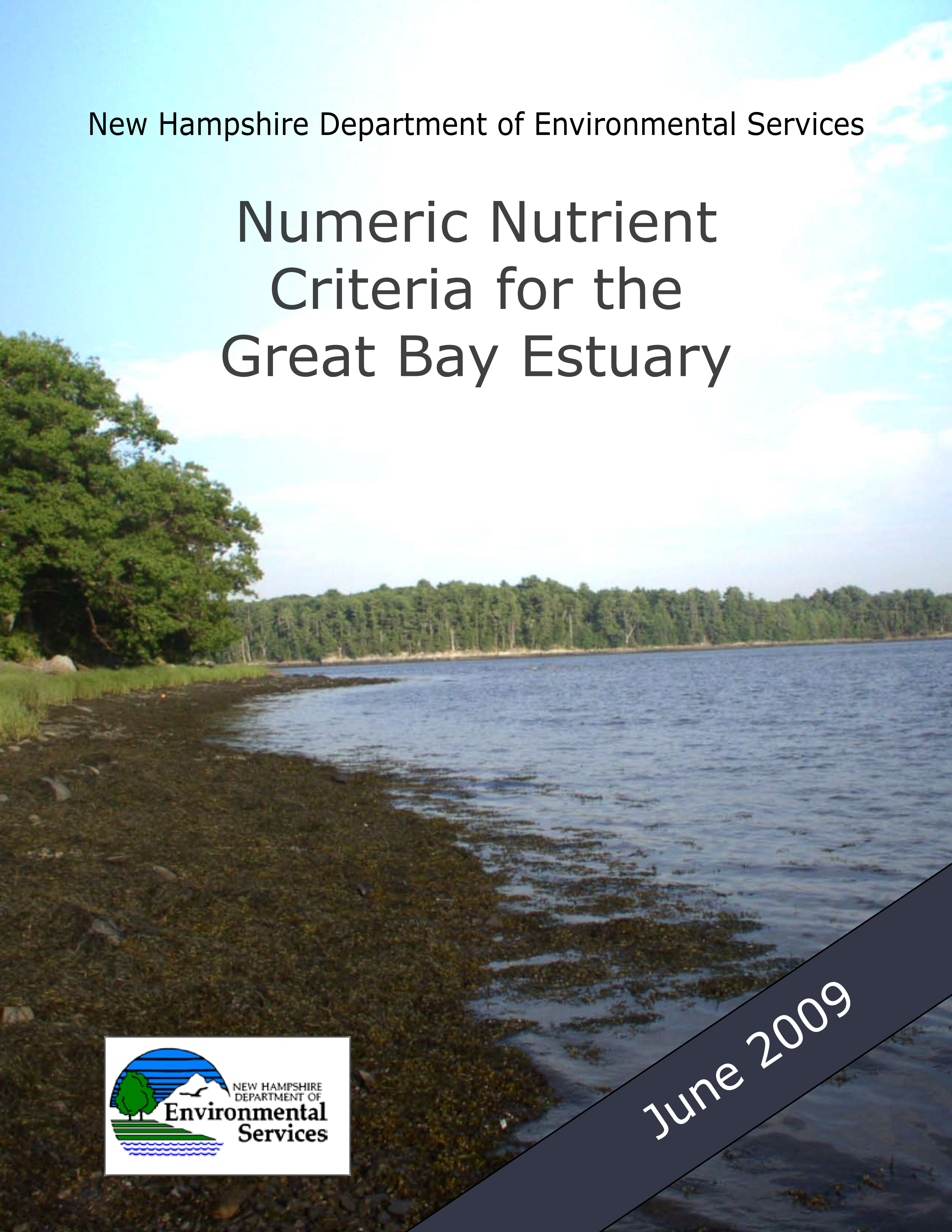

New Hampshire Department of Environmental Services

# Numeric Nutrient Criteria for the Great Bay Estuary

June 2009

NEW HAMPSHIRE
DEPARTMENT OF
Environmental
Services

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# Numeric Nutrient Criteria for the Great Bay Estuary

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# Executive Summary

The New Hampshire Department of Environmental Services has developed numeric water quality criteria for the Great Bay Estuary. Numeric nutrient criteria were needed because New Hampshire's water quality standards contain only narrative criteria for nutrients to protect designated uses. Narrative standards are difficult to apply for impairment and permitting decisions. DES received considerable assistance with the criteria development from the Piscataqua Region Estuaries Partnership (PREP). The PREP dedicated staff time to develop methods, formed a technical working group to review approaches and proposed criteria, and funded additional research to fill data gaps.

A variety of data sources were evaluated to provide multiple lines of evidence relative to appropriate thresholds for nutrients in the Great Bay Estuary. Each data source was chosen because of its relevance to the conceptual model for eutrophication in estuaries from the National Estuarine Eutrophication Assessment Update. A weight of evidence approach was used to combine information from the disparate sources. First, water quality measurements from different sections of the estuary were used to develop linear regressions between nitrogen concentrations and chlorophyll-*a*, dissolved oxygen, and water clarity. Second, continuous monitoring of dissolved oxygen with in-situ sensors provided detailed information related to dissolved oxygen impairments. Finally, relationships between water quality and water clarity were quantified based on light attenuation measurements by in-situ sensors and hyperspectral imagery.

Numeric criteria were developed for the aquatic life use support designated use because this use is the most sensitive to nutrient enrichment. DES considered low dissolved oxygen and loss of eelgrass habitat as the most important impacts to aquatic life from nutrient enrichment for the Great Bay Estuary. For each of these impacts, DES established a threshold for the total nitrogen concentration and a threshold for a response variable. Specifically, in order to maintain instantaneous dissolved oxygen concentrations greater than 5 mg/L and average daily concentrations greater than 75% saturation, the annual median total nitrogen concentration should be less than or equal to 0.45 mg N/L and the 90th percentile chlorophyll-a concentration should be less than or equal to 10 ug/L. For the protection of eelgrass habitat, the annual median total nitrogen concentration should be less than or equal to 0.25-0.30 mg N/L and the annual median light attenuation coefficient (a measure of water clarity) should be less than or equal to 0.5-0.75 $m^{-1}$ depending on the eelgrass restoration depth. Thresholds were not established for phosphorus because nitrogen is the limiting nutrient in the majority of the estuary.

The numeric criteria will first be used as interpretations of the water quality standards narrative criteria for DES' Consolidated Assessment and Listing Methodology for 305(b) assessments. Later, DES will promulgate these values as water quality criteria in Env-Wq 1700.

# Introduction

In 1998, the U.S. Environmental Protection Agency published the Clean Water Action Plan (EPA, 1998) to improve the water quality in the nation's lakes, rivers and estuaries. One component of this plan was the development of numeric criteria for nutrients (i.e., nitrogen and phosphorous) in water bodies. National criteria were not considered appropriate due to the variety of water body types across the country and the diversity of natural nutrient background concentrations and biotic conditions prevailing in different ecoregions. Therefore, EPA asked each state to develop numeric nutrient criteria for its own water bodies. EPA provided the states with technical guidance for developing nutrient criteria for lakes, rivers and estuaries (EPA, 2000a; EPA, 2000b; EPA, 2001).

In New Hampshire, the Department of Environmental Services is responsible for developing nutrient criteria for New Hampshire's estuaries. The Piscataqua Region Estuaries Partnership (PREP) facilitated the nutrient criteria development process by dedicating significant PREP staff time to research and develop methods to establish numeric nutrient criteria, forming a technical working group in 2005 to provide input on the methods, and supporting additional research to assist in the development of the criteria. Information from the workgroup meetings is available at www.prep.unh.edu/programs/nutrient.htm.

New Hampshire's Water Quality Standards currently contain only narrative criteria for nutrients to protect designated uses. Narrative standards are difficult to apply for impairment and permitting decisions. This report contains proposals for numeric nutrient criteria for different designated uses in the Great Bay Estuary, the largest estuary in the State, based on the weight of evidence from the multiple sources of information. Several thresholds for nitrogen and chlorophyll-a concentrations and light attenuation coefficients were developed because different eutrophication indicators and thresholds were deemed appropriate for different designated uses and locations in the estuary. The numeric criteria will first be used to implement the narrative criteria as thresholds for impairment determinations in the State of New Hampshire 303(d) list in 2010. Later, the thresholds will be proposed as new water quality criteria in Env-Wq 1700.

The designated uses considered for this analysis were primary contact recreation (swimming use) and aquatic life use support. For aquatic life use support, DES investigated nutrient thresholds for the protection of the benthic invertebrate community, dissolved oxygen, and eelgrass. Chlorophyll-a and nitrogen concentrations were evaluated for the primary contact recreation designated use.

# Regulatory Authority

The narrative standard for nutrients, Env-Wq 1703.14, provides DES with the regulatory authority to set thresholds for impairments associated with nutrients and other parameters associated with eutrophication. The narrative standard for estuarine waters, which are Class B, states that: "Class B waters shall contain no phosphorus or nitrogen in such concentrations that would impair any existing or designated uses, unless naturally occurring."

## Precedents from Other States

Numeric nutrient criteria have been established for relatively few estuaries but the criteria that have been set typically fall between 0.35 and 0.49 mg N/L. The criteria have been used as both water quality standards and modeling targets for Total Maximum Daily Load studies. In New England, the Massachusetts Estuaries Project has established water quality thresholds for total maximum daily loads for dozens of estuaries, predominantly on Cape Cod and in Buzzards Bay (reports available at http://www.oceanscience.net/estuaries/index.htm). While the thresholds are site-specific, many of the nitrogen thresholds set for the protection of eelgrass habitat are similar and fall between 0.35 and 0.38 mg N/L for a tidally averaged concentration at a sentinel site. Total nitrogen thresholds as low as 0.30 mg N/L have been adopted for some Massachusetts estuaries. A nitrogen threshold of 0.49 mg N/L has been adopted for Pensacola Bay in Florida. This threshold was derived from current concentrations because eutrophication symptoms in Pensacola Bay were not apparent at the current concentrations.

## Methods

The overall approach was to divide the estuary into 22 different segments and to develop correlations between median values (or other statistics) for nutrients and response variables in the different segments. States with many different estuaries are able to compare median nutrient concentrations and response variables across estuaries. New Hampshire could not follow this approach because there is only one large estuary in the state, the Great Bay Estuary. However, the Great Bay Estuary is composed of eight tidal rivers and several distinct embayments. The nutrient concentrations in these different segments span a wide range and have differing levels of eutrophic response. Therefore, DES decided to split the estuary into 22 assessment zones of approximately homogeneous water quality and to look for correlations across the assessment zones. The advantage of this approach was that variability in the datasets was muted by taking median values for each assessment zone, which improved the quality of the correlations. This approach is supported by Li et al. (2008) who observed that correlations between nitrogen and chlorophyll-a in Canadian estuaries were only evident when data were aggregated over longer time periods and across biogeochemical ocean provinces. The disadvantage of the approach is that spatial and temporal variability of water quality within an assessment zone was lost. However, this month-to-month variability is typically confounded by the complexity of phytoplankton population dynamics. On balance, the advantages of this approach outweighed the disadvantages.

Several different nutrient concentration thresholds for different designated uses and environmental conditions were developed because different eutrophication indicators occur for different levels of nutrient enrichment. For example, the nutrient concentration threshold to protect against large phytoplankton blooms would be expected to be higher than the threshold to maintain submerged aquatic vegetation. In addition to the thresholds for nutrient concentrations, thresholds for response variables such as chlorophyll-a and water clarity were also developed. These response thresholds provide a means to determine impairments based on measurements of eutrophic effects if nutrient concentration data are missing. The nutrient and response thresholds will be used together to make impairment determinations.

## *Conceptual Model*

The estuarine eutrophication model used by the National Oceanic and Atmospheric Administration relates external nutrient inputs to primary and secondary symptoms of eutrophication (Bricker et al., 2007). Phytoplankton blooms (as measured by chlorophyll-a concentrations) and proliferation of macroalgae are primary symptoms of eutrophication, while low dissolved oxygen, loss of submerged aquatic vegetation (e.g., eelgrass), and harmful algal blooms are secondary symptoms. Harmful algal blooms, the proliferation of certain species of phytoplankton or cyanobacteria which produce toxins, typically occur offshore in the Gulf of Maine so this indicator was not considered for the Great Bay Estuary (Townsend et al., 2005). Instead, the secondary effects of accumulated organic matter in sediments on benthic infauna were considered. This approach is consistent with the conceptual model of coastal eutrophication presented by Cloern (2001) and the guidance for developing numeric nutrient criteria for estuaries from EPA (2001). DES used a variety of data sources to estimate thresholds for nutrients and response variables for each of the primary and secondary indicators in the conceptual model. The methods used for each indicator are described in the following sections.

## *Nutrient Concentrations*

All valid data for nitrogen and phosphorus species from the Great Bay Estuary collected between January 1, 2000 and December 31, 2008 were queried from the DES Environmental Monitoring Database. The majority of the data was from the following programs: Great Bay National Estuarine Research Reserve System Wide Monitoring Program (http://nerrs.noaa.gov/Monitoring/), University of New Hampshire Tidal Water Quality Monitoring Program, and the National Coastal Assessment (http://www.epa.gov/emap/nca/). Results from the Great Bay National Estuarine Research Reserve Diel Sampling were excluded because of outliers and overlap with the System Wide Monitoring Program samples taken at the same stations.

For each parameter, the minimum, 10th percentile, median, 90th percentile, and maximum concentrations were calculated from all the measurements between 2000 and 2008 in each assessment area shown on Figure 1 and for each trend station shown in Figure 2. Data from all seasons were used to calculate these statistics. A shorter index period was considered to constrain the data but the relationships between parameters were found to be best when using data from all four seasons. Results reported as less than the method detection level were included with a value equal to the reporting detection limit. This approach is justified because less than 10% of the results for any parameter were reported as being less than the method detection level; therefore, percentiles equal to or greater than 10% would not be affected by the censored results. To generate the complete list of independent results in each assessment unit and for each trend station, pairs of field duplicate samples were first averaged (which is equivalent to a median). Then, if there were multiple samples taken at the station on the same date (e.g., from different depths or at different times), the maximum value for the day was calculated. The summary statistics for each assessment unit were then calculated using this list of independent samples. A sample size of greater than 20 was preferred to be representative of an assessment zone. Exceptions to this rule are noted on graphs.

If total nitrogen concentrations were not measured directly, total nitrogen was calculated from the sum of total dissolved nitrogen and particulate nitrogen. Dissolved inorganic nitrogen was calculated from the sum of nitrate+nitrite and ammonia or nitrate, nitrite, and ammonia. If total phosphorus concentrations were not measured directly, total phosphorus was calculated from the sum of dissolved phosphorus and particulate phosphorus.

The aggregate statistics for each assessment zone could not illustrate some aspects of nutrient cycling in the estuary because these statistics did not represent the concentrations of nitrogen, phosphorus, and other parameters at the same station at the same time. For example, it is more accurate to calculate the molar ratio of nitrogen to phosphorus in individual grab samples and then average the ratios, than to calculate the molar ratio from average concentrations of nitrogen and phosphorus for an assessment zone. The three topics that required calculations on individual sample data were (1) the percentages of nitrogen and phosphorus in different fraction types (e.g., dissolved, particulate); (2) the molar ratios between nitrogen and phosphorus; and (3) the monthly median concentrations of nitrogen and phosphorus concentrations. For these calculations, the relevant parameters were queried for a trend station. The necessary calculations were performed for each date with complete data for all parameters (using daily maximum values as described earlier) and then the median value of the result was computed for each station on each date. Measurements reported as below the method detection limit were included in these calculations and assigned a value of the method detection limit. Additional information on the methods used for the three different calculations are presented in the following paragraphs.

The percent of the total nitrogen in different fractions was calculated in order to determine how much of the nitrogen was bioavailable or associated with phytoplankton. The fractions that were considered were dissolved inorganic nitrogen, dissolved organic nitrogen, nitrogen in phytoplankton, and nitrogen in all other particulate organic matter. Dissolved inorganic nitrogen is the sum of nitrate, nitrite, and ammonia, which were measured directly. Dissolved organic nitrogen was calculated as the difference between total dissolved nitrogen (measured directly) and dissolved inorganic nitrogen. Nitrogen in phytoplankton was calculated from the chlorophyll-a concentration in the sample and assuming that chlorophyll-a, carbon, and nitrogen comprised 5%, 50%, and 6% of biomass by dry weight, respectively. The percentages for chlorophyll-a and carbon were taken from EPA modeling guidance (EPA, 1985). The percentage for nitrogen was calculated from the ratio of particulate carbon to particulate nitrogen in 127 water samples from the estuary. This calculated percentage is consistent with estimates from the EPA modeling guidance (EPA, 1985). While this percentage can change, the median value should be sufficiently accurate for the purposes of this report. Finally, nitrogen in other particulate organic matter was calculated as the difference between total particulate nitrogen (measured directly) and the estimates of nitrogen in phytoplankton. The percentage of phosphorus in different fractions was calculated using similar methods. The percent of phytoplankton biomass dry weight that is phosphorus was calculated to be 1.3% based on the measured ratio of particulate phosphorus to particulate carbon in 83 water samples. This percentage is consistent with modeling guidance from EPA (EPA, 1985). Otherwise, the assumptions used for the phosphorus fractionation calculations were the same as those used for the nitrogen calculations described above.

The concentrations of nitrogen and phosphorus vary over the course of the year. The seasonal patterns in the concentrations of these parameters provide information about critical periods and which nutrient is limiting growth. To illustrate the seasonal patterns, the median monthly concentrations for total nitrogen, dissolved inorganic nitrogen, and orthophosphate were calculated and graphed versus month.

The molar ratio of nitrogen to phosphorus is an indicator for which nutrient limits primary productivity in a waterbody (Howarth and Marino, 2006; NRC, 2000). According to the Redfield Ratio, nitrogen is the limiting nutrient for ratios less than 16 and phosphorus limits for ratios greater than 16. This ratio is best interpreted as an indicator rather than a definitive determination of the limiting nutrient. The ratio can change due to cycling of nitrogen and phosphorus between different fractions (e.g., dissolved, particulate) and media (e.g., water, sediment). Therefore, N:P ratios greater than 16 do not necessarily mean phosphorus limitation or visa versa. Concentrations of nitrogen and phosphorus in units of mg/L were converted to units of mmol/L using the atomic masses of nitrogen (14.0067 g/mol) and phosphorus (30.9738 g/mol). The ratio was calculated for total nitrogen and total phosphorus as well as for dissolved inorganic nitrogen and orthophosphate for each date with complete data. The latter of these two ratios is more representative of bioavailable fractions. The median value of the ratios was computed for each station and plotted against the median salinity for the station. In addition, the chlorophyll-a concentration in samples from trend stations in the tidal rivers was plotted against the N:P ratio from the same sample to provide more information on whether nitrogen or phosphorus was the limiting nutrient during phytoplankton blooms.

The relationships between median nutrient concentrations and other parameters were explored through univariate regressions using summary statistics for each assessment area and trend station. A regression was deemed acceptable for setting thresholds if it met the following criteria. First, the regression had to be statistically significant ($p<0.05$). Second, the regression could not be used to extrapolate beyond the range of available data. Third, assessment zones or trend stations included in the regression had to have sample sizes for summary statistics greater than 20, unless noted otherwise. Fourth, the data for both variables in the regression were limited to the 17 trend stations and only for the years during which both parameters were measured at each station. This last criterion was adopted to avoid false correlations due to mismatched data. Some parameters were not measured every year during the 2000-2008 period. It would be inappropriate to match the median total nitrogen concentration from 2003-2006 at a station with the chlorophyll-a concentrations for 2000-2008. To make this process explicit to the reader, each point on the regression curves has been labeled with the station name and the years of data used to calculate the statistics. Finally, the standard error of the regression was used to estimate 95th percentile confidence limits around the regression line (Helsel and Hirsch, 1992). These confidence limits were used to determine the uncertainty in any threshold derived from the regression. The goal was to have uncertainty less than 0.1 mg N/L for nitrogen thresholds and 3 ug/L for chlorophyll-a thresholds. These values were chosen because they are approximately 20% of the observed range for total nitrogen and chlorophyll-a, respectively.

**Figure 1: Assessment Zones in the Great Bay Estuary**

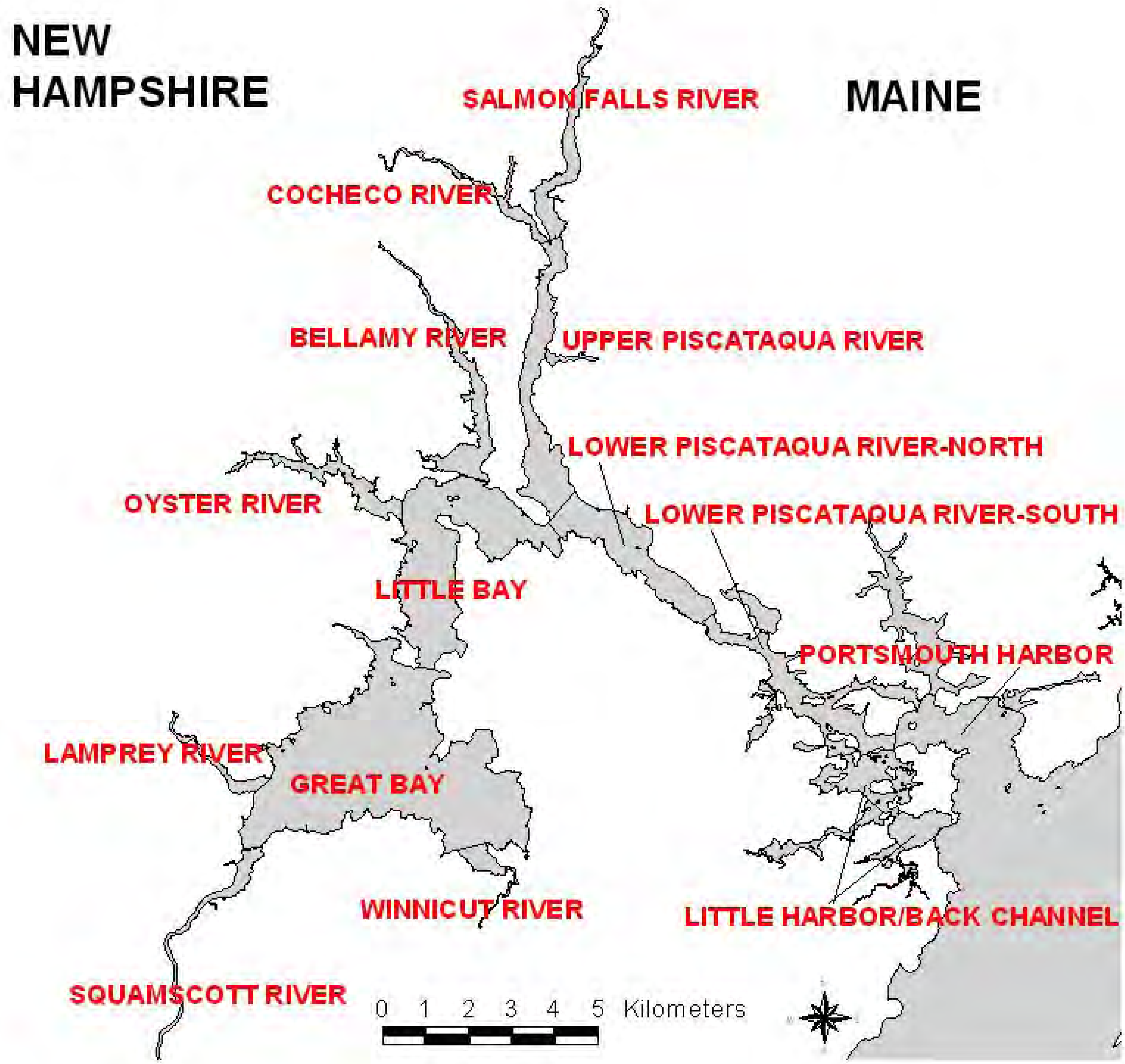


**Figure 2: Trend Monitoring Stations for Water Quality in the Great Bay Estuary**

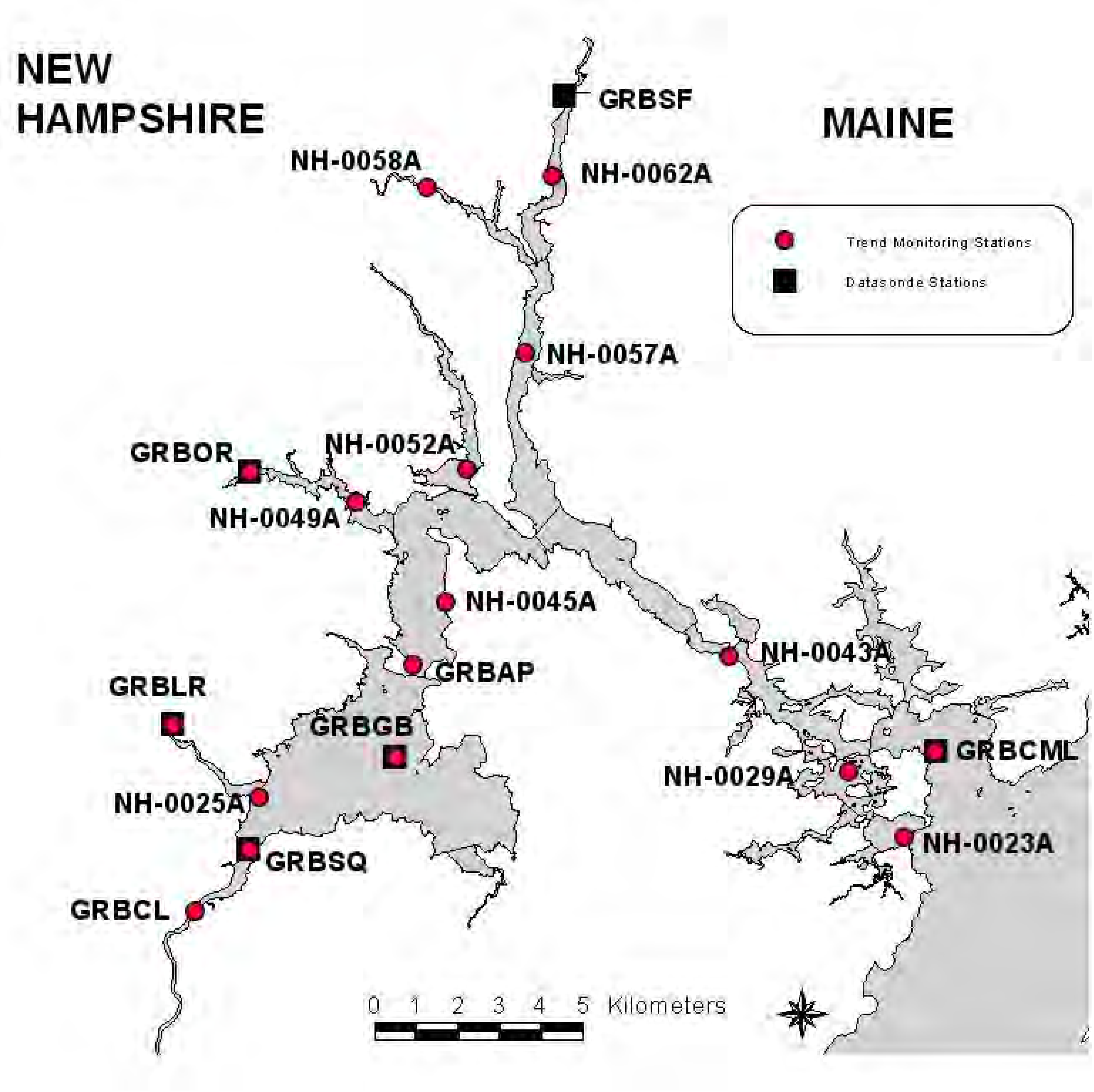


**Table 1: Trend Monitoring Stations for Water Quality**

| Station | Location | Latitude | Longitude |
|---|---|---|---|
| GRBAP | JACKSON ESTUARINE LABORATORY | 43.0922 | -70.8650 |
| GRBCL | CHAPMANS LANDING | 43.0394 | -70.9283 |
| GRBCML | COASTAL MARINE LABORATORY | 43.0724 | -70.7103 |
| GRBGB | GREAT BAY DATASONDE | 43.0722 | -70.8694 |
| GRBLR | LAMPREY RIVER DATASONDE | 43.0800 | -70.9344 |
| GRBOR | OYSTER RIVER DATASONDE | 43.1340 | -70.9110 |
| GRBSF | SALMON FALLS RIVER DATASONDE | 43.2142 | -70.8172 |
| GRBSQ | SQUAMSCOTT RIVER DATASONDE | 43.0417 | -70.9222 |
| NH-0023A | LITTLE HARBOR | 43.0538 | -70.7202 |
| NH-0025A | LAMPREY RIVER | 43.0638 | -70.9096 |
| NH-0029A | BACK CHANNEL | 43.0682 | -70.7366 |
| NH-0043A | LOWER PISCATAQUA RIVER | 43.0933 | -70.7712 |
| NH-0045A | LITTLE BAY | 43.1056 | -70.8542 |
| NH-0049A | OYSTER RIVER | 43.1270 | -70.8805 |
| NH-0052A | BELLAMY RIVER | 43.1340 | -70.8470 |
| NH-0057A | UPPER PISCATAQUA RIVER | 43.1589 | -70.8302 |
| NH-0058A | COCHECO RIVER | 43.1950 | -70.8580 |
| NH-0062A | SALMON FALLS RIVER | 43.1970 | -70.8210 |

# *Primary Indicators*

## Chlorophyll-a

All valid data for chlorophyll-a from the Great Bay Estuary collected between January 1, 2000 and December 31, 2008 were queried from the DES Environmental Monitoring Database. The majority of the data was from the following programs: Great Bay National Estuarine Research Reserve System Wide Monitoring Program (http://nerrs.noaa.gov/Monitoring/), University of New Hampshire Tidal Water Quality Monitoring Program, and the National Coastal Assessment (http://www.epa.gov/emap/nca/). Results from the Great Bay National Estuarine Research Reserve Diel Sampling were excluded because of outliers and overlap with the System Wide Monitoring Program samples taken at the same stations.

