Visualization of Productivity Zones Based on Nitrogen Mass Balance Model in Narragansett Bay, Rhode Island

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Abstract

Primary productivity in the coastal regions, linked to eutrophication and hypoxia, provides a critical understanding of ecosystem function. Although primary productivity largely depends on riverine nutrient inputs, estimation of the extent of riverine nutrient influences in the coastal regions is challenging. A nitrogen mass balance model is a practical tool to evaluate coastal ocean productivity to understand biological mechanisms beyond data observations. This study visualizes the biological production zones in Narragansett Bay, Rhode Island, USA, where hypoxia frequently occurs, by applying a nitrogen mass balance model. The Bay is divided into three zones - brown, green, and blue zones - based on primary productivity, which are defined by the mass balance model results. Brown, green, and blue zones represent a high physical process, a high biological process, and a low biological process zone, depending on river flow, nutrient concentrations, and mixing rates. The results of this study can better inform nutrient management in the coastal ocean in response to hypoxia and eutrophication.

Introduction

Primary productivity, the production of organic compounds by phytoplankton, fuels ecosystem food webs, and is important for understanding the system's function in response to environmental changes[1,2]. Estuarine primary productivity is also closely linked to eutrophication which is defined as excessive nutrients in the ecosystem[1], causing several harmful consequences in the coastal regions, such as an overgrowth of phytoplankton leading to large algal blooms and subsequent hypoxia[3,4]. Importantly, primary productivity in estuaries is highly dependent on the riverine nutrient loading, particularly nitrogen concentrations, which are the typical limiting nutrient in most temperate ocean ecosystems[5,6]. However, an estimation of the extent of riverine nitrogen impacts in coastal areas remains challenging.

To estimate the estuarine primary productivity, a nitrogen (N) mass balance model is a useful tool to calculate nitrogen fluxes[2]. The N-mass balance model also provides an understanding of biological mechanisms beyond data observations, revealing information at the edges of different primary productivity zones[7]. Three different zones[8], defined as brown, green, and blue zones, are particularly useful for predicting the impact of nutrient loading in hypoxic regions. The brown zone, defined as the nearest region of a river mouth, represents a high physical process, the green zone has high biological productivity, and the blue zone represents low biological process. The boundary of each zone depends on river flow, nutrient concentrations, and mixing rates[8].

Narragansett Bay (NB) is a coastal, temperate estuary in Rhode Island, USA, supporting economic and ecological services and goods[9,10,11], in which hypoxia has been consistently occurring. These hypoxic events, defined as the period of low dissolved oxygen (i.e., less than 2-3 mg of oxygen per liter), are particularly prevalent in July and August and are heavily impacted by riverine nitrogen loading during these months[12]. With an increase in primary production and hypoxia due to anthropogenic emissions of nutrients[13], understanding the nitrogen inputs into NB is critical to managing and addressing coastal issues such as eutrophication and hypoxia. Thus, in this study, the rate of primary production in NB is calculated from the N-mass balance model using historically observed nutrient data, especially dissolved inorganic nitrogen (DIN). Based on the results of the N-mass balance model by converting to carbon units using the Redfield ratio, three different primary productivity zones were identified to visualize the extent of nitrogen influence from the river in NB. The model was then recreated into a 3D representation to better visualize the different zones. The products produced from this study can better inform nutrient management in NB in response to hypoxia and eutrophication. Further, results from this study are applicable to other coastal regions to visualize the effects of riverine transport on nutrients and primary productivity.

Protocol

1. Applying the N-mass balance model

1. Download the dissolved inorganic nitrogen (DIN) data from the US Environmental Protection Agency (USEPA) for 166 stations in Narragansett Bay from 1990 to 2015.

   NOTE: In this study, the sum of ammonium (NH_4^+), nitrite (NO_2^-), and nitrate (NO_3^-) concentrations were considered as the DIN concentration.

2. Split the Narragansett Bay into fifteen boxes along its axis modified from the previous study[14] using Adobe Illustrator to divide the Bay in the map (**Figure 1**).

