus) are estimated from USGS data for the river and from CTDEEP data for Niantic Bay; details are provided below on how these quantities are estimated (Section 5.5.2, page 53; Section 5.5.2, page 53).
- In the User Interface Excel file, the user has the option of using dissolved inorganic nutrients or dissolved total nutrients (inorganic + organic). If organic nutrients are chosen, the user also must designate the fraction of riverine organic matter expected to be labile (available to biological processes within the residence time of the embayment). Riverine organic N lability is typically 10% to 30% for groundwater originating from a variety of land use categories and 30% to 60% for atmospheric deposition from urban runoff (Table 5-6). Completely forested watersheds tend to have a lower fraction of bioavailable N while atmospheric deposition not filtered through groundwater tends to be more highly bioavailable (Petrone et al. 2009; Seitzinger et al. 2002). Organic P is currently set with a range from 0.5 to 0.9, though this is likely much lower.
phosphorus, the particulate phosphorus is included in the estimate of dissolved organic phosphorus in the User Interface Excel file, as P binds tightly to sediment in freshwater and is liberated in salt water due to chemical (especially pH) differences in the freshwater versus the estuary (Bianchi 2007; O’Mara et al. 2019). It is assumed that oceanic organic N and P are largely refractory, as the marine organisms have been working on the breakdown for quite some time. Organic N in the oceanic waters is assigned a lability of 10% and organic P is assigned a lability of 2%.

Table 5-6: Fraction of DON that is Bioavailable.

<table>
<thead>
<tr>
<th>source</th>
<th>watershed type</th>
<th>Location</th>
<th>DON that is bioavailable, % (avg ± std dev; or range)</th>
<th>citation</th>
</tr>
</thead>
<tbody>
<tr>
<td>ground water – spring</td>
<td>agricultural (animals)</td>
<td>NJ, USA</td>
<td>44 ± 4.7</td>
<td>(Seitzinger et al. 2002)</td>
</tr>
<tr>
<td>ground water – summer</td>
<td>agricultural (animals)</td>
<td>NJ, USA</td>
<td>32 ± 9.7</td>
<td>(Seitzinger et al. 2002)</td>
</tr>
<tr>
<td>ground water – fall</td>
<td>agricultural (animals)</td>
<td>NJ, USA</td>
<td>14 ± 5.5</td>
<td>(Seitzinger et al. 2002)</td>
</tr>
<tr>
<td>ground water – annual</td>
<td>agricultural (animals)</td>
<td>NJ, USA</td>
<td>30 ± 14</td>
<td>(Seitzinger et al. 2002)</td>
</tr>
<tr>
<td>ground water – winter</td>
<td>mixed (ag, natural)</td>
<td>TX, USA</td>
<td>15 - 38</td>
<td>(Wu et al. 2019)</td>
</tr>
<tr>
<td>ground water – summer</td>
<td>mixed (ag, natural)</td>
<td>TX, USA</td>
<td>9 - 15</td>
<td>(Wu et al. 2019)</td>
</tr>
<tr>
<td>ground water – annual</td>
<td>mixed (ag, natural)</td>
<td>TX, USA</td>
<td>9 - 38</td>
<td>(Wu et al. 2019)</td>
</tr>
<tr>
<td>ground water – summer</td>
<td>mixed (ag, natl, urban)</td>
<td>AUS</td>
<td>20 - 44</td>
<td>(Petrone et al. 2009)</td>
</tr>
<tr>
<td>ground water – spring</td>
<td>forest</td>
<td>NJ, USA</td>
<td>12 ± 14</td>
<td>(Seitzinger et al. 2002)</td>
</tr>
<tr>
<td>ground water – summer</td>
<td>forest</td>
<td>NJ, USA</td>
<td>35 ± 19</td>
<td>(Seitzinger et al. 2002)</td>
</tr>
<tr>
<td>ground water – fall</td>
<td>forest</td>
<td>NJ, USA</td>
<td>26 ± 12</td>
<td>(Seitzinger et al. 2002)</td>
</tr>
<tr>
<td>ground water – annual</td>
<td>forest</td>
<td>NJ, USA</td>
<td>24 ± 17</td>
<td>(Seitzinger et al. 2002)</td>
</tr>
<tr>
<td>ground water – summer</td>
<td>forest</td>
<td>AUS</td>
<td>4</td>
<td>(Petrone et al. 2009)</td>
</tr>
<tr>
<td>atm. dep. – spring</td>
<td>urban/suburban runoff</td>
<td>NJ, USA</td>
<td>68 ± 7.3</td>
<td>(Seitzinger et al. 2002)</td>
</tr>
<tr>
<td>atm. dep. – summer</td>
<td>urban/suburban runoff</td>
<td>NJ, USA</td>
<td>50 ± 7.4</td>
<td>(Seitzinger et al. 2002)</td>
</tr>
<tr>
<td>atm. dep. – fall</td>
<td>urban/suburban runoff</td>
<td>NJ, USA</td>
<td>59 ± 11</td>
<td>(Seitzinger et al. 2002)</td>
</tr>
<tr>
<td>atm. dep. – annual</td>
<td>urban/suburban runoff</td>
<td>NJ, USA</td>
<td>59 ± 11</td>
<td>(Seitzinger et al. 2002)</td>
</tr>
<tr>
<td>atm dep. – summer</td>
<td>100% urban, drains</td>
<td>AUS</td>
<td>27 - 46</td>
<td>(Petrone et al. 2009)</td>
</tr>
</tbody>
</table>
5.5.1 Boundary Conditions – oxygen

Oxygen data are not consistently available for the river nor for the ocean (Niantic Bay) boundaries. The assumption of 100% saturation was applied to both boundaries, with saturation calculated as a function of temperature and salinity, per the equations applied in the model (see Section 5.3.10, page 47).

In short, water density was calculated from salinity and water temperature using the "Seawater Version 3.0" toolbox in MatLab. Salinity in the river was set at 0 ppt, salinity in Niantic Bay was set using the boundary conditions (Figure 22). Equations for oxygen at equilibrium were applied to temperature, salinity, and density data (Garcia and Gordon 1992). Temperature data were not available for 2017 & 2018; these dates were set equal to the temperature in 2016 on the corresponding date. The date range spans from 1/1/1981 to 12/22/2018 (Figure 23).
Figure 23: Oxygen Concentration in the River and Ocean Boundaries.

Oxygen at equilibrium was used as the boundary condition. Density is calculated in MatLab from temperature and salinity. A set of equations are used to estimate oxygen equilibrium from temperature, salinity, and density. Temperature data were not available for 2017 & 2018; these dates were set equal to the temperature in 2016 on the corresponding date. The difference between the river and the ocean are due to salinity differences as the same temperature was used for both.

5.5.2 Ocean Boundary – phytoplankton and nutrients

CTDEEP data from stations K2 and M3 were used to estimate phytoplankton and nutrient concentrations in Niantic Bay. These two stations are located in Long Island Sound, to the east and west of Niantic Bay (Figure 24). Data are available from 1991 through 2017. With a few exceptions that are addressed later in this section, data are collected monthly throughout the year.

Figure 24: CTDEEP Station Locations.

Locations of CTDEEP stations in the vicinity of Niantic River Estuary are noted by yellow tags, with station name indicated.

These two stations will be considered representative of the water in Niantic Bay. To confirm this decision, data for each available parameter were plotted by station for visual confirmation of comparability and trends (Appendix B, page 75). The parameters compared include: chlorophyll a, total...
dissolved phosphorus, dissolved inorganic phosphorus, particulate phosphorus, total dissolved nitrogen, dissolved ammonium, dissolved nitrate plus nitrite, and particulate nitrogen.

Data from the two stations were compared using a paired t-test to confirm that phytoplankton and nutrients were similar among the stations on a given date; results of the t-test are referenced on the plots available in Appendix B (page 75). The two stations were similar across all parameters; thus the average of the two stations on a particular date is used when data are available at both stations and data from either station may be used if one station does not have data on a particular day.

To determine if trends occurred over the 26-year data record, data from 1991 through 1993 were averaged by season and subtracted from all data based on season (winter = December, January, February; spring = March, April, May; summer = June, July, August; fall = September, October, November), see Appendix B (page 75). These plots provided a first glimpse of possible trends; the figures were reviewed visually, no statistics were run on these results because 1991-1993 may not be representative of the appropriate base condition and the seasonal averaging may have issues that would confound statistical analysis.

The next step was to determine how to interpolate between the monthly data and what value to use when sampling events occurred more than a month apart. The visual investigation of trends suggested that no parameter showed a strong trend over the 26-year dataset, though some periods of years were higher or lower than the 1991-1993 seasonal averages (Appendix B, page 75). For modeling purposes, daily estimates of the parameters are determined by drawing a straight line between sampling events – a linear interpolation of the monthly data to daily data. To account for longer time intervals between sampling events, if the time interval between sampling dates is greater than 40 days, an alternate method of estimating the daily data is needed. A sinusoidal curve often fits annual nutrient and chlorophyll data; this was confirmed by plotting the data on the ordinal date, for all 26 years of data (Figure 25).
Figure 25: Boundary Conditions versus Ordinal Date

Each panel plots all available parameter data from 1991 to 2017 CTDEEP surveys as the average of stations M3 and K2 versus the ordinal date. All data follow a sinusoidal pattern over the annual cycle with DON showing the weakest sinusoidal pattern.

A MatLab function written by Chad Greene in 2018 titled “Sine Fit” was designed to fit a least-squares estimate of a sinusoid to time series data that have a periodicity of 1 year. The routine was designed for climatological data with more than 1 year of data. The routine generates the terms of the sinusoidal equation (amplitude, phase shift) and assumes a period of 1 year (Table 5-7). The routine also estimates a linear trend over the entire time series and calculates the root mean square error (a measure of goodness of fit) for the sine curve relative to the data; for all parameters, the linear trend was not ecologically meaningful (Table 5-7).

The sine equation used to estimate daily parameter values when sampling dates were more than 40 days apart and prior to the start of CTDEEP sampling efforts was:

\[ y(\text{date}) = \text{amplitude} \times \sin (\text{period} \times \text{date} + \text{phase shift}) - \text{constant offset} \]  

(eqn. 41)

where the amplitude, phase shift, and constant offset are provided in Table 5-7 and the period is equivalent to 1 year, calculated as \( 2\pi/365 \). Plots of daily data are provided in Figures 26 through 30.
Table 5-7: Results of Sinusoidal Fit to Boundary Conditions

Data represent the output from the MatLab function SineFit. The period for the sine curve is 365 days. Dates were coded as MatLab numbers where 1/1/1991 = 727199. In the column headings, “amount” equates to the units shown in the first column, by parameter.