The minimum, 10th percentile, median, 90th percentile, and maximum chlorophyll-a concentrations were calculated from all the measurements between 2000 and 2008 in each assessment area shown on Figure 1 and for each trend station shown in Figure 2. The data reduction methods used for the nitrogen and phosphorus concentrations were also used for the chlorophyll-a results.

The concentrations of chlorophyll-a vary over the course of the year. The seasonal patterns in the concentrations of these parameters provide information about critical periods and which nutrient is limiting growth. To illustrate the seasonal patterns, the median monthly concentrations for chlorophyll-a were calculated and graphed versus month.

The relationships between 90th percentile chlorophyll-a concentrations and other parameters were explored through univariate regressions using summary statistics for each assessment area and trend station using the methods described in the "Nutrient Concentrations" section.

## Macroalgae

The coverage of nuisance macroalgae in the estuary was mapped in 2007 by UNH with funding from EPA. On August 29, 2007, hyperspectral imagery was collected by plane with a visible near infrared spectrograph. The imagery was collected during a spring low tide and had a spatial resolution of 2.5 meters for the area of interest. For each pixel, calibrated irradiance from 64 spectral channels with a nominal spectral resolution of 10 nm between 430 nm to 1000 nm was reported. Ground truth data on eelgrass and macroalgae beds were collected in 2007 for a different study (Short, 2008). UNH processed the imagery to generate maps of macroalgae cover and eelgrass in Great Bay. The 2007 macroalgae cover in Great Bay was also plotted over eelgrass cover in 1996 and 2007 as mapped by UNH for a separate project (Short, 2008) to determine the locations where macroalgae has replaced eelgrass. Important details on methods used for these analyses are provided below and in a technical report from UNH (Pe'eri et al., 2008).

Pe'eri et al. (2008) reported a problem with the hyperspectral imagery in the spectral range below 550 nm wavelength. The problem was that the spectral calibration was incorrect, not that the remote sensing equipment was faulty or the data were lost. The result was that below 550 nm the absolute values for reflectance and irradiance were incorrect; however, relative differences between wavelengths were still accurate. Therefore, Pe'eri et al. (2008) avoided classical remote sensing algorithms which rely on absolute values and instead used algorithms based on relative differences. The reported problems with the imagery below 550 nm only prompted a change in the data analysis procedures. The reported problems did not mean the hyperspectral imagery dataset was fully compromised and not useable.

The hyperspectral imagery was collected on August 29, 2007. Weather conditions were ideal: Clear skies, light winds, and no rainfall in the previous 12 days. Haze was only observed over land in a couple of flight lines in the northern part of the dataset over Dover, NH. Moreover, the imagery was corrected for haze and cirrus clouds using the TAFKAA algorithm. The flight coincided with spring low tide (-0.6 feet at Dover Point), as planned, to maximize opportunities for mapping submerged aquatic vegetation. The recurrence interval of this spring low tide is not relevant to the quality of the imagery because it only served to make visible more of the submerged aquatic vegetation that was present already.

Since hyperspectral imagery was only collected for the Great Bay Estuary, it was not possible to calibrate the algorithms on one estuary and validate them on another. However, eight flight lines of imagery were collected for the Great Bay. Pe'eri et al. (2008) used one of the flight lines to calibrate the algorithms based on ground truth data and then validated the algorithms with the other seven flight lines. Therefore, for most of the mapped area, the same imagery was not used to both calibrate and validate the results.

Ground truth observations for eelgrass and macroalgae in Great Bay were made in August 2007 by Fred Short of UNH as part of the annual eelgrass survey of the Great Bay Estuary (Short, 2008). These observations were not made on the exact day of the hyperspectral overflight but eelgrass and macroalgae beds are not likely to have changed over a matter of weeks. The ground truth observations were used to calibrate the algorithms on one flight line and then validate the algorithm output on the other seven flight lines. There was good correspondence between the ground truth observations and the algorithms in the validation step. Fringing salt marsh boundaries from a 2004 mapping survey were also used to calibrate the algorithms to discriminate between salt marsh and submerged aquatic vegetation.

The algorithms from Great Bay were used to predict locations of macroalgae in other sections of the estuary including the tidal tributaries; however, there were no ground truth observations in areas outside of Great Bay. In the lower salinity, tidal river environments it is possible that the algorithms would not perform as well as they did in Great Bay. Therefore, only the macroalgae maps for Great Bay were considered valid and used in this analysis.

## *Secondary Indicators*

### Benthic Invertebrates and Sediment Quality

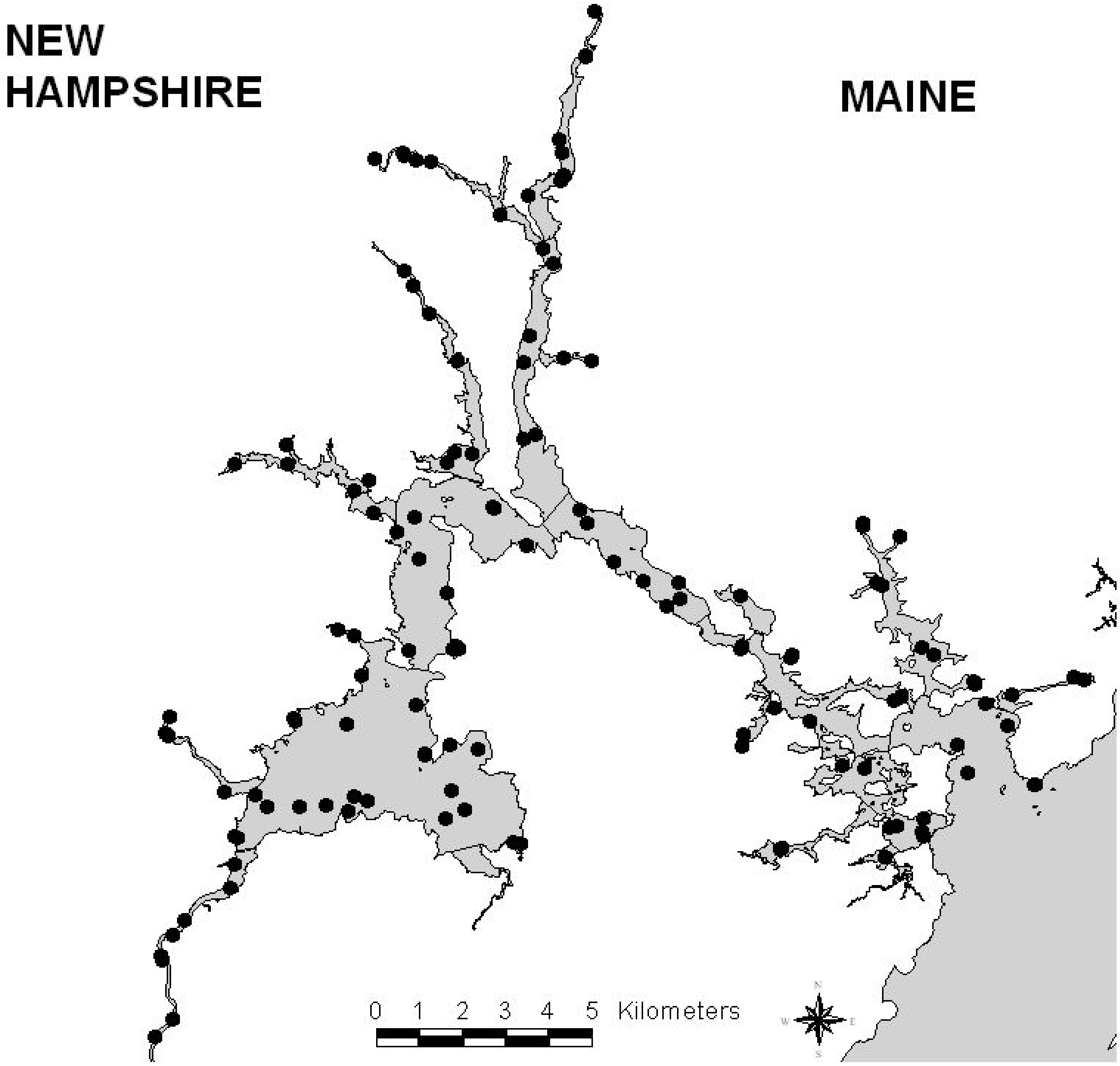
Grab samples of sediment have been collected throughout the Great Bay Estuary for the National Coastal Assessment (http://www.epa.gov/emap/nca/) (Figure 3). The sediment quality measurements that are relevant to eutrophication are the benthic index of biologic integrity (B-IBI), total organic carbon content, and grain size. Elevated total organic carbon in the sediments can result from accumulation of organic matter when phytoplankton and other organisms die and settle to the bottom (Cloern, 2001). Low dissolved oxygen and elevated total organic carbon in the sediments can disrupt the normal community of benthic invertebrates (Diaz and Rosenberg, 2008). To measure the quality of the benthic community, DES used a benthic index for Gulf of Maine sediments developed by the Atlantic Ecology Division of EPA. The index was calculated as follows:

B-IBI = 0.494 * Shannon + 0.670 * MN_ES50.05 – 0.034 * PctCapitellidae
where:
Shannon = Shannon-Wiener H’ diversity index
MN_ES50.05 = Station mean of 5th percentile of total abundance frequency distribution of each species in relation to its ES50 value, where ES50 is the expected number of species in a sample of 50 individuals
PctCapitellidae = percent abundance of capitellid polychaetes
The benthic index was considered poor for values less than 4

Median values for B-IBI, total organic carbon, and grain size were calculated from all the sediment samples collected from each assessment zone of the estuary between 2000 and 2005. These average values were compared to statistics for nutrients, chlorophyll-a, and salinity in these assessment zones to identify causal relationships.

The benthic macroinvertebrate B-IBI used in this report was developed by EPA for the Acadian Province using the 2000-2001 dataset from the National Coastal Assessment. The Acadian Province index was developed because the B-IBI for the Virginian Province did not perform well for sediment samples from the Acadian Province. EPA selected stations with high and low benthic environmental quality based on non-biological data and then used discriminant analysis to identify the best metrics from a list of 40 candidate metrics from the literature. The combination of metrics used in the B-IBI correctly classified over 80% of stations in the calibration dataset and approximately 75% of sites in validation datasets. The selected metrics were the Shannon-Weiner H' Diversity Index, percent abundance of capitellid polychaetes, and a species tolerance value calculated following Rosenberg et al. (2004). Because the National Coastal Assessment collected few samples from oligohaline and mesohaline areas, EPA cautioned that the applicability of the B-IBI to low salinity areas was unknown. EPA subsequently developed another version of the B-IBI which found the same metrics to be important but combined them using logistic regression rather than multivariate regression (Hale and Heltshe, 2008). The new B-IBI did not have improved discriminatory power for New Hampshire's estuaries and was still unproven in low salinity areas, so DES opted to continue with the old B-IBI to maintain year to year consistency. DES investigated the utility of adding other metrics that might be more sensitive to nutrient enrichment (e.g., tubicifids, *Streblospio* sp., etc.) without success. Therefore, despite the limitations of the B-IBI for low salinity areas, DES believes this index is the best available currently. Additional research is needed at the regional level to develop an index for low salinity environments but that work is beyond the scope of the nutrient criteria development process.

**Figure 3: Sediment Stations Monitored by the National Coastal Assessment between 2000 and 2005**



## Dissolved Oxygen

Two data sources were used to evaluate the relationship between nutrients and dissolved oxygen: Grab samples of dissolved oxygen and datasonde measurements of dissolved oxygen.

All valid data from grab samples for dissolved oxygen from the Great Bay Estuary collected between January 1, 2000 and December 31, 2008 were queried from the DES Environmental Monitoring Database. The majority of the data was from the following programs: Great Bay National Estuarine Research Reserve System Wide Monitoring Program (http://nerrs.noaa.gov/Monitoring/), University of New Hampshire Tidal Water Quality Monitoring Program, and the National Coastal Assessment (http://www.epa.gov/emap/nca/).

The minimum, 10th percentile, median, 90th percentile, and maximum dissolved oxygen concentrations were calculated from all the measurements between 2000 and 2008 in each assessment area shown on Figure 1 and for each trend station shown in Figure 2. The data reduction methods used for the nitrogen and phosphorus concentrations were also used for the dissolved oxygen results except that multiple values from the same station on the same data were aggregated by taking the minimum, not maximum, value. The relationships between dissolved oxygen, chlorophyll-a, and nitrogen concentrations were explored through univariate regressions using summary statistics for each assessment area and trend station following the methods described in the "Nutrient Concentrations" section.

Six datasondes are deployed in the Great Bay Estuary each year as part of the Great Bay National Estuarine Research Reserve System Wide Monitoring Program and the UNH Datasonde Program (http://nerrs.noaa.gov/Monitoring/, Pennock, 2008). These instruments record near continuous measurements (typically 30 minute intervals) of water temperature, salinity, dissolved oxygen, pH, and turbidity. The datasondes are the only source of information on daily swings in dissolved oxygen, both the daily minimum concentration and the daily average saturation. Datasondes are located at stations GRBCML, GRBGB, GRBSF, GRBOR, GRBLR, and GRBSQ as shown on Figure 2. At the river stations and in Portsmouth Harbor, the datasondes have been deployed at fixed locations less than 1 meter from the bottom. The datasonde in Great Bay was deployed in the same manner through 2004, after which it was suspended 1 meter below the surface from a buoy.

The valid dissolved oxygen data for each datasonde station between 2000 and 2008 were compiled. Daily minimum dissolved oxygen (in mg/L) and daily average percent saturation were computed for all dates in June through September. For the daily average percent saturation calculation, only dates with at least 36 half-hour readings or 72 quarter-hour readings were included (i.e. 75% complete). The daily minimum and daily average percent saturation values during the summer months were plotted together to illustrate typical conditions over multiple years for each station. With only six stations, it was not possible to obtain statistically significant regressions between the dissolved oxygen concentrations and median nitrogen at each datasonde station. Instead, the nitrogen concentrations at stations where the dissolved oxygen concentrations fell below the water quality standard were compared to nitrogen concentrations at stations without violations to bracket the range of possible nitrogen thresholds.

The results from the analyses of the grab samples and the datasondes were combined using a weight of evidence approach to determine appropriate nitrogen thresholds for this indicator.

## Eelgrass

Multiple lines of evidence were evaluated to determine a nitrogen threshold for this indicator.

Eelgrass is sensitive to water clarity. Therefore, measurements of the light attenuation coefficient ($K_d$) were compiled from across the estuary. All valid data for $K_d$ from the Great Bay Estuary collected between January 1, 2000 and December 31, 2008 were queried from the DES Environmental Monitoring Database. The majority of the data was from the following programs: Great Bay National Estuarine Research Reserve System Wide Monitoring Program (http://nerrs.noaa.gov/Monitoring/), University of New Hampshire Tidal Water Quality Monitoring Program, and the National Coastal Assessment (http://www.epa.gov/emap/nca/).

The minimum, 10th percentile, median, 90th percentile, and maximum $K_d$ values were calculated from all the measurements between 2000 and 2008 in each assessment area shown on Figure 1 and for each trend station shown in Figure 2. The data reduction methods used for the nitrogen and phosphorus concentrations were also used for the $K_d$ results. The relationships between nutrient and chlorophyll-a concentrations and $K_d$ were explored through univariate regressions using summary statistics for each assessment area and trend station following the methods described in the “Nutrient Concentrations” section.

An analytical model from Koch (2001) was used to predict the minimum requirements for $K_d$ in the Great Bay Estuary for the existence of eelgrass. The model was ground truthed using the median values of $K_d$ in different assessment zones and the presence or absence of eelgrass as documented by DES and PREP (NHDES, 2008b; PREP, 2009).

The causal linkage of nitrogen to water clarity was explored through multiple methods.

First, UNH equipped a buoy in Great Bay with light and water quality sensors through a grant to the PREP from EPA. Instantaneous measurements of light attenuation, chlorophyll-a, turbidity, and colored dissolved organic matter (CDOM) were collected between April 4 and December 1, 2007. The measurements were used to develop a multivariate linear regression between $K_d$ and chlorophyll-a, turbidity, and CDOM. This relationship was confirmed to be applicable to all areas of the estuary through analysis of the hyperspectral imagery described in the macroalgae section. UNH processed the imagery to calculate the light attenuation coefficient throughout the estuary. Ground truthing measurements of water quality were made using ship track surveys and grab samples at the same time as the overflights. Additional details on methods used for this analysis are provided in a technical report from UNH (Morrison et al., 2008).

Second, the relationships between particulate organic carbon, turbidity, and nitrogen concentrations in grab samples were explored using univariate regressions. Particulate organic carbon data were queried from the DES Environmental Monitoring Database and processed using the same methods as for the other grab sample data. Median concentrations of particulate organic carbon at trend stations were compared to expected values based on chlorophyll-a concentrations and regressed against nitrogen concentrations. The median turbidity at each datasonde was calculated using all valid data from the years when total nitrogen was monitored at each station. The observations typically spanned the period from March to December. The median was calculated by first selecting days with at least 75% complete data for turbidity and then calculating the average turbidity on those dates. The overall median over the period of record was calculated from these daily average values. The median turbidity for each station was regressed against the median total nitrogen concentration at the six datasonde stations to evaluate the relationship between these two parameters.

The nitrogen threshold for the protection of eelgrass was derived using a weight of evidence approach which included the thresholds for macroalgae proliferation, regressions between total nitrogen and the light attenuation coefficient, offshore water background concentrations, reference concentrations in areas of the estuary which still support eelgrass, and the thresholds that have been set for other New England estuaries.

# Results and Discussion

## Nutrient Concentrations

In the Great Bay Estuary, nitrogen concentrations are highest in the tidal tributaries and are progressively diluted by ocean water down to the mouth of the estuary. Table 2 and Figure 4 show the median concentrations of total nitrogen in each assessment zone between 2000 and 2008. The highest total nitrogen concentrations are in the Squamscott and Cocheco Rivers followed by the Salmon Falls River, Oyster River, and the Upper Piscataqua River. The distribution of total nitrogen concentrations at stations throughout the estuary are shown in Figure 6.

In estuarine waters, nitrogen occurs in several different fractions. Water quality measurements from three trend stations (GRBCL, GRBAP, and GRBCML) were compiled to estimate the percentage of the total nitrogen in each fraction (Table 3). These stations were selected because they represent a range of salinities and nitrogen concentrations. The results showed that nitrogen associated with organic matter (both dissolved and particulate) accounted for 59-62% of the total. However, nitrogen in phytoplankton was only 1% of the total. Dissolved inorganic nitrogen was 36-41% of the total nitrogen. The percentages were similar at all three stations despite the differences in salinity and total nitrogen concentrations at the stations.

The concentrations shown in Table 3 are median values for the whole year for each station. Some stations are monitored monthly throughout the year. The rest of the stations are monitored at least from April through December which span the range of seasons from spring to early winter. Therefore, the percent of total nitrogen in each fraction shown on Table 3 represent central tendency values over the whole year.

Total nitrogen concentrations in Great Bay at Adams Point remain relatively constant throughout the year (Figure 7); however, the concentrations and percentages between the different fractions can change seasonally due to phytoplankton blooms and nutrient cycling reactions. The maximum monthly total nitrogen concentrations occur in the spring and minimum concentrations occur in the summer. However, the maximum and minimum monthly total nitrogen concentrations only deviate from the annual median by less than 30%. In contrast, the bioavailable dissolved inorganic nitrogen concentration is significantly drawn down or depleted during the summer growing season (Figure 8). Unlike the relatively steady total nitrogen concentrations, the maximum monthly dissolved inorganic nitrogen concentrations are nearly 100% higher than the annual median values.

The Great Bay Estuary receives ocean water from the Gulf of Maine. The nitrogen concentration in these offshore waters provides a boundary condition on nutrient criteria because it would be impossible to achieve concentrations lower than the ocean water given that river inflow to the estuary is only 2% of the tidal prism exchange (NHEP, 2007). While uptake by eelgrass and other organisms might reduce nitrogen concentrations in the estuary, the declining trends in eelgrass make this scenario impractical to consider at this time. The UNH Coastal Ocean Observing Center measured concentrations of dissolved inorganic nitrogen and particulate organic nitrogen in 2005-2007 along a cruise track offshore from Portsmouth Harbor to the Wilkinson Basin (http://www.cooa.unh.edu/index.jsp). The transect begins at the mouth of Portsmouth Harbor and extends 45 miles offshore. The median dissolved inorganic nitrogen and particulate organic nitrogen concentrations in 2005-2007 from surface waters (<50 meters in depth) in the first 10 miles of the transect were 0.069 and 0.033 mg N/L, respectively. The data from these transects provide the best estimate of the offshore background concentrations of dissolved inorganic nitrogen and particulate organic nitrogen; however, dissolved organic nitrogen was not measured. Total nitrogen is the sum of dissolved inorganic nitrogen, particulate organic nitrogen, and dissolved organic nitrogen. Love et al. (2005) monitored dissolved organic nitrogen in offshore transects in Casco Bay to study the origins of harmful algal blooms. Typical surface concentrations of dissolved organic nitrogen were 0.085-0.106 mg N/L. In 1999, Townsend (*personal communication*) measured dissolved organic nitrogen concentrations of 0.130 mg N/L (median value) during cruises off Georges Bank. The concentrations were highest in the productive areas over Georges Bank with 25th and 75th percentile concentrations of 0.106 and 0.178 mg N/L, respectively. More generally, in the mid-Atlantic and the mid-Pacific oceans, surface concentrations of dissolved organic nitrogen were 0.143 and 0.085 mg N/L, respectively (Hopkinson et al., 2002; Jackson and Williams, 1985). Finally, the median dissolved organic nitrogen concentration at the mouth of Portsmouth Harbor at station GRBCML between 2000 and 2007 was 0.111 mg N/L. Taking all of the available data together, a reasonable estimate of surface dissolved organic nitrogen concentration in Gulf of Maine immediately offshore of the Great Bay Estuary would be on the order of 0.1 mg N/L. Combining the median dissolved inorganic nitrogen and particulate organic nitrogen concentrations from the Wilkinson Basin transects and the estimate of dissolved organic nitrogen concentrations in offshore waters, the total nitrogen concentration in offshore waters is 0.2 mg N/L. This estimate seems reasonable given that it is slightly lower than the median total nitrogen concentration that has been measured at the mouth of the estuary in Portsmouth Harbor (0.29 mg N/L). If this estimate is accurate, the total nitrogen concentration in Gulf of Maine offshore from New Hampshire is approximately 0.07 mg N/L lower than the total nitrogen concentration for Nantucket Sound (0.267 mg N/L) (Howes et al., 2006). For this report, we will assume that the nitrogen concentration in offshore waters is not changing. However, it is possible that the concentration is slowly increasing due to nitrogen loads from the Gulf of Maine watershed.

**Figure 4: Median Concentrations of Total Nitrogen in Regions of the Great Bay Estuary Calculated from Samples Collected in All Seasons in 2000-2008**

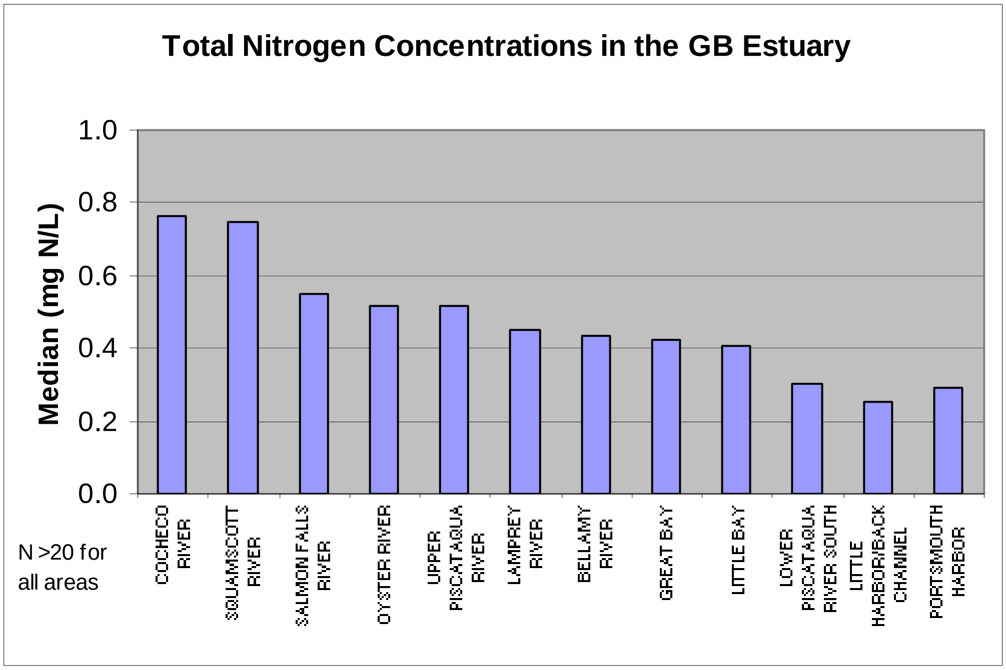


**Figure 5: Median Concentrations of Total Phosphorus in Regions of the Great Bay Estuary Calculated from Samples Collected in All Seasons in 2000-2008**

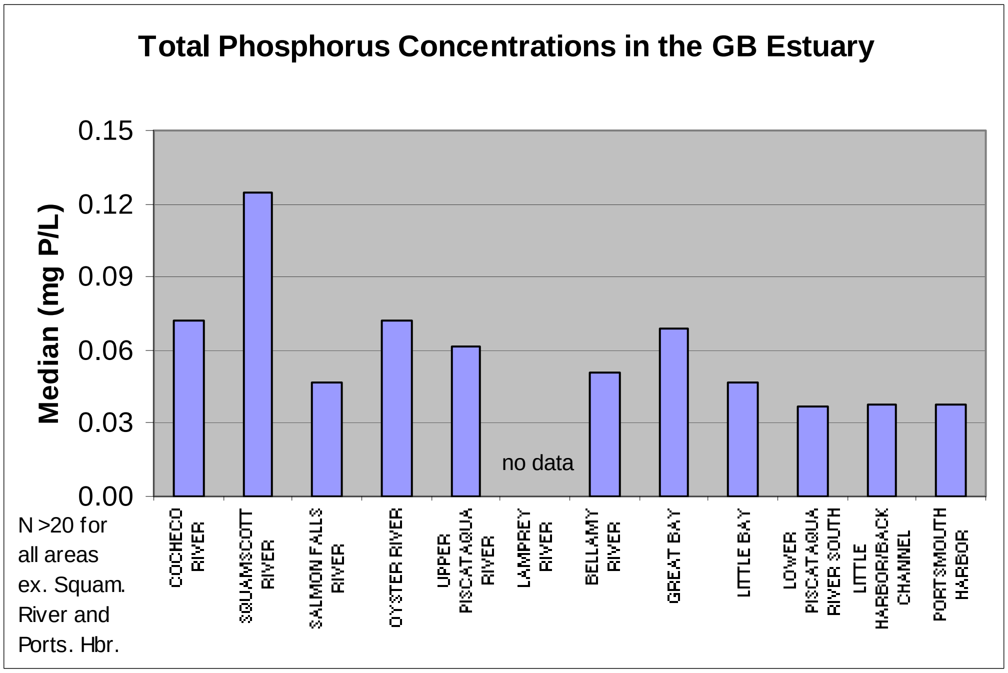
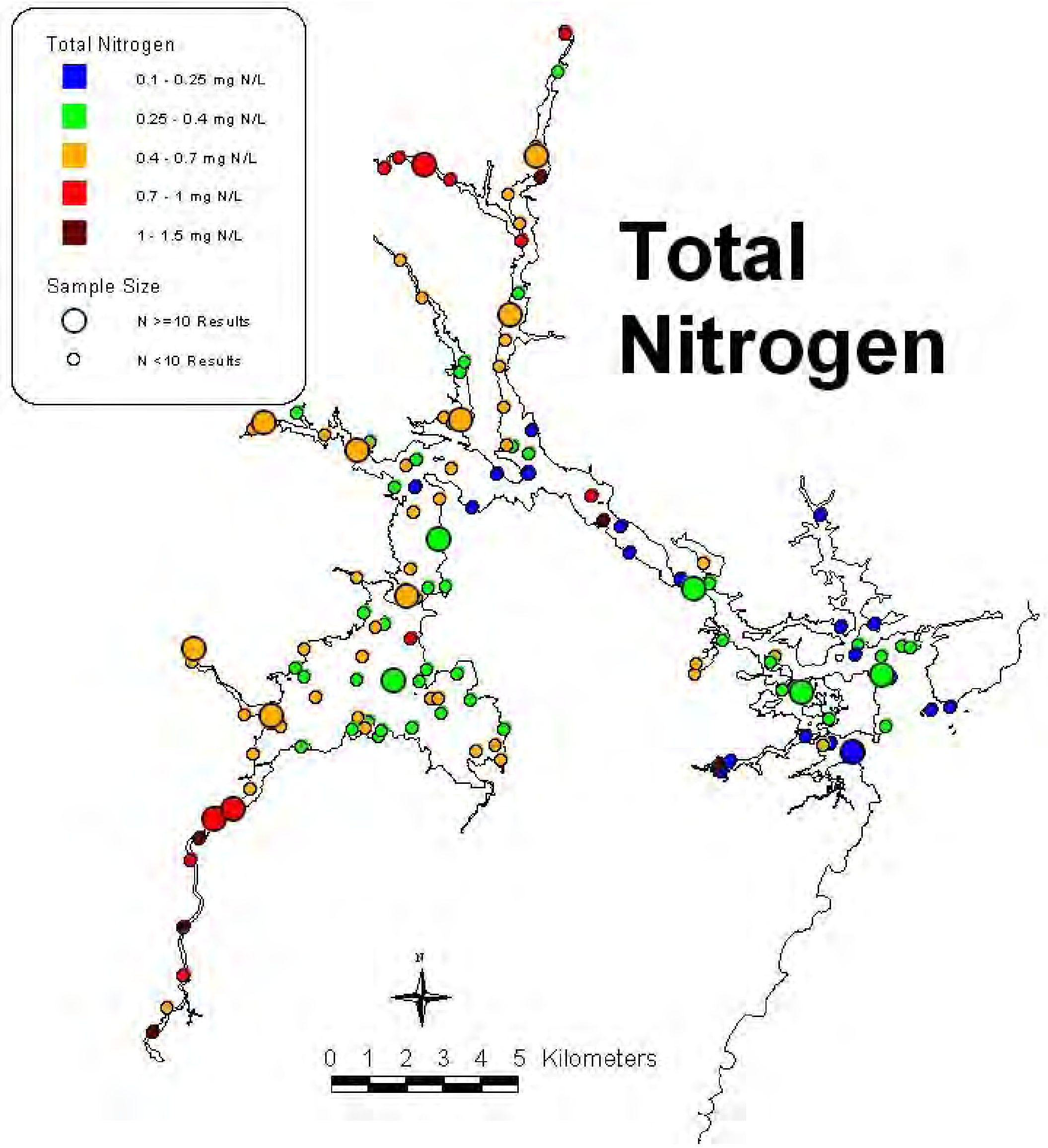