3. Apply the N-mass balance model to calculate the mean concentration of DIN at each box.

   NOTE: In this study, the N-mass balance model, consisting of DIN input and output terms, was modified from previous studies[2,15] and applied to each box (1-15) of the Narragansett Bay as Equation 1.

   $$F_{River}^{DIN} + F_{Atmosphere}^{DIN} + F_{Benthic}^{DIN} - F_{Denitrification}^{DIN} - F_{Export}^{DIN} = F_{Removal}^{DIN}$$

   Eq. (1)

   Table 1 shows the definitions of each term and unit used in this model of Narragansett Bay. The model calculates the mean DIN concentration by determining the difference in each box of Narragansett Bay, representing the net DIN removal by biological production. Detailed information on the N-mass balance model is shown in the previous studies[2,15]. The detailed values used in the model of this study were derived from the previous studies[14].

4. Calculate the potential primary production (PPP) rate based on the N-mass balance model results by converting the net DIN removal to carbon units using the Redfield ratio (C: N = 106: 16, molar ratio) in a spreadsheet file.

2. Visualizing three zones in the map of Narragansett Bay

1. Plot the identified three zones in the map of Narragansett Bay as a contour plot using the Ocean Data View software.
   1. Save the PPP rate data of each box as a text file (.txt) from the spreadsheet file.
      NOTE: The .txt file also includes the location of each box number as latitude and longitude. Put the longitude as a negative value. The PPP rate data is labeled as PPP [gC·m^{-2}·day^{-1}].
   2. Load the PPP rate data into the Ocean Data View software.
      1. Go to open in the **File** menu.
      2. Click **Associate Variables Box, Latitude, Longitude with Station, latitude [degrees_north]**, and **Longitude [degrees_east]**, in the **Metadata Variable Association** window, then click the **OK** button.
      3. Click the **OK** button in the **Import** window.
   3. Draw the contour plot to show the PPP ranges in the map of Narragansett Bay.
      1. Right-click on the map, click **Zoom**, drag the red box to zoom into the data area of the map, and then click on **Enter**.
      2. Click the **1 SCATTER** window of the **Layout Templates** in the **View** menu.
      3. Right-click in the **Sample** panel and select **Derived Variables**.
      4. Click the **Add** button after selecting **Latitude** under **Metadata** from the list of **Choices** panel. Do the same thing for **Longitude** and then click the **OK** button.
      5. Select **drvd: Longitude [degrees_East]** as X-Variable by right-clicking on the scatter window.
      6. Select **drvd: Latitude [degrees_North]** as Y-Variable by right-clicking on the scatter window.
      7. Select **PPP [gC·m^{-2}·day $^{-1}$]** as Z-Variable by right-clicking on the scatter window.
      8. Select **Properties** by right-clicking on the scatter window and go to the **Display Style** option.
         1. Select the **Gridded** field.
         2. Go to the **Contours** option and click the << button to make 0, 0.1, and 2 values only remain in the **Already Defined Panes** of the left.
         3. Click the **OK** button.
2. Based on the contour plot from the Ocean Data View Software, define the edge of the brown, green, and blue zones in Narraganset Bay, and visualize the zones using Adobe Illustrator to plot three zones in the map.
   NOTE: Following the previous study[15], the PPP rate of the brown zone was over 2 gC·m^{-2}·day^{-1}, the green zone was between 0.1-2 gC·m^{-2}·day^{-1}, and the blue zone was less than 0.1 gC·m^{-2}·day^{-1}, respectively.

3. Converting the contour plot of three zones into the three-dimensional (3D) frame with LED light

1. Etch three acrylic panels as 5.5" x 8" with a laser cutter to show the boundary of each zone.
2. Stack three acrylic panels in an illuminated frame.Overlap each acrylic panel showing the blue, green, and brown zones. Place a panel showing green zones on top of the blue zones panel and a brown zones panel on top of that.
3. For the second physical model, etch four acrylic sheets as 5.5" x 8" with a laser cutter, with the UV printed three boundaries of zones and one panel to represent the entire Narragansett Bay (as per steps 3.1-3.2).
4. Change the color of each zone into brown, green, and blue using the LEDs placed at the bottom of the frame.