<table>
<thead>
<tr>
<th>parameter</th>
<th>amplitude (amount)</th>
<th>phase shift (day of year corresponding to max value)</th>
<th>constant offset on the y-axis = mean of the data (amount)</th>
<th>estimate of the linear trend (amount / year)</th>
<th>estimate of the linear trend (amount / 26-year period)</th>
<th>root mean square error (amount, lower is better)</th>
</tr>
</thead>
<tbody>
<tr>
<td>chlorophyll a (µg/L)</td>
<td>0.4859</td>
<td>187.233</td>
<td>2.4134</td>
<td>0.02760</td>
<td>0.717</td>
<td>1.50</td>
</tr>
<tr>
<td>DIN (mg/L)</td>
<td>0.0429</td>
<td>0.211</td>
<td>0.0614</td>
<td>-0.00079</td>
<td>-0.021</td>
<td>0.03</td>
</tr>
<tr>
<td>DON (mg/L)</td>
<td>0.0172</td>
<td>181.609</td>
<td>0.1347</td>
<td>-0.00088</td>
<td>-0.023</td>
<td>0.07</td>
</tr>
<tr>
<td>DIP (mg/L)</td>
<td>0.0110</td>
<td>337.00</td>
<td>0.0269</td>
<td>0.00034</td>
<td>0.009</td>
<td>0.01</td>
</tr>
<tr>
<td>DOP (mg/L)</td>
<td>0.0011</td>
<td>296.327</td>
<td>0.0103</td>
<td>0.00008</td>
<td>0.002</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Figure 26: DIN Daily Data – Boundary Conditions

Red circles show the CTDEEP data, the average of station M3 and K2. The pink line in the background shows the sine curve fit to the data (Table 5-7). The blue line is the daily data used in the model. When CTDEEP sample dates are within 40 days of each other, the linear interpolation between data are used to estimate the daily data. If sampling events are more than 40 days apart, the more conservative estimate of the sine curve is used to estimate the daily data. ppm = mg/L = g/m³, as N
Figure 27: DON Daily Data – Boundary Conditions
Red circles show the CTDEEP data, the average of station M3 and K2. The pink line in the background shows the sine curve fit to the data (Table 5-7). The blue line is the daily data used in the model. When CTDEEP sample dates are within 40 days of each other, the linear interpolation between data are used to estimate the daily data. If sampling events are more than 40 days apart, the more conservative estimate of the sine curve is used to estimate the daily data. ppm = mg/L = g/m³, as N

Figure 28: DIP Daily Data – Boundary Conditions
Red circles show the CTDEEP data, the average of station M3 and K2. The pink line in the background shows the sine curve fit to the data (Table 5-7). The blue line is the daily data used in the model. When CTDEEP sample dates are within 40 days of each other, the linear interpolation between data are used to estimate the daily data. If sampling events are more than 40 days apart, the more conservative estimate of the sine curve is used to estimate the daily data. ppm = mg/L = g/m³, as P
Figure 29: DOP Daily Data – Boundary Conditions
Red circles show the CTDEEP data, the average of station M3 and K2. The pink line in the background shows the sine curve fit to the data (Table 5-7). The blue line is the daily data used in the model. When CTDEEP sample dates are within 40 days of each other, the linear interpolation between data are used to estimate the daily data. If sampling events are more than 40 days apart, the more conservative estimate of the sine curve is used to estimate the daily data. ppm = mg/L = g/m³, as P

Figure 30: Chlorophyll a Daily Data – Boundary Conditions
Red circles show the CTDEEP data, the average of station M3 and K2. The pink line in the background shows the sine curve fit to the data (Table 5-7). The blue line is the daily data used in the model. When CTDEEP sample dates are within 40 days of each other, the linear interpolation between data are used to estimate the daily data. If sampling events are more than 40 days apart, the more conservative estimate of the sine curve is used to estimate the daily data. The exception was between 2/27/1998 and 4/14/98, a 46-day difference, where linear interpolation was applied rather than the sine curve due to unusually low values in 1998. NOTE – the unit used for phytoplankton biomass in the model is gC m⁻³. Data are imported from the User Excel interface as chlorophyll a (µg/L), converted to gCHL m⁻³, then converted to gC m⁻³ using the C:CHL ratio defined in the model. This insures that if the C:CHL ratio is changed in the model, that change is propagated through the chlorophyll data for the boundary condition. ppb = µg/L = mg/m³

5.5.3 River Boundary – nutrients
Nutrient data from the incoming water collected by USGS, Millstone Environmental Lab (MEL), and the Niantic River Watershed Commission (NRWC) between 2008 and 2017 were used to estimate the
nutrient concentrations in the incoming freshwater riverine and groundwater sources (Figure 31). Data are available from USGS for 8/20/08 to 9/11/12, from MEL for 4/15/15 to present, and from NRWC from 4/13/12 to present; only data through the end of 2016 were analyzed, though more data are now available for later years.

Figure 31: Station Locations of Latimer Brook Nutrient Data.
The stations designated as MEL, USGS, and NRWC, 14 were used to estimate nutrient concentrations in the incoming freshwater from all riverine and groundwater sources.
Figure 32: Nitrate data for Latimer Brook.
Nitrate is the only nitrogen species collected by all three groups. USGS and MEL collect other species of N, NRWC does not.

Figure 33: DIP data for Latimer Brook.
Dissolved inorganic phosphorus (DIP, ortho-phosphate as P) is collected only by USGS and MEL.
Nitrogen species included in this model include dissolved inorganic nitrogen (DIN) which is the sum of nitrate (NO$_3^-$), nitrite (NO$_2^-$), and ammonium (NH$_4^+$); and dissolved organic nitrogen (DON). Phosphorus species include dissolved inorganic phosphorus (as ortho-phosphate, PO$_4^{3-}$), dissolved organic phosphorus (DOP), and particulate phosphorus (PP). The USGS data is the only set which includes information on all species, MEL and NRWC are both missing some of the data (Table 5-8).

Table 5-8: Summary of Nutrient Data Availability in Latimer Brook, as used in the model.
Data are collected monthly for the date ranges shown. Data for DON will be available from MEL, once reanalyzed.

<table>
<thead>
<tr>
<th>Nutrient Species</th>
<th>USGS</th>
<th>MEL</th>
<th>NRWC</th>
</tr>
</thead>
<tbody>
<tr>
<td>nitrate (NO$_3^-$)</td>
<td>8/20/08 to 9/11/12</td>
<td>4/15/15 to 12/14/16</td>
<td>4/13/12 to 11/17/16</td>
</tr>
<tr>
<td>nitrite (NO$_2^-$)</td>
<td>8/20/08 to 9/11/12</td>
<td>4/15/15 to 12/14/16</td>
<td></td>
</tr>
<tr>
<td>ammonium (NH$_4^+$)</td>
<td>8/20/08 to 9/11/12</td>
<td>4/15/15 to 12/14/16</td>
<td></td>
</tr>
<tr>
<td>dissolved inorganic N (DIN)</td>
<td>8/20/08 to 9/11/12</td>
<td>4/15/15 to 12/14/16</td>
<td>estimated from NO$_3^-$</td>
</tr>
<tr>
<td>dissolved organic N (DON)</td>
<td>8/20/08 to 9/11/12</td>
<td>TBD</td>
<td></td>
</tr>
<tr>
<td>dissolved inorganic P (PO$_4^{3-}$)</td>
<td>8/20/08 to 9/11/12</td>
<td>4/15/15 to 12/14/16</td>
<td></td>
</tr>
<tr>
<td>dissolved organic P (DOP)</td>
<td>8/20/08 to 9/11/12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>particulate phosphorus (PP)</td>
<td>8/20/08 to 9/11/12</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Using the USGS data, we can compare the relative contributions of the nitrogen species to the total dissolved nitrogen. When looking at only DIN, nitrate accounts for an average of 94% of the dissolved inorganic nitrogen, with a range of 84% to 98% (Figure 34). For this reason, the NRWC nitrate data was determined to be a good estimate of DIN, without adjustments.

Figure 34: Nitrate as a Fraction of DIN.
USGS monthly data from Latimer Brook for the period of 8/20/2008 to 9/11/2012 were used to evaluate nitrate as a fraction of DIN, to ascertain if nitrate was a good estimate of DIN. The pie chart on the left shows the average relative contribution of each species to DIN. The box plot on the right shows the data distribution; the lower end of the box is the 25th percentile, the upper edge is the 75th percentile, the line in the box indicates the median (50th percentile) with whiskers representing the 10th and 90th percentile and the points indicating the 5th and 95th percentiles.
The USGS dataset provides four years of monthly data for Latimer Brook nutrients. To apply the
sinusoidal modeling approach used for the ocean boundary data (Section 5.5.2, page 53), we want to
maximize the amount of data available. It was determined that nitrate is a sufficient proxy of DIN data in
the previous paragraph; the question now is the amount of DON present in the incoming freshwater. For
the four years of monthly data, the data indicates DON accounts for 26% to 49% of the TDN (Figure 35),
using the 25th and 75th percentiles as indicators, with a median of 33%. We can widen this range by using
the 10th and 90th percentiles, which yield a range of 20% to 63% for DON as a fraction of TDN. The
median of 33% (DON / TDN) will be used to estimate DON, where DON is equal to DIN × 33 / 67 (see pie
chart in Figure 35). While there is a fair bit of error in this estimate of DON, recall from the introduction
of this section that riverine organic N ranges from a lability if 0.1 (fraction) for groundwater to 0.6 for
atmospheric deposition. Thus, only 10 to 60% of the DON entering from the freshwater sources
contribute to productivity in the model, reducing the impact of the error.

Figure 35: USGS Nitrogen Data from Latimer Brook.
USGS monthly data from Latimer Brook for the period of 8/20/2008 to 9/11/2012 were used to evaluate the species distribution
of nitrogen, specifically looking at the contribution of dissolved inorganic nitrogen (DIN) and dissolved organic nitrogen (DON) to
the total (TDN). The color coding of the pie chart follows the color scheme of other figures in this panel, with NO$_3$ contributing
58% to TDN and DON contributing 38% to TDN; NO$_2$ accounts for less than 1% of TDN. For the box plots, the lower end of the
box is the 25th percentile, the upper edge is the 75th percentile, the line in the box indicates the median (50th percentile) with
whiskers representing the 10th and 90th percentile and the points indicating the 5th and 95th percentiles.
In general, phosphorus in freshwater is tightly bound to sediments, including particulates floating in the river water. Once the particulates encounter salt water, the chemistry of seawater allows for the release of phosphorus from sediment binding sites (Bianchi 2007; O’Mara et al. 2019). Some fraction of this released phosphorus is labile, and thus available to biological processes in the estuary. Thus, particulate phosphorus (PP) is included when estimating the phosphorus input from the riverine and groundwater sources. In the model, PP is grouped with dissolved organic phosphorus (DOP) in the Excel user interface worksheet. At this point, 50% to 90% is assumed to be labile (Bianchi 2007); this figure should be further refined if P is thought to have a bigger influence in this system. PP and DIP are roughly equivalent in amount, with DOP accounting for ~10% of the total phosphorus (TP) (Figure 36).