**Figure 6: Median Concentrations of Total Nitrogen at Water Quality Stations**



## Table 2: Summary Statistics for Total Nitrogen (mg N /L) Calculated from Samples Collected in All Seasons in 2000-2008

**(A) Assessment Zones**

| Assessment Zone | N | Min | 10th%ile | Median | 90th%ile | Max |
|---|---|---|---|---|---|---|
| BELLAMY RIVER | 38 | 0.200 | 0.266 | 0.434 | 0.585 | 0.670 |
| COCHECO RIVER | 21 | 0.416 | 0.520 | 0.763 | 1.393 | 1.492 |
| GREAT BAY | 82 | 0.200 | 0.276 | 0.421 | 0.588 | 1.056 |
| LAMPREY RIVER | 39 | 0.265 | 0.370 | 0.451 | 0.589 | 0.970 |
| LITTLE BAY | 93 | 0.146 | 0.244 | 0.409 | 0.571 | 1.085 |
| LITTLE HARBOR/BACK CHANNEL | 42 | 0.151 | 0.193 | 0.252 | 0.418 | 0.935 |
| LOWER PISCATAQUA RIVER NORTH | 8 | 0.199 | 0.205 | 0.247 | 1.015 | 1.426 |
| LOWER PISCATAQUA RIVER SOUTH | 23 | 0.167 | 0.210 | 0.300 | 0.439 | 0.602 |
| NORTH MILL POND | 4 | 0.242 | 0.246 | 0.333 | 0.676 | 0.790 |
| OYSTER RIVER | 41 | 0.266 | 0.311 | 0.519 | 0.676 | 1.669 |
| PORTSMOUTH HARBOR | 55 | 0.146 | 0.186 | 0.291 | 0.382 | 0.493 |
| SAGAMORE CREEK | 4 | 0.165 | 0.168 | 0.186 | 1.110 | 1.501 |
| SALMON FALLS RIVER | 25 | 0.295 | 0.335 | 0.552 | 0.773 | 1.224 |
| SPINNEY CREEK | 1 | 0.558 | 0.558 | 0.558 | 0.558 | 0.558 |
| SPRUCE CREEK | 2 | 0.200 | 0.200 | 0.201 | 0.201 | 0.202 |
| SQUAMSCOTT RIVER | 68 | 0.352 | 0.551 | 0.748 | 1.094 | 1.898 |
| UPPER PISCATAQUA RIVER | 37 | 0.195 | 0.383 | 0.519 | 0.777 | 1.093 |

**(B) Trend Monitoring Stations**

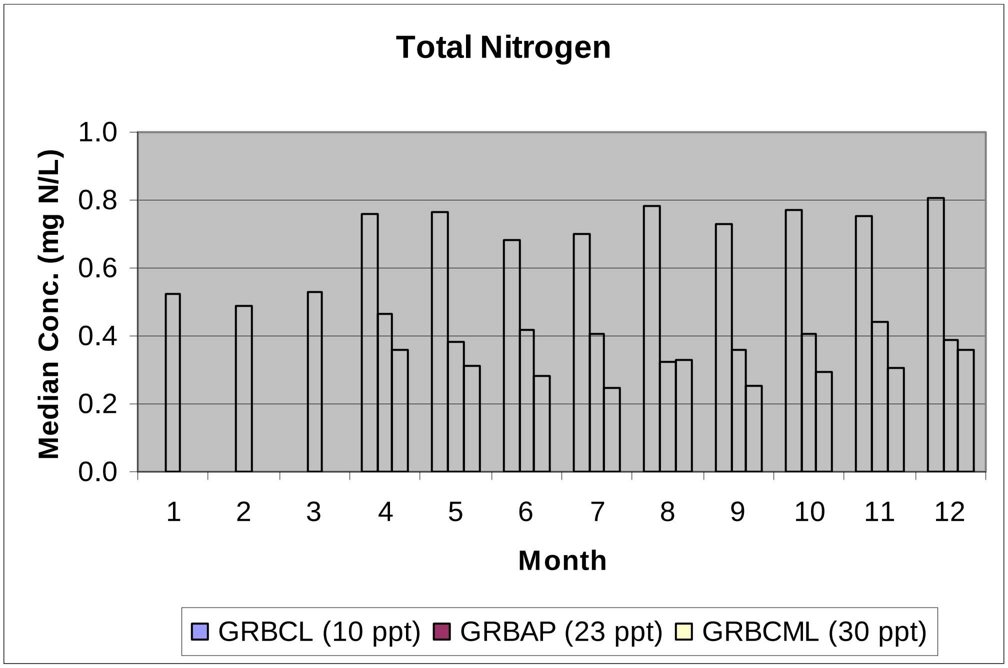
| Station | N | Min | 10th%ile | Median | 90th%ile | Max |
|---|---|---|---|---|---|---|
| GRBAP | 62 | 0.190 | 0.287 | 0.410 | 0.586 | 0.699 |
| GRBCL | 31 | 0.431 | 0.609 | 0.735 | 0.916 | 1.165 |
| GRBCML | 44 | 0.167 | 0.223 | 0.304 | 0.383 | 0.493 |
| GRBGB | 29 | 0.200 | 0.264 | 0.390 | 0.487 | 0.590 |
| GRBLR | 34 | 0.265 | 0.370 | 0.445 | 0.542 | 0.785 |
| GRBOR | 21 | 0.311 | 0.450 | 0.567 | 0.646 | 0.869 |
| GRBSQ | 27 | 0.352 | 0.550 | 0.735 | 0.976 | 1.496 |
| NH-0023A | 17 | 0.151 | 0.183 | 0.249 | 0.427 | 0.830 |
| NH-0025A | 16 | 0.382 | 0.404 | 0.526 | 0.688 | 1.056 |
| NH-0029A | 17 | 0.161 | 0.198 | 0.251 | 0.332 | 0.423 |
| NH-0043A | 16 | 0.167 | 0.214 | 0.303 | 0.417 | 0.530 |
| NH-0045A | 15 | 0.146 | 0.198 | 0.364 | 0.520 | 0.671 |
| NH-0049A | 14 | 0.266 | 0.297 | 0.430 | 0.637 | 1.669 |
| NH-0052A | 32 | 0.200 | 0.257 | 0.434 | 0.586 | 0.670 |
| NH-0057A | 28 | 0.382 | 0.421 | 0.537 | 0.775 | 1.093 |
| NH-0058A | 17 | 0.436 | 0.534 | 0.772 | 1.340 | 1.492 |
| NH-0062A | 17 | 0.295 | 0.354 | 0.516 | 0.654 | 0.731 |

**Table 3: Median Concentrations and Percent of Total for Nitrogen Fractions at Trend Stations Calculated from Samples Collected in All Seasons in 2000-2008**

| Fraction | Species | GRBCL | | GRBAP | | GRBCML | |
|---|---|---|---|---|---|---|---|
| | | mg/L | % | mg/L | % | mg/L | % |
| Dissolved | Ammonia | 0.125 | 16% | 0.053 | 13% | 0.052 | 18% |
| | Nitrate+Nitrite | 0.165 | 21% | 0.100 | 24% | 0.069 | 23% |
| | In Organic Matter | 0.290 | 38% | 0.170 | 41% | 0.114 | 39% |
| Particulate | In Phytoplankton | 0.010 | 1% | 0.006 | 1% | 0.002 | 1% |
| | In Organic Matter | 0.180 | 23% | 0.090 | 22% | 0.059 | 20% |
| Total | | 0.769 | 100% | 0.418 | 100% | 0.295 | 100% |

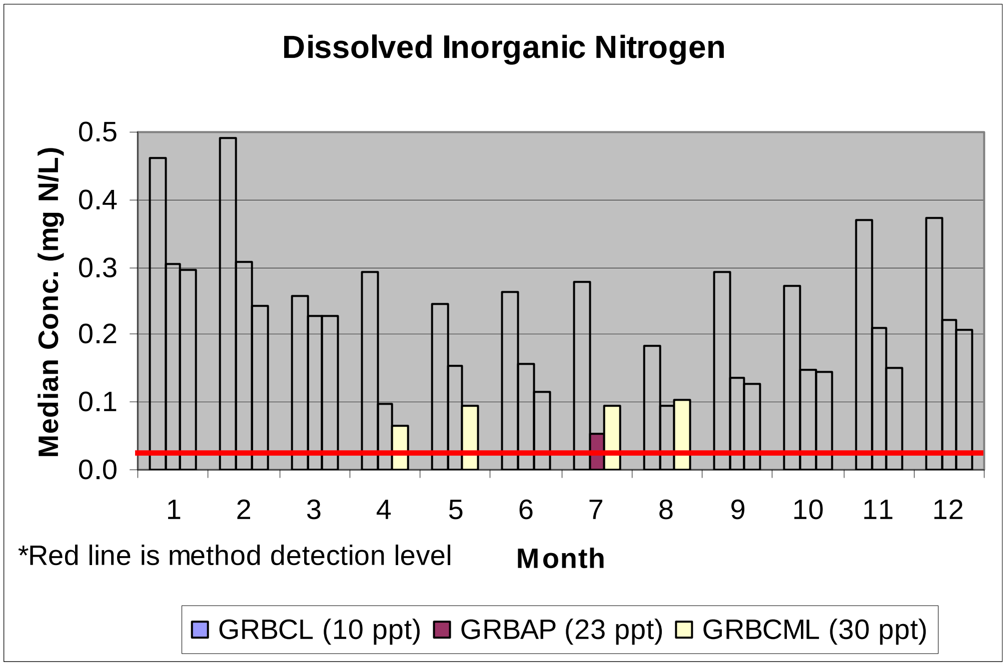
* The sample size for each station was 31, 59, and 37 for GRBCL, GRBAP, and GRBCML, respectively.
** The values for total nitrogen do not match reported values for these stations on Table 2 because the totals on this table were calculated in a different way (e.g., only samples with data for all nitrogen species were included).

**Figure 7: Seasonal Pattern of Total Nitrogen Concentrations at Trend Stations with Different Salinities**



All available data for these stations in 2000 - 2008 were included in this graph, which amounts to:
GRBAP: (Jan-Mar) 2006, 2007, 2008; (Apr-Dec) 2003, 2004, 2005, 2006, 2007, 2008
GRBCL: (Jan-Mar) None; (Apr-Dec) 2003, 2004, 2005, 2006
GRBCML: (Jan-Mar) None; (Apr-Dec) 2003, 2004, 2005, 2006, 2007, 2008

**Figure 8: Seasonal Pattern for Dissolved Inorganic Nitrogen at Trend Stations with Different Salinities**

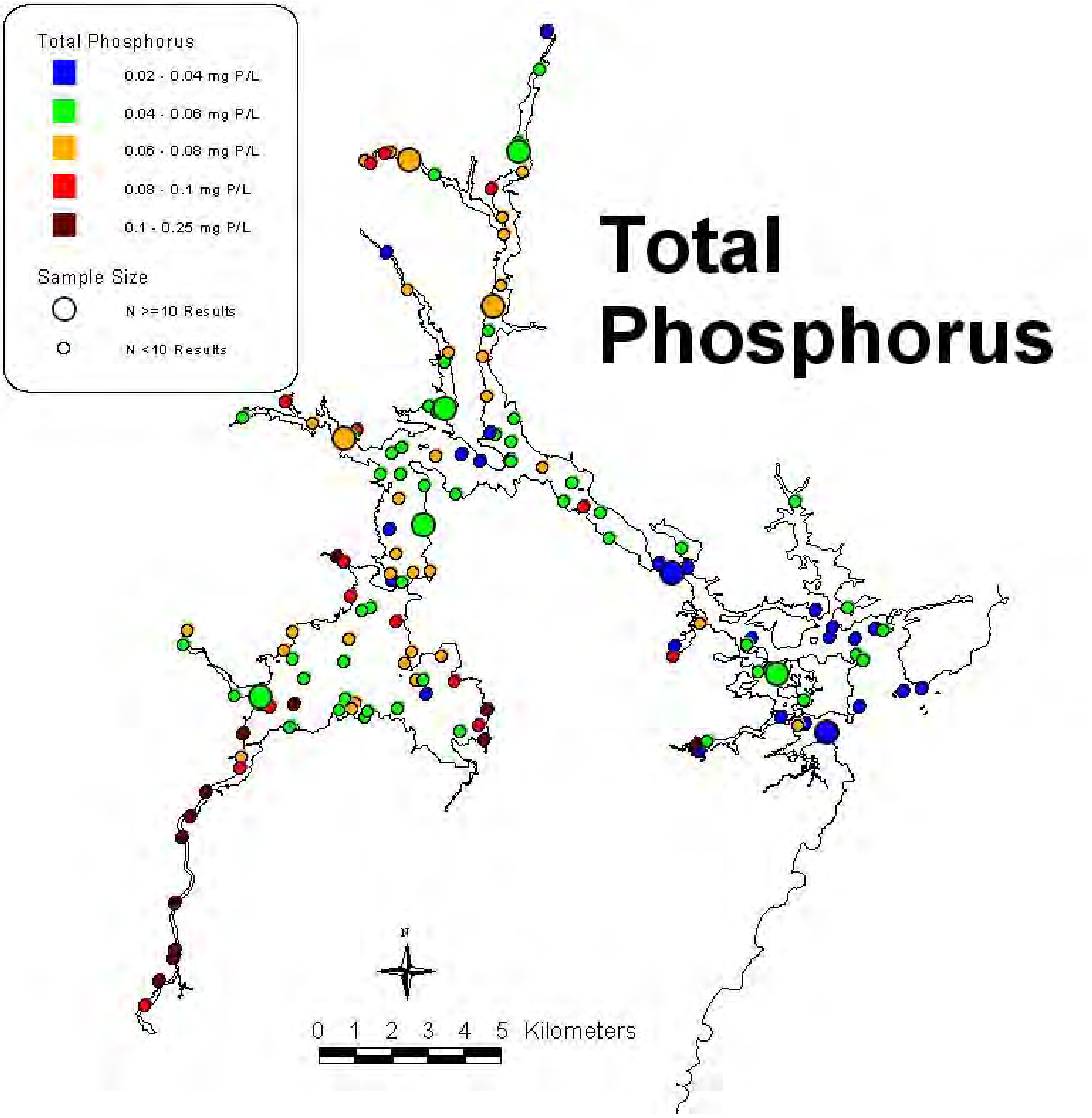


All available data for these stations in 2000 - 2008 were included in this graph, which amounts to:
GRBAP: (Jan-Mar) 2000, 2001, 2006, 2007, 2008; (Apr-Dec) 2000 through 2008
GRBCL: (Jan-Mar) 2000, 2001; (Apr-Dec) 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2008
GRBCML: (Jan-Mar) 2001; (Apr-Dec) 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2008

The available data show that total phosphorus concentrations are highest in the Squamscott River (Table 4, Figure 5). Elevated total phosphorus concentrations have also been measured in the Cocheco and Oyster Rivers and Great Bay. Downstream of Great Bay the total phosphorus concentrations decrease due to dilution from ocean. Fewer measurements are available for total phosphorus than for total nitrogen so some of the median values were calculated from less than 20 samples. Specifically, the median values for the Squamscott River and Portsmouth are based on only 12 and 11 measurements, respectively. Only five measurements of total phosphorus were available from the Lamprey River so this assessment zone was not included in the graph.

The percentages of phosphorus in different fractions were calculated from median concentrations of phosphorus species select trend stations (Table 5). The percentage of phosphorus associated with organic matter ranged from 48% to 74%, but phosphorus in phytoplankton only accounted for 1% of the total. As with nitrogen, the concentration of the bioavailable orthophosphate species changes with the season (Figure 10). This species is drawn down or depleted during the spring and reaches a maximum value in the fall. There were insufficient data to determine intra-annual trends for total phosphorus concentrations.

**Figure 9: Median Concentrations of Total Phosphorus at Water Quality Stations**



## Table 4: Summary Statistics for Total Phosphorus (mg P /L) Calculated from Samples Collected in All Seasons in 2000-2008

### (A) Assessment Zones

| Assessment Zone | N | Min | 10th%ile | Median | 90th%ile | Max |
|---|---|---|---|---|---|---|
| BELLAMY RIVER | 36 | 0.022 | 0.031 | 0.051 | 0.081 | 0.091 |
| COCHECO RIVER | 30 | 0.025 | 0.0384 | 0.072 | 0.1082 | 0.132 |
| GREAT BAY | 59 | 0.024 | 0.044 | 0.069 | 0.117 | 0.254 |
| LAMPREY RIVER | 5 | 0.036 | 0.043 | 0.053 | 0.092 | 0.118 |
| LITTLE BAY | 36 | 0.030 | 0.034 | 0.047 | 0.073 | 0.086 |
| LITTLE HARBOR/BACK CHANNEL | 41 | 0.023 | 0.026 | 0.038 | 0.056 | 0.129 |
| LOWER PISCATAQUA RIVER NORTH | 10 | 0.023 | 0.030 | 0.044 | 0.075 | 0.088 |
| LOWER PISCATAQUA RIVER SOUTH | 24 | 0.025 | 0.029 | 0.037 | 0.056 | 0.072 |
| NORTH MILL POND | 4 | 0.036 | 0.037 | 0.053 | 0.081 | 0.087 |
| OYSTER RIVER | 22 | 0.026 | 0.046 | 0.072 | 0.108 | 0.205 |
| PORTSMOUTH HARBOR | 11 | 0.025 | 0.031 | 0.038 | 0.049 | 0.058 |
| SAGAMORE CREEK | 4 | 0.034 | 0.035 | 0.045 | 0.135 | 0.170 |
| SALMON FALLS RIVER | 24 | 0.028 | 0.033 | 0.047 | 0.073 | 0.102 |
| SPINNEY CREEK | 1 | 0.058 | 0.058 | 0.058 | 0.058 | 0.058 |
| SPRUCE CREEK | 2 | 0.046 | 0.046 | 0.047 | 0.048 | 0.048 |
| SQUAMSCOTT RIVER | 12 | 0.044 | 0.069 | 0.125 | 0.166 | 0.248 |
| UPPER PISCATAQUA RIVER | 40 | 0.026 | 0.036 | 0.062 | 0.083 | 0.227 |

### (B) Trend Monitoring Stations

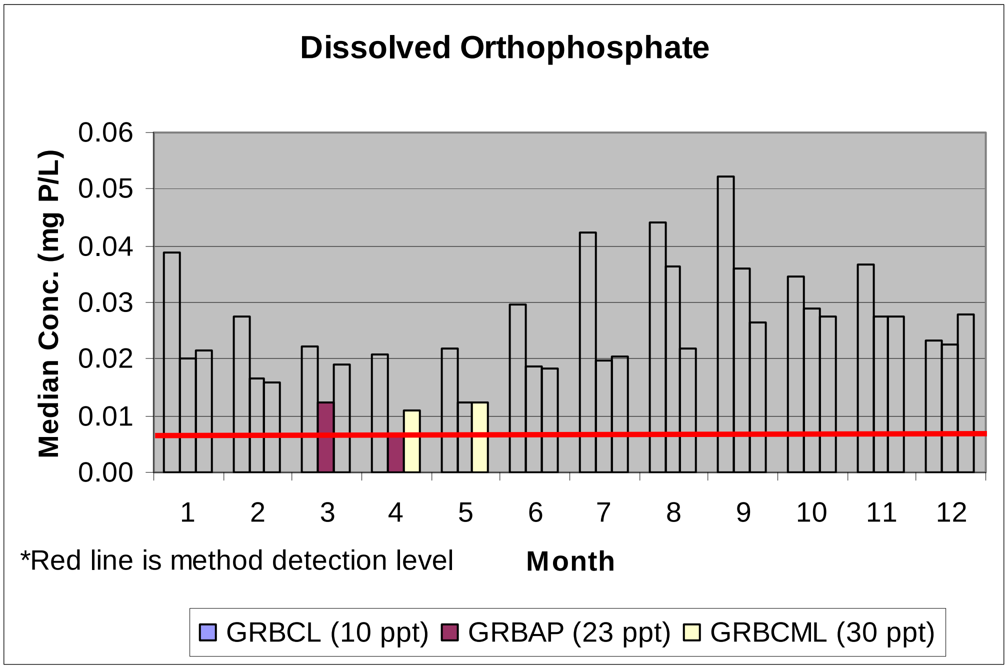
| Station | N | Min | 10th%ile | Median | 90th%ile | Max |
|---|---|---|---|---|---|---|
| GRBAP | 1 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 |
| NH-0023A | 17 | 0.023 | 0.0246 | 0.037 | 0.0502 | 0.129 |
| NH-0025A | 15 | 0.024 | 0.0396 | 0.06 | 0.1178 | 0.254 |
| NH-0029A | 15 | 0.023 | 0.0278 | 0.039 | 0.0542 | 0.056 |
| NH-0043A | 16 | 0.025 | 0.0285 | 0.0365 | 0.057 | 0.072 |
| NH-0045A | 17 | 0.03 | 0.0322 | 0.045 | 0.076 | 0.086 |
| NH-0049A | 16 | 0.032 | 0.0465 | 0.077 | 0.142 | 0.205 |
| NH-0052A | 27 | 0.028 | 0.038 | 0.056 | 0.0866 | 0.091 |
| NH-0057A | 28 | 0.026 | 0.0374 | 0.0645 | 0.0922 | 0.227 |
| NH-0058A | 14 | 0.039 | 0.0459 | 0.073 | 0.1094 | 0.118 |
| NH-0062A | 14 | 0.028 | 0.0352 | 0.0465 | 0.0633 | 0.102 |

**Table 5: Median Concentrations and Percent in Different Phosphorus Fractions at Trend Stations Calculated from Samples Collected in All Seasons in 2000-2008**

| Fraction | Species | LP* | | UP Tribs* | | GB Tribs* | |
|---|---|---|---|---|---|---|---|
| | | mg/L | % | mg/L | % | mg/L | % |
| Dissolved | Orthophosphate | 0.024 | 52% | 0.016 | 25% | 0.024 | 36% |
| | In Organic Matter | 0.011 | 24% | 0.023 | 37% | 0.021 | 31% |
| Particulate | In Phytoplankton | 0.0002 | 1% | 0.0003 | 1% | 0.0004 | 1% |
| | In Organic Matter | 0.011 | 24% | 0.023 | 37% | 0.022 | 32% |
| Total | | 0.046 | 100% | 0.062 | 100% | 0.067 | 100% |

* Data from trend stations with similar concentrations were combined to increase the sample size. "GB Tribs" includes data from NH-0025A, NH-0049A, and NH-0052A (n=33). "UP Tribs" includes data from NH-0057A, NH-0058A, and NH-0062A (n=26). "LP" includes data from NH-0023A, NH-0029A, and NH-0043A (n=24).

**Figure 10: Seasonal Pattern for Dissolved Orthophosphate at Trend Stations with Different Salinities**



All available data for these stations in 2000 - 2008 were included in this graph, which amounts to:
GRBAP: (Jan-Mar) 2000, 2001, 2006, 2007, 2008; (Apr-Dec) 2000 through 2008
GRBCL: (Jan-Mar) 2000, 2001; (Apr-Dec) 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2008
GRBCML: (Jan-Mar) 2001; (Apr-Dec) 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2008

Nitrogen is typically the limiting nutrient for primary productivity in estuaries (Howarth and Marino, 2006; NRC, 2000). However, phosphorus can be important in riverine estuaries with low salinities. Data from Great Bay Estuary follow these expected patterns.

The ratio of nitrogen to phosphorus concentrations indicates that nitrogen is the limiting nutrient in the majority of the Great Bay Estuary. The median molar ratios of total nitrogen to total phosphorus and dissolved inorganic nitrogen to orthophosphate (bioavailable fractions) were calculated for the trend monitoring stations in the estuary. According to the Redfield Ratio, nitrogen will be the limiting nutrient if the N:P molar ratio is 16 or less (Howarth and Marino, 2006). Given that kinetics often limit transitions between bioavailable and total fractions, the threshold of 16 is not precise, but is a useful guide. Figure 11 shows that the ratio of total nitrogen to total phosphorus is clustered around 16 and the ratio of bioavailable nitrogen to bioavailable phosphorus is well below 16 for stations with average salinity greater than 20 ppt. Most of the estuary is in this salinity range (88% by volume). However, in the low salinity tidal tributaries the ratio for totals climbs to around 25 and the ratio for bioavailable fractions reaches as high as 60, which indicates phosphorus limitation. This effect is most pronounced in the Cocheco, Salmon Falls, and Upper Piscataqua Rivers. Despite these high N:P ratios in the tidal rivers, Figure 12 shows that elevated chlorophyll-a concentrations in these tidal rivers do not occur during periods of phosphorus limitation (i.e., when the N:P ratio is high). The pattern of increasing N:P ratios with decreasing salinity is probably representative of freshwater inputs to the estuary, with phosphorus being the limiting nutrient during periods of high flows when the tidal tributaries are more like freshwater rivers than estuaries. However, the rapid flushing caused by the high flows tends to inhibit phytoplankton blooms during these periods. Therefore, nitrogen will be considered the limiting nutrient for primary productivity in the majority of the estuary during the majority of the year. Any impacts of phosphorus on productivity in the estuary during high flows will be controlled by numeric water quality criteria for phosphorus in rivers that are being developed by DES.