Representative Results

Three theoretical zones of Narragansett Bay based on the N-mass balance model

The three theoretical zones in Narragansett Bay (NB) were defined based on the N-mass balance model results, in which the DIN data were applied to fifteen boxes of NB, and then the mean DIN in each box was converted to the PPP rates for the summer period. As shown in **Figure 2**, based on the mean summer (June to September) PPP rates of each box, three (brown, green, and blue) zones in NB were identified as following the criteria of the PPP rates of each zone from the previous study[15]. During the summer period, boxes 1, 2, 5, 6, 7, and 10, mostly located near the river mouth, were defined as brown zones with high PPP rates greater than 2 $gC{\cdot}m^{-2}{\cdot}day^{-1}$, indicating there was a strong physical process and biological process with high turbidity and light limitation. Boxes 3, 4, 8, 9, and 11 were classified as green zones, having PPP ranges from 0.1-2 $gC{\cdot}m^{-2}{\cdot}day^{-1}$, where a strong biological process occurred, showing nutrient limitation and high primary production. Due to high turbidity in the brown zone, the penetration of light was limited, which was a significant difference from the green zone. In contrast, blue zones, with low PPP rates of less than 0.1 $gC{\cdot}m^{-2}{\cdot}day^{-1}$, were identified in boxes 12, 13, 14, and 15 and were the furthest offshore, representing low biological productivity.

Visualization of three zones of Narragansett Bay using physical frameworks

To visually implement the boundaries of three theoretical zones in NB, a 3D representation was created in which layered acrylic panels were used and etched, creating two physical frameworks as described in section 3. As shown in **Figure 3**, three acrylic panels were used with the LED lights on the bottom of the frame, which can be changed to show a better representation of the characteristics of each boundary. In addition, dot-matrix patterns were etched with a different degree to represent the amount of sediment turbidity in each zone. **Figure 4** shows the second physical framework with four acrylic sheets containing three boundaries of each zone, UV printed, and one layer etched to show the entire NB. The images of the development stage of the second framework are shown in **Figure 4A**, with three sheets representing each zone and one additional sheet showing the entire three zones. In **Figure 4B**, the second physical framework was illuminated by the LED lights and showed the overlaps of the boundaries for each zone.