**Figure 36: USGS Phosphorus Data from Latimer Brook.**

USGS monthly data from Latimer Brook for the period of 8/20/2008 to 9/11/2012 were used to evaluate the species distribution of phosphorus. The color coding of the pie chart follows the color scheme of other figures in this panel, with DIP contributing 40% to TP and PP contributing 50% to TP; DOP accounts for 10% of TP. For the box plots, the lower end of the box is the 25th percentile, the upper edge is the 75th percentile, the line in the box indicates the median (50th percentile) with whiskers representing the 10th and 90th percentile and the points indicating the 5th and 95th percentiles.
The sinusoidal modeling approach used for the ocean boundary data (Section 5.5.2, page 53) was applied to the riverine data, resulting in estimates of nutrient concentrations in incoming freshwater (Table 5-9, Figures 37 to 40). The small amplitude of the sine curve relative to the data indicates the sine curve is not always a good approximation. While the sine curve amplitude is small, it was significant; thus, the sine model results are used versus using a straight average of data to account for estimates of nutrient concentrations in years without data.

For the model, DOP + PP is calculated as PP + PP * 10 / 50 (see pie chart in Figure 36).

Table 5-9: Results of Sinusoidal Fit to River Boundary Conditions

<table>
<thead>
<tr>
<th>parameter</th>
<th>amplitude (amount)</th>
<th>phase shift (day of year corresponding to max value)</th>
<th>constant offset on the y-axis = mean of the data (amount)</th>
<th>estimate of the linear trend (amount / year)</th>
<th>estimate of the linear trend (amount / 8-year period)</th>
<th>root mean square error (amount, lower is better)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIN (mg/L)</td>
<td>0.0395</td>
<td>219.6201</td>
<td>0.4074</td>
<td>0.0228</td>
<td>0.1821</td>
<td>0.1884</td>
</tr>
<tr>
<td>DON (mg/L)</td>
<td>0.0447</td>
<td>235.8071</td>
<td>0.1723</td>
<td>-0.0103</td>
<td>-0.0821</td>
<td>0.0716</td>
</tr>
<tr>
<td>DIP (mg/L)</td>
<td>0.0005</td>
<td>292.4606</td>
<td>0.0055</td>
<td>-0.0004</td>
<td>-0.0032</td>
<td>0.0023</td>
</tr>
<tr>
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Figure 37: DIN Daily Data – River Boundary Conditions

Red circles show the USGS, MEL, and NRWC data. The pink line in the background shows the sine curve fit to the data (Table 5-9). The blue line is the daily data used in the model. When sample dates are within 40 days of each other, the linear interpolation between data are used to estimate the daily data. If sampling events are more than 40 days apart, the more conservative estimate of the sine curve is used to estimate the daily data. ppm = mg/L = g/m³, as N
Figure 38: DON Daily Data – River Boundary Conditions
Red circles show the USGS data and DON estimated from DIN for MEL and NRWC data. The pink line in the background shows the sine curve fit to the data (Table 5-9). The blue line is the daily data used in the model. When sample dates are within 40 days of each other, the linear interpolation between data are used to estimate the daily data. If sampling events are more than 40 days apart, the more conservative estimate of the sine curve is used to estimate the daily data. ppm = mg/L = g/m³, as N

Figure 39: DIP Daily Data – River Boundary Conditions
Red circles show the USGS and MEL data. The pink line in the background shows the sine curve fit to the data (Table 5-9). The blue line is the daily data used in the model. When sample dates are within 40 days of each other, the linear interpolation between data are used to estimate the daily data. If sampling events are more than 40 days apart, the more conservative estimate of the sine curve is used to estimate the daily data. ppm = mg/L = g/m³, as P
6 Hydrodynamic Model Results

6.1 Comparison to Other Estimates of Residence Time

7 Biogeochemical Model Results

7.1 Skill Assessment

7.1.1 Skill Metrics - Description

7.2 Scenarios

7.2.1 Using NLM to modify the N load
8 Works Cited


University of Connecticut and Cornell Cooperative Extension of Suffolk County. contact:
jamie.vaudrey@uconn.edu.


9 Appendix A – Salinity Data

The Officer box model approach requires daily salinity values in each box of the model domain and at the boundaries. Given the sparsity of salinity data, modeled salinity from Dr. Nickitas Georgas at Stevens Institute of Technology will be used to inform the development of the box model hydrodynamics. Dr. Georgas uses a model called NYHOPS (New York Harbor Observing and Prediction System) for hindcasting salinity (as well as other parameters) in the Long Island Sound area. Access to model results is available at [http://hudson.dl.stevens-tech.edu/maritimeforecast/maincontrol.shtml](http://hudson.dl.stevens-tech.edu/maritimeforecast/maincontrol.shtml) (on the right hand side, under Region, select Long Island Sound). Dr. Georgas states, “The contributing watershed name in NYHOPS is "Southeast Shoreline 17, CT." It covers 42.54 square miles. Flow is estimated by watershed-area-adjusting the Shetucket near Willimantic gaged USGS daily flow (404 miles). The freshwater yield (discharge in the model) is split into three NYHOPS receiving water cells,” within the Niantic River Estuary. One at the very head of the River (where Latimer Brook enters NRE), one at the adjacent cell to the south (where Stony Brook comes in), and one just west of Niantic Bay’s mouth from several tributaries. River water temperature is assigned from the nearby Connecticut River at Essex gage. Niantic River has three model boxes, with more boxes in Niantic Bay (Figure 41). Unfortunately, the NYHOPS model does not include the restriction at the south end of Niantic created by the road and train bridge. Comparison of model predictions with salinity data will be used to evaluate the impact of this missing restriction. If the NYHOPS modeled salinity accurately captures the major trends in salinity in Niantic River and Bay, the 35-year model predictions would be of great use to hindcasting the ecological model to explore the pressures impacting the state variables within the system.

Figure 41: Bathymetry from the NYHOPS model. Provided by Dr. Nickitas Georgas, Stevens Institute of Technology. Niantic River and Bay are identified by the yellow oval. (Image courtesy of Dr. Georgas.)

Salinity data from the NYHOPS model is modeled at 11 depths, with the distance between each depth changing with the total depth in the model box. For comparison to field data, the surface layer was
calculated as the average of the top five depths and the bottom was calculated as the average of the bottom six depths.

The NYHOPS data from a box was compared to the corresponding NREEM model box (Figure 42). The field data used for comparison included any data collected in Niantic River and collated as part of this project. A key point to remember is that the field data was collected at one location in the box, at one depth, and at a single point in time whereas the NYHOPS salinity is the daily averaged salinity across the whole model box for the surface or bottom layer.

In general, the NYHOPS model slightly underestimates salinity with the closest match found in the arm and the worst match found in Niantic Bay (Figures 43 to 46). The NYHOPS model also misses some low salinity events in the arm and upper basin (Figures 43 & 44). Overall, the match between the NYHOPS model output and field data is good, especially considering the mismatch in data type (daily, box-wide average versus single point data).

Figure 42: NYHOPS model boxes vs. NREEM model boxes.

Salinity from the NYHOPS model was used to estimate salinity in NRE, to drive hydrodynamic mixing in the model. The figure on the right shows the NYHOPS model boxes with the blue arrows indicating the corresponding NREEM model boxes.
Figure 43: NYHOPS Salinity vs. Field Salinity – Arm
Comparison of the daily and box-wide average surface and bottom layer for NYHOPS salinity to field data in the respective layer (from a single location in the box, a single depth, at one point in time in the day). (LEFT) Depth-averaged NYHOPS model data is shown by the black line with the cyan line indicating the minimum and maximum salinity values for the layer. Red points are field data. Green circles are field data from north of the NYHOPS box (Figure 42). (RIGHT) Plot of NYHOPS data on field data, the identity line (1:1) is shown in cyan.

Figure 44: NYHOPS Salinity vs. Field Salinity – Upper Basin
Comparison of the daily and box-wide average surface and bottom layer for NYHOPS salinity to field data in the respective layer (from a single location in the box, a single depth, at one point in time in the day). (LEFT) Depth-averaged NYHOPS model data is shown by the black line with the cyan line indicating the minimum and maximum salinity values for the layer. Red points are field data. (RIGHT) Plot of NYHOPS data on field data, the identity line (1:1) is shown in cyan.
Figure 45: NYHOPS Salinity vs. Field Salinity – Lower Basin
Comparison of the daily and box-wide average surface and bottom layer for NYHOPS salinity to field data in the respective layer (from a single location in the box, a single depth, at one point in time in the day). (LEFT) Depth-averaged NYHOPS model data is shown by the black line with the cyan line indicating the minimum and maximum salinity values for the layer. Red points are field data. (RIGHT) Plot of NYHOPS data on field data, the identity line (1:1) is shown in cyan.

Figure 46: NYHOPS Salinity vs. Field Salinity – Niantic Bay
Comparison of the daily and box-wide average surface and bottom layer for NYHOPS salinity to field data in the respective layer (from a single location in the box, a single depth, at one point in time in the day). (LEFT) Depth-averaged NYHOPS model data is shown by the black line with the cyan line indicating the minimum and maximum salinity values for the layer. Red points are field data. (RIGHT) Plot of NYHOPS data on field data, the identity line (1:1) is shown in cyan.
9.1 Estimating Niantic Bay Salinity Beyond NYHOPS End Date

NYHOPS has an end date of 10/31/2013, for data in the Niantic River Estuary region. Salinity in the Niantic Bay is required to run the model. Salinity data in Niantic Bay was estimated from river flow using a linear regression on all available daily data (1/1/1981 to 10/31/2013). Regression results are shown below. Statistical analyses were conducted in *JMP* 13.0.0, a SAS product.

Salinity in Niantic Bay (ppt) = River Flow (m$^3$ d$^{-1}$) * $-0.00000393 + 28.511953$

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### Parameter Estimates

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Figure 47: Chlorophyll a, Niantic Bay Boundary Conditions.

The top panel shows the available data from stations M3 and K2 of the CTDEEP Long Island Sound sampling program (see Figure 24, page 53 for a map of station locations). Data were compared by date using a Paired t-test and when the assumption of normality was not met, a Signed Rank test; results are shown in the in-figure caption. The bottom panel shows the data from the top panel minus the seasonal average from 1991-1993; data values above the origin indicate increases relative to the 1991-93 period and below indicate decreases.
Figure 48: Total Dissolved Phosphorus, Niantic Bay Boundary Conditions.
The top panel shows the available data from stations M3 and K2 of the CTDEEP Long Island Sound sampling program (see Figure 24, page 53 for a map of station locations). Data were compared by date using a Paired t-test and when the assumption of normality was not met, a Signed Rank test; results are shown in the in-figure caption. The bottom panel shows the data from the top panel minus the seasonal average from 1991-1993; data values above the origin indicate increases relative to the 1991-93 period and below indicate decreases.
Figure 49: Dissolved Inorganic Phosphorus, Niantic Bay Boundary Conditions.

The top panel shows the available data from stations M3 and K2 of the CTDEEP Long Island Sound sampling program (see Figure 24, page 53 for a map of station locations). Data were compared by date using a Paired t-test and when the assumption of normality was not met, a Signed Rank test; results are shown in the in-figure caption. The bottom panel shows the data from the top panel minus the seasonal average from 1991-1993; data values above the origin indicate increases relative to the 1991-93 period and below indicate decreases.