**Figure 11: Molar Ratio of Nitrogen to Phosphorus Versus Salinity at Trend Monitoring Stations Calculated from Samples Collected in All Seasons in 2000-2008**

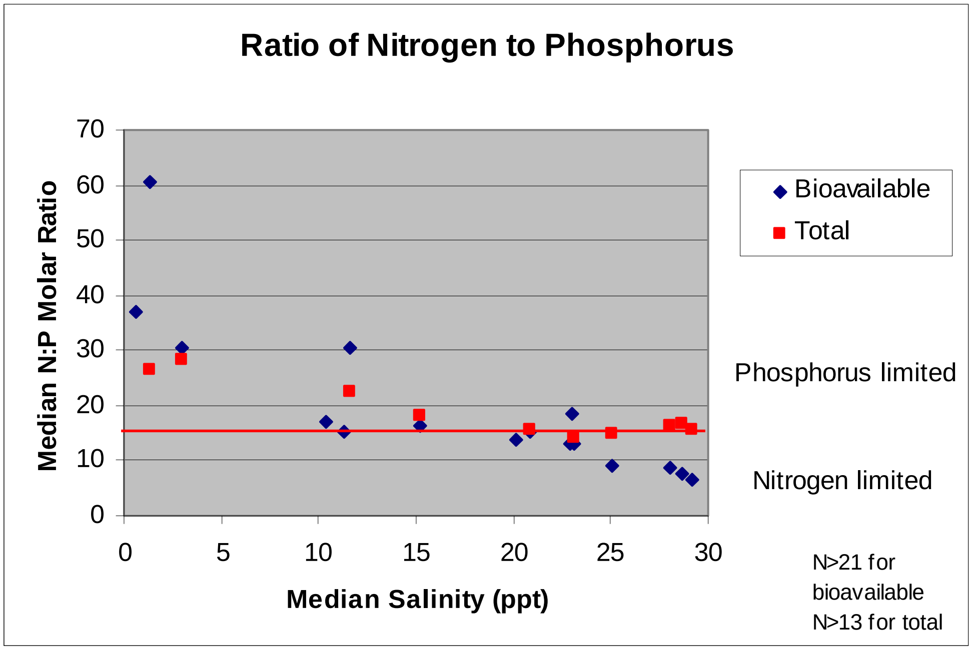
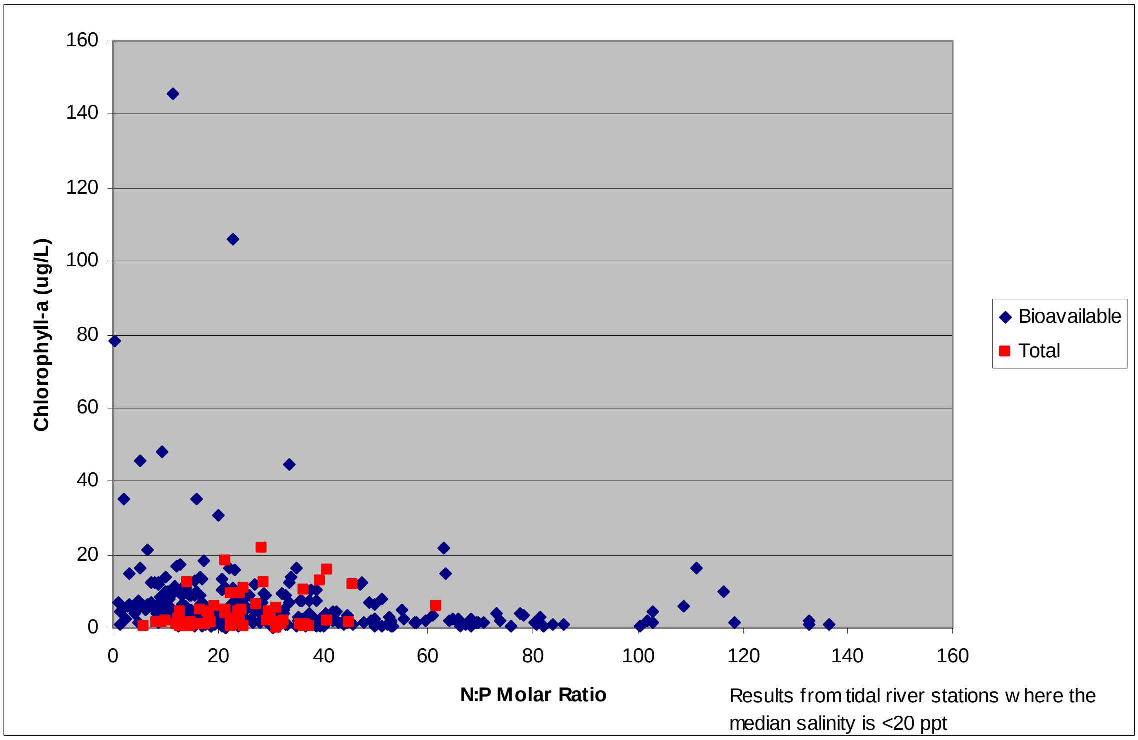


**Figure 12: Relationship between Chlorophyll-a Concentrations and the Nitrogen to Phosphorus Ratio at Low Salinity (<20 ppt) Trend Stations**



## *Primary Indicators*

### Chlorophyll-a

The most common indicator of primary eutrophic response is phytoplankton blooms as measured by chlorophyll-a concentrations (Bricker et al, 2007; Cloern, 2001; NRC, 2000; EPA, 2001). Phytoplankton blooms will occur when there are sufficient amounts of bioavailable nitrogen and phosphorus and adequate water clarity. In nitrogen limited systems, such as estuaries, increasing nitrogen concentrations should result in increased phytoplankton blooms, although the phytoplankton population can be mediated by top-down predation (Heck and Valentine, 2007).

The highest concentrations of chlorophyll-a occur in the Squamscott, Cocheco, Lamprey, and Salmon Falls Rivers, which follows a similar spatial pattern as total nitrogen (Figure 13). Typical peak chlorophyll-a concentrations were calculated from the 90th percentile values using data from all seasons. Table 6 contains summary statistics for chlorophyll-a concentrations in different assessment zones and at trend stations using data from all four seasons. The distribution of 90th percentile chlorophyll-a concentrations at stations in the estuary during all four seasons is shown in Figure 14.

Total nitrogen concentrations are the best explanatory variable for peak chlorophyll-a concentrations. The magnitude of chlorophyll-a concentrations in each assessment zone during blooms was estimated by calculating the 90th percentile concentration using all valid results during all seasons in 2000-2008 (Table 6). These values were compared to the median concentrations of total nitrogen, total dissolved nitrogen, and dissolved inorganic nitrogen, total phosphorus, and orthophosphate. The best relationship was between chlorophyll-a and total nitrogen ($r^2$=0.72, Figure 15). It is not surprising that there were inferior relationships between chlorophyll-a and dissolved inorganic nitrogen ($r^2$=0.40) and total dissolved nitrogen ($r^2$=0.67) because the concentrations of these species are variable due to biological uptake. The relationship between chlorophyll-a and total phosphorus was not as good ($r^2$=0.64) as the one with total nitrogen. Orthophosphate was poorly correlated with chlorophyll-a concentrations ($r^2$=0.03).

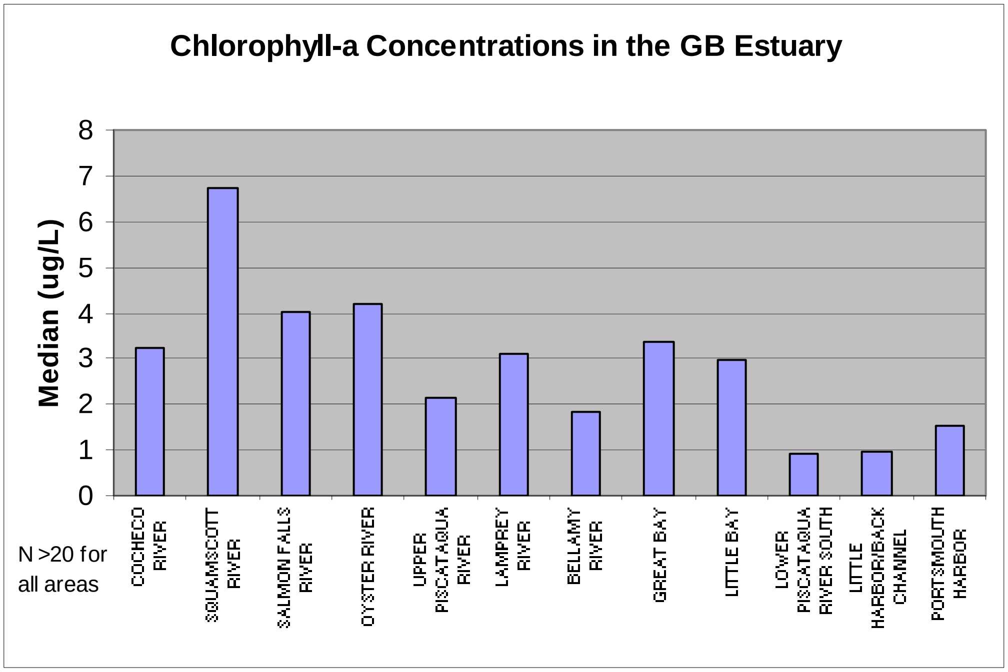
One concern about the correlations between total nitrogen and chlorophyll-a is the autocorrelation introduced by the nitrogen included in the tissues of phytoplankton. In Table 3, the percent of total nitrogen in different fractions has been estimated. The nitrogen in living phytoplankton accounts for approximately 1% of the total. Therefore, there does not appear to be any significant autocorrelation in this relationship.

The seasonal patterns of median chlorophyll-a concentrations in three different salinity zones are shown in Figure 16. At a low salinity station (station GRBCL), there is no spring bloom but rather a long summer growing period peaking in June-August. In Great Bay (station GRBAP), there is a distinct spring bloom in April which corresponds to the period of orthophosphate depletion as shown in Figure 10. A longer summer growing period follows during June through September during which dissolved inorganic nitrogen in the water column is depleted (see Figure 8). At the mouth of the harbor (station GRBCML), chlorophyll-a concentrations remain low in spring, summer, fall, and early winter. The patterns in Figure 16 show that March through October is the critical period for elevated chlorophyll-a concentrations.

While large phytoplankton blooms result in many secondary effects (discussed later in this report), the immediate impact of blooms is to impair the primary contact recreation designated use (swimming use). Since 2004, DES has used a threshold of 20 ug/L for chlorophyll-a to determine impairments of this designated use for 305(b) assessments as described in the Consolidated Assessment and Listing Methodology (NHDES, 2008a). DES established this threshold as an interpretation of the narrative standard for nutrients (Env-Wq 1703.14). The threshold chosen matches the 20 ug/L threshold that EPA uses to determine “poor” water quality from chlorophyll-a measurements in the National Coastal Condition reports ( EPA, 2006). The National Oceanic and Atmospheric Administration also uses 20 ug/L as a threshold to distinguish “high” chlorophyll-a in estuaries (Bricker et al., 2007). DES uses a slightly lower value (15 ug/L) as the threshold for determining chlorophyll-a impairments of primary contact recreation in lakes. The threshold for lakes was chosen because DES felt that this level of chlorophyll-a would interfere with the aesthetic enjoyment of swimming in a lake. Despite this apparent inconsistency, DES feels that 20 ug/L is the appropriate threshold for primary contact recreation impairments due to chlorophyll-a in estuaries. It is reasonable for the chlorophyll-a thresholds for lakes and estuaries to not be equal because most people expect lower water clarity and higher productivity in estuaries than in lakes. For the 305(b) reports, the algorithm to determine impairments of the primary contact recreation designated use is primarily based on whether greater than 10% of the chlorophyll-a concentrations exceed the threshold. This algorithm is roughly equivalent to making assessment using a threshold for the 90th percentile concentration.

Unfortunately, the nitrogen concentration associated with the chlorophyll-a threshold of 20 ug/L could not be determined with the available data. In Figure 17, a statistically significant regression was developed between median nitrogen concentrations and 90th percentile chlorophyll-a concentrations during all seasons using summary statistics for trend stations. While the relationship was statistically significant, the range of chlorophyll-a values for this regression does not contain 20 ug/L. Estimating a nitrogen threshold based on this regression would require extrapolation, which is not justified. **Therefore, DES will continue to use the 20 ug/L threshold for chlorophyll-a to determine impairments of the primary contact recreation designated use. However, nitrogen will also be listed as a pollutant for any impairments because the regression in Figure 17 proves that primary productivity in the form of phytoplankton blooms is associated with nitrogen concentrations.**

**Figure 13: 90th Percentile Concentrations of Chlorophyll-a in Regions of the Great Bay Estuary Calculated from Samples Collected in All Seasons in 2000-2008**



## Table 6: Summary Statistics for Chlorophyll-a (ug/L) Calculated from Samples Collected in All Seasons in 2000-2008

**(A) Assessment Zones**

| Assessment Zone | N | Min | 10th%ile | Median | 90th%ile | Max |
|---|---|---|---|---|---|---|
| BELLAMY RIVER | 67 | 0.10 | 0.42 | 1.84 | 6.06 | 12.79 |
| BERRYS BROOK | 1 | 1.56 | 1.56 | 1.56 | 1.56 | 1.56 |
| COCHECO RIVER | 46 | 0.20 | 0.54 | 3.23 | 12.28 | 24.97 |
| GREAT BAY | 162 | 0.17 | 1.20 | 3.36 | 7.52 | 24.66 |
| LAMPREY RIVER | 142 | 0.33 | 1.07 | 3.12 | 12.40 | 145.45 |
| LITTLE BAY | 145 | 0.11 | 1.07 | 2.96 | 8.24 | 13.69 |
| LITTLE HARBOR/BACK CHANNEL | 93 | 0.08 | 0.32 | 0.98 | 1.99 | 10.00 |
| LOWER PISCATAQUA RIVER NORTH | 15 | 0.20 | 0.41 | 1.30 | 2.09 | 6.75 |
| LOWER PISCATAQUA RIVER SOUTH | 41 | 0.08 | 0.43 | 0.90 | 2.20 | 2.65 |
| NORTH MILL POND | 5 | 0.20 | 0.31 | 1.12 | 1.58 | 1.60 |
| OYSTER RIVER | 133 | 0.17 | 1.05 | 4.21 | 14.63 | 76.10 |
| PORTSMOUTH HARBOR | 78 | 0.20 | 0.77 | 1.53 | 3.22 | 5.25 |
| SAGAMORE CREEK | 6 | 0.63 | 0.67 | 0.80 | 1.37 | 1.60 |
| SALMON FALLS RIVER | 42 | 0.20 | 1.00 | 4.04 | 12.90 | 18.52 |
| SPINNEY CREEK | 1 | 2.70 | 2.70 | 2.70 | 2.70 | 2.70 |
| SPRUCE CREEK | 2 | 1.30 | 1.64 | 2.98 | 4.32 | 4.65 |
| SQUAMSCOTT RIVER | 150 | 0.20 | 2.82 | 6.75 | 17.37 | 106.07 |
| UPPER PISCATAQUA RIVER | 87 | 0.08 | 0.41 | 2.14 | 7.54 | 78.10 |

**(B) Trend Monitoring Stations**

| Station | N | Min | 10th%ile | Median | 90th%ile | Max |
|---|---|---|---|---|---|---|
| GRBAP | 88 | 0.74 | 1.49 | 4.08 | 9.00 | 13.69 |
| GRBCL | 77 | 0.57 | 2.77 | 7.00 | 16.53 | 106.07 |
| GRBCML | 62 | 0.48 | 0.84 | 1.69 | 3.34 | 5.25 |
| GRBGB | 61 | 0.59 | 1.59 | 3.97 | 9.32 | 18.36 |
| GRBLR | 81 | 0.33 | 0.84 | 2.23 | 7.50 | 145.45 |
| GRBOR | 55 | 0.23 | 1.56 | 5.05 | 14.26 | 64.71 |
| GRBSQ | 52 | 1.06 | 2.97 | 5.52 | 12.14 | 35.03 |
| NH-0023A | 28 | 0.08 | 0.20 | 0.80 | 1.56 | 4.81 |
| NH-0025A | 28 | 0.17 | 0.53 | 1.86 | 4.71 | 12.25 |
| NH-0029A | 29 | 0.31 | 0.41 | 0.96 | 1.80 | 10.00 |
| NH-0043A | 28 | 0.08 | 0.47 | 0.90 | 2.20 | 2.65 |
| NH-0045A | 26 | 0.20 | 0.95 | 1.88 | 5.16 | 6.17 |
| NH-0049A | 28 | 0.17 | 0.88 | 1.82 | 8.54 | 20.31 |
| NH-0052A | 47 | 0.10 | 0.37 | 1.60 | 6.06 | 10.40 |
| NH-0057A | 59 | 0.08 | 0.58 | 2.14 | 7.61 | 78.10 |
| NH-0058A | 27 | 0.27 | 0.50 | 1.60 | 11.28 | 21.90 |
| NH-0062A | 27 | 0.53 | 1.02 | 4.08 | 13.71 | 18.52 |

**Figure 14: 90th Percentile Concentrations of Chlorophyll-a at Water Quality Stations**

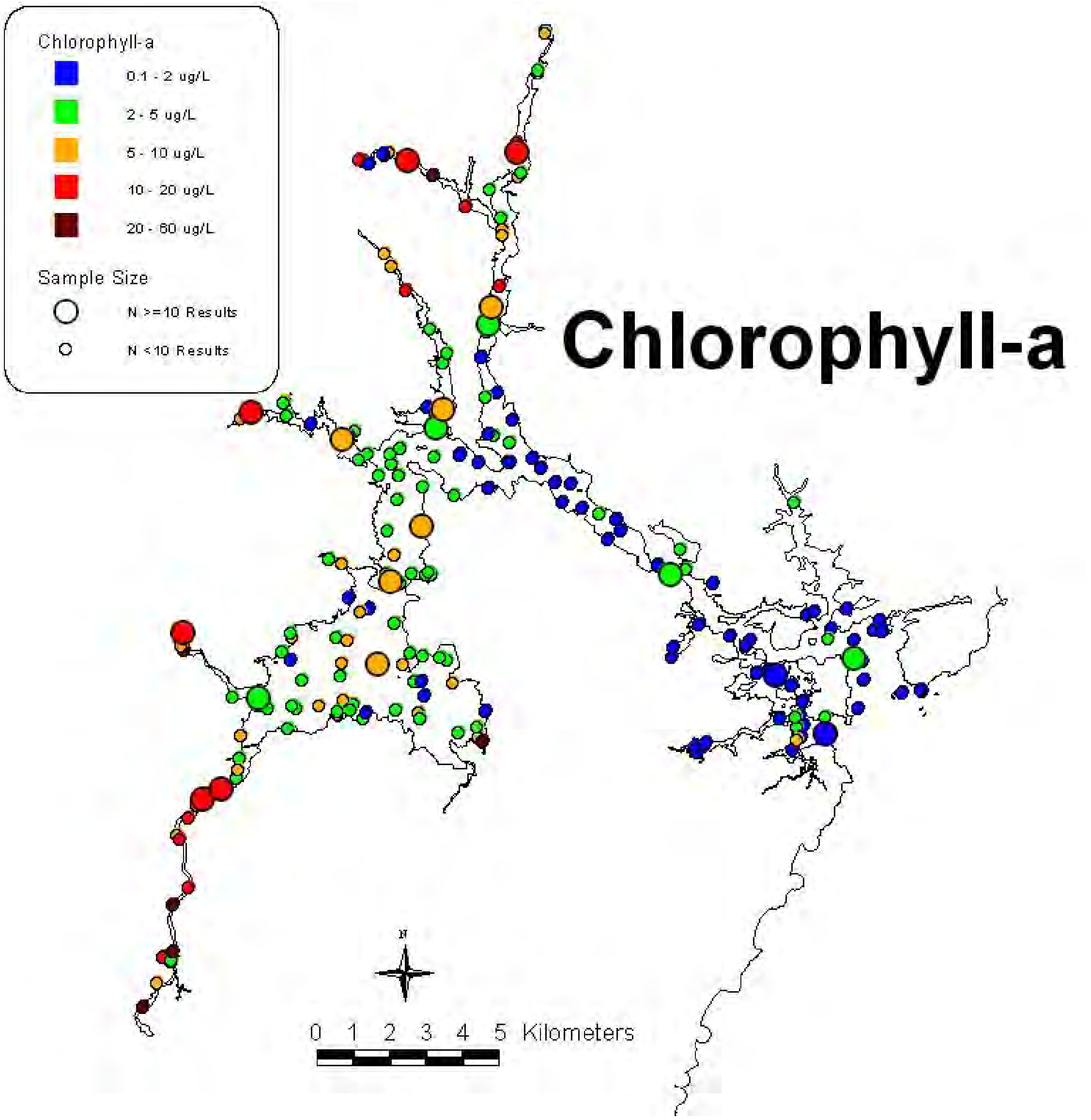
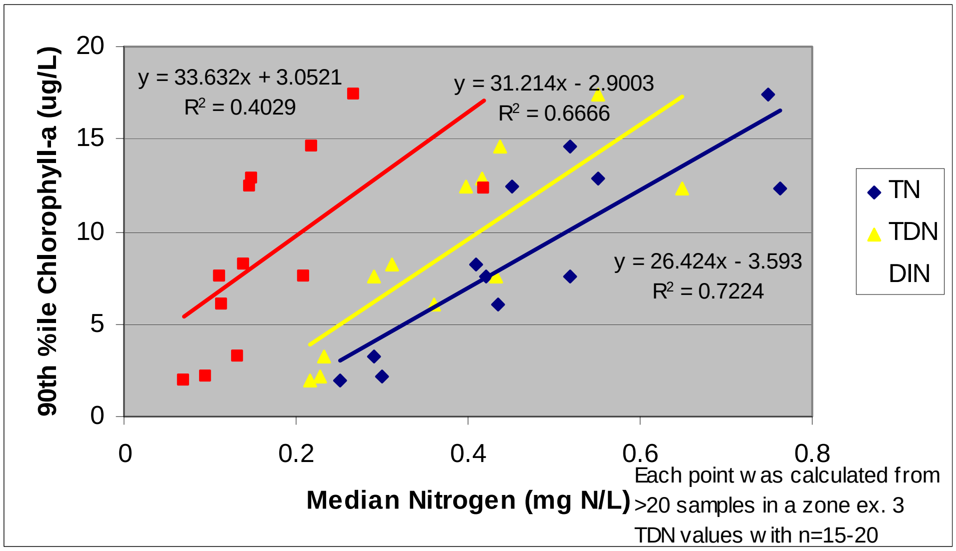
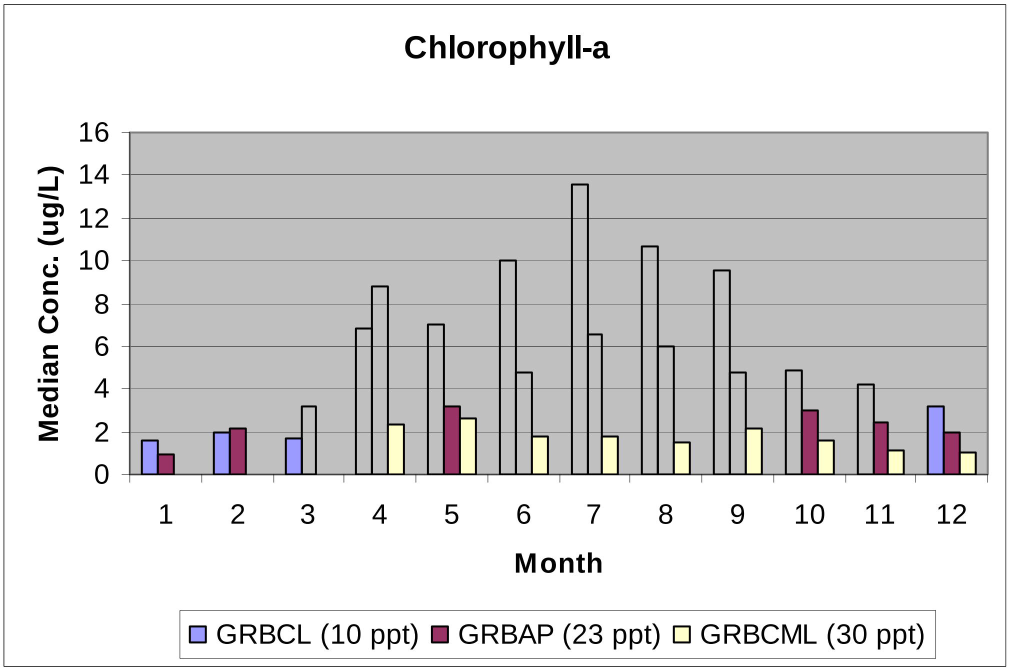


**Figure 15: Relationship between Nitrogen and Chlorophyll-a Concentrations in Assessment Zones**



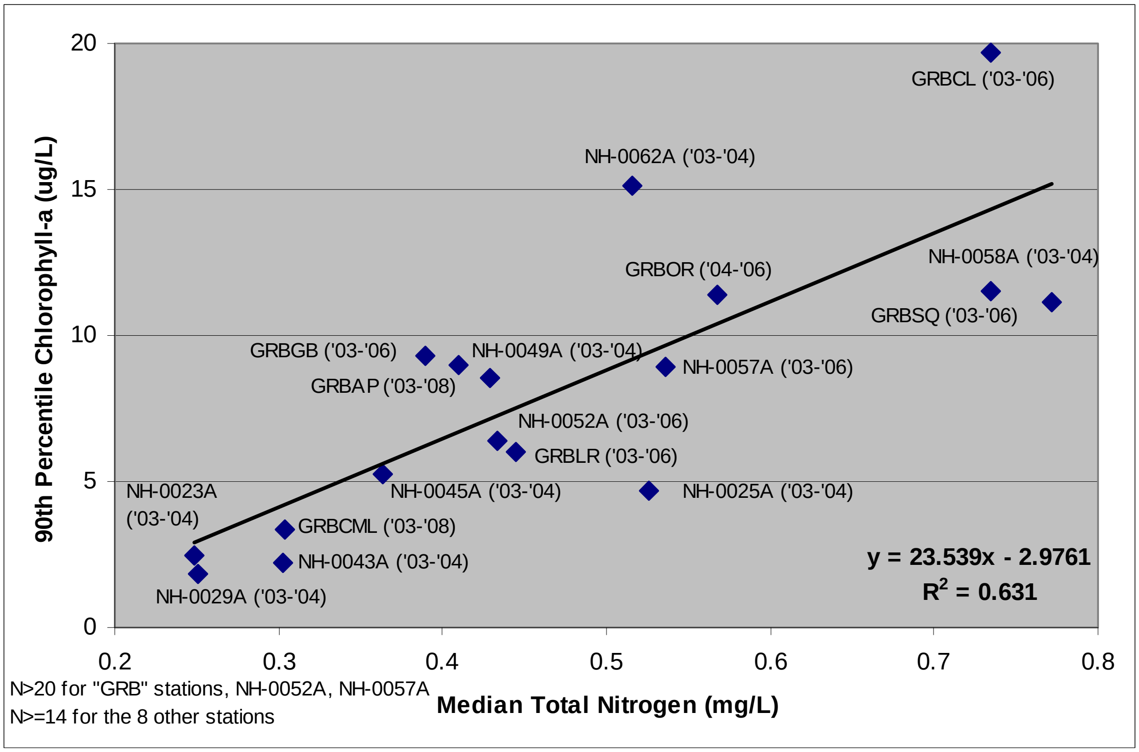
Each point was calculated from >20 samples in a zone ex. 3 TDN values with n=15-20

**Figure 16: Seasonal Patterns of Chlorophyll-a at Trend Monitoring Stations with Different Salinities**



All available data for these stations in 2000 - 2008 were included in this graph, which amounts to:
GRBAP: (Jan-Mar) 2000, 2001, 2006, 2007, 2008; (Apr-Dec) 2000 through 2008
GRBCL: (Jan-Mar) 2000, 2001; (Apr-Dec) 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2008
GRBCML: (Jan-Mar) None; (Apr-Dec) 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2008

**Figure 17: Relationship between Nitrogen and Chlorophyll-a Concentrations at Trend Stations**



## Macroalgae

Increasing nitrogen concentrations in shallow estuaries favor the proliferation of ephemeral macroalgae over seagrasses and other perennial submerged aquatic vegetation (McGlathery et al., 2007; Fox et al., 2008). Macroalgae have lower light requirements for survival than seagrasses and thrive in high nutrient environments (Fox et al. 2008). The proliferation of macroalgae species can be responsible for eelgrass loss due to shading and changes in water chemistry near the sediments (Hauxwell et al., 2001; Hauxwell et al., 2003). When macroalgae forms dense mats on the sediment surface, it can prevent the re-establishment of eelgrass in these areas (Short and Burdick, 1996). The shift to macroalgae dominance is likely to increase the rate of nitrogen export from estuaries to the ocean (McGlathery et al., 2007).

Several studies of macroalgae were completed in the Great Bay Estuary in the 1980s. Mathieson and Hehre (1986) documented the distribution of different macroalgae species throughout the tidal shoreline of New Hampshire, including the Isles of Shoals. Chock and Mathieson (1983) and Hardwick-Witman and Mathieson (1983) studied the species composition at particular locations in the estuary. These studies provide a baseline record of macroalgae species and distribution in the estuary. There have been anecdotal reports of increases in the abundance of different species of nuisance macroalgae by researchers at UNH, but the studies from the 1980s have not been repeated to document the changes.