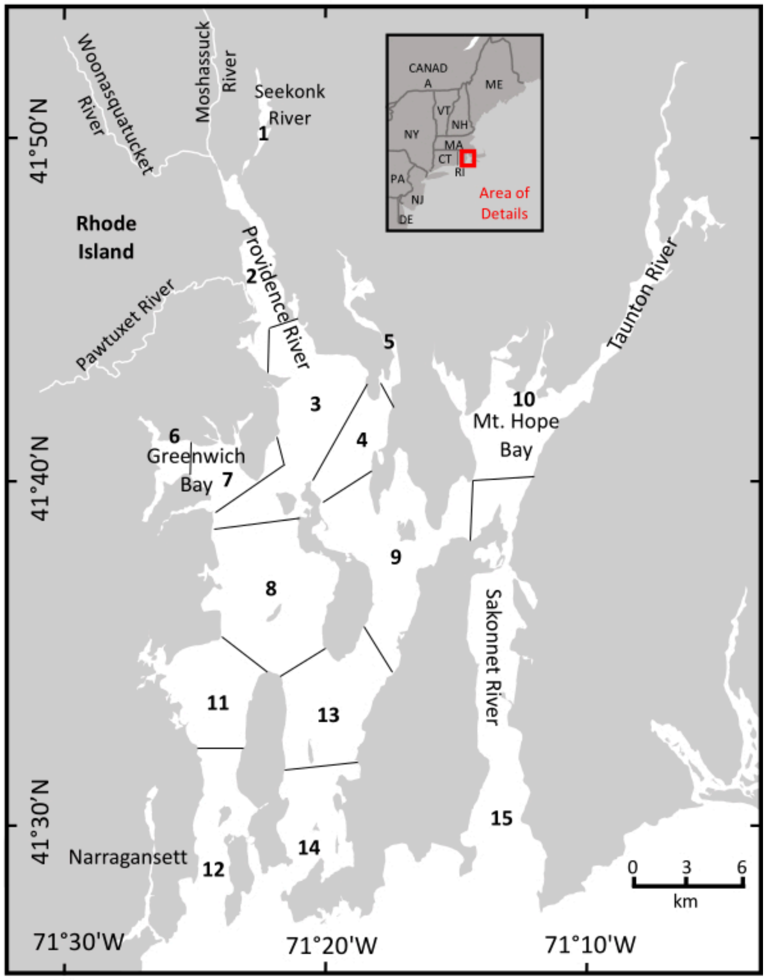

Figure 1: Map of Narragansett Bay. The numbered segments show the 15 boxes along the axis, which is modified from a previous study[14]. Please click here to view a larger version of this figure.

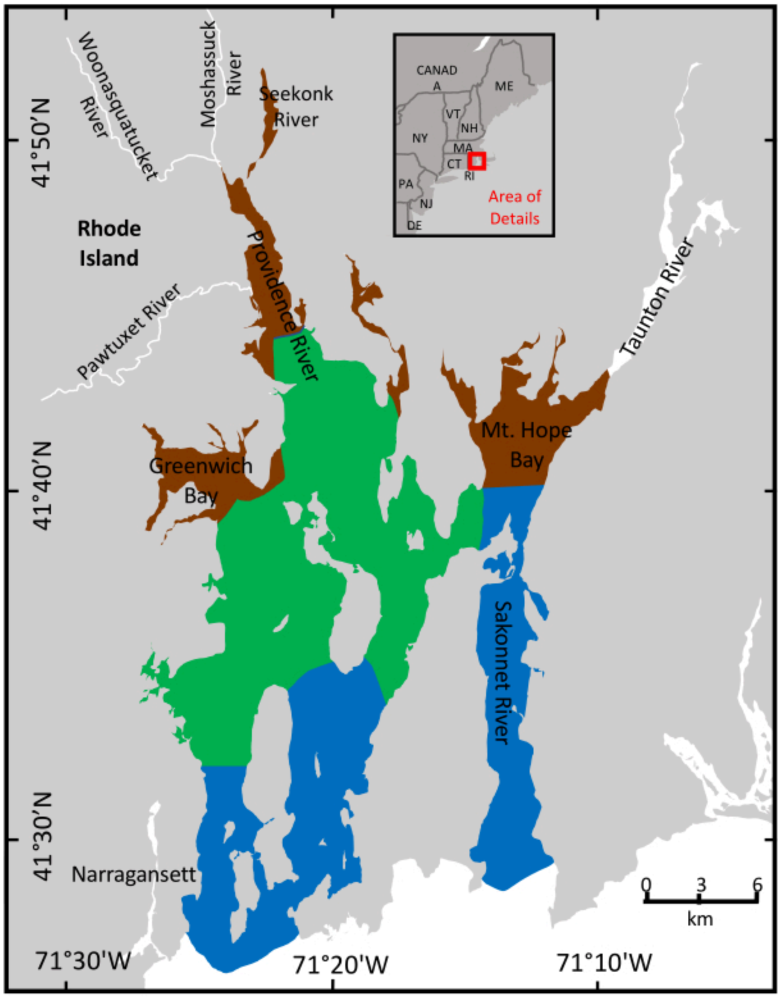

Figure 2: Extent of the three theoretical zones in Narragansett Bay. Zones were defined based on the N-mass balance model results. Each zone is divided by the mean summer (June to September) potential primary production (PPP) rates, which are converted to the N-mass balance model results defined from the previous study[15]. The mean summer PPP rate of brown zones is over 2 $gC \cdot m^{-2} \cdot day^{-1}$, the green zones is between 0.1-2 $gC \cdot m^{-2} \cdot day^{-1}$, and the blue zones is less than 0.1 $gC \cdot m^{-2} \cdot day^{-1}$. Please click here to view a larger version of this figure.