Paired t-test: significantly different by < 0.003 ppm; p-value < 0.001.
Not an ecologically significant difference, data from either station or the average may be used.
Figure 50: Particulate Phosphorus, Niantic Bay Boundary Conditions. The top panel shows the available data from stations M3 and K2 of the CTDEEP Long Island Sound sampling program (see Figure 24, page 53 for a map of station locations). Data were compared by date using a Paired t-test and when the assumption of normality was not met, a Signed Rank test; results are shown in the in-figure caption. The bottom panel shows the data from the top panel minus the seasonal average from 1991-1993; data values above the origin indicate increases relative to the 1991-93 period and below indicate decreases. Paired t-test: significantly different by < 0.002 ppm; p-value < 0.001. Not an ecologically significant difference, data from either station or the average may be used.
Figure 51: Dissolved Inorganic Phosphorus and Dissolved Organic Phosphorus, Niantic Bay Boundary Conditions.

Data averaged from stations M3 and K2 of the CTDEEP Long Island Sound sampling program (see Figure 24, page 53 for a map of station locations). DOP is only calculated when DIP and TDP were both available. The bottom panel shows the data from the top panel minus the seasonal average from 1991-1993; data values above the origin indicate increases relative to the 1991-93 period and below indicate decreases.
Figure 52: Total Dissolved Nitrogen (TDN), Niantic Bay Boundary Conditions.

The top panel shows the available data from stations M3 and K2 of the CTDEEP Long Island Sound sampling program (see Figure 24, page 53 for a map of station locations). Data were compared by date using a Paired t-test and when the assumption of normality was not met, a Signed Rank test; results are shown in the in-figure caption. The bottom panel shows the data from the top panel minus the seasonal average from 1991-1993; data values above the origin indicate increases relative to the 1991-93 period and below indicate decreases.

Paired t-test: significantly different by < 0.03 ppm; p-value < 0.001.

Not an ecologically significant difference, data from either station or the average may be used.
Figure 53: Dissolved Ammonium, Niantic Bay Boundary Conditions.
The top panel shows the available data from stations M3 and K2 of the CTDEEP Long Island Sound sampling program (see Figure 24, page 53 for a map of station locations). Data were compared by date using a Paired t-test and when the assumption of normality was not met, a Signed Rank test; results are shown in the in-figure caption. The bottom panel shows the data from the top panel minus the seasonal average from 1991-1993; data values above the origin indicate increases relative to the 1991-93 period and below indicate decreases.
Figure 54: Dissolved Nitrate + Nitrite, Niantic Bay Boundary Conditions.

The top panel shows the available data from stations M3 and K2 of the CTDEEP Long Island Sound sampling program (see Figure 24, page 53 for a map of station locations). Data were compared by date using a Paired t-test and when the assumption of normality was not met, a Signed Rank test; results are shown in the in-figure caption. The bottom panel shows the data from the top panel minus the seasonal average from 1991-1993; data values above the origin indicate increases relative to the 1991-93 period and below indicate decreases.
Figure 55: Particulate Nitrogen, Niantic Bay Boundary Conditions.

The top panel shows the available data from stations M3 and K2 of the CTDEEP Long Island Sound sampling program (see Figure 24, page 53 for a map of station locations). Data were compared by date using a Paired t-test and when the assumption of normality was not met, a Signed Rank test; results are shown in the in-figure caption. The bottom panel shows the data from the top panel minus the seasonal average from 1991-1993; data values above the origin indicate increases relative to the 1991-93 period and below indicate decreases.
Figure 56: Dissolved Inorganic Nitrogen and Dissolved Organic Nitrogen, Niantic Bay Boundary Conditions.

Data averaged from stations M3 and K2 of the CTDEEP Long Island Sound sampling program (see Figure 24, page 53 for a map of station locations). DIN is only calculated for dates when ammonium and nitrate + nitrite were both available. DON is only calculated when DIN and TDN were both available. The bottom panel shows the data from the top panel minus the seasonal average from 1991-1993; data values above the origin indicate increases relative to the 1991-93 period and below indicate decreases.
### 11.1 C:N molar ratios for macrophytes, by ordinal date

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<th><em>Ulva sp.</em>, blade form C:N molar ratio</th>
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1590 12 Appendix D – Statistical Results

1591 12.1 Agardhiella subulata non-winter C:N molar ratio

1592 Note: X is ordinal date.

1593 Nonlinear Regression

1594 Data Source: Data 2 in MacrophyteCN.JNB

1595 Equation: Polynomial, Cubic

f = y0 + ax + bx^2 + cx^3

1596

1597 R  Rsqr  Adj Rsqr  Standard Error of Estimate

1598

1599 Coefficient  Std. Error  t  P

1600 y0  2.1855  6.3945  0.3418  0.7337

1601 a  0.0575  0.1069  0.5379  0.5926

1602 b  3.2202E-005  0.0005  0.0589  0.9532

1603 c  -4.6103E-007  8.6619E-007 -0.5322  0.5964

1604

1605 Analysis of Variance:

1606

1607 DF  SS  MS

1608 Regression 4  7456.1860  1864.0465

1609 Residual 63  199.4844  3.1664

1610 Total 67  7655.6704  114.2637

1611 Corrected for the mean of the observations:

1612

1613 DF  SS  MS  F  P

1614 Regression 3  100.5877  33.5292  10.5890 <0.0001

1615 Residual 63  199.4844  3.1664

1616 Total 66  300.0721  4.5465

1617 Statistical Tests:

1618 Normality Test (Shapiro-Wilk) Failed (P = 0.0448)

1619 W Statistic= 0.9632  Significance Level = 0.0500

1620 Constant Variance Test Passed (P = 0.3797)

Page 94 of 127
Fit Equation Description:

[Variables]

x = col(9)
y = col(7)
reciprocal_y = 1/abs(y)
reciprocal_ysquare = 1/y^2

'Automatic Initial Parameter Estimate Functions
F(q)=ape(x,y,3,0,1)

[Parameters]
y0 = F(0)[1] "Auto [[previous: 2.18554]]
a = F(0)[2] "Auto [[previous: 0.0575006]]
b = F(0)[3] "Auto [[previous: 3.22019e-005]]
c = F(0)[4] "Auto [[previous: -4.61028e-007]]

[Equation]
f=y0+a*x+b*x^2+c*x^3

fit f to y

"fit f to y with weight reciprocal_y
"fit f to y with weight reciprocal_ysquare

[Options]
tolerance=1e-10
stepsize=1
iterations=200

Number of Iterations Performed = 1

12.2 Ulva sp., blade form non-winter C:N molar ratio

Note: X is ordinal date.

Nonlinear Regression  Sunday, June 04, 2017, 4:51:37 PM

Data Source: Copy of Data 2 in MacrophyteCN.JNB
Equation: Polynomial, Cubic

f=y0+a*x+b*x^2+c*x^3

R  Rsqr  Adj Rsqr  Standard Error of Estimate
0.5090 0.2591 0.2443  6.6434

Coefficient  Std. Error  t  P

y0  -3.9563  6.6285 -0.5969  0.5515
a  0.4356  0.1305  3.3375  0.0011
b  -0.0018  0.0008 -2.3526  0.0199
c  2.0453E-006 1.3748E-006 1.4877  0.1389

Analysis of Variance:

Analysis of Variance:

DF  SS  MS
Corrected for the mean of the observations:

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<th>F</th>
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Statistical Tests:

- Normality Test (Shapiro-Wilk) Failed (P = 0.0331)
- Constant Variance Test Passed (P = 0.2539)

Fit Equation Description:

Variables:
- x = col(9)
- y = col(7)
- reciprocal_y = 1/abs(y)
- reciprocal_ysquare = 1/y^2

Automatic Initial Parameter Estimate Functions
- F(q)=ape(x,y,3,0,1)

Parameters:
- y0 = F(0)[1] "Auto [[previous: -3.95632]]
- a = F(0)[2] "Auto [[previous: 0.4356]]
- b = F(0)[3] "Auto [[previous: -0.00181005]]
- c = F(0)[4] "Auto [[previous: 2.04529e-006]]

Equation:
- f=y0+a*x+b*x^2+c*x^3
- fit f to y
- fit f to y with weight reciprocal_y
- fit f to y with weight reciprocal_ysquare

Options:
- tolerance=1e-10
- stepsize=1
- iterations=200

Number of Iterations Performed = 1

12.3 Zostera marina non-winter C:N molar ratio

Nonlinear Regression

Data Source: Copy of Copy of Data 2 in MacrophyteCN.JNB
Equation: Polynomial, Cubic
f=y0+a*x+b*x^2+c*x^3
R    Rsqr   Adj Rsqr   Standard Error of Estimate
0.7009 0.4913 0.4747 5.9015

Coefficient    Std. Error   t    P
y0       -440.2775  129.8478  -3.3907  0.0010
a            5.6432   1.8002   3.1347  0.0023
b          -0.0214   0.0082  -2.6162  0.0104
c    2.5763E-005 1.2235E-005  2.1057  0.0380

Analysis of Variance:

DF  SS     MS
Regression  4 109541.3522 27385.3380
Residual 92 3204.1499  34.8277
Total   96 112745.5021 1174.4323

Corrected for the mean of the observations:

DF  SS     MS   F   P
Regression 3 3094.7100 1031.5700 29.6192 <0.0001
Residual 92 3204.1499  34.8277
Total  95 6298.8599  66.3038

Statistical Tests:

Normality Test (Shapiro-Wilk)  Passed  (P = 0.9494)
W Statistic= 0.9940  Significance Level = 0.0500

Constant Variance Test  Failed  (P = 0.0077)

Fit Equation Description:

x = col(9)
y = col(7)
reciprocal_y = 1/abs(y)
reciprocal_ysquare = 1/y^2
'Automatic Initial Parameter Estimate Functions
F(q)=ape(x,y,3,0,1)

[Parameters]
y0 = F(0)[1] "Auto [[previous: -440.278]]
a = F(0)[2] "Auto [[previous: 5.64317]]
b = F(0)[3] "Auto [[previous: -0.0214138]]
c = F(0)[4] "Auto [[previous: 2.5763e-005]]

Equation
f=y0+a*x+b*x^2+c*x^3

fit f to y
"fit f to y with weight reciprocal_y
"fit f to y with weight reciprocal_ysquare
[Constraints]
[Options]
tolerance=1e-10
13 Appendix E – Model Box Hypsography Calculations

Following are output from the program Surfer, from which the volume and area at various box depths were calculated for model boxes. The volume is listed as the “Positive Volume [Cut]”. Area is listed as the “Positive Planar Area”.