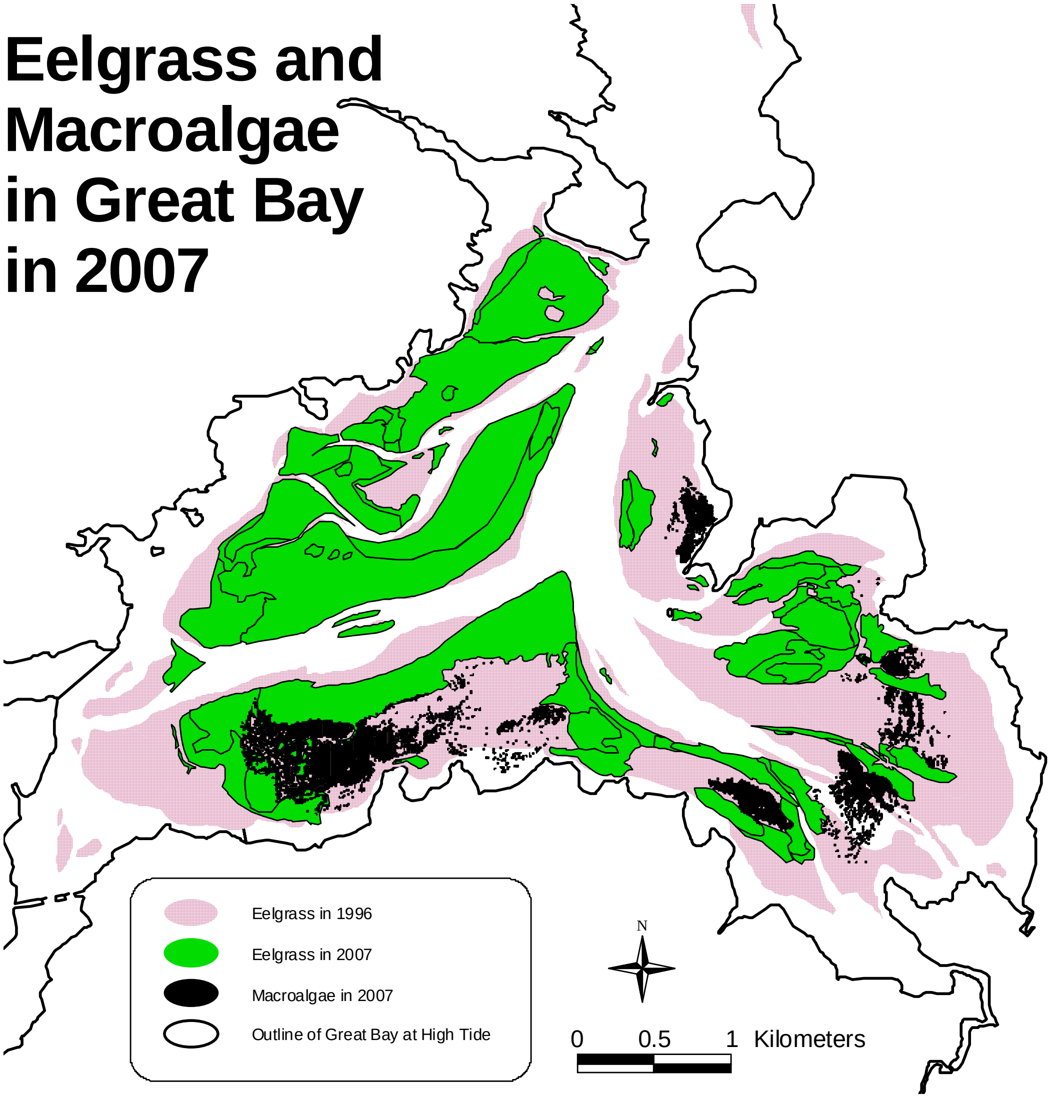
In 2007, UNH, through a project coordinated by the PREP with funding from EPA, collected hyperspectral imagery of the Great Bay Estuary. This imagery was used to map eelgrass beds and large macroalgae mats based on unique spectral signatures of the species. The hyperspectral imagery was collected on August 29, 2007 on a spring low tide. Ground truthing data for water quality, but not submerged aquatic vegetation, were collected during the overflight, although ground truth data on macroalgae and eelgrass beds in Great Bay in 2007 were available from another study (Short, 2008). The ground truth observations of macroalgae were used to generate a classification training set to classify the spectral signatures of eelgrass and macroalgae species. The nuisance macroalgae species of interest were: multiple *Ulva* species, *Gracilaria* (e.g. *G. tikvahiae*), epiphytic red algae (e.g., ceramialean red algae) and detached/entangled *Chaetomorpha* populations. Additional details about the data collection and analysis methods for this study are available in a technical report (Pe'eri et al., 2008).

The locations of macroalgae in Great Bay in 2007 (mapped using hyperspectral imagery) relative to eelgrass cover in 1996 and 2007 (mapped using aerial photography) are shown in Figure 18. The largest macroalgae mats in 2007 were located in the intertidal region in the southern part of the bay. Overall, 137 acres of macroalgae and 1,246 acres of eelgrass were identified in Great Bay in 2007. In contrast, the maximum extent of eelgrass in Great Bay in 1996 was 2,421 acres. The macroalgae was predominantly located in areas where eelgrass formerly existed. Therefore, macroalgae mats have now replaced nearly 5.7% of the area formerly occupied by eelgrass in Great Bay where the median total nitrogen concentration is 0.42 mg N/L.

The presence of any nuisance macroalgae, let alone 137 acres of macroalgae mats, is typically an indication of elevated nutrients and eutrophication (McGlathery et al., 2007). The study by Pe'eri et al. (2008) shows that significant amounts of eelgrass are replaced by macroalgae in Great Bay where the median total nitrogen concentration is 0.42 mg N/L. To approximate the nitrogen concentration where eelgrass replacement does not occur DES applied a margin of safety of 10 to 20 percent to the observed concentration. This approach indicates that the total nitrogen concentrations should be less than 0.34-0.38 mg N/L to prevent replacement of eelgrass by macroalgae in Great Bay. With the available data, it is not clear whether this same threshold would be applicable to other sections of the estuary besides Great Bay.

Proliferation of macroalgae is one way that nitrogen enrichment can affect eelgrass. The other primary mechanism is loss of water clarity. The relationship between water clarity and nitrogen will be evaluated later in this report to determine whether a threshold lower than 0.34-0.38 mg N/L is needed for the protection of eelgrass in Great Bay.

**Figure 18: Eelgrass and Macroalgae in Great Bay in 2007**



## *Secondary Indicators*

### Benthic Invertebrates and Sediment Quality

Sediment samples were collected during approximately 130 station visits in the Great Bay Estuary for the National Coastal Assessment (http://www.epa.gov/emap/nca/) during field seasons from 2000 through 2005. A summary of the methods used by this program as well as the results for samples collected through 2003 is available in the National Estuary Program Coastal Condition Report ( EPA, 2006).

The samples were analyzed for toxic contaminant concentrations, grain size, total organic carbon, and benthic invertebrates. The condition of the benthic infaunal community was evaluated with a benthic index of biological integrity (B-IBI) developed by EPA. While the B-IBI was well correlated with nitrogen concentrations (Figure 19), the best explanatory variable for B-IBI was salinity (Figure 20). Diversity and abundance of benthic infauna species are strongly affected by salinity. The B-IBI algorithm developed by EPA does not correct for the effect of salinity on benthic community composition and is most accurate for higher salinity areas as discussed in Hale and Heltshe (2008). Therefore, the relationship between B-IBI and nitrogen concentrations is probably just an apparent correlation caused by the inverse relationship of nitrogen and salinity in the estuary (Figure 21).

The National Coastal Assessment also measured total organic carbon content and grain size of the sediments with units of percent of dry weight. Total organic carbon is conceptually related to eutrophication. Organic matter from primary producers such as phytoplankton and macroalgae settles through the water column to the sediments. Some of this organic matter is respired in the water column but the rest becomes incorporated in the sediments. Respiration of organic matter in the sediments can consume all of oxygen in the sediments and pore waters, which affects the benthic infaunal community (Cloern, 2001). The good relationship between median total organic carbon in the sediments and chlorophyll-a concentrations in the water column illustrates the linkage between primary productivity and accumulation of organic matter in the sediments (Figure 22). Given that chlorophyll-a concentrations are related to nitrogen concentrations, it is not surprising that total organic carbon in sediments are also correlated to nitrogen concentrations as shown in Figure 23.

Elevated total organic carbon concentrations are scattered across the whole estuary but are predominantly located in the tidal tributaries or creeks. Some of the pattern in total organic carbon can be explained by its association with grain size (Figure 24). The fine grained sediments in tidal creeks lined by salt marsh would be expected to have higher total organic carbon than sandy sediments in higher energy environments. However, there is an apparent threshold at 5% total organic carbon above which total organic carbon does not appear to be controlled by grain size. For the National Coastal Condition Report, EPA also used 5% total organic carbon as a threshold indicative of organic enrichment in sediments (EPA, 2006).

Unfortunately, the nitrogen and chlorophyll-a concentrations associated with the total organic carbon threshold of 5% could not be determined with the available data. While the relationships between these parameters were statistically significant, the range of median total organic carbon values in the regressions does not contain 5%. Estimating nitrogen and chlorophyll-a thresholds based on these regression would require extrapolation, which is not justified. However, the regressions still prove that total organic carbon content in sediments is associated with nitrogen and chlorophyll-a concentrations.

**Figure 19: Relationship between Benthic Infaunal Community B-IBI and Total Nitrogen in Assessment Zones**

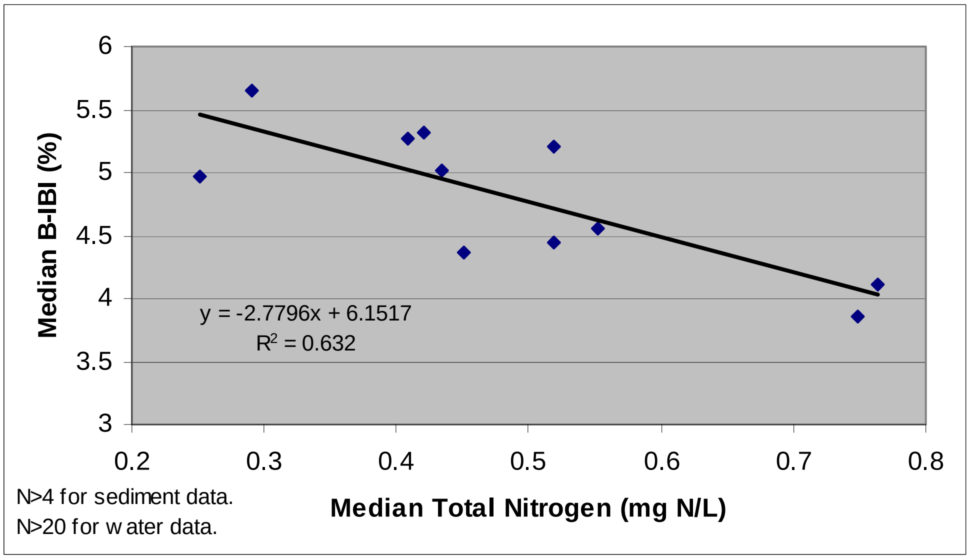


**Figure 20: Relationship between Benthic Infaunal Community B-IBI and Salinity in Assessment Zones**

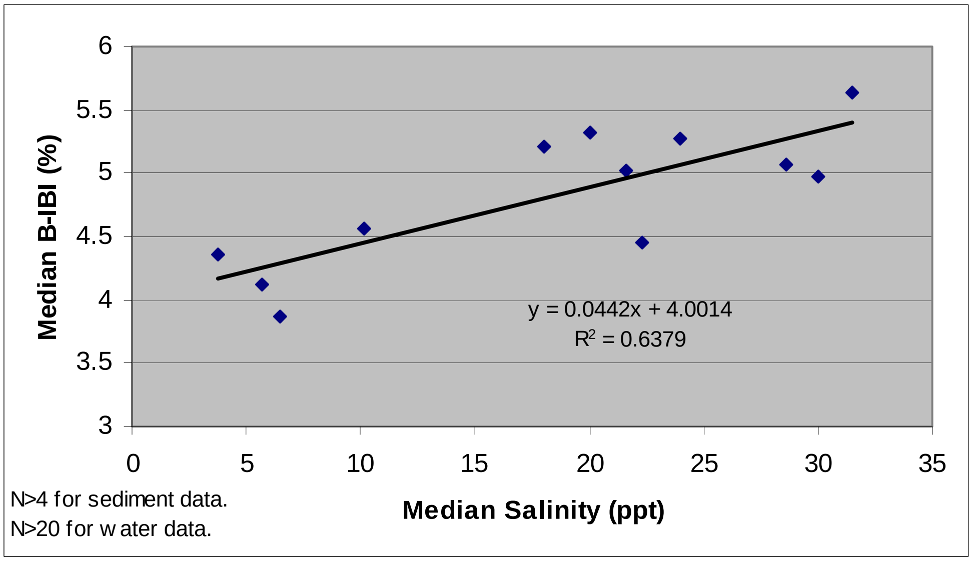


**Figure 21: Relationship between Total Nitrogen and Salinity in Assessment Zones**

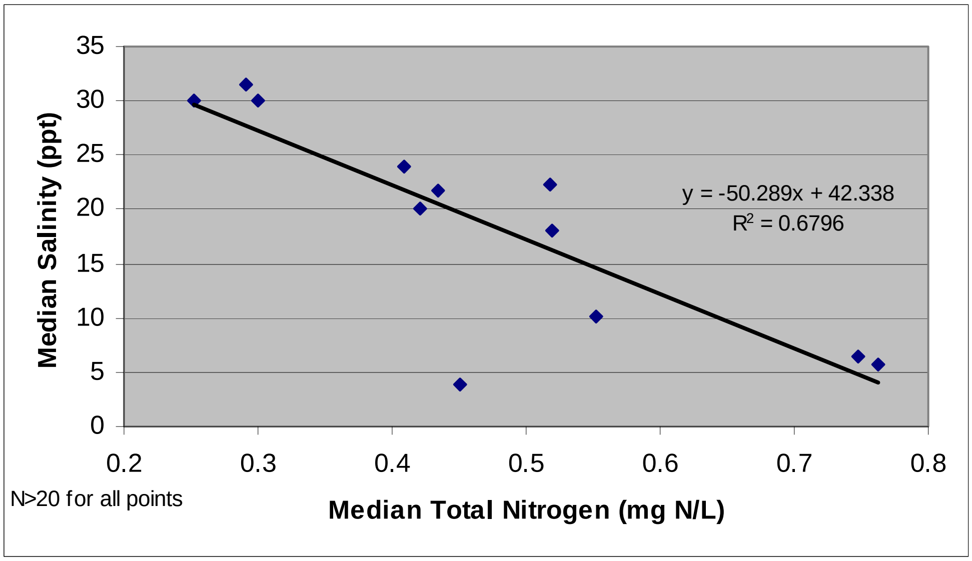


**Figure 22: Relationship between Total Organic Carbon in Sediments and Chlorophyll-a in Assessment Zones**

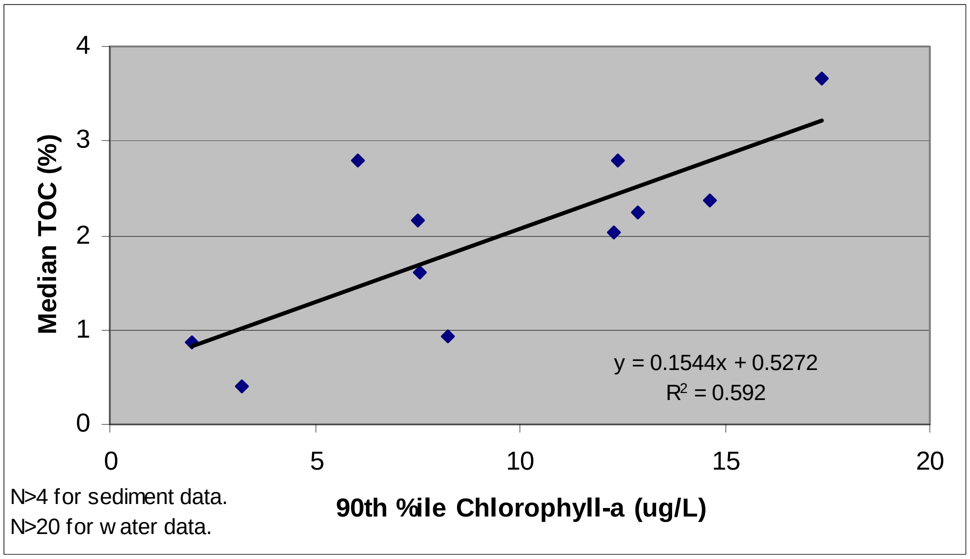


**Figure 23: Relationship between Total Organic Carbon in Sediments and Total Nitrogen in Assessment Zones**

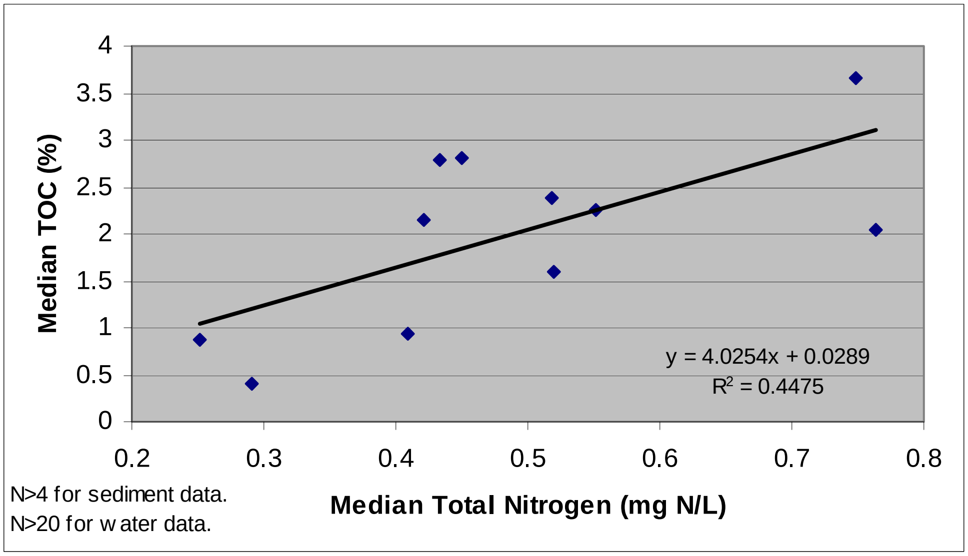
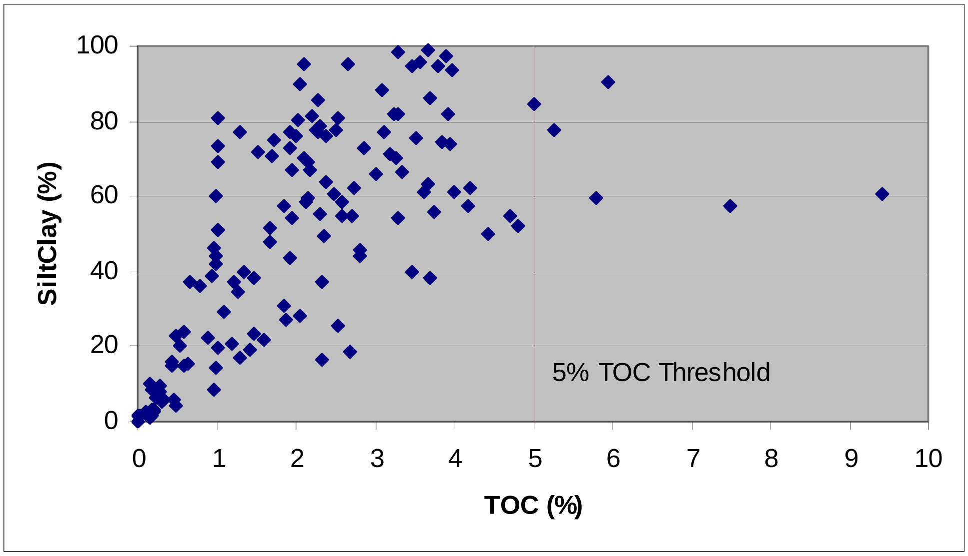


**Figure 24: Relationship between Grain Size and Total Organic Carbon in Sediment Samples**



## Dissolved Oxygen

Low dissolved oxygen is a well established indicator of eutrophication (NRC, 2000; Cloern, 2001; Bricker et al., 2007; EPA, 2001). Respiration of organic matter in the water column and the sediments consumes oxygen. The resulting areas of hypoxia affect fish and benthic communities (Diaz and Rosenberg, 2008; Cloern, 2001; Bricker et al. 2007). New Hampshire already has a water quality standard for dissolved oxygen in tidal waters. For class B waters, which includes estuaries, RSA 485-A:8 and Env-Wq 1703.07 state that dissolved oxygen must be at least 5 mg/L at all times and that the daily average of dissolved oxygen saturation should be at least 75% (http://www.gencourt.state.nh.us/rsa/html/L/485-A/485-A-8.htm). Hypoxia is typically defined as a dissolved oxygen concentration less than 2 mg/L. Therefore violations of the water quality standard occur before true hypoxia develops.

Summary statistics for dissolved oxygen measured in grab samples at multiple stations in the estuary are provided in Table 7. Figure 25 shows the minimum dissolved oxygen concentrations from stations around the estuary. These measurements show that concentrations of dissolved oxygen below the State standard occur primarily in the tidal tributaries, particularly the Squamscott River.

The minimum and maximum dissolved oxygen concentration in surface grab samples collected within each assessment zone are correlated with chlorophyll-a, one of the primary indicators of eutrophication (Figure 26).This figure clearly shows both a decrease in the minimum and an increase in the maximum dissolved oxygen concentrations with increasing chlorophyll-a concentrations. This effect would be expected when phytoplankton blooms oxygenate the water during photosynthesis and deplete oxygen during respiration. Figure 27 shows the statistically significant regression between dissolved oxygen and chlorophyll-a using data that were collected at trend stations in the same years. The minimum dissolved oxygen concentrations are also correlated with nitrogen concentrations as shown in Figure 28 and Figure 29. The best relationship was derived from statistics at trend stations and relates median total nitrogen to minimum dissolved oxygen concentrations using data collected in the same years for both parameters (Figure 29).

The regressions shown in Figure 27 and Figure 29 can be used to establish thresholds for chlorophyll-a and nitrogen associated with violations of the minimum dissolved oxygen standard (5 mg/L). The regression on Figure 27 predicts that the minimum dissolved oxygen concentration at a station will fall below 5 mg/L for 90th percentile chlorophyll-a concentrations greater than 11 ug/L. Likewise, the total nitrogen threshold would be 0.71 mg N/L based on the regression shown on Figure 29. The uncertainty in these thresholds was estimated, using the methods from Helsel and Hirsch (1992), to be +/- 7 ug/L for chlorophyll-a and +/-0.44 mg N/L for total nitrogen due to the small sample size and the imperfect correlations.

Unfortunately, the uncertainties in the chlorophyll-a and nitrogen thresholds are too high for setting water quality criteria. DES set a goal that the uncertainty for chlorophyll-a and nitrogen thresholds should be less than +/-3 ug/L and +/-0.1 mg N/L, respectively. However, the large uncertainty in the regressions shown in Figure 27 and Figure 29 is not unexpected. Surface grab sample measurements are a gross indicator of dissolved oxygen concentrations. The daily fluctuations of dissolved oxygen due to photosynthesis and respiration can only be measured accurately using in-situ datasondes. In fact, it is remarkable that statistically significant relationships between dissolved oxygen, chlorophyll-a and nitrogen were found using surface grab sample data.

## Table 7: Summary Statistics for Dissolved Oxygen (mg/L) Calculated from Samples Collected in All Seasons in 2000-2008

**(A) Assessment Zones**

| Assessment Zone | N | Min | 10th%ile | Median | 90th%ile | Max |
|---|---|---|---|---|---|---|
| BELLAMY RIVER | 87 | 5.30 | 6.54 | 7.90 | 10.54 | 14.40 |
| BERRYS BROOK | 2 | 9.20 | 9.22 | 9.30 | 9.38 | 9.40 |
| COCHECO RIVER | 181 | 3.60 | 7.10 | 8.90 | 11.40 | 14.38 |
| GREAT BAY | 266 | 5.20 | 6.90 | 8.40 | 10.86 | 14.10 |
| LAMPREY RIVER | 369 | 3.92 | 5.58 | 8.33 | 11.23 | 17.05 |
| LITTLE BAY | 349 | 4.90 | 6.80 | 8.00 | 10.80 | 14.63 |
| LITTLE HARBOR/BACK CHANNEL | 180 | 5.40 | 7.37 | 8.90 | 10.80 | 12.22 |
| LOWER PISCATAQUA RIVER NORTH | 91 | 6.50 | 7.40 | 8.10 | 9.80 | 12.00 |
| LOWER PISCATAQUA RIVER SOUTH | 49 | 4.60 | 7.44 | 8.20 | 9.72 | 11.10 |
| NORTH MILL POND | 124 | 6.10 | 6.84 | 8.88 | 11.87 | 15.00 |
| OYSTER RIVER | 179 | 3.54 | 5.38 | 7.50 | 10.02 | 13.90 |
| PORTSMOUTH HARBOR | 134 | 5.50 | 6.70 | 8.20 | 9.87 | 14.05 |
| SAGAMORE CREEK | 10 | 7.00 | 7.45 | 8.05 | 8.60 | 8.60 |
| SALMON FALLS RIVER | 53 | 5.20 | 6.42 | 8.60 | 11.16 | 12.90 |
| SOUTH MILL POND | 150 | 3.90 | 6.00 | 7.90 | 10.60 | 14.80 |
| SPINNEY CREEK | 1 | 10.20 | 10.20 | 10.20 | 10.20 | 10.20 |
| SPRUCE CREEK | 2 | 7.40 | 7.49 | 7.85 | 8.21 | 8.30 |
| SQUAMSCOTT RIVER | 260 | 3.51 | 5.38 | 8.05 | 11.60 | 17.10 |
| UPPER PISCATAQUA RIVER | 168 | 6.00 | 6.84 | 8.20 | 10.90 | 14.60 |
| WINNICUT RIVER | 64 | 4.20 | 6.00 | 7.90 | 9.97 | 11.00 |

**(B) Trend Monitoring Stations**

| Station | N | Min | 10th%ile | Median | 90th%ile | Max |
|---|---|---|---|---|---|---|
| GRBAP | 80 | 5.70 | 7.38 | 9.60 | 13.73 | 15.70 |
| GRBCL | 69 | 4.22 | 6.16 | 8.40 | 13.40 | 15.35 |
| GRBCML | 48 | 6.30 | 7.17 | 8.40 | 10.07 | 14.05 |
| GRBGB | 54 | 5.20 | 6.70 | 8.60 | 11.20 | 12.10 |
| GRBLR | 71 | 5.10 | 7.00 | 9.80 | 14.98 | 17.05 |
| GRBOR | 43 | 4.20 | 5.62 | 7.50 | 12.06 | 13.20 |
| GRBSQ | 49 | 4.59 | 5.10 | 7.79 | 11.60 | 13.80 |
| NH-0023A | 56 | 5.40 | 7.75 | 9.15 | 10.35 | 11.80 |
| NH-0025A | 29 | 5.90 | 6.56 | 8.00 | 11.96 | 14.10 |
| NH-0029A | 30 | 7.20 | 7.98 | 8.80 | 10.43 | 11.50 |
| NH-0043A | 30 | 6.40 | 7.59 | 8.15 | 9.93 | 11.10 |
| NH-0045A | 30 | 7.20 | 7.29 | 8.50 | 10.22 | 14.60 |
| NH-0049A | 30 | 6.50 | 6.80 | 7.80 | 10.14 | 13.90 |
| NH-0052A | 55 | 5.80 | 6.60 | 8.40 | 10.72 | 14.40 |
| NH-0057A | 70 | 6.00 | 6.89 | 8.60 | 12.01 | 14.60 |
| NH-0058A | 28 | 3.60 | 6.84 | 9.75 | 12.35 | 13.70 |
| NH-0062A | 28 | 5.30 | 6.19 | 9.55 | 11.70 | 12.90 |