Figure 3: The first physical framework of the three zones in Narragansett Bay. The physical framework uses three acrylic panels and dot-matrix patterns to represent the amount of sediment turbidity in each zone. Please click here to view a larger version of this figure.

Figure 4: The second physical framework of three theoretical zones in Narragansett Bay. (**A**) The schematic images of the entire three zones in the Bay for UV printing and stacking of the second physical framework. (**B**) The framework created using four acrylic sheets to show overlaps of zones' boundaries. Please click here to view a larger version of this figure.

Unit	Definitions
F_{River}^{DIN}	DIN flux from each river discharge
$F_{Atmosphere}^{DIN}$	Diffusive flux from atmospheric deposition
$F_{Benthic}^{DIN}$	Benthic flux from the bottom sediments
$F_{Denitrification}^{DIN}$	Denitrification in the water column
F_{Export}^{DIN}	An advection term which calculated from the current velocity
$F_{Removal}^{DIN}$	Removal by biological production

Table 1: Definitions of each term in N mass balance model. The detailed values used in the model were derived from previous studies[14,16,17].

Discussion

This study estimated the extent of nutrient impacts from riverine inputs in Narraganset Bay (NB) based on the N-mass balance model by defining the three theoretical zones. Historically, hypoxic zones appeared near the Providence River, the western side of Greenwich Bay, and Mount Hope Bay during the summer period[18], which were defined as brown zones in this study. Moreover, the zonation of NB is comparable to the results of a previous study[19], which examined nutrient concentration and primary production in NB. Both highlight the importance of nutrient reduction efforts. In addition, the boundaries of each zone in this study were similar to results from a previous study[19], indicating that hypoxia in the upper bay of NB may be controlled by the advection of organic matter from the Providence River, yielding elevated respiration with high productivity over 2.6 gC·m^{-2}·day^{-1}. These results in the upper bay of NB were represented by the brown zone in this study. In addition, productivity continued to decrease towards the ocean, indicated by the green and blue zones.

In contrast, during the summer season, Mt. Hope Bay (box 10) was defined as the brown zone in this study, showing higher primary productivity over 2 gC·m^{-2}·day^{-1} compared to the previous study[19]. This increased productivity indicates that other nutrient input sources, in addition to the riverine nitrogen input, might affect this region and should be considered as another DIN input term in N-mass balance models. The zonation in this study is expected to inform better management efforts for nutrients in NB aimed at reducing riverine nitrogen discharge as well as atmospheric nitrogen deposition, which has been highlighted in other estuarine systems, including the Chesapeake Bay[2,20]. Oviatt et al. (2002) found that mixing rate and light penetration influenced PPP[21], but future work is needed to better quantify these factors attributed to high PPP in the brown zones.

Finally, by representing the three theoretical zones of NB as two physical frameworks, an improved understanding of the extent of riverine or other nutrient inputs to the coastal area is visually achieved. While frameworks can have fixed boundaries for each zone, in our framework, flexibility is additionally shown to inform that the three theoretical zones can change from month to month according to the nutrient concentrations of freshwater, mixing rate, and river flow, as pointed out from the previous applications of the N-mass balance model[2,15]. For example, several boxes in **Figure 3** and **Figure 4** were represented as mixed zones because they were categorized as different zones monthly during summer periods based on N-mass balance model results. The frameworks show the effect of riverine nutrients in NB by providing an integrated visualization of scientific biogeochemical data through an art form, which is useful for nutrient management in the coastal area and for scientific communication.

Disclosures

The authors have no conflicts of interest to declare.

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