VOLUME COMPUTATIONS

UPPER SURFACE
Grid File: C:\Users\Vaudrey\Dropbox\bathymetry\Niantic\NRE model 2018\NRbathCCmean_out_UPPER_2018.grd
Grid size as read: 100 cols by 285 rows
Delta X: 17.5590585859
Delta Y: 17.2143333451
X-Range: 229335.0473 to 231073.3941
Y-Range: 54701.06707 to 59589.93774
Z-Range: -0.106743097696 to 7.11382401109

LOWER SURFACE
Level Surface defined by Z = 0

VOLUMES
Approximated Volume by
Trapezoidal Rule: 1946086.13002
Simpson’s Rule: 1944194.88825
Simpson’s 3/8 Rule: 1946227.0003

CUT & FILL VOLUMES
Positive Volume [Cut]: 1946110.50655
Negative Volume [Fill]: 24.3765256193
Cut minus Fill: 1946086.13002

AREAS
Positive Planar Area
(Upper above Lower): 608589.825729
Negative Planar Area
(Lower above Upper): 25.7608001781
Blanked Planar Area: 7889937.09828
Total Planar Area: 8498552.68481

Positive Surface Area
(Upper above Lower): 609233.011375
Negative Surface Area

(Lower above Upper): 25.8395440627

VOLUME COMPUTATIONS

UPPER SURFACE

Grid File: C:\Users\Vaudrey\Dropbox\bathymetry\Niantic\NRE model 2018\NRbathCCmean_out_UPPER_2018.grd

Grid size as read: 100 cols by 285 rows

Delta X: 17.5590585859

Delta Y: 17.2143333451

X-Range: 229335.0473 to 231073.3941

Y-Range: 54701.06707 to 59589.93774

Z-Range: -0.106743097696 to 7.11382401109

LOWER SURFACE

Level Surface defined by Z = 0.5

VOLUMES

Approximated Volume by

Trapezoidal Rule: 1615405.49845

Simpson's Rule: 1613379.91558

Simpson's 3/8 Rule: 1616382.32725

CUT & FILL VOLUMES

Positive Volume [Cut]: 1626654.01474

Negative Volume [Fill]: 11248.5162899

Cut minus Fill: 1615405.49845

AREAS

Positive Planar Area

(Upper above Lower): 587671.140076

Negative Planar Area

(Lower above Upper): 20944.4464531

Blanked Planar Area: 7889937.09828

Total Planar Area: 8498552.68481

Positive Surface Area

(Upper above Lower): 588300.574076

Negative Surface Area

(Lower above Upper): 20958.276436

VOLUME COMPUTATIONS

UPPER SURFACE

Grid File: C:\Users\Vaudrey\Dropbox\bathymetry\Niantic\NRE model 2018\NRbathCCmean_out_UPPER_2018.grd
Grid size as read: 100 cols by 285 rows
Delta X: 17.5590585859
Delta Y: 17.2143333451
X-Range: 229335.0473 to 231073.3941
Y-Range: 54701.06707 to 59589.93774
Z-Range: -0.106743097696 to 7.11382401109

LOWER SURFACE
Level Surface defined by Z = 1

VOLUMES
Approximated Volume by
Trapezoidal Rule: 1284724.86689
Simpson's Rule: 1282564.9429
Simpson's 3/8 Rule: 1286537.6542

CUT & FILL VOLUMES
Positive Volume [Cut]: 1330928.87615
Negative Volume [Fill]: 46204.0092697
Cut minus Fill: 1284724.86689

AREAS
Positive Planar Area
(Upper above Lower): 549434.038268
Negative Planar Area
(Lower above Upper): 59181.5482614
Blanked Planar Area: 7889937.09828
Total Planar Area: 8498552.68481
Positive Surface Area
(Upper above Lower): 550014.718271
Negative Surface Area
(Lower above Upper): 59244.1326481

VOLUME COMPUTATIONS

UPPER SURFACE
Grid File: C:\Users\Vaudrey\Dropbox\bathymetry\Niantic\NRE model 2018\NRbathCCmean_out_UPPER_2018.grd
Grid size as read: 100 cols by 285 rows
Delta X: 17.5590585859
Delta Y: 17.2143333451
X-Range: 229335.0473 to 231073.3941
Y-Range: 54701.06707 to 59589.93774
Z-Range: -0.106743097696 to 7.11382401109

LOWER SURFACE
1926 Level Surface defined by $Z = 1.5$
1927
1928 VOLUMES
1929 Approximated Volume by
1930 Trapezoidal Rule: 954044.235317
1931 Simpson's Rule: 951749.970228
1932 Simpson's 3/8 Rule: 956692.981152
1933
1934 CUT & FILL VOLUMES
1935 Positive Volume [Cut]: 1066972.97662
1936 Negative Volume [Fill]: 112928.741301
1937 Cut minus Fill: 954044.235317
1938
1939 AREAS
1940 Positive Planar Area
1941 (Upper above Lower): 485076.506607
1942 Negative Planar Area
1943 (Lower above Upper): 123539.079922
1944 Blanked Planar Area: 788937.09828
1945 Total Planar Area: 8498552.68481
1946
1947 Positive Surface Area
1948 (Upper above Lower): 485587.75343
1949 Negative Surface Area
1950 (Lower above Upper): 123671.097489
1951
1952 VOLUME COMPUTATIONS
1953
1954 UPPER SURFACE
1955 Grid File: C:\Users\Vaudrey\Dropbox\bathymetry\Niantic\NRE model 2018\NRbathCCmean_out_UPPER_2018.grd
1956 Grid size as read: 100 cols by 285 rows
1957 Delta X: 17.5590585859
1958 Delta Y: 17.2143333451
1959 X-Range: 229335.0473 to 231073.3941
1960 Y-Range: 54701.06707 to 59589.93774
1961 Z-Range: -0.106743097696 to 7.11382401109
1962
1963 LOWER SURFACE
1964 Level Surface defined by $Z = 2$
1965
1966 VOLUMES
1967 Approximated Volume by
1968 Trapezoidal Rule: 623363.603748
1969 Simpson's Rule: 620934.997554
1971
1972
<table>
<thead>
<tr>
<th>Year</th>
<th>CUT &amp; FILL VOLUMES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1973</td>
<td>Positive Volume [Cut]: 832014.371205</td>
</tr>
<tr>
<td>1974</td>
<td>Negative Volume [Fill]: 208650.767457</td>
</tr>
<tr>
<td>1975</td>
<td>Cut minus Fill: 623363.603748</td>
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<table>
<thead>
<tr>
<th>Year</th>
<th>AREAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1979</td>
<td>Positive Planar Area</td>
</tr>
<tr>
<td>1980</td>
<td>(Upper above Lower): 437586.029887</td>
</tr>
<tr>
<td>1981</td>
<td>Negative Planar Area</td>
</tr>
<tr>
<td>1982</td>
<td>(Lower above Upper): 171029.556642</td>
</tr>
<tr>
<td>1983</td>
<td>Blanked Planar Area: 7889937.09828</td>
</tr>
<tr>
<td>1984</td>
<td>Total Planar Area: 8498552.68481</td>
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</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>VOLUME COMPUTATIONS</th>
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<tbody>
<tr>
<td>1985</td>
<td>UPPER SURFACE</td>
</tr>
<tr>
<td>1994</td>
<td>Grid File: C:\Users\Vaudrey\Dropbox\bathymetry\Niantic\NRE model 2018\NRbathCCmean_out_UPPER_2018.grd</td>
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<tr>
<td>1995</td>
<td>Grid size as read: 100 cols by 285 rows</td>
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<tr>
<td>1996</td>
<td>Delta X: 17.5590585859</td>
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<tr>
<td>1997</td>
<td>Delta Y: 17.2143333451</td>
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<tr>
<td>1998</td>
<td>X-Range: 229335.0473 to 231073.3941</td>
</tr>
<tr>
<td>1999</td>
<td>Y-Range: 54701.06707 to 59589.93774</td>
</tr>
<tr>
<td>2000</td>
<td>Z-Range: -0.106743097696 to 7.11382401109</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>LOWER SURFACE</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003</td>
<td>Level Surface defined by Z = 2.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>VOLUMES</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>Approximated Volume by</td>
</tr>
<tr>
<td>2008</td>
<td>Trapezoidal Rule: 292682.97218</td>
</tr>
<tr>
<td>2009</td>
<td>Simpson's Rule: 290120.02488</td>
</tr>
<tr>
<td>2010</td>
<td>Simpson's 3/8 Rule: 297003.635057</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>CUT &amp; FILL VOLUMES</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013</td>
<td>Positive Volume [Cut]: 623525.159625</td>
</tr>
<tr>
<td>2014</td>
<td>Negative Volume [Fill]: 330842.187446</td>
</tr>
<tr>
<td>2015</td>
<td>Cut minus Fill: 292682.97218</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Year</th>
<th>AREAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>2018</td>
<td>Positive Planar Area</td>
</tr>
<tr>
<td>2019</td>
<td>(Upper above Lower): 384399.547469</td>
</tr>
</tbody>
</table>
2020 Negative Planar Area
2021 (Lower above Upper): 224216.03906
2022 Blanked Planar Area: 7889937.09828
2023 Total Planar Area: 8498552.68481
2024 Positive Surface Area
2025 (Upper above Lower): 384748.73674
2026 Negative Surface Area
2027 (Lower above Upper): 224510.11418

VOLUME COMPUTATIONS

UPPER SURFACE

Grid File: C:\Users\Vaudrey\Dropbox\bathymetry\Niantic\NRE model 2018\NRbathCCmean_out_UPPER_2018.grd
Grid size as read: 100 cols by 285 rows
Delta X: 17.5590585859
Delta Y: 17.2143333451
X-Range: 229335.0473 to 231073.3941
Y-Range: 54701.06707 to 59589.93774
Z-Range: -0.106743097696 to 7.11382401109

LOWER SURFACE

Level Surface defined by Z = 3

VOLUMES

Approximated Volume by
Trapezoidal Rule: -37997.6593889
Simpson’s Rule: -40694.9477943
Simpson’s 3/8 Rule: -32841.0379911

CUT & FILL VOLUMES

Positive Volume [Cut]: 447810.592183
Negative Volume [Fill]: 485808.251572
Cut minus Fill: -37997.6593889

AREAS

Positive Planar Area
(Upper above Lower): 309019.769831
Negative Planar Area
(Lower above Upper): 299595.816698
Blanked Planar Area: 7889937.09828
Total Planar Area: 8498552.68481

Positive Surface Area
(Upper above Lower): 309291.81243
Negative Surface Area
VOLUME COMPUTATIONS

UPPER SURFACE

Grid File: C:\Users\Vaudrey\Dropbox\bathymetry\Niantic\NRE model 2018\NRbathCCmean_out_UPPER_2018.grd

Grid size as read: 100 cols by 285 rows

Delta X: 17.5590585859
Delta Y: 17.2143333451

X-Range: 229335.0473 to 231073.3941
Y-Range: 54701.06707 to 59589.93774
Z-Range: -0.106743097696 to 7.11382401109

LOWER SURFACE

Level Surface defined by Z = 3.5

VOLUMES

Approximated Volume by
Trapezoidal Rule: -368678.290957
Simpson's Rule: -371509.920468
Simpson's 3/8 Rule: -362685.711039

CUT & FILL VOLUMES

Positive Volume [Cut]: 305880.973592
Negative Volume [Fill]: 674559.264549
Cut minus Fill: -368678.290957

AREAS

Positive Planar Area
(Upper above Lower): 253258.222302
Negative Planar Area
(Upper above Lower): 355797.426178
Blanked Planar Area: 7889937.09828
Total Planar Area: 8498552.68481

Positive Surface Area
(Upper above Lower): 253461.424742
Negative Surface Area
(Upper above Lower): 355797.426178

VOLUME COMPUTATIONS

UPPER SURFACE

Grid File: C:\Users\Vaudrey\Dropbox\bathymetry\Niantic\NRE model 2018\NRbathCCmean_out_UPPER_2018.grd