**Figure 25: Minimum Concentrations of Dissolved Oxygen at Water Quality Stations**

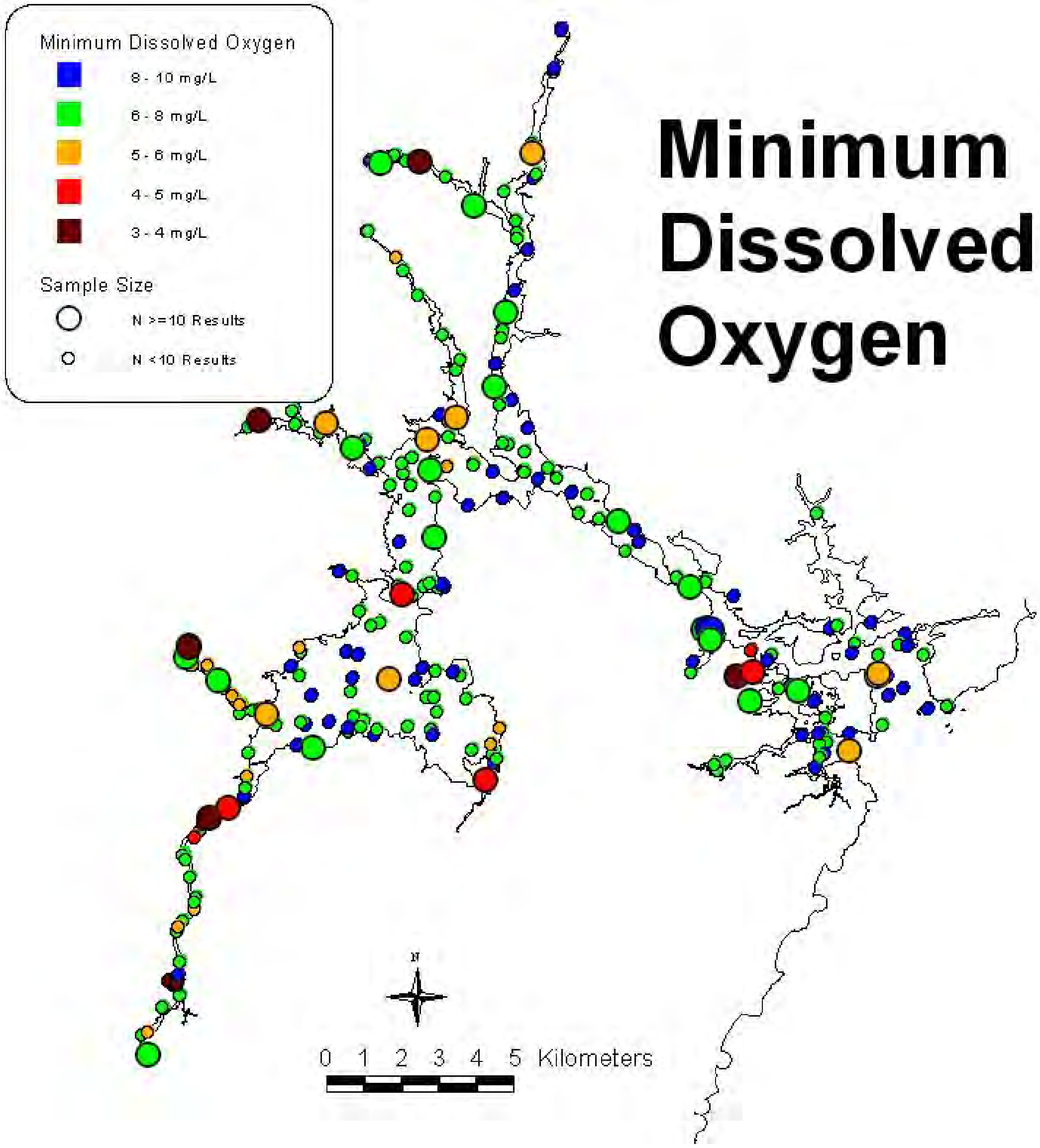


**Figure 26: Relationship between Dissolved Oxygen and Chlorophyll-a in Assessment Zones**

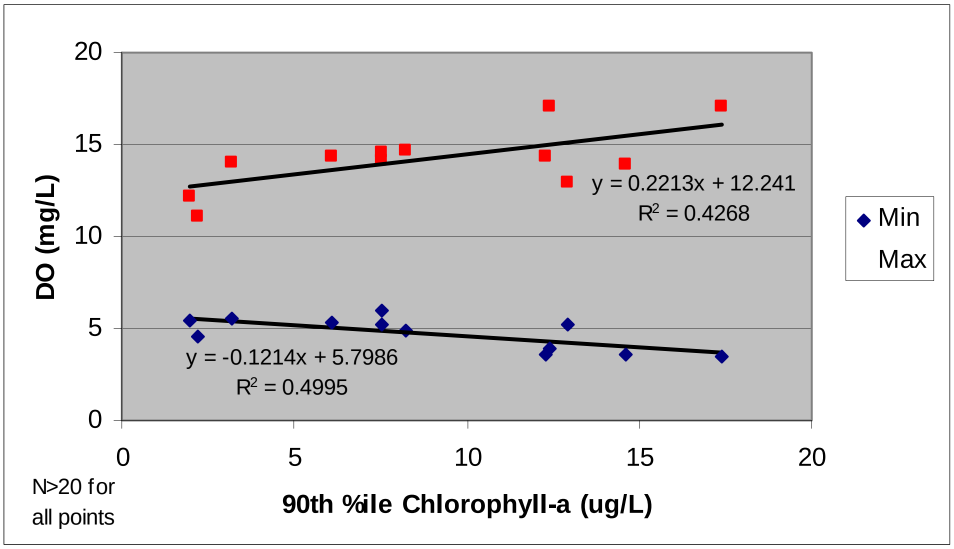


**Figure 27: Relationship between Minimum Dissolved Oxygen and Chlorophyll-a at Trend Stations**

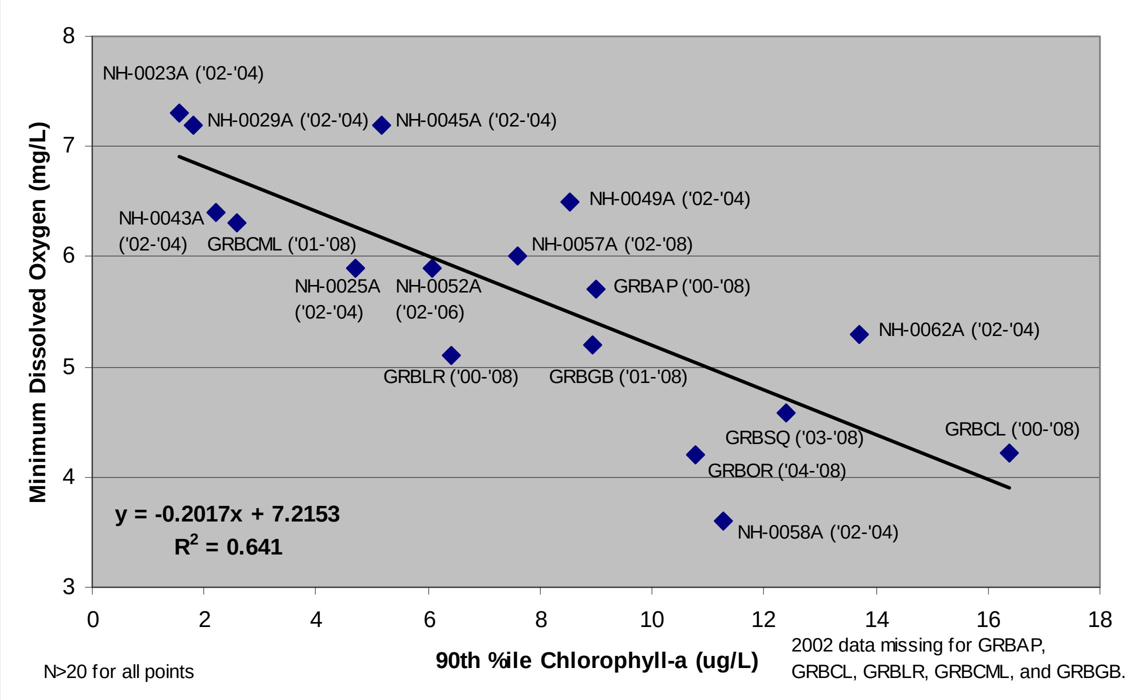
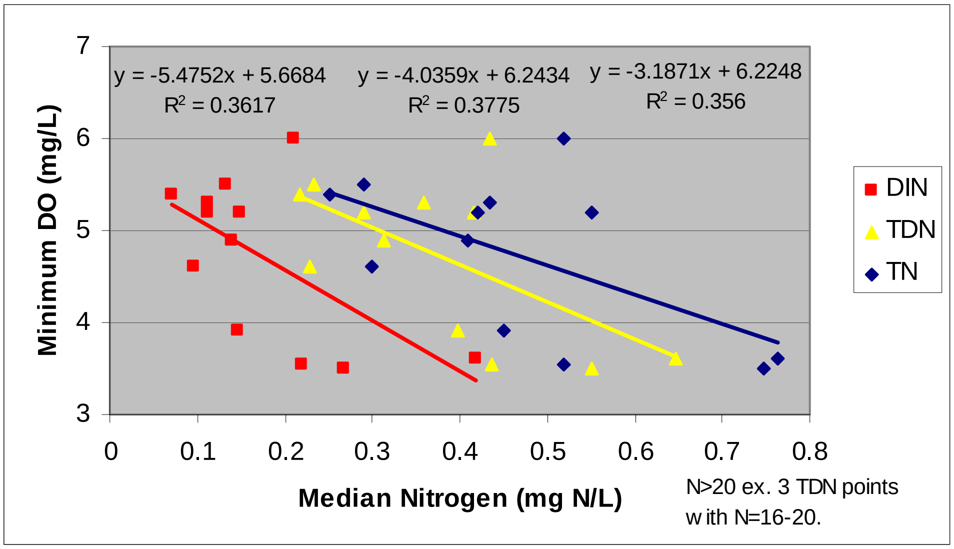
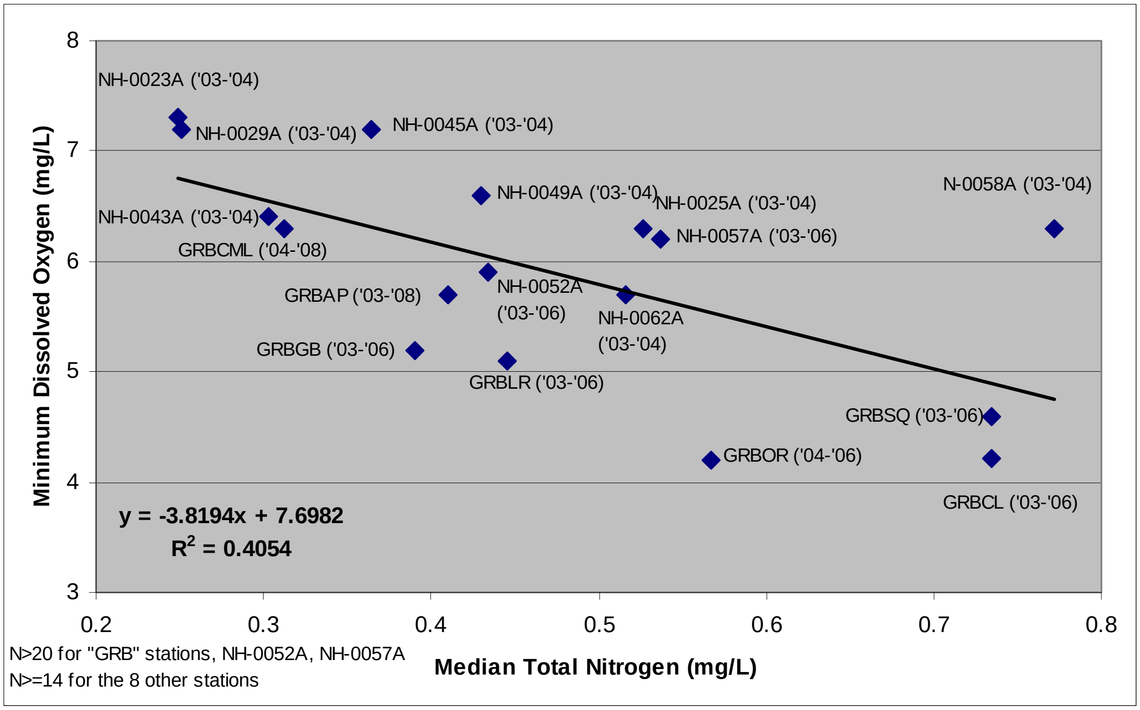


**Figure 28: Relationship between Dissolved Oxygen and Nitrogen in Assessment Zones**



N>20 ex. 3 TDN points with N=16-20.

**Figure 29: Relationship between Dissolved Oxygen and Nitrogen at Trend Stations**



N>20 for "GRB" stations, NH-0052A, NH-0057A
N>=14 for the 8 other stations

Datasonde measurements provide a richer perspective on dissolved oxygen concentrations because of the large number of measurements and their deployment near the bottom of the water column. The datasondes provide information on seasonal patterns of daily minimum dissolved oxygen and better information on typical concentrations at several key locations.

Figure 30 and Figure 31 show the daily minimum concentrations of dissolved oxygen (in mg/L) and daily average dissolved oxygen saturation (in %) for valid measurements at the datasondes during summer months between 2000 and 2008. Dissolved oxygen concentrations at the mouth of Portsmouth Harbor (GRBCML) never fell below 5 mg/L or 75% saturation (daily average). In Great Bay (GRBGB), the daily minimum dissolved oxygen value fell below the standard on only one day but the daily average saturation never fell below 75%. By comparison, the datasondes at all of the tributary stations recorded repeated instances of dissolved oxygen less than the state standards of 5 mg/L for daily minimum and 75% for daily average saturation. The lowest dissolved oxygen concentrations were recorded in the Lamprey River (GRBLR). A study by UNH in 2004 (Pennock, 2005) determined that the low dissolved oxygen in the river was isolated to a basin that experiences salinity stratification under neap tide conditions. Therefore, the datasonde measurements at GRBLR may not be representative of typical conditions in this tributary and should be interpreted with caution.

The chlorophyll-a concentrations (expressed as 90th percentiles) and total nitrogen concentrations (expressed as medians) were between 3.3 and 9.3 ug/L and between 0.30 and 0.39 mg N/L, respectively, at stations where the datasonde measurements rarely if ever indicate violations of the water quality standard for dissolved oxygen (GRBGB, GRBCML). For stations GRBSQ, GRBOR, and GRBSF, where the datasonde data clearly demonstrated impairments, the chlorophyll-a concentrations and total nitrogen concentrations ranged from 12.1 to 14.3 ug/L and from 0.52 to 0.74 mg N/L, respectively. (Note: water quality data from station NH-0062A were used to represent GRBSF.) Finally, the chlorophyll-a concentration and total nitrogen concentration were 7.5 ug/L and 0.45 mg N/L, respectively, at station GRBLR in the Lamprey River where dissolved oxygen impairments were observed but were likely amplified by stratification and possibly sediment oxygen demand (Pennock, 2005). Therefore, the detailed information from the datasondes suggests that the chlorophyll-a and total nitrogen thresholds associated with the dissolved oxygen standard should be between 9.3 and 12.1 ug/L and 0.39 and 0.52 mg N/L, respectively. Absent additional information, the most appropriate method to balance the decision errors in setting the thresholds is to take the middle values of these ranges: 10.7 ug/L for 90th percentile chlorophyll-a and 0.45 mg N/L for median total nitrogen. Given the range of possible values, the uncertainty in these thresholds would be +/- 1.4 ug/L for chlorophyll-a and +/-0.07 mg N/L for total nitrogen. DES considers this level of uncertainty to be acceptable for establishing water quality criteria.

The large volume of data produced by datasondes give this source greater weight than the grab samples. Datasondes collect measurements during early morning hours and other worst-case conditions while grab samples are taken once per month typically in the middle of the day. The continuous measurements of dissolved oxygen by datasondes also made it possible to consider both the daily minimum dissolved oxygen (in mg/L) and the daily average dissolved oxygen saturation. Most importantly, the uncertainty in the thresholds was much lower for the datasonde records than for the grab samples. **Therefore, DES finds that the most appropriate threshold for total nitrogen to prevent violations of the dissolved oxygen standard, in support of the aquatic life support designed use, is 0.45 mg N/L. Also, the threshold for 90th percentile chlorophyll-a concentrations corresponding to the dissolved oxygen standard should be 10 ug/L (rounded down from 10.7 ug/L).**

The one challenge to using a nitrogen threshold of 0.45 mg N/L is the data from the Lamprey River datasonde. The median total nitrogen concentration at the datasonde (station GRBLR) is 0.45 mg N/L. There have been frequent episodes of low dissolved oxygen measured by this datasonde. However, these episodes appear to be related to more than just ambient nitrogen concentrations. Stratification during neap tides and sediment oxygen demand also play a role (Pennock, 2005). Moreover, the nitrogen concentrations at the datasonde, which is near the tidal dam, are probably not representative of the whole river. At the mouth of the river at station NH-0025A, the median total nitrogen concentration is 0.53 mg N/L. For these reasons, DES feels that it is still appropriate to use 0.45 mg N/L as a threshold despite the observations at station GRBLR.

**Figure 30: Daily Minimum Dissolved Oxygen (mg/L) Measured by Datasondes in Summer (June-September)**

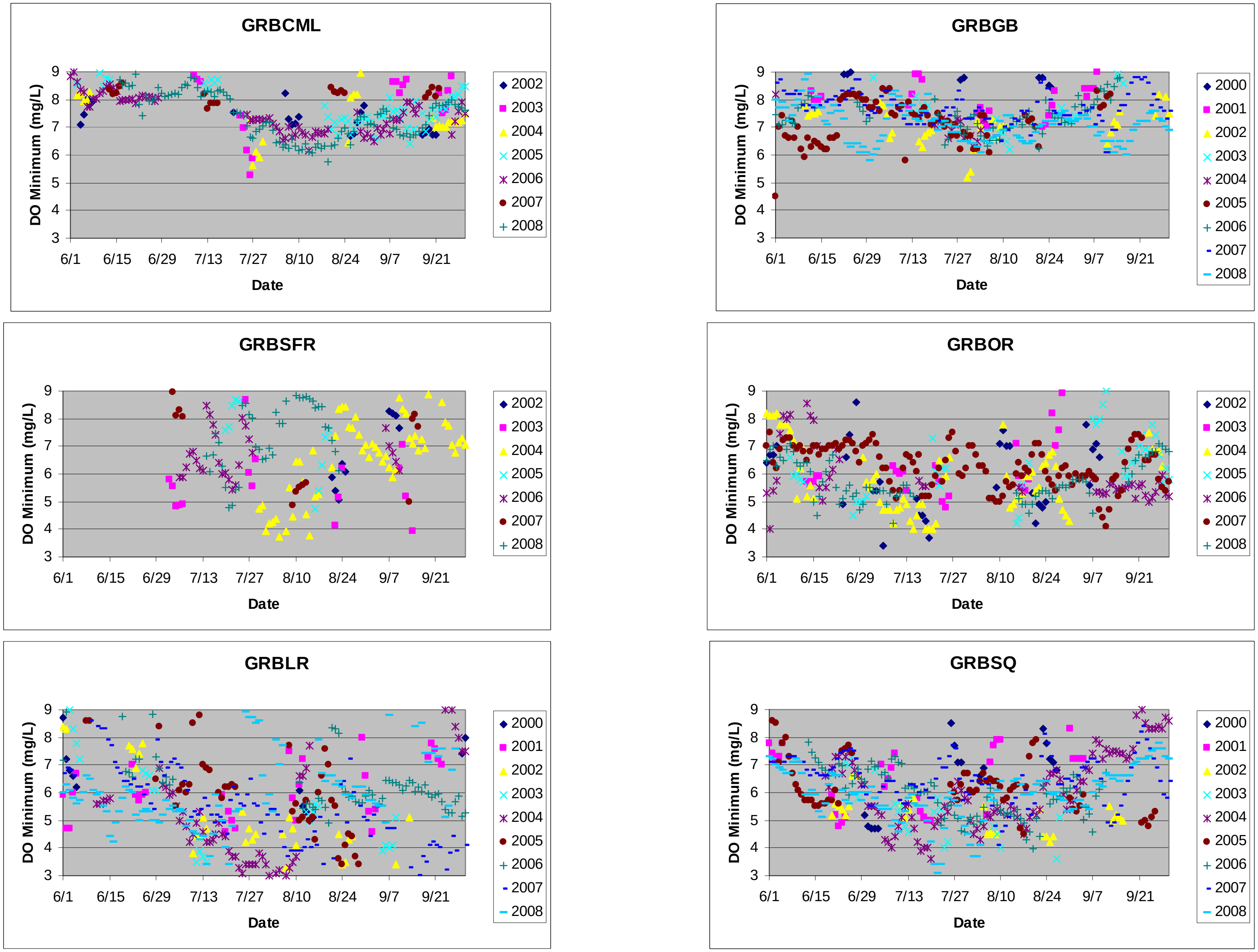
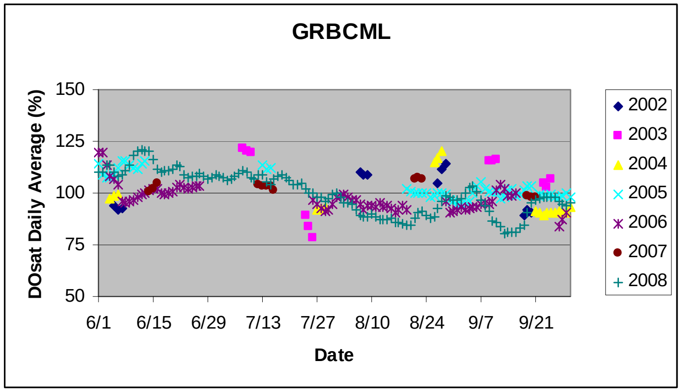
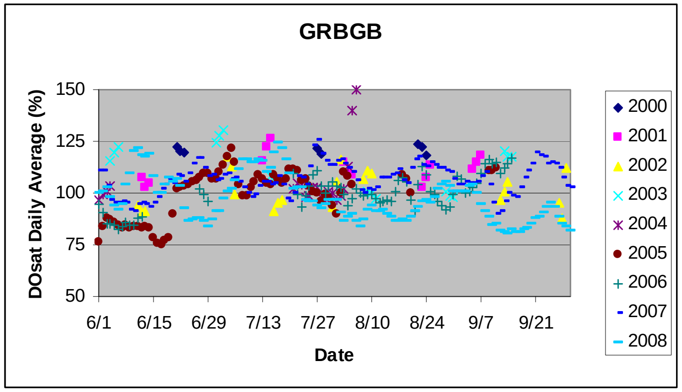
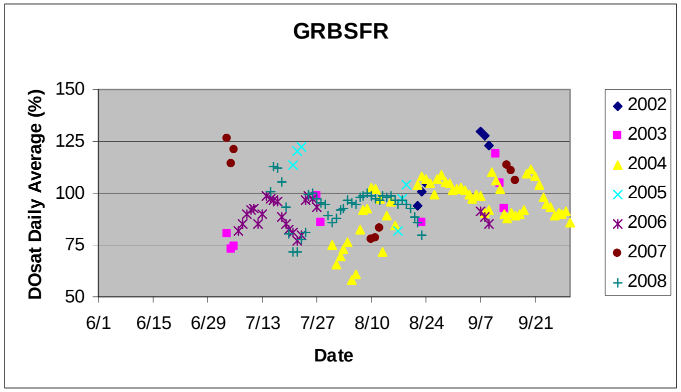
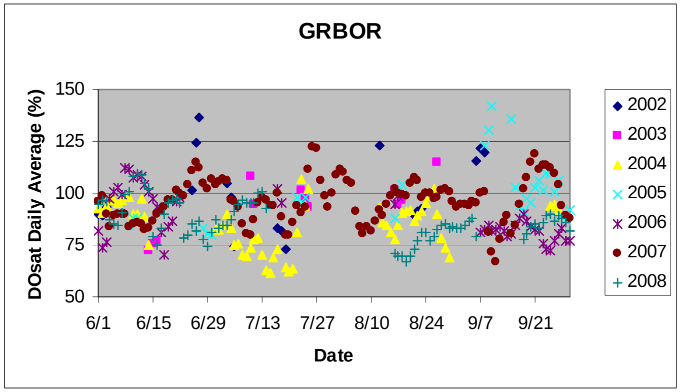


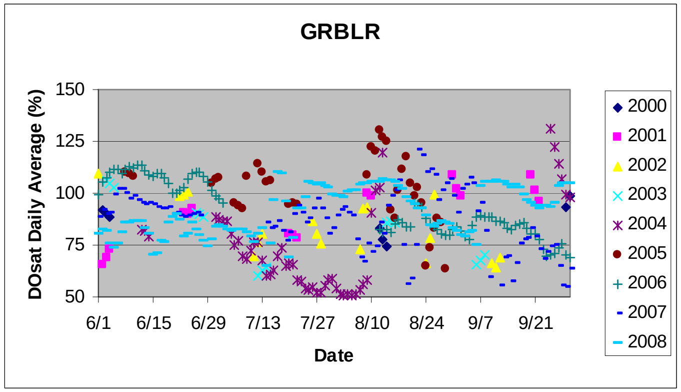
**Figure 31: Daily Average Dissolved Oxygen Saturation (%) Measured by Datasondes in Summer (June-September)**

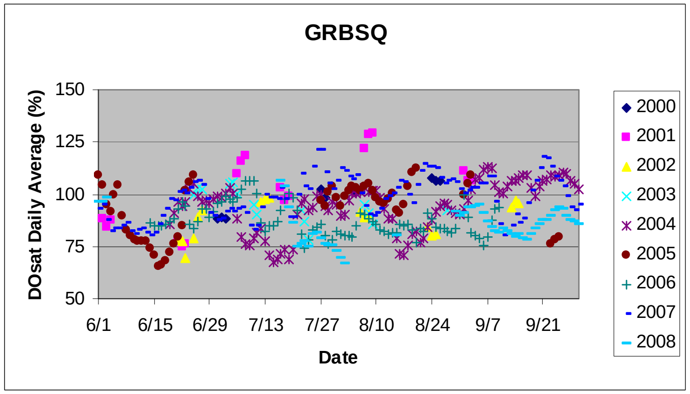

GRBCML
DOsat Daily Average (%)
150
125
100
75
50
6/1
6/15
6/29
7/13
7/27
8/10
8/24
9/7
9/21
Date
2002
2003
2004
2005
2006
2007
2008


GRBGB
DOsat Daily Average (%)
150
125
100
75
50
6/1
6/15
6/29
7/13
7/27
8/10
8/24
9/7
9/21
Date
2000
2001
2002
2003
2004
2005
2006
2007
2008


GRBSFR
DOsat Daily Average (%)
150
125
100
75
50
6/1
6/15
6/29
7/13
7/27
8/10
8/24
9/7
9/21
Date
2002
2003
2004
2005
2006
2007
2008


GRBOR
DOsat Daily Average (%)
150
125
100
75
50
6/1
6/15
6/29
7/13
7/27
8/10
8/24
9/7
9/21
Date
2002
2003
2004
2005
2006
2007
2008


GRBLR
DOsat Daily Average (%)
150
125
100
75
50
6/1
6/15
6/29
7/13
7/27
8/10
8/24
9/7
9/21
Date
2000
2001
2002
2003
2004
2005
2006
2007
2008


GRBSQ
DOsat Daily Average (%)
150
125
100
75
50
6/1
6/15
6/29
7/13
7/27
8/10
8/24
9/7
9/21
Date
2000
2001
2002
2003
2004
2005
2006
2007
2008

## Eelgrass

Eelgrass (*Zostera marina*) is the base of the estuarine food web in the Great Bay Estuary. Healthy eelgrass beds filter water and stabilize sediments (Short and Short, 1984) and provide habitat for fish and shellfish (Duarte, 2001; Heck et al., 2003). While eelgrass is only one species in the estuarine community, the presence of eelgrass is critical for the survival of many species. Loss of eelgrass habitat would change the species composition of the estuary resulting in a detrimental difference in community structure and function. In particular, if eelgrass habitat is lost, the estuary will likely be colonized by macroalgae species which do not provide the same habitat functions as eelgrass (Short et al., 1995; Hauxwell et al., 2003; McGlathery et al, 2007).

Cultural eutrophication from increased nitrogen loads to estuaries has been shown to be a major cause of seagrass disappearance worldwide (Burkholder et al., 2007; Short and Wyllie-Echeverria, 1996). Excess nitrogen contributes to eelgrass loss by increasing phytoplankton blooms which decrease water clarity and promoting the proliferation of epiphytes and ephemeral macroalgal species on and around seagrasses (Short et al., 1995; Hauxwell et al., 2001; Hauxwell et al., 2003). However, eelgrass can be lost due to other factors such as disease (Short et al., 1986; Muehlstein et al., 1991), sedimentation, and construction of boat moorings, docks or other structures.

A previous section of this report summarized the available information on macroalgae and its effects on eelgrass in the Great Bay. Proliferation of ephemeral macroalgae, which occupies eelgrass habitat, appears to have occurred in the Great Bay where the median total nitrogen concentration is 0.42 mg N/L. By applying a 10 to 20% margin of safety, DES estimated that the total nitrogen concentration in Great Bay should be less than 0.34-0.38 mg N/L to prevent macroalgae proliferation. It is uncertain whether this threshold is appropriate for other locations in the estuary. In the following section, the effects of water clarity on eelgrass survival and the relationship between nitrogen and water clarity will be evaluated to determine whether a lower nitrogen threshold is needed for the protection of eelgrass habitat.

Eelgrass is sensitive to water clarity (Short et al., 1995). Cultural eutrophication from excess nitrogen and suspended sediments in estuaries cause phytoplankton blooms, periphyton growth on eelgrass leaves, and light attenuation from non-algal particles (Short et al., 1995; Hauxwell et al., 2003; McGlathery et al, 2007). Water clarity can be quantified using the light attenuation coefficient ($K_d$) for photosynthetically active radiation. Summary statistics of $K_d$ for different regions of the estuary are shown in Table 8 and Figure 32.

Despite the complexities of the estuarine system, a relatively simple model from Koch (2001) can be used to predict the presence or absence of eelgrass in different areas of the Great Bay Estuary. The minimum depth of eelgrass beds ($Z_{min}$) can be predicted from the tide height in the estuary because eelgrass cannot survive above the mean low water line. The tidal range in the estuary is approximately 2 meters. Therefore, ignoring effects of wave action, $Z_{min}$ will be 1 meter below mean tidal level throughout the estuary. The maximum depth of eelgrass beds ($Z_{max}$) in different areas can be predicted from measurements of the light attenuation coefficient and the minimum transmission of surface irradiance needed by eelgrass for survival. The difference between $Z_{min}$ and $Z_{max}$ can be used to predict the presence or absence of eelgrass. Koch and Beer (1996) determined that $Z_{max}$ should be at least 1 meter below (less than) $Z_{min}$ for eelgrass survival.