Grid size as read: 100 cols by 285 rows

Page 104 of 127
Delta X: 17.5590585859
Delta Y: 17.2143333451
X-Range: 229335.0473 to 231073.3941
Y-Range: 54701.06707 to 59589.93774
Z-Range: -0.106743097696 to 7.11382401109

LOWER SURFACE
Level Surface defined by Z = 4

VOLUMES
Approximated Volume by
Trapezoidal Rule: -699358.922526
Simpson's Rule: -702324.893143
Simpson's 3/8 Rule: -692530.384087

CUT & FILL VOLUMES
Positive Volume [Cut]: 189516.305145
Negative Volume [Fill]: 888875.227671
Cut minus Fill: -699358.922526

AREAS
Positive Planar Area
(Upper above Lower): 206388.339232
Negative Planar Area
(Lower above Upper): 402227.247297
Blanked Planar Area: 7889937.09828
Total Planar Area: 8498552.68481

Positive Surface Area
(Upper above Lower): 206528.7256
Negative Surface Area
(Lower above Upper): 402730.125319

VOLUME COMPUTATIONS

UPPER SURFACE
Grid File: C:\Users\Vaudrey\Dropbox\bathymetry\Niantic\NRE model 2018WRbathCCmean_out_UPPER_2018.grd
Grid size as read: 100 cols by 285 rows
Delta X: 17.5590585859
Delta Y: 17.2143333451
X-Range: 229335.0473 to 231073.3941
Y-Range: 54701.06707 to 59589.93774
Z-Range: -0.106743097696 to 7.11382401109

LOWER SURFACE
Level Surface defined by Z = 4.5
VOLUMES

Approximated Volume by

Trapezoidal Rule: -1030039.55409

Simpson's Rule: -1033139.86582

Simpson's 3/8 Rule: -1022375.05713

CUT & FILL VOLUMES

Positive Volume [Cut]: 95713.0994418

Negative Volume [Fill]: 1125752.65354

Cut minus Fill: -1030039.55409

AREAS

Positive Planar Area

(Upper above Lower): 161880.90723

Negative Planar Area

(Lower above Upper): 446734.679299

Blanked Planar Area: 7889937.09828

Total Planar Area: 8498552.68481

Positive Surface Area

(Upper above Lower): 161967.161141

Negative Surface Area

(Lower above Upper): 447291.689778

VOLUME COMPUTATIONS

UPPER SURFACE

Grid File: C:\Users\Vaudrey\Dropbox\bathymetry\Niantic\NRE model 2018\NRbathCCmean_out_UPPER_2018.grd

Grid size as read: 100 cols by 285 rows

Delta X: 17.5590585859

Delta Y: 17.2143333451

X-Range: 229335.0473 to 231073.3941

Y-Range: 54701.06707 to 59589.93774

Z-Range: -0.106743097696 to 7.11382401109

LOWER SURFACE

Level Surface defined by Z = 5

VOLUMES

Approximated Volume by

Trapezoidal Rule: -1360720.18566

Simpson's Rule: -1363954.83849

Simpson's 3/8 Rule: -1352219.73018

CUT & FILL VOLUMES
Positive Volume [Cut]: 29683.7191839
Negative Volume [Fill]: 1390403.90485
Cut minus Fill: -1360720.18566

AREAS
Positive Planar Area
(Upper above Lower): 92279.1236833
Negative Planar Area
(Lower above Upper): 516336.462846
Blanked Planar Area: 788937.09828
Total Planar Area: 8498552.68481

Positive Surface Area
(Upper above Lower): 92323.7727569
Negative Surface Area
(Lower above Upper): 516935.078163

VOLUME COMPUTATIONS
UPPER SURFACE
Grid File: C:\Users\Vaudrey\Dropbox\bathymetry\Niantic\NRE model 2018\NRbathCCmean_out_UPPER_2018.grd
Grid size as read: 100 cols by 285 rows
Delta X: 17.5590585859
Delta Y: 17.2143333451
X-Range: 229335.0473 to 231073.3941
Y-Range: 54701.06707 to 59589.93774
Z-Range: -0.106743097696 to 7.11382401109

LOWER SURFACE
Level Surface defined by Z = 5.5

VOLUMES
Approximated Volume by
Trapezoidal Rule: -1691400.81723
Simpson's Rule: -1694769.81117
Simpson's 3/8 Rule: -1682064.40323

CUT & FILL VOLUMES
Positive Volume [Cut]: 5864.13679473
Negative Volume [Fill]: 1697264.95403
Cut minus Fill: -1691400.81723

AREAS
Positive Planar Area
(Upper above Lower): 17472.2188078
Negative Planar Area
VOLUME COMPUTATIONS

UPPER SURFACE

Grid File: \Users\Vaudrey\Dropbox\bathymetry\Niantic\NRE model 2018\NRbathCCmean_out_UPPER_2018.grd
Grid size as read: 100 cols by 285 rows
Delta X: 17.5590585859
Delta Y: 17.2143333451
X-Range: 229335.0473 to 231073.3941
Y-Range: 54701.06707 to 59589.93774
Z-Range: -0.106743097696 to 7.11382401109

LOWER SURFACE

Level Surface defined by Z = 6

VOLUMES

Approximated Volume by
Trapezoidal Rule: -2022081.4488
Simpson's Rule: -2025584.78384
Simpson's 3/8 Rule: -2011909.07628

CUT & FILL VOLUMES

Positive Volume [Cut]: 1233.98848933
Negative Volume [Fill]: 2023315.43729
Cut minus Fill: -2022081.4488

AREAS

Positive Planar Area
(Upper above Lower): 3501.76497884
Negative Planar Area
(Lower above Upper): 605113.821551
Blanked Planar Area: 788937.09828
Total Planar Area: 8498552.68481

Positive Surface Area
(Upper above Lower): 3508.44204028
Negative Surface Area
(Upper above Lower): 591768.467998
VOLUME COMPUTATIONS

UPPER SURFACE
Grid File: C:\Users\Vaudrey\Dropbox\bathymetry\Niantic\NRE model 2018\NRbathCCmean_out_MID_2018.grd
Grid size as read: 100 cols by 285 rows
Delta X: 17.5590585859
Delta Y: 17.2143333451
X-Range: 229335.0473 to 231073.3941
Y-Range: 54701.06707 to 59589.93774
Z-Range: -0.0566458832731 to 6.710455571

LOWER SURFACE
Level Surface defined by Z = 0

VOLUMES
Approximated Volume by
Trapezoidal Rule: 2880061.05517
Simpson's Rule: 2879341.25147
Simpson's 3/8 Rule: 2880165.85919

CUT & FILL VOLUMES
Positive Volume [Cut]: 2880127.32452
Negative Volume [Fill]: 66.2693513709
Cut minus Fill: 2880061.05517

AREAS
Positive Planar Area
(Upper above Lower): 917857.378046
Negative Planar Area
(Lower above Upper): 4965.26197137
Blanked Planar Area: 7575730.04479
Total Planar Area: 8498552.68481

Positive Surface Area
(Upper above Lower): 918237.092028
Negative Surface Area
(Lower above Upper): 4965.31459899

VOLUME COMPUTATIONS

UPPER SURFACE
LOWER SURFACE

Level Surface defined by Z = 0.5

VOLUMES

Approximated Volume by
Trapezoidal Rule: 2391899.0625
Simpson's Rule: 2390843.40603
Simpson's 3/8 Rule: 2391597.69459

CUT & FILL VOLUMES

Positive Volume [Cut]: 2408044.56755
Negative Volume [Fill]: 16145.5050508
Cut minus Fill: 2391899.0625

AREAS

Positive Planar Area
(Upper above Lower): 897495.838806
Negative Planar Area
(Lower above Upper): 25326.8012111
Blanked Planar Area: 7575730.04479
Total Planar Area: 8498552.68481

Positive Surface Area
(Upper above Lower): 897864.274056
Negative Surface Area
(Lower above Upper): 25338.1325713

VOLUME COMPUTATIONS

UPPER SURFACE

Grid File: C:\Users\Vaudrey\Dropbox\bathymetry\Niantic\NRE model 2018\NRbathCCmean_out_MID_2018.grd

Grid size as read: 100 cols by 285 rows
Delta X: 17.5590585859
Delta Y: 17.2143333451
X-Range: 229335.0473 to 231073.3941
Y-Range: 54701.06707 to 59589.93774
Z-Range: -0.0566458832731 to 6.710455571
LOWER SURFACE
Level Surface defined by Z = 1

VOLUMES
Approximated Volume by
Trapezoidal Rule: 1903737.06983
Simpson's Rule: 1902345.56059
Simpson's 3/8 Rule: 1903029.52998

CUT & FILL VOLUMES
Positive Volume [Cut]: 1955424.41304
Negative Volume [Fill]: 51687.343217
Cut minus Fill: 1903737.06983

AREAS
Positive Planar Area (Upper above Lower): 865215.118635
Negative Planar Area (Lower above Upper): 57607.5213819
Blanked Planar Area: 7575730.04479
Total Planar Area: 8498552.68481

Positive Surface Area (Upper above Lower): 865548.907176
Negative Surface Area (Lower above Upper): 57653.4994507

VOLUME COMPUTATIONS
UPPER SURFACE
Grid File: C:\Users\Vaudrey\Dropbox\bathymetry\Niantic\NRE model 2018\NRbathCCmean_out_MID_2018.grd
Grid size as read: 100 cols by 285 rows
Delta X: 17.5590585859
Delta Y: 17.2143333451
X-Range: 229335.0473 to 231073.3941
Y-Range: 54701.06707 to 59589.93774
Z-Range: -0.0566458832731 to 6.710455571

LOWER SURFACE
Level Surface defined by Z = 1.5

VOLUMES
Approximated Volume by
Trapezoidal Rule: 1415575.07716
Simpson's Rule: 1413847.71516
Simpson's 3/8 Rule: 1414461.36537

CUT & FILL VOLUMES
Positive Volume [Cut]: 1525704.21346
Negative Volume [Fill]: 110129.136299
Cut minus Fill: 1415575.07716

AREAS
Positive Planar Area (Upper above Lower): 822835.421387
Negative Planar Area (Lower above Upper): 99987.2186296
Blanked Planar Area: 7575730.04479
Total Planar Area: 8498552.68481

Positive Surface Area (Upper above Lower): 823117.143809
Negative Surface Area (Lower above Upper): 100085.262818

VOLUME COMPUTATIONS
UPPER SURFACE
Grid File: C:\Users\Vaudrey\Dropbox\bathymetry\Niantic\NRE model 2018\NRbathCCmean_out_MID_2018.grd
Grid size as read: 100 cols by 285 rows
Delta X: 17.5590585859
Delta Y: 17.2143333451
X-Range: 229335.0473 to 231073.3941
Y-Range: 54701.06707 to 59589.93774
Z-Range: -0.0566458832731 to 6.710455571

LOWER SURFACE
Level Surface defined by Z = 2

VOLUMES
Approximated Volume by Trapezoidal Rule: 927413.084484
Simpson's Rule: 925349.869722
Simpson's 3/8 Rule: 925893.20076