The EPA Chesapeake Bay Program Office uses 22% for the minimum transmission of surface irradiance needed for eelgrass survival (EPA, 2003). This value is supported by Steward et al. (2005) which documented that 20% was the minimum annual light requirement for the maintenance of existing eelgrass beds. A higher percentage of surface irradiance would be needed for eelgrass to thrive or to restore eelgrass where it has been lost. However, for the purposes of establishing nutrient criteria to be representative of impaired conditions, DES will use the 22% light transmission value which has been adopted by the EPA Chesapeake Bay Program Office.

In Table 9, the measured $K_d$ values for each section of the estuary have been paired with tidal amplitudes to estimate $Z_{min}$ and $Z_{max}$ following the procedures in Koch (2001). The depths in this table are relative to mean tidal level (e.g., mid-tide). In the Squamscott, Lamprey, Oyster, Bellamy, Cocheco, and Salmon Falls Rivers, the model predicts that $Z_{max}$ is above (greater than) $Z_{min}$, which matches observations that eelgrass does not currently exist in these areas (PREP, 2009; NHDES, 2008b). In the Great Bay, Little Bay, and Upper Piscataqua River, the $Z_{max}$ is below (less than) $Z_{min}$ but the difference is less than 1 meter. This result is consistent with observations that eelgrass in these areas is either declining or has recently disappeared (PREP, 2009; NHDES, 2008b). Only in the Lower Piscataqua River, Portsmouth Harbor, and Little Harbor/Back Channel was $Z_{max}$ more than one meter below $Z_{min}$. The presence of persistent eelgrass beds in Little Harbor and Portsmouth Harbor confirms the model for these areas. However, the results for the Lower Piscataqua River are confusing because very little eelgrass remains in this area despite the apparent good water clarity (NHDES, 2008b; PREP, 2009). This discrepancy is most likely the result of incomplete data on water clarity from this area. Only a total of 13 $K_d$ measurements have been made in the Lower Piscataqua River assessment zones (north and south). The measured median $K_d$ in this area (0.50-0.59 $m^{-1}$) is lower than would be expected given the median values observed upstream (1.30 $m^{-1}$) and downstream (0.63 $m^{-1}$) and is probably not correct.

Given that the model accurately predicts existing conditions in the Great Bay Estuary, the model can also be used to determine the minimum thresholds for water clarity to support eelgrass in the Great Bay Estuary. Throughout the estuary, $Z_{min}$ is approximately 1 meter. Consequently, at a minimum, a restoration depth of 2 meters would be needed for $Z_{max}$ to be more than one meter below $Z_{min}$ such that any eelgrass can exist. In some areas of the estuary, a restoration depth of 2.5 or 3 meters may be necessary to either maintain existing or restore deeper eelgrass beds. **For the 2, 2.5, and 3 meter restoration depths, the Koch (2001) model predicts that median light attenuation coefficients of 0.75, 0.60 and 0.50 $m^{-1}$, respectively, would be needed for the survival of eelgrass.** It is important to remember that these thresholds represent minimal levels for the survival of existing eelgrass beds. The model assumes that eelgrass need transmission of 22% of surface irradiance (EPA, 2003). This transmission rate is the minimum light requirement for maintenance of existing eelgrass beds, but not thriving or expanding eelgrass bed or restoration of beds that have been lost.

The appropriate restoration depth for each assessment zone will be determined based on site-specific information. In the tidal tributaries, Great Bay, Little Bay, and Lower Piscataqua River North, where eelgrass beds are either already missing or are shrinking rapidly, the initial restoration depth target will be 2 meters. This restoration depth will maintain any existing beds and hopefully permit the recolonization of areas where eelgrass has been lost. A more ambitious goal can be adopted once this initial goal is achieved. In Portsmouth Harbor, Little Harbor, and the Lower Piscataqua River South where deeper eelgrass beds still may exist, restoration depths of 2.5 or 3 meters may be necessary. The depth of the existing eelgrass beds in these areas should be determined.

## Table 8: Summary Statistics for Light Attenuation Coefficient ($m^{-1}$) Calculated from Field Measurements Collected in All Seasons in 2000-2008

**(A) Assessment Zones**

| Assessment Zone | N | Min | 10th%ile | Median | 90th%ile | Max |
|---|---|---|---|---|---|---|
| BELLAMY RIVER | 2 | 1.24 | 1.27 | 1.42 | 1.57 | 1.61 |
| COCHECO RIVER | 2 | 2.61 | 2.81 | 3.60 | 4.39 | 4.59 |
| GREAT BAY | 48 | 0.06 | 0.65 | 1.11 | 2.10 | 6.25 |
| LAMPREY RIVER | 42 | 0.05 | 1.31 | 1.90 | 3.08 | 4.61 |
| LITTLE BAY | 59 | 0.07 | 0.71 | 1.06 | 1.68 | 3.74 |
| LITTLE HARBOR/BACK CHANNEL | 25 | 0.04 | 0.12 | 0.58 | 1.14 | 5.75 |
| LOWER PISCATAQUA RIVER NORTH | 8 | 0.04 | 0.05 | 0.59 | 1.06 | 1.31 |
| LOWER PISCATAQUA RIVER SOUTH | 5 | 0.33 | 0.40 | 0.50 | 0.60 | 0.63 |
| NORTH MILL POND | 1 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| OYSTER RIVER | 37 | 0.11 | 1.15 | 1.80 | 3.05 | 5.16 |
| PORTSMOUTH HARBOR | 46 | 0.04 | 0.28 | 0.63 | 1.26 | 2.08 |
| SAGAMORE CREEK | 1 | 0.82 | 0.82 | 0.82 | 0.82 | 0.82 |
| SALMON FALLS RIVER | 3 | 1.01 | 1.25 | 2.20 | 4.86 | 5.53 |
| SPRUCE CREEK | 1 | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 |
| SQUAMSCOTT RIVER | 74 | 0.12 | 1.60 | 2.96 | 4.97 | 7.98 |
| UPPER PISCATAQUA RIVER | 21 | 0.11 | 0.88 | 1.30 | 2.43 | 2.95 |

**(B) Trend Monitoring Stations**

| Station | N | Min | 10th%ile | Median | 90th%ile | Max |
|---|---|---|---|---|---|---|
| GRBAP | 46 | 0.07 | 0.78 | 1.08 | 1.72 | 3.74 |
| GRBCL | 35 | 0.12 | 1.91 | 3.34 | 4.63 | 6.02 |
| GRBCML | 35 | 0.27 | 0.47 | 0.69 | 1.29 | 2.08 |
| GRBGB | 40 | 0.36 | 0.66 | 1.09 | 2.13 | 6.25 |
| GRBLR | 41 | 0.05 | 1.31 | 1.85 | 3.01 | 4.61 |
| GRBOR | 36 | 0.56 | 1.19 | 1.84 | 3.06 | 5.16 |
| GRBSQ | 32 | 0.14 | 1.59 | 2.85 | 5.54 | 7.98 |
| NH-0023A | 2 | 0.14 | 0.20 | 0.44 | 0.68 | 0.74 |
| NH-0029A | 20 | 0.04 | 0.11 | 0.57 | 1.02 | 1.18 |
| NH-0045A | 2 | 0.95 | 1.01 | 1.23 | 1.45 | 1.51 |
| NH-0049A | 1 | 0.11 | 0.11 | 0.11 | 0.11 | 0.11 |
| NH-0052A | 1 | 1.24 | 1.24 | 1.24 | 1.24 | 1.24 |
| NH-0057A | 13 | 0.81 | 0.90 | 1.35 | 2.33 | 2.85 |
| NH-0062A | 1 | 1.01 | 1.01 | 1.01 | 1.01 | 1.01 |

**Figure 32: Median Light Attenuation Coefficient at Water Quality Stations**

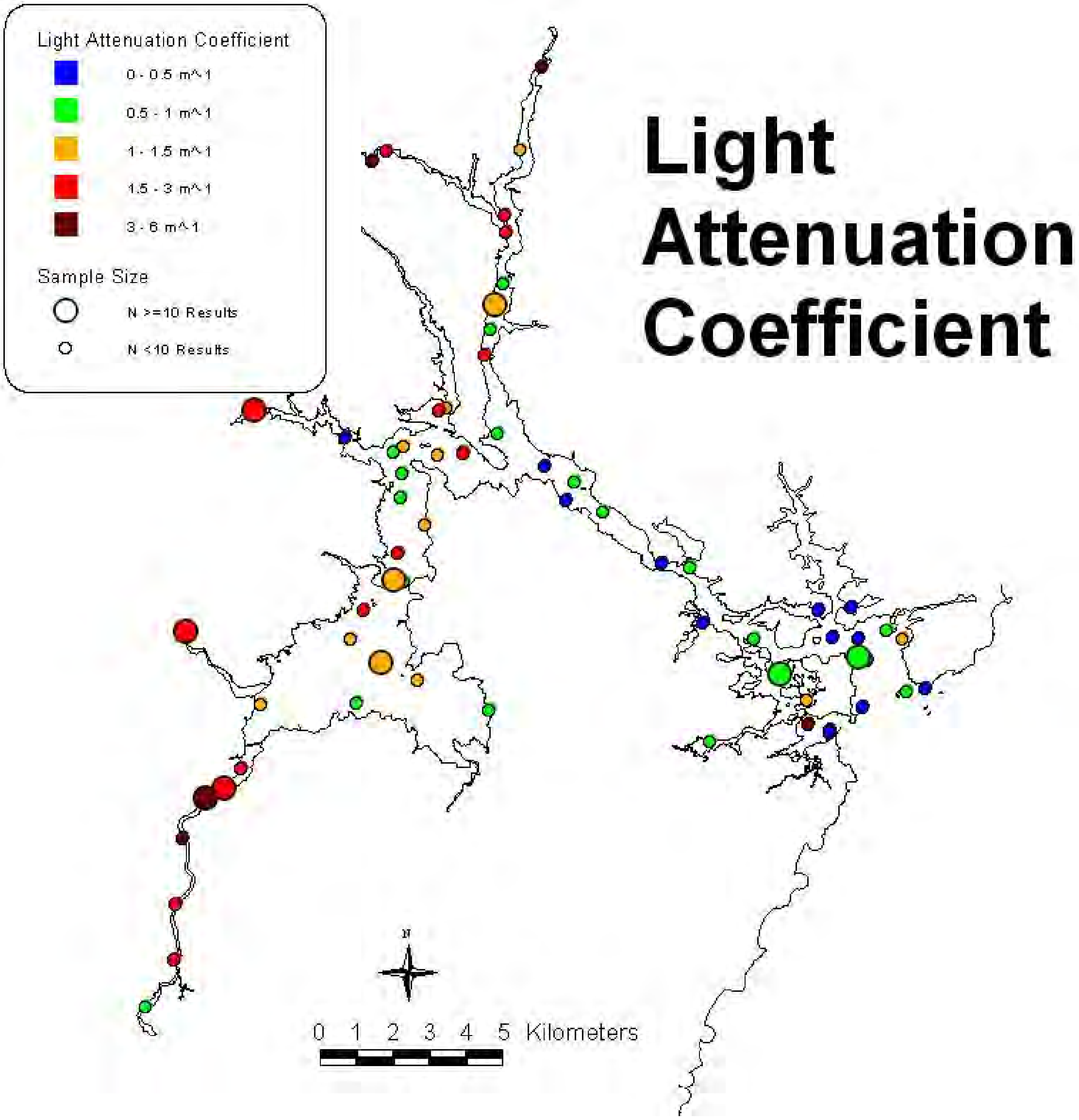


**Table 9: Predicted Eelgrass Depths in Different Regions of the Estuary**

| Assessment Zone | $K_d$ ($m^{-1}$) | | Modeled Depth (m MTL) | | | Eelgrass |
|---|---|---|---|---|---|---|
| | N | Median | $Z_{min}$ | $Z_{max}$ | $Z_{min}$-$Z_{max}$ | Predicted |
| SQUAMSCOTT RIVER | 74 | 2.96 | -1.0 | -0.5 | -0.5 | No |
| LAMPREY RIVER | 42 | 1.90 | -1.0 | -0.8 | -0.2 | No |
| OYSTER RIVER | 37 | 1.80 | -1.0 | -0.8 | -0.2 | No |
| BELLAMY RIVER | 2 | 1.42 | -1.0 | -1.1 | 0.1 | No |
| COCHECO RIVER | 2 | 3.60 | -1.0 | -0.4 | -0.6 | No |
| SALMON FALLS RIVER | 3 | 2.20 | -1.0 | -0.7 | -0.3 | No |
| GREAT BAY | 48 | 1.11 | -1.0 | -1.4 | 0.4 | Partial |
| LITTLE BAY | 59 | 1.06 | -1.0 | -1.4 | 0.4 | Partial |
| UPPER PISCATAQUA RIVER | 21 | 1.30 | -1.0 | -1.2 | 0.2 | Partial |
| LOWER PISCATAQUA RIVER NORTH | 8 | 0.59 | -1.0 | -2.6 | 1.6 | Yes |
| LOWER PISCATAQUA RIVER SOUTH | 5 | 0.50 | -1.0 | -3.0 | 2.0 | Yes |
| PORTSMOUTH HARBOR | 46 | 0.63 | -1.0 | -2.4 | 1.4 | Yes |
| LITTLE HARBOR/BACK CHANNEL | 25 | 0.58 | -1.0 | -2.6 | 1.6 | Yes |

1. $Z_{max} = \ln(0.22)/K_d$

Water clarity is a function of absorption and scattering of light by phytoplankton, turbidity, colored dissolved organic matter (CDOM), and water itself. In order to establish a nitrogen threshold associated with the water clarity thresholds, the causal relationships between nitrogen and these factors were determined through a two-step process. First, the relative importance of each light attenuation factor was measured using high frequency buoy observations in 2007. Second, the relationship of each of the factors to nitrogen was evaluated using evidence from grab samples and other data sources.

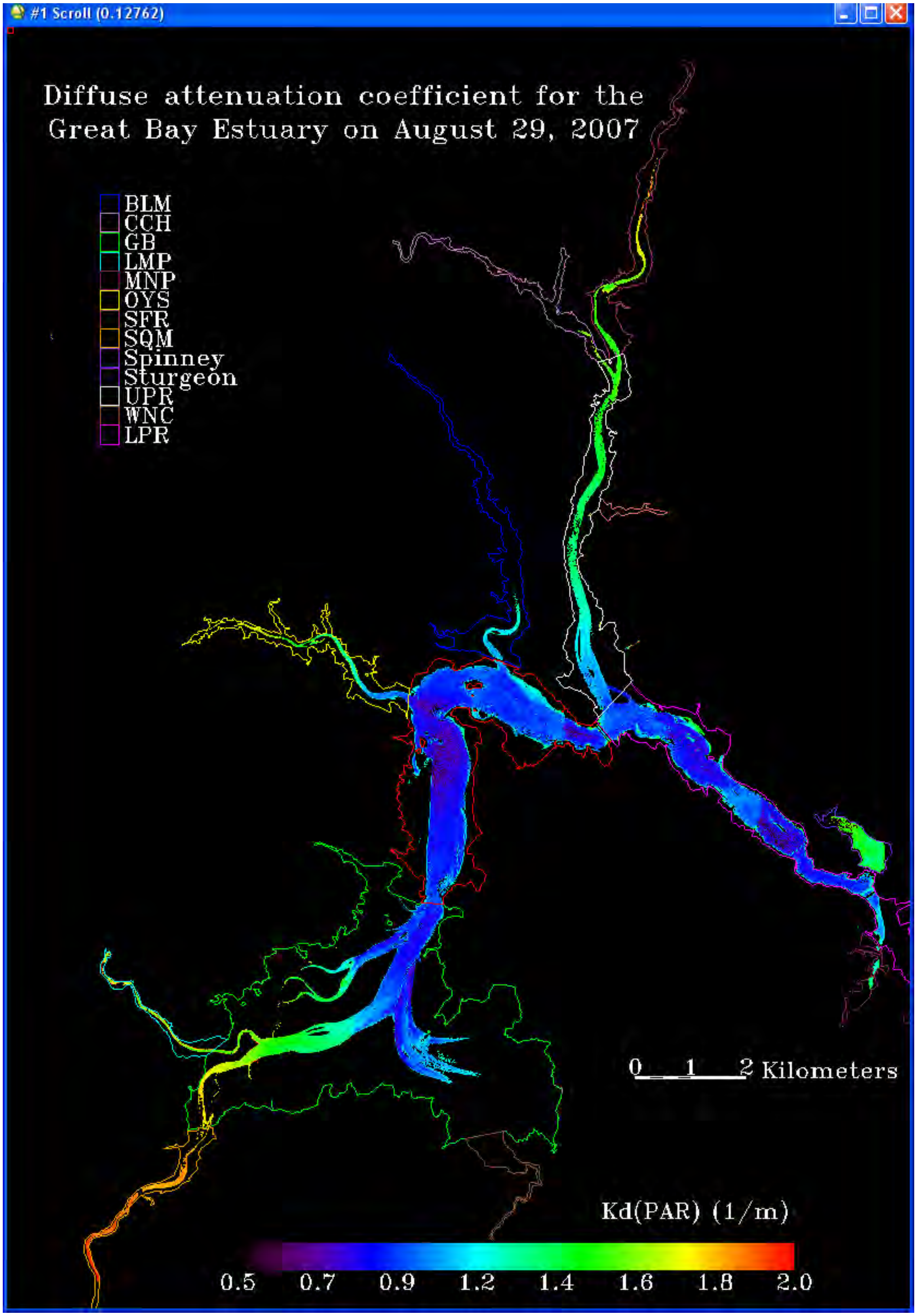
In 2007, PREP provided funding from EPA to UNH to collect high frequency observations of light attenuation and water quality in Great Bay. The purpose of the research was to collect enough data points to develop a statistically significant, multivariate regression between the light attenuation coefficient and water quality. Between April 4 and December 1, 2007, light attenuation coefficient, chlorophyll-a, CDOM, and turbidity were measured at the buoy at 15 to 30 minute intervals. The measurements of the light attenuation coefficient were regressed against values of chlorophyll-a, non-algal turbidity, and CDOM using a multivariate linear model. The regression produced a statistically significant relationship which explained 95 percent of the variance in the observed light attenuation measurements (Morrison et al., 2008):

$$\frac{K_d\,(PAR)}{Do} = 0.2449 + 0.0188.[Chl] + 0.0101.[CDOM\,] + 0.0784.[NAP] \qquad (8.1)$$

with the units of the concentration terms reflecting those used by buoy instrumentations ([Chl] in mg m-3, [CDOM] in ppb QSE, and [NAP] in chlorophyll adjusted turbidity NTUs). Through this regression equation, UNH was able to determine that over the course of the buoy deployment, water accounted for 32%, chlorophyll-a accounted for 12%, CDOM accounted for 27%, and turbidity accounted for 29% of the light attenuation in the middle of Great Bay (Morrison et al., 2008).

The regression relationship established by the buoy observations was confirmed using hyperspectral imagery collected during a spring low tide on August 29, 2007. The imagery was processed to generate a map of light attenuation throughout the bay and in the tributaries on that date (Figure 33). The light attenuation coefficient throughout the estuary was also predicted from ship track measurements of chlorophyll-a, turbidity, and CDOM taken during the overflight and the regression equation listed above. The light attenuation coefficient values from both methods agreed, which indicates that the regression equation from the buoy measurements was valid and applicable throughout the estuary (Morrison et al., 2008). However, the percentage of light attenuation attributable to each factor will not be the same in all areas because the relative concentrations of the different factors are not the same in all areas of the estuary.

**Figure 33: Light Attenuation Coefficient from Hyperspectral Imagery on August 29, 2007**



The relationship of each of the light attenuation factors to nitrogen was evaluated using evidence from grab samples and other data sources. The attenuation by water can be ignored because it is constant. CDOM is important to attenuation in the Great Bay Estuary but is not controllable and does not appear to be related to primary production in the estuary. This parameter is largely based on delivery of dissolved organic carbon from the decomposition of plants and organic soils in the watershed (Keith et al., 2002), which occurs over long time periods. However, CDOM should still be correlated with nitrogen concentrations because of the nitrogen bound up in organic matter. Chlorophyll-a concentrations are strongly correlated with nitrogen as has been demonstrated in this report. Therefore, the critical causal relationship to define is the one between turbidity and nitrogen.

Turbidity is a measure of scattering in the water column due to particulate organic matter and inorganic particles. Particulate organic matter is composed of living phytoplankton (as measured by chlorophyll-a), zooplankton and other consumers, and detrital organic matter. Paired measurements of particulate organic carbon and chlorophyll-a in estuary assessment zones show that living phytoplankton constitute less than 5% of the particulate organic matter (Figure 34). For this calculation it was assumed that phytoplankton biomass is 50% carbon and 5% chlorophyll-a based on guidance from EPA (EPA, 1985). Therefore, chlorophyll-a measurements underestimate the amount of organic matter in the water column by a factor of at least 20, on average. Moreover, the concentrations of this particulate organic matter are correlated with nitrogen concentrations (Figure 34), which suggests that this organic matter was generated by primary productivity within the estuary (autochthonous). For this graph, dissolved nitrogen concentrations were used to avoid spurious correlations due to nitrogen bound in organic matter.

The presence of particulate organic matter in excess of living phytoplankton is important because it accounts for nearly half of the turbidity. Daily average turbidity measurements at datasondes were paired with particulate organic carbon measurements from same station on the same date using data through 2007. Extreme values were trimmed from the dataset. Figure 35 shows that particulate organic carbon accounts for 47% of the daily turbidity variance measured by the datasondes. A perfect correlation between these two variables would not be expected because of the effects of inorganic particles on turbidity.

The relationship between median turbidity and nitrogen at datasonde stations indicates an even better relationship. At each datasonde, daily average turbidity concentrations were calculated for days (typically between March and December) with at least 36 valid turbidity measurements (i.e., 75% complete). Median turbidity values were calculated from all of the daily average turbidity values between 2000 and 2008 at each station. Therefore, each median turbidity value on Figure 36 was derived from greater than 15,000 individual measurements of turbidity at each station. These median values were well correlated with the median total nitrogen concentrations at these stations. The relationship holds up when the date range is limited to years in which total nitrogen and turbidity were measured at the stations (Figure 37). This result suggests that particulate organic matter and nitrogen may be responsible for more than 47% of turbidity.

**Figure 34: Relationship between Particulate Organic Carbon and Dissolved Nitrogen in Assessment Zones**

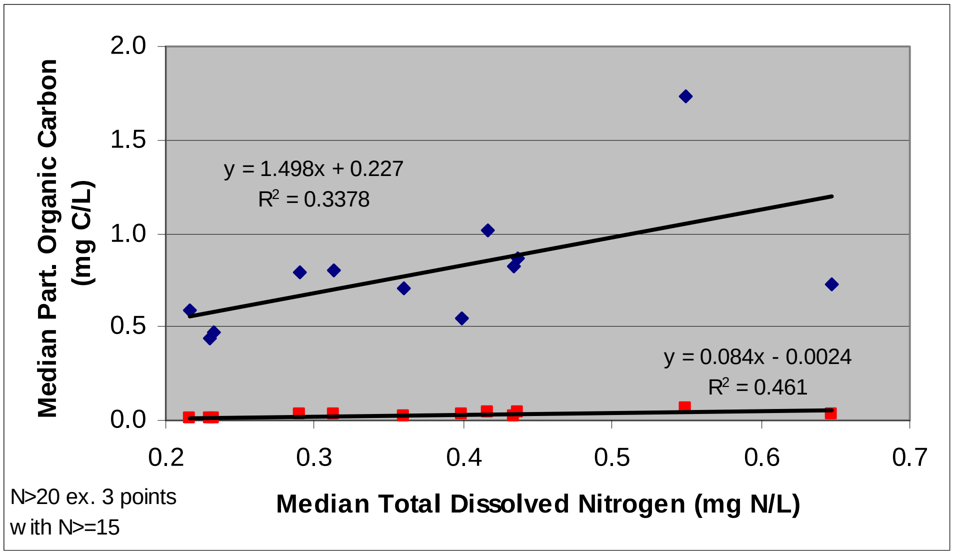


**Figure 35: Relationship between Daily Average Turbidity Measured by Datasondes and Particulate Organic Carbon on the Same Day in 2000-2007**

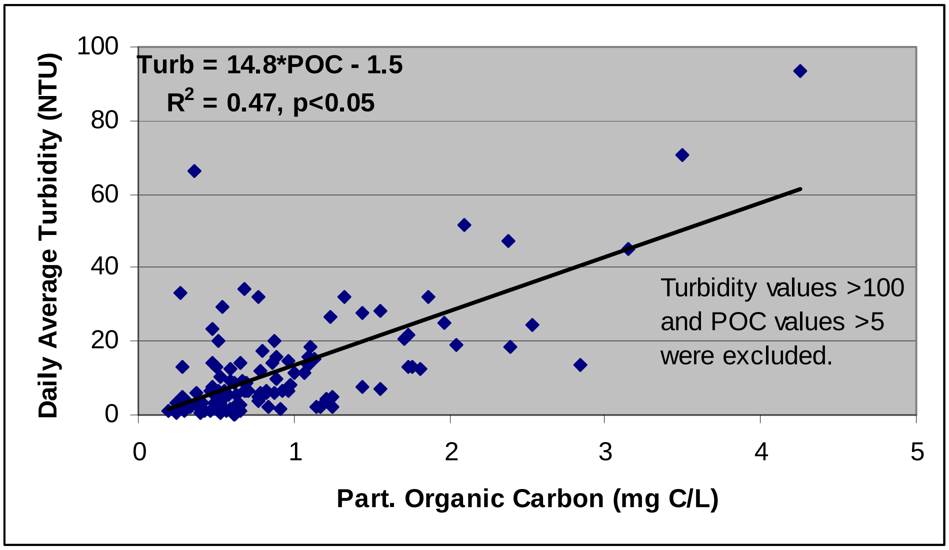


**Figure 36: Relationship between Turbidity and Nitrogen Concentrations During All Seasons at Datasonde Stations in 2000-2008**

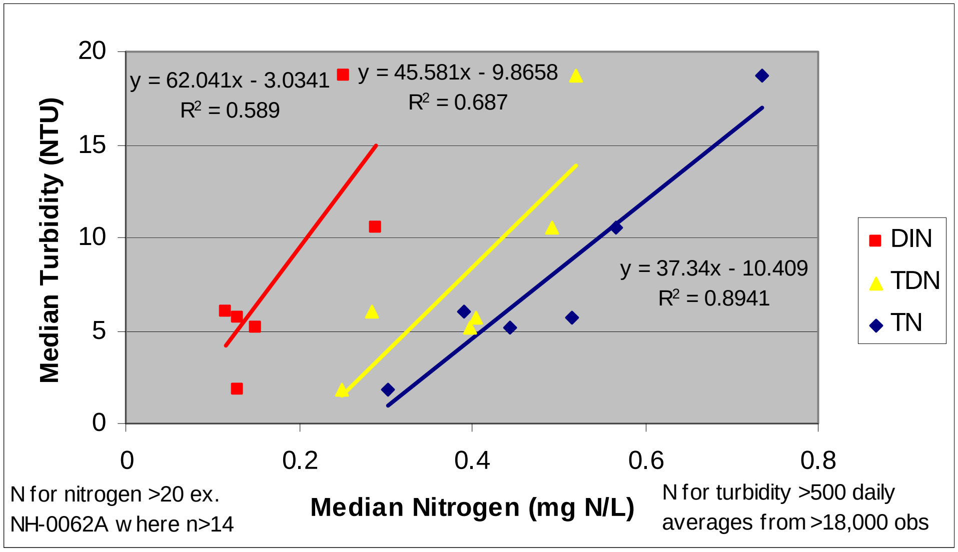
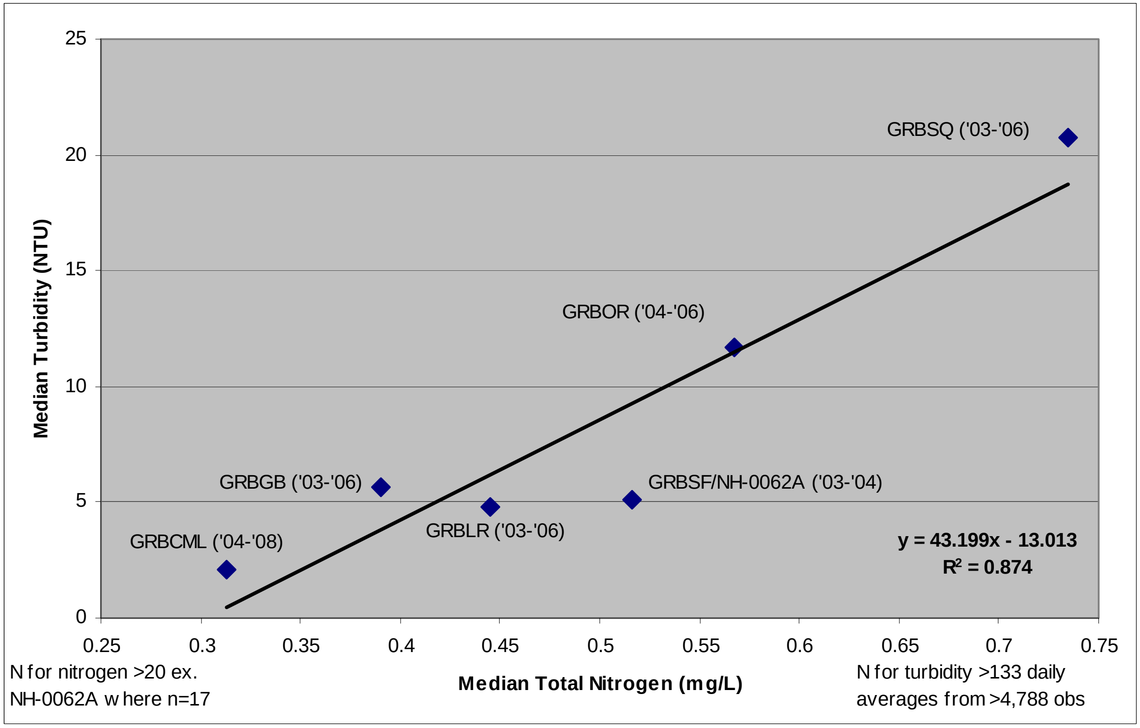


**Figure 37: Relationship between Turbidity and Nitrogen from Measurements During All Seasons at Datasonde Stations**



Given that chlorophyll-a and at least half of turbidity are causally linked to nitrogen concentrations and CDOM contains nitrogen, light attenuation in the estuary should be a function of nitrogen as well. In Figure 38, the median light attenuation coefficient in different assessment zones is well correlated with both dissolved and total nitrogen concentrations. This relationship is refined in Figure 39 where the median total nitrogen and median light attenuation coefficient are plotted for trend stations only using data from years when both parameters were measured. Based on the regression between total nitrogen and $K_d$ on Figure 39, a total nitrogen threshold of 0.30 mg N/L would be needed to meet the water clarity threshold for eelgrass habitat of 0.75 $m^{-1}$ (2 meter restoration depth). For the water clarity thresholds of 0.6 and 0.5 $m^{-1}$ (2.5 and 3 meter restoration depths), the total nitrogen thresholds would be 0.27 and 0.25 mg N/L, respectively. The uncertainty in these thresholds due to the low samples size and the imperfect correlations is +/-0.12 mg N/L based on the standard error of the regression (Helsel and Hirsh, 1992). This uncertainty is close to the goal of having uncertainties in nitrogen thresholds less than +/-0.1 mg N/L.