CUT & FILL VOLUMES
Positive Volume [Cut]: 1122121.61887
Negative Volume [Fill]: 194708.534382
Cut minus Fill: 927413.084484

AREAS
Positive Planar Area
(Upper above Lower): 762942.291929
Negative Planar Area
(Lower above Upper): 159880.348088
Blanked Planar Area: 7575730.04479
Total Planar Area: 8498552.68481

Positive Surface Area
(Upper above Lower): 763164.09629
Negative Surface Area
(Lower above Upper): 160038.310337

VOLUME COMPUTATIONS

UPPER SURFACE
Grid File: C:\Users\Vaudrey\Dropbox\bathymetry\Niantic\NRE model 2018\NRbathCCmean_out_MID_2018.grd
Grid size as read: 100 cols by 285 rows
Delta X: 17.5590585859
Delta Y: 17.2143333451
X-Range: 229335.0473 to 231073.3941
Y-Range: 54701.06707 to 59589.93774
Z-Range: -0.0566458832731 to 6.710455571

LOWER SURFACE
Level Surface defined by Z = 2.5

VOLUMES
Approximated Volume by Trapezoidal Rule: 439251.091812
Simpson's Rule: 436852.024286
Simpson's 3/8 Rule: 437325.036152

CUT & FILL VOLUMES
Positive Volume [Cut]: 759604.858315
Negative Volume [Fill]: 320353.766503
Cut minus Fill: 439251.091812

AREAS
Positive Planar Area
(Upper above Lower): 672668.084765
Negative Planar Area
(Lower above Upper): 250154.555252
Blanked Planar Area: 7575730.04479
Total Planar Area: 8498552.68481

Positive Surface Area
(Upper above Lower): 672831.974334
Negative Surface Area
(Lower above Upper): 250370.432293

VOLUME COMPUTATIONS

UPPER SURFACE
Grid File: C:\Users\Vaudrey\Dropbox\bathymetry\Niantic\NRE model 2018\NRbathCCmean_out_MID_2018.grd
Grid size as read: 100 cols by 285 rows
Delta X: 17.5590585859
Delta Y: 17.2143333451
X-Range: 229335.0473 to 231073.3941
Y-Range: 54701.06707 to 59589.93774
Z-Range: -0.0566458832731 to 6.710455571

LOWER SURFACE
Level Surface defined by Z = 3

VOLUMES
Approximated Volume by
Trapezoidal Rule: -48910.90086
Simpson's Rule: -51645.8211502
Simpson's 3/8 Rule: -51243.1284568

CUT & FILL VOLUMES
Positive Volume [Cut]: 447847.123755
Negative Volume [Fill]: 496758.024615
Cut minus Fill: -48910.90086

AREAS
Positive Planar Area
(Upper above Lower): 551960.430792
Negative Planar Area
(Lower above Upper): 370862.209225
Blanked Planar Area: 7575730.04479
Total Planar Area: 8498552.68481

Positive Surface Area
(Upper above Lower): 552074.55412
Negative Surface Area
(Lower above Upper): 371127.852508

VOLUME COMPUTATIONS

UPPER SURFACE
Grid File: C:\Users\Vaudrey\Dropbox\bathymetry\Niantic\NRE model 2018\NRbathCCmean_out_MID_2018.grd

Grid size as read: 100 cols by 285 rows
Delta X: 17.5590585859
Delta Y: 17.2143333451
X-Range: 229335.0473 to 231073.3941
Y-Range: 54701.06707 to 59589.93774
Z-Range: -0.0566458832731 to 6.710455571

LOWER SURFACE
Level Surface defined by Z = 3.5

VOLUMES
Approximated Volume by
Trapezoidal Rule: -537072.893532
Simpson's Rule: -540143.666586
Simpson's 3/8 Rule: -539811.293065

CUT & FILL VOLUMES
Positive Volume [Cut]: 220657.658516
Negative Volume [Fill]: 757730.552048
Cut minus Fill: -537072.893532

AREAS
Positive Planar Area (Upper above Lower): 355274.393694
Negative Planar Area (Lower above Upper): 567548.246323
Blanked Planar Area: 7575730.552048
Total Planar Area: 8498552.68481

POSITIVE SURFACE AREA
(Upper above Lower): 355348.867051
NEGATIVE SURFACE AREA
(Lower above Upper): 567853.539576

VOLUME COMPUTATIONS

UPPER SURFACE
Grid File: C:\Users\Vaudrey\Dropbox\bathymetry\Niantic\NRE model 2018\NRbathCCmean_out_MID_2018.grd
Grid size as read: 100 cols by 285 rows
Delta X: 17.5590585859
Delta Y: 17.2143333451
X-Range: 229335.0473 to 231073.3941
Y-Range: 54701.06707 to 59589.93774
Z-Range: -0.0566458832731 to 6.710455571
LOWER SURFACE

Level Surface defined by Z = 4

VOLUMES

Approximated Volume by

Trapezoidal Rule: -1025234.8862

Simpson's Rule: -1028641.5120

Simpson's 3/8 Rule: -1028379.4576

CUT & FILL VOLUMES

Positive Volume [Cut]: 95989.9780408

Negative Volume [Fill]: -1121224.8642

Cut minus Fill: -1025234.8862

AREAS

Positive Planar Area (Upper above Lower): 152547.2923

Negative Planar Area (Lower above Upper): 770275.3476

Blanked Planar Area: 7575730.0447

Total Planar Area: 8498552.6848

Positive Surface Area (Upper above Lower): 152592.4754

Negative Surface Area (Lower above Upper): 770609.9312

VOLUME COMPUTATIONS

UPPER SURFACE

Grid File: C:\Users\Vaudrey\Dropbox\bathymetry\Niantic\NRE model 2018\NRbathCCmean_out_MID_2018.grd

Grid size as read: 100 cols by 285 rows

Delta X: 17.5590585859

Delta Y: 17.2143333451

X-Range: 229335.0473 to 231073.3941

Y-Range: 54701.06707 to 59589.93774

Z-Range: -0.0566458832731 to 6.710455571

LOWER SURFACE

Level Surface defined by Z = 4.5

VOLUMES

Approximated Volume by

Trapezoidal Rule: -1513396.8788

Simpson's Rule: -1517139.3574
Simpson's 3/8 Rule: -1516947.62228

CUT & FILL VOLUMES
Positive Volume [Cut]: 43340.2501048
Negative Volume [Fill]: 1556737.12898
Cut minus Fill: -1513396.87888

AREAS
Positive Planar Area (Upper above Lower): 67672.9035464
Negative Planar Area (Lower above Upper): 855149.736471
Blanked Planar Area: 7575730.04479
Total Planar Area: 8498552.68481

Positive Surface Area (Upper above Lower): 67700.4865589
Negative Surface Area (Lower above Upper): 855501.920068

VOLUME COMPUTATIONS
UPPER SURFACE
Grid File: C:\Users\Vaudrey\Dropbox\bathymetry\Niantic\NRE model 2018\WrbathCCmean_out_MID_2018.grd
Grid size as read: 100 cols by 285 rows
Delta X: 17.5590585859
Delta Y: 17.2143333451
X-Range: 229335.0473 to 231073.3941
Y-Range: 54701.06707 to 59589.93774
Z-Range: -0.0566458832731 to 6.710455571

LOWER SURFACE
Level Surface defined by Z = 5

VOLUMES
Approximated Volume by
Trapezoidal Rule: -2001558.87155
Simpson's Rule: -2005637.20289
Simpson's 3/8 Rule: -2005515.78689

CUT & FILL VOLUMES
Positive Volume [Cut]: 16585.6928057
Negative Volume [Fill]: 2018144.56435
Cut minus Fill: -2001558.87155

AREAS
Positive Planar Area
(Upper above Lower): 37935.7566796
Negative Planar Area
(Lower above Upper): 884886.883338
Blanked Planar Area: 7575730.04479
Total Planar Area: 8498552.68481

Positive Surface Area
(Upper above Lower): 37950.7750565
Negative Surface Area
(Lower above Upper): 885251.631571

VOLUME COMPUTATIONS

UPPER SURFACE
Grid File: C:\Users\Vaudrey\Dropbox\bathymetry\Niantic\NRE model 2018\NRbathCCmean_out_MID_2018.grd
Grid size as read: 100 cols by 285 rows
Delta X: 17.5590585859
Delta Y: 17.2143333451
X-Range: 229335.0473 to 231073.3941
Y-Range: 54701.06707 to 59589.93774
Z-Range: -0.0566458832731 to 6.710455571

LOWER SURFACE
Level Surface defined by Z = 5.5

VOLUMES
Approximated Volume by
Trapezoidal Rule: -2489720.86422
Simpson's Rule: -2494135.04833
Simpson's 3/8 Rule: -2494083.9515

CUT & FILL VOLUMES
Positive Volume [Cut]: 3885.94312719
Negative Volume [Fill]: 2493606.80735
Cut minus Fill: -2489720.86422

AREAS
Positive Planar Area
(Upper above Lower): 12727.1708714
Negative Planar Area
(Lower above Upper): 910095.469146
Blanked Planar Area: 7575730.04479
Total Planar Area: 8498552.68481

Positive Surface Area
VOLUME COMPUTATIONS

UPPER SURFACE
Grid File: C:\Users\Vaudrey\Dropbox\bathymetry\Niantic\NRE model 2018\NRbathCCmean_out_MID_2018.grd
Grid size as read: 100 cols by 285 rows
Delta X: 17.5590585859
Delta Y: 17.2143333451
X-Range: 229335.0473 to 231073.3941
Y-Range: 54701.06707 to 59589.93774
Z-Range: -0.0566458832731 to 6.710455571

LOWER SURFACE
Level Surface defined by Z = 6

VOLUMES
Approximated Volume by
Trapezoidal Rule: -2977882.85689
Simpson's Rule: -2982632.89377
Simpson's 3/8 Rule: -2982652.11611

CUT & FILL VOLUMES
Positive Volume [Cut]: 418.474738025
Negative Volume [Fill]: 2978301.33163
Cut minus Fill: -2977882.85689

AREAS
Positive Planar Area
(Upper above Lower): 2204.75259987
Negative Planar Area
(Upper above Lower): 207.01150309
Blanked Planar Area: 7575730.04479
Total Planar Area: 8498552.68481

Positive Surface Area
(Upper above Lower): 2207.01150309
Negative Surface Area
(Upper above Lower): 920995.395124
UPPER SURFACE

Grid File: C:\Users\Vaudrey\Dropbox\bathymetry\Niantic\NRE model 2018\WRbathCCmean_out_LOWER_2018.grd

Grid size as read: 100 cols by 285 rows
Delta X: 17.5590585859
Delta Y: 17.2143333451
X-Range: 229335.0473 to 231073.3941
Y-Range: 54701.06707 to 59589.93774
Z-Range: -0.119693311644 to 4.16498545386

LOWER SURFACE

Level Surface defined by Z = 0

VOLUMES

Approximated Volume by
Trapezoidal Rule: 2131303.13199
Simpson's Rule: 2131870.03508
Simpson's 3/8 Rule: 2129842.19271

CUT & FILL VOLUMES

Positive Volume [Cut]: 2131341.0067
Negative Volume [Fill]: 37.8747111329
Cut minus Fill: 2131303.13199

AREAS

Positive Planar Area
(Upper above Lower): 1403335.9004
(Negative Planar Area
(Lower above Upper): 243.178838157
Blanked Planar Area: 7094973.60557
Total Planar Area: 8498552.68481

Positive Surface Area
(Upper above Lower): 1403711.84297
(Negative Surface Area
(Lower above Upper): 243.2028634

VOLUME COMPUTATIONS

UPPER SURFACE

Grid File: C:\Users\Vaudrey\Dropbox\bathymetry\Niantic\NRE model 2018\WRbathCCmean_out_LOWER_2018.grd

Grid size as read: 100 cols by 285 rows
Delta X: 17.5590585859
Delta Y: 17.2143333451
X-Range: 229335.0473 to 231073.3941
Y-Range: 54701.06707 to 59589.93774

Page 120 of 127
Z-Range: -0.119693311644 to 4.16498545386

LOWER SURFACE
Level Surface defined by Z = 0.5

VOLUMES
Approximated Volume by
Trapezoidal Rule: 1393014.79323
Simpson’s Rule: 1393161.88036
Simpson’s 3/8 Rule: 1391612.89056

CUT & FILL VOLUMES
Positive Volume [Cut]: 1423642.70029
Negative Volume [Fill]: 30627.9070607
Cut minus Fill: 1393014.79323

AREAS
Positive Planar Area (Upper above Lower): 1327996.3562
Negative Planar Area (Lower above Upper): 75582.7230357
Blanked Planar Area: 7094973.60557
Total Planar Area: 8498552.68481

Positive Surface Area (Upper above Lower): 1328356.29255
Negative Surface Area (Lower above Upper): 75598.7532807

VOLUME COMPUTATIONS

UPPER SURFACE
Grid File: C:\Users\Vaudrey\Dropbox\bathymetry\Niantic\NRE model 2018\NRbathCCmean_out_LOWER_2018.grd
Grid size as read: 100 cols by 285 rows
Delta X: 17.5590585859
Delta Y: 17.2143333451
X-Range: 229335.0473 to 231073.3941
Y-Range: 54701.06707 to 59589.93774
Z-Range: -0.119693311644 to 4.16498545386

LOWER SURFACE
Level Surface defined by Z = 1

VOLUMES
Approximated Volume by
Trapezoidal Rule: 654726.454469
Simpson's Rule: 654453.725642
Simpson's 3/8 Rule: 653383.588418

CUT & FILL VOLUMES
Positive Volume [Cut]: 775672.59286
Negative Volume [Fill]: 120946.138391
Cut minus Fill: 654726.454469

AREAS
Positive Planar Area (Upper above Lower): 1197081.0468
Negative Planar Area (Lower above Upper): 206498.032438
Blanked Planar Area: 7094973.60557
Total Planar Area: 8498552.68481

Positive Surface Area (Upper above Lower): 1197400.74145
Negative Surface Area (Lower above Upper): 206554.30438

VOLUME COMPUTATIONS
UPPER SURFACE
Grid File: C:\Users\Vaudrey\Dropbox\bathymetry\Niantic\NRE model 2018\NRbathCCmean_out_LOWER_2018.grd
Grid size as read: 100 cols by 285 rows
Delta X: 17.5590585859
Delta Y: 17.2143333451
X-Range: 229335.0473 to 231073.3941
Y-Range: 54701.06707 to 59589.93774
Z-Range: -0.119693311644 to 4.16498545386

LOWER SURFACE
Level Surface defined by Z = 1.5

VOLUMES
Approximated Volume by Trapezoidal Rule: -83561.8842938
Simpson's Rule: -84254.4290752
Simpson's 3/8 Rule: -84845.7137261

CUT & FILL VOLUMES
Positive Volume [Cut]: 322873.298372
Negative Volume [Fill]: 406435.182666
Cut minus Fill: -83561.8842938
AREAS

Positive Planar Area
(Upper above Lower): 538895.866977

Negative Planar Area
(Lower above Upper): 864683.212263

Blanked Planar Area: 7094973.60557

Total Planar Area: 8498552.68481

Positive Surface Area
(Upper above Lower): 539153.501851

Negative Surface Area
(Lower above Upper): 864801.543979

VOLUME COMPUTATIONS

UPPER SURFACE

Grid File: C:\Users\Vaudrey\Dropbox\bathymetry\Niantic\NRE model 2018\NRbathCCmean_out_LOWER_2018.grd

Grid size as read: 100 cols by 285 rows

Delta X: 17.5590585859
Delta Y: 17.2143333451

X-Range: 229335.0473 to 231073.3941
Y-Range: 54701.06707 to 59589.93774
Z-Range: -0.119693311644 to 4.16498545386

LOWER SURFACE

Level Surface defined by Z = 2

VOLUMES

Approximated Volume by

Trapezoidal Rule: -821850.223056
Simpson's Rule: -822962.583793
Simpson's 3/8 Rule: -823075.01587

CUT & FILL VOLUMES

Positive Volume [Cut]: 150530.179633
Negative Volume [Fill]: 972380.402689
Cut minus Fill: -821850.223056

AREAS

Positive Planar Area
(Upper above Lower): 225236.170104

Negative Planar Area
(Lower above Upper): 1178342.90914

Blanked Planar Area: 7094973.60557

Total Planar Area: 8498552.68481
3002 Positive Surface Area
3003 (Upper above Lower): 225415.276274
3004 Negative Surface Area
3005 (Lower above Upper): 1178539.76956
3006
3007 VOLUME COMPUTATIONS
3008
3009 UPPER SURFACE
3010 Grid File: C:\Users\Vaudrey\Dropbox\bathymetry\Niantic\NRE model 2018\NRbathCCmean_out_LOWER_2018.grd
3012 Grid size as read: 100 cols by 285 rows
3013 Delta X: 17.5590585859
3014 Delta Y: 17.2143333451
3015 X-Range: 229335.0473 to 231073.3941
3016 Y-Range: 54701.06707 to 59589.93774
3017 Z-Range: -0.119693311644 to 4.16498545386
3018
3019 LOWER SURFACE
3020 Level Surface defined by Z = 2.5
3021
3022 VOLUMES
3023 Approximated Volume by
3024 Trapezoidal Rule: -1560138.56182
3025 Simpson's Rule: -1561670.73851
3026 Simpson's 3/8 Rule: -1561304.31801
3027
3028 CUT & FILL VOLUMES
3029 Positive Volume [Cut]: 63017.5577738
3030 Negative Volume [Fill]: 1623156.11959
3031 Cut minus Fill: -1560138.56182
3032
3033 AREAS
3034 Positive Planar Area
3035 (Upper above Lower): 129104.01182
3036 Negative Planar Area
3037 (Lower above Upper): 1274475.06742
3038 Blanked Planar Area: 7094973.60557
3039 Total Planar Area: 8498552.68481
3040
3041 Positive Surface Area
3042 (Upper above Lower): 129212.89521
3043 Negative Surface Area
3044 (Lower above Upper): 1274742.14991
3045
3046 VOLUME COMPUTATIONS
3047
3048 UPPER SURFACE
Grid File: C:\Users\Vaudrey\Dropbox\bathymetry\Niantic\NRE model 2018\NRbathCCmean_out_LOWER_2018.grd

Grid size as read: 100 cols by 285 rows
Delta X: 17.5590585859
Delta Y: 17.2143333451
X-Range: 229335.0473 to 231073.3941
Y-Range: 54701.06707 to 59589.93774
Z-Range: -0.119693311644 to 4.16498545386

LOWER SURFACE
Level Surface defined by Z = 3

VOLUMES
Approximated Volume by
Trapezoidal Rule: -2298426.90058
Simpson's Rule: -2300378.89323
Simpson's 3/8 Rule: -2299533.62016

CUT & FILL VOLUMES
Positive Volume [Cut]: 16631.3595701
Negative Volume [Fill]: 2315058.26015
Cut minus Fill: -2298426.90058

AREAS
Positive Planar Area (Upper above Lower): 55576.9763848
Negative Planar Area (Lower above Upper): 1348002.10286
Blanked Planar Area: 7094973.60557
Total Planar Area: 8498552.68481

Positive Surface Area (Upper above Lower): 55627.0397632
Negative Surface Area (Lower above Upper): 1348328.00607

VOLUME COMPUTATIONS

UPPER SURFACE
Grid File: C:\Users\Vaudrey\Dropbox\bathymetry\Niantic\NRE model 2018\NRbathCCmean_outLOWER_2018.grd
Grid size as read: 100 cols by 285 rows
Delta X: 17.5590585859
Delta Y: 17.2143333451
X-Range: 229335.0473 to 231073.3941
Y-Range: 54701.06707 to 59589.93774
Z-Range: -0.119693311644 to 4.16498545386
LOWER SURFACE
Level Surface defined by Z = 3.5

VOLUMES
Approximated Volume by
Trapezoidal Rule: -3036715.23934
Simpson's Rule: -3039087.04795
Simpson's 3/8 Rule: -3037762.9223

CUT & FILL VOLUMES
Positive Volume [Cut]: 2112.75440496
Negative Volume [Fill]: -3038827.99375
Cut minus Fill: -3036715.23934

AREAS
Positive Planar Area (Upper above Lower): 11020.2011188
Negative Planar Area (Lower above Upper): 1392558.87812
Blanked Planar Area: 7094973.60557
Total Planar Area: 8498552.68481

Positive Surface Area (Upper above Lower): 11033.5436069
Negative Surface Area (Lower above Upper): 1392921.50222

VOLUME COMPUTATIONS
UPPER SURFACE
Grid File: C:\Users\Vaudrey\Dropbox\bathymetry\Niantic\NRE model 2018\NRbathCCmean_out_LOWER_2018.grd
Grid size as read: 100 cols by 285 rows
Delta X: 17.5590585859
Delta Y: 17.2143333451
X-Range: 229335.0473 to 231073.3941
Y-Range: 54701.06707 to 59589.93774
Z-Range: -0.119693311644 to 4.16498545386

LOWER SURFACE
Level Surface defined by Z = 4

VOLUMES
Approximated Volume by
Trapezoidal Rule: -3775003.57811
Simpson's Rule: -3777795.20266
Simpson's 3/8 Rule: -3777262.9223
Simpson's 3/8 Rule: -3775992.22444

CUT & FILL VOLUMES
Positive Volume [Cut]: 25.233158399
Negative Volume [Fill]: 3775028.81126
Cut minus Fill: -3775003.57811

AREAS
Positive Planar Area
(Upper above Lower): 421.908081785
Negative Planar Area
(Lower above Upper): 1403157.17116
Blanked Planar Area: 7094973.60557
Total Planar Area: 8498552.68481

Positive Surface Area
(Upper above Lower): 422.365678914
Negative Surface Area
(Lower above Upper): 1403532.68015
check this equation –max specific growth rate seems high (0.8/d)

\[ \mu_{\text{max}} = 0.0183 \]

(Duarte 1995; Short et al. 1993)

\[ k \text{ for light} \]

(mol m\(^{-2}\) d\(^{-1}\))

5

(Short et al. 1993)