While none of the individual data sources provides conclusive thresholds for eelgrass protection, all of the data sources can be combined using a weight of evidence approach to determine a nitrogen threshold. The range of possible thresholds is bound by the total nitrogen concentration in offshore waters in the Gulf of Maine (0.20 mg N/L) as a minimum and the nitrogen concentration associated with macroalgae proliferation in Great Bay (0.34-0.38 mg N/L) as a probable maximum. Within that range, the best estimate for the threshold based on the analysis of water clarity is 0.25 to 0.30 mg N/L depending on the restoration depth. Another source of information is the nitrogen concentrations in areas where eelgrass is still healthy. The only major assessment zones that DES did not determine to be impaired for eelgrass loss were in Portsmouth Harbor and Little Harbor (NHDES, 2008b), although recent declines in eelgrass cover show that these areas are not pristine (PREP, 2009). Following EPA guidance for the reference concentration approach, the threshold should be bound by the 75th percentile concentration in the reference area (EPA, 2001). For the Portsmouth Harbor and Little Harbor area, this reference concentration for total nitrogen is 0.34 mg N/L. This concentration is likely too high because of the declining trends in eelgrass in these areas. Finally, the total nitrogen criteria which have been established for other estuaries in New England predominantly fall between 0.35 and 0.38 mg N/L. These criteria were established for smaller estuaries on Cape Cod with higher nitrogen concentrations in offshore waters (by 0.07 mg/L), and are based on tidally averaged concentrations at sentinel sites in the upper reaches of the estuary, not median values. **The combination of these various pieces of information strongly support the nitrogen thresholds of 0.25, 0.27, and 0.30 mg N/L that were derived from the regression between total nitrogen and light attenuation for restoration depths of 3, 2.5, and 2 meters, respectively.** Given the range of possible values (0.20 to 0.38 mg N/L), the maximum uncertainty in this estimate is +/-0.09 mg N/L. However, uncertainty is likely smaller because the reference concentration approach narrowed the range of possible values to less than 0.34 mg N/L. Regardless, the uncertainty in these thresholds is lower than the goal set by DES for the uncertainty in total nitrogen thresholds to be less than +/-0.1 mg N/L. DES considers this level of uncertainty to be acceptable for establishing water quality criteria.

**Figure 38: Relationship between Light Attenuation Coefficient and Nitrogen in Assessment Zones**

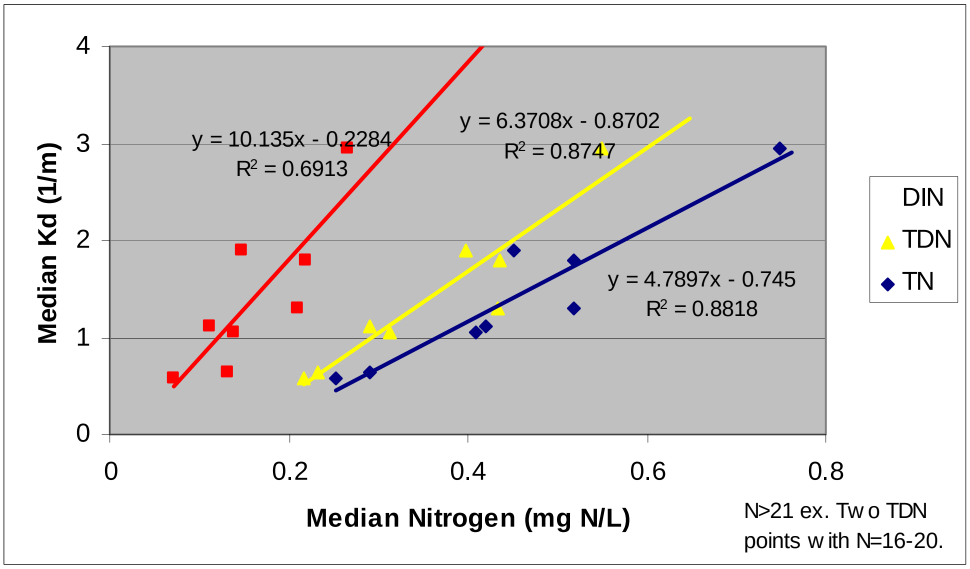
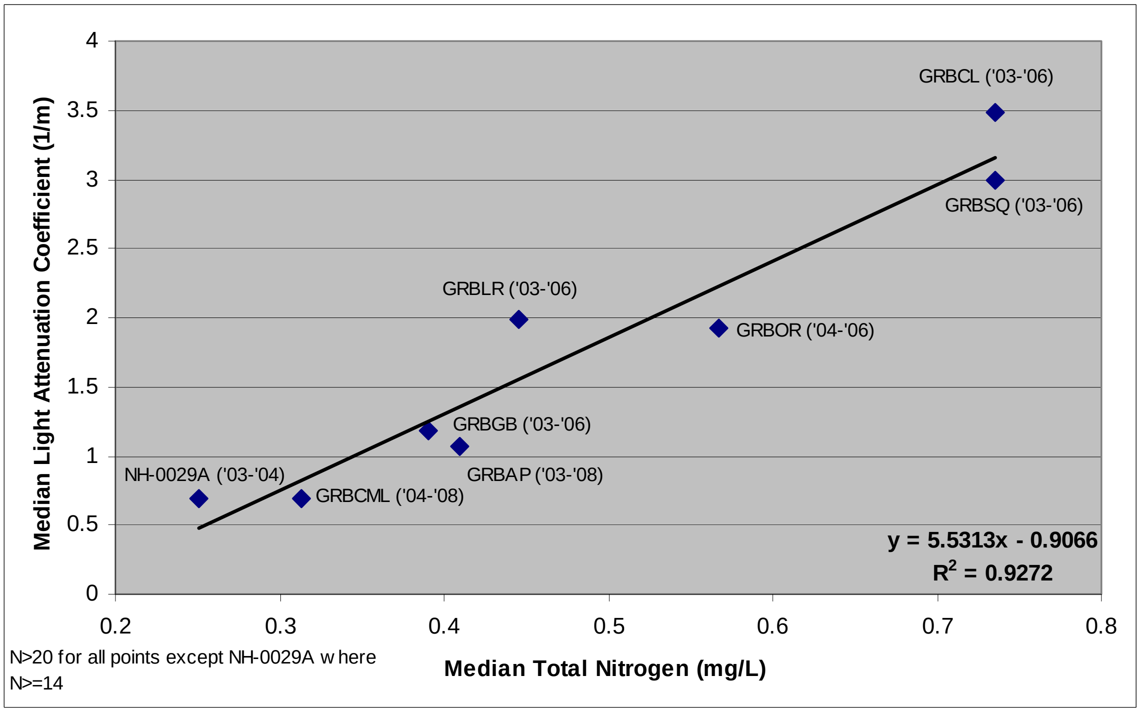


**Figure 39: Relationship between Light Attenuation Coefficient and Total Nitrogen at Trend Stations**



# Summary of Proposed Numeric Nutrient Criteria

1. DES is proposing the following numeric nutrient criteria for New Hampshire estuarine waters in the Great Bay Estuary. These values will first be used as interpretations of the water quality standards narrative criteria for DES' Consolidated Assessment and Listing Methodology for 305(b) assessments. Later, DES will promulgate these values as water quality criteria in Env-Wq 1700.

| Designated Use / Regulatory Authority | Parameter | Threshold | Statistic[5] | Comments |
|---|---|---|---|---|
| Primary Contact Recreation [1,2]<br>(Env-Wq 1703.14) | Chlorophyll-a | 20 ug/L | 90th percentile | This criterion has been used by DES for 305(b) assessments since 2004. |
| Aquatic Life Use Support – to protect Dissolved Oxygen [1,3]<br>(RSA 485-A:8 and Env-Wq 1703.07) | Total Nitrogen | 0.45 mg N/L | Median | |
| | Chlorophyll-a | 10 ug/L | 90th percentile | |
| Aquatic Life Use Support – to protect Eelgrass [1,4]<br>(Env-Wq 1703.14) | Total Nitrogen | 0.30 mg N/L<br>0.27 mg N/L<br>0.25 mg N/L | Median | The range of values for the criteria corresponds to the range of eelgrass restoration depths: 2 m, 2.5 m, and 3 m. |
| | Light Attenuation Coefficient (Water Clarity) | 0.75 m$^{-1}$<br>0.60 m$^{-1}$<br>0.50 m$^{-1}$ | Median | |

<u>Notes</u>

1. Maine tidal waters are not covered by these criteria, nor are tidal waters in New Hampshire that are not part of the Great Bay Estuary (i.e., Hampton-Seabrook Harbor, Rye Harbor, offshore coastal waters).
2. If an assessment unit is impaired for chlorophyll-a for the primary contact recreation designated use, it will also be listed as impaired for nitrogen due to the strong causal relationship between chlorophyll-a and total nitrogen.
3. The criteria to prevent low dissolved oxygen apply in sections of the Great Bay Estuary where eelgrass has not historically existed, which are typically the upper reaches of the tidal rivers.
4. The criteria to protect eelgrass apply in sections of the Great Bay Estuary where eelgrass has historically existed, which is some or all of each of the tidal rivers, Great Bay, Little Bay, Piscataqua River, Portsmouth Harbor, Little Harbor, Back Channel, and Sagamore Creek. Additional research on the extent of historical eelgrass in the tidal rivers is needed, especially in the Upper Piscataqua, Cocheco, and Salmon Falls Rivers. The applicable criteria for each assessment zone will be the one corresponding to the restoration depth assigned to the zone. Initially, the restoration depth will be 2 meters for all areas except the Lower Piscataqua River-South, Portsmouth Harbor, and Little Harbor/Back Channel areas. In these areas, a restoration depth of 2.5 or 3 meters should be chosen. Additional research is needed to determine the appropriate restoration depth for these areas. Eelgrass cover mapped using aerial photography will be assessed separately for 305(b) reports using the protocol published in NHDES (2008b).
5. Median and 90th percentile concentrations should be calculated using data from all seasons over the most recent five year period of record.

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# Appendix A: Responses to Comments on Review Draft

The proposed nutrient criteria were first reviewed by the Technical Advisory Committee for the Piscataqua Region Estuaries Partnership on November 12, 2008. This committee had been expanded from its core membership to include anyone with an interest in the nutrient criteria. DES received oral comments at a meeting of this committee on November 17, 2008 and written comments from eight individuals.

After revising the report, DES released a draft for public comment on December 30, 2008. Comments were solicited from the Technical Advisory Committee, the Water Quality Standards Advisory Committee, municipalities in the Great Bay watershed, neighboring states, and environmental advocacy organizations. DES presented the proposed criteria to the Water Quality Standards Advisory Committee on January 22, 2009 and March 18, 2009. The public comment period ended on March 20, 2009.

A total of 135 comments were submitted by the following 12 individuals/organizations:

| Name | Organization |
|---|---|
| Steve Tapley | Town of Kittery, Maine |
| Ray Konisky | The Nature Conservancy |
| Michelle Daley | University of New Hampshire |
| Bill McDowell | University of New Hampshire |
| Dan Dudley | DES Wastewater Engineering Bureau |
| Fred Short | University of New Hampshire |
| Steve Silva | EPA Region I |
| Tom Irwin | Conservation Law Foundation |
| Steve Clifton | Underwood Engineers |
| Ed Dettmann | EPA Office of Research and Development |
| Jim Stahlnecker/Tom Danielson | Maine Department of Environmental Protection |
| Various | Coalition Communities* |

* The Coalition Communities are the municipalities of Portsmouth, Exeter, Durham, Newmarket, Rochester, and Dover, New Hampshire.

The majority of the comments were related to a few topics. DES has grouped and paraphrased these “meta-comments” below and provided responses. If DES added significant text to the report to address the comment, the reader is referred to the relevant page of the report for the additional information. The meta-comments were grouped into questions about data, data analysis, interpretation and regulatory issues. For comments from reviewers that were not covered by these meta-comments, DES prepared individual responses at the end of this appendix. Editorial comments were generally accepted but are not listed in this appendix.

### “Data” Issues

<u>Provide information on how data were quality assured.</u>
Response: The major monitoring programs for nutrient and eutrophication parameters are the Great Bay National Estuarine Research Reserve System Wide Monitoring Program (http://nerrs.noaa.gov/Monitoring/), University of New Hampshire Tidal Water Quality Monitoring Program, and the National Coastal Assessment (http://www.epa.gov/emap/nca/). The GBNERR System Wide Monitoring Program and the UNH Tidal Water Quality Monitoring Program are implemented using national protocols from the NOAA Central Data Management Office. The National Coastal Assessment is implemented in NH by UNH following the Quality Assurance Project Plan from EPA. Each year, DES provides an additional quality assurance review of the data for these programs before the data are entered into the Environmental Monitoring Database. This quality assurance review consists of: (1) Evaluation of field duplicate samples; (2) Review of laboratory quality control results and methods; (3) Comparison of measured concentrations to results in previous years to identify outliers; and (4) Cross check of station visit information. The data that DES determines to be valid through this process are entered into the Environmental Monitoring Database and are used for Surface Water Quality Assessments (305b/303d Listing).

<u>Justify the metrics used in the benthic macroinvertebrate IBI indicator.</u>
Response: DES added information relative to the IBI indicator and other possible indicators of benthic macroinvertebrates to the methods section of the report on page 12.

<u>Due to equipment problems, weather conditions, the absence of a validation dataset, and limited ground truth observations, the macroalgae maps generated from the hyperspectral imagery should not be considered valid. More specifically:</u>

- <u>Did the conditions on day of data collection (weather, tide stage, etc.) compromise the dataset?</u>
- <u>Is it valid to generate maps from the same dataset used to create the algorithm?</u>
- <u>What were the specific ground truthing methods.</u>
- <u>Was there good agreement between the predicted macroalgae locations using the algorithm and field measurements?</u>
- <u>Should the macroalgae maps outside of the ground-truthed area be used?</u>
- <u>Has the hyperspectral analysis been peer-reviewed? It is too complicated for most reviewers.</u>
- <u>Should the hyperspectral imagery be repeated?</u>
- <u>The macroalgae map has some errors for eelgrass and salt marsh which should be acknowledged.</u>

Response: The hyperspectral imagery dataset generated valid data on macroalgae populations in Great Bay. Hyperspectral imagery is a powerful tool for investigating and mapping habitats. It is also very complicated. Reviewers raised a number of questions about the use of hyperspectral imagery to create maps of macroalgae in the estuary. Each of these issues has been addressed by adding information to the methods section of the report on page 10. A manuscript containing the macroalgae mapping procedures will be submitted to the peer-reviewed journal Estuaries and Coasts in 2009. UNH is submitting a proposal to collect another round of hyperspectral imagery to repeat the research. The figure showing macroalgae distributions in Great Bay was based on a draft GIS datalayer. The figure will be regenerated using the final GIS datalayer. The graph showing the percent cover of macroalgae in multiple areas of the estuary was removed for the report because ground truthing for macroalgae was only completed in the Great Bay.

More data are needed to improve the accuracy of the criteria.
Response: The Great Bay Estuary has been monitored for years by a number of overlapping programs. As a result, there is a sample density for nutrients and eutrophication parameters which is unparalleled in northern New England. From 2000 to 2008, the database contains approximately 1,500 results each for dissolved nutrient, chlorophyll-a, and suspended sediment concentrations. This number of results averages out to three samples per year for each parameter for every square kilometer of surface water in the Great Bay Estuary. Therefore, DES believes that there are more than sufficient data to develop nutrient criteria for the estuary. For this latest draft of the report, the water quality data from 2008 were imported to the database and included in the analyses. These samples did not change the conclusions significantly. If future monitoring suggests that the criteria are incorrect, DES will re-evaluate the criteria.

### “Data Analysis” Issues

Results reported as “below detection limit” should be included.
Response: Results reported as “below detection limit” were added to the database to calculate summary statistics for assessment zones and trend stations. For these results, the reporting detection limit was used as the value. The percentages of samples with censored results for the different parameters are shown in the following table. The substitution was deemed appropriate because median and 90th percentile values are insensitive to non-detect results in small percentages. Non-detect results were also included in the paired sample analysis in the original draft report.

| Parameter | N BDL | N Total | % BDL | Max RDL | Units |
|---|---|---|---|---|---|
| CHLOROPHYLL-A | 59 | 3158 | 1.9% | 0.2 | UG/L |
| DISSOLVED OXYGEN | 0 | 5212 | 0.0% | NA | MG/L |
| LIGHT ATTENUATION COEFFICIENT | 0 | 538 | 0.0% | NA | 1/M |
| NITROGEN |  | 101 | 0.0% | NA | MG/L |
| NITROGEN, DISSOLVED | 8 | 1531 | 0.5% | 0.1 | MG/L |
| NITROGEN, SUSPENDED | 10 | 999 | 1.0% | 0.025 | MG/L |
| NITROGEN, AMMONIA AS N | 113 | 2205 | 5.1% | 0.5 | MG/L |
| NITROGEN, NITRITE (NO2) + NITRATE (NO3) AS N | 70 | 2251 | 3.1% | 0.05 | MG/L |
| PHOSPHORUS (DISSOLVED) | 23 | 329 | 7.0% | 0.017 | MG/L |
| PHOSPHORUS (SUSPENDED) | 15 | 319 | 4.7% | 0.005 | MG/L |
| TOTAL PHOSPHORUS | 0 | 117 | 0.0% | NA | MG/L |
| PHOSPHORUS, ORTHOPHOSPHATE AS P | 220 | 2296 | 9.6% | 0.005 | MG/L |
| SOLIDS, SUSPENDED | 16 | 2109 | 0.8% | 1 | MG/L |
| SILICA | 18 | 1910 | 0.9% | 0.1 | MG/L |

The report should not mix parametric and non-parametric statistics (e.g., means and medians).
Response: The majority of the statistics used for the draft nutrient criteria report were non-parametric. However, arithmetic means were used in a few situations where it was computationally convenient. Recognizing the importance of consistency, DES has replaced the arithmetic mean values with non-parametric statistics wherever possible. Specifically, arithmetic means used to calculate the total nitrogen concentration in offshore waters have been replaced with medians. Figures showing the arithmetic mean concentration at stations throughout the estuary have been replaced with figures showing the median concentrations. These figures were exclusively used for illustrative purposes anyway. Finally, in the previous draft report, all results for a parameter from each station visit were averaged to represent the station visit. In this revised report, the results from any field duplicate or split samples are averaged first and then the maximum (or minimum) value from samples taken at multiple depths or during multiple station visits was used to represent the concentration at that station on that date. Using the average of duplicate samples is consistent with the non-parametric approach because the arithmetic mean of two samples is the same as the median.

The relationships between total nitrogen and response variables should be based on results from the same summer index period (not a mixture of annual and summer values). Lengthen the summer index period to include the spring bloom.
Response: In the draft report, chlorophyll-a concentrations were defined using the 90th percentile concentration during summer while nitrogen and other parameters were represented by annual median values. This approach mixed two different time periods and ignored the spring phytoplankton bloom. DES repeated the calculations using data for all parameters for a March through October index period and for the whole year. The relationships between parameters were best for data from the whole year period. Therefore, the statistic representing chlorophyll-a concentrations was changed to be the 90th percentile concentration using data from the whole year. The statistics representing the other parameters were already based on the whole year.

The Lower Piscataqua River assessment unit is too big and not homogeneous. Eelgrass has been lost almost completely in the upper portion. The AU should be split.
Response: DES agrees that the Lower Piscataqua River assessment zone is too large to be considered homogeneous. The northern portion of the zone is much wider than the southern portion of the zone. DES has split this assessment zone in half just upstream of the Schiller Station where the channel narrows. The northern half of the assessment zone will be called “Lower Piscataqua River-North”. The southern half of the assessment zone will be called “Lower Piscataqua River-South”. The majority of data from this assessment zone was from the southern half of the assessment zone. Therefore, the Lower Piscataqua River-North assessment zone will likely have too little data to make assessments. Similarly, DES also decided to split up the Portsmouth Harbor/Little Harbor assessment zone so that Portsmouth Harbor and Little Harbor/Back Channel could be assessed separately.

<u>The regressions should use data from individual samples instead of median values (or other statistics) for different assessment zones.</u>
Response: Li et al. (2009) investigated the importance of spatial and temporal scales on apparent relationships between nitrogen and chlorophyll-a concentrations. They found that good relationships were evident at short time scales (hourly to weekly) and at very long time scales (decadal). At the intermediate time scales, the relationships were obscured by the complexity of the interactions between hydrodynamics and phytoplankton population dynamics. The researchers also found that the relationships were evident when comparing central tendency values from different biogeochemical ocean provinces. At the shorter time scales, the relationships are largely controlled by cellular biology and, therefore, are predictable. At longer time scales, the effects of species composition, interactions, and succession as well as variability in weather and thermal stratification play dominant roles in controlling the relationships. However, at the decadal scale, all of the variability introduced at the intermediate scales can be averaged out (Li et al., 2009).

In the Great Bay Estuary, nutrient and eutrophication response parameters are measured monthly at trend stations and sporadically at other sites. Therefore, most of the data for this estuary are collected at the intermediate time scale for which the nutrient and response relationships will be difficult to discern. However, by aggregating the nutrient and response measurements over multiple years, the relationships between these variables become clearer as predicted by Li et al. (2009). For example, if the light attenuation coefficient and total nitrogen concentrations from the same sample are regressed, the $r^2$ of the relationship is 0.40 due to the complex, contingent relationships involving nutrients, phytoplankton, weather and hydrodynamics. If the median values of these parameters from multiple years are regressed, the $r^2$ of the relationship jumps to 0.93. Therefore, aggregating the results within different assessment zones and over multiple years is absolutely necessary in order to reveal the underlying relationships between nutrients and eutrophication parameters.

<u>Improve the estimated total nitrogen concentration in the offshore GOM waters (particularly dissolved organic nitrogen concentrations).</u>
Response: DES conducted additional research on the concentrations of nitrogen in different forms in the Gulf of Maine waters offshore of Portsmouth Harbor. The results are summarized in the results section on page 18.

<u>DO saturation should be included in the analysis.</u>
Response: The daily average dissolved oxygen saturation was calculated for each of the datasondes for all days in June through September with data in 2000-2008 (see page 54). The same patterns were evident with dissolved oxygen saturation as had been previously shown with the daily minimum dissolved oxygen.

### “Interpretation” Issues

<u>There should be dissolved inorganic criteria in addition to the total nitrogen criteria.</u>

Response: Nitrogen cycling results in constant shifts between the different forms of nitrogen. Setting criteria for dissolved inorganic nitrogen is problematic because the concentrations of this species is drawn down or fully depleted during periods of high productivity. Therefore, DES feels that total nitrogen is a more stable indicator to use for the water quality criteria. In guidance for establishing nutrient criteria for estuaries, EPA identified total nitrogen as the causal variable of specific concern (EPA, 2001).

<u>The correlations provided in the report do not prove causality. For example, justify that elevated nitrogen causes turbidity and is not caused by it.</u>
Response: The correlations between nitrogen, chlorophyll-a, dissolved oxygen, and water clarity included in this report were all anticipated based on well-established conceptual models for estuarine eutrophication (Bricker et al., 2007; Cloern, 2001; McGlathery et al. 2007). Therefore, the statistically significant relationships between these parameters should be interpreted as more than mere correlations. Additional information from maps of macroalgae species and high frequency measurements of dissolved oxygen by datasondes provided additional support for the relationships. For turbidity in particular, information was presented to show that the turbidity was largely caused by autochthonous suspended organic matter.

<u>The N:P ratios indicate phosphorus limitation in the tidal rivers where high chlorophyll-a exists. There should be phosphorus criteria for the estuary too.</u>
Response: DES reviewed the chlorophyll-a concentrations in samples from the tidal rivers compared to the N:P ratio (see page 29). The results show that chlorophyll-a concentrations are not high during periods of apparent phosphorus limitation. This analysis confirms that nitrogen is the limiting nutrient in the majority of the estuary. Intermittent periods of phosphorus limitation in the tidal rivers will be addressed through numeric criteria for phosphorus in freshwater rivers being developed by DES.

<u>The light requirements for eelgrass are greater than 22%. Eelgrass survival is affected by other factors besides water clarity.</u>
Response: For this report, DES has decided to use the 22% light transmission requirement from EPA (2003). This threshold has been thoroughly peer-reviewed and incorporated into a water quality criterion for the largest estuary in the United States. DES acknowledges the arguments that a higher light transmission requirement would be needed and has added statements to that effect in the report on page 56. If monitoring shows that the 22% threshold is not adequate to protect eelgrass, the threshold will be adjusted in the future.

DES also acknowledges that other factors besides water quality can damage eelgrass populations, such as moorings and poor substrate (see page 55). However, water clarity is a requirement for eelgrass survival. Without adequate water clarity, there would be no eelgrass present to be impacted by these other factors. The criteria presented in this report focus on the water quality requirements for light transmission needed for eelgrass survival.

The macroalgae proliferation threshold is not sufficiently justified. If macroalgae actually does proliferate at 0.40 mg/L, you cannot use this as a threshold without a margin of safety.
Response: DES has added a 10-20 percent margin of safety to the nitrogen concentrations observed in Great Bay to estimate the threshold for macroalgae proliferation (page 38).

### "Regulatory" Issues

The 305b/303d listing methodology and sampling requirements must be defined.
Response: The purpose of this document is to identify the numeric criteria based on the best available science. The 305(b)/303(d) listing methodology for the proposed nutrient criteria is beyond the scope of this report. This methodology will be published in the Consolidated Assessment and Listing Methodology for the 2010 305(b)/303(d) report during the summer of 2009. There will be a public comment period on this report during which DES will accept comments on the methodology.

Maintaining the dissolved oxygen standard is not sufficient to protect all aquatic life uses (e.g., fish species with sensitive oxygen requirements) in areas without eelgrass.
Response: The proposed thresholds for total nitrogen and chlorophyll-a to prevent violations of the dissolved oxygen standard are not the only criteria that would be relevant to the aquatic life designated use in estuarine areas without eelgrass. The standards for pH and toxic contaminants would also apply. These criteria were not discussed in this report because they are not related to eutrophication; however, they will still be part of the 305b/303d assessment process. The dissolved oxygen standard of 5 mg/L or 75% saturation has already been established by rule in Env-Wq 1703.07. It is beyond the scope of this report to consider changes to this standard in order to protect species with more sensitive oxygen requirements. DES investigated thresholds for the protection of benthic macroinvertebrates and sediment quality (page 40). While numeric criteria could not be developed, the relationships indicated that the total nitrogen threshold for the protection of benthic invertebrates would be much higher than the threshold developed for maintaining dissolved oxygen.

Justify the 20 ug/L limit for chlorophyll-a for primary contact recreation. Why is it different from the threshold for freshwaters?
Response: DES added a justification for the 20 ug/L threshold for chlorophyll-a on page 31.

The regulatory impacts of the criteria should be listed.
Will the criteria be adopted by Maine DEP for the Maine side of the Piscataqua River?
How will waste load allocations, TMDLs, and other implementation issues be addressed?
Response: The purpose of this document is to justify the numeric criteria based on the best available science. Discussions on the impacts of regulations and plans for waste load allocations are beyond the scope of this document.

## Responses to Individual Comments Not Covered by Meta-Comments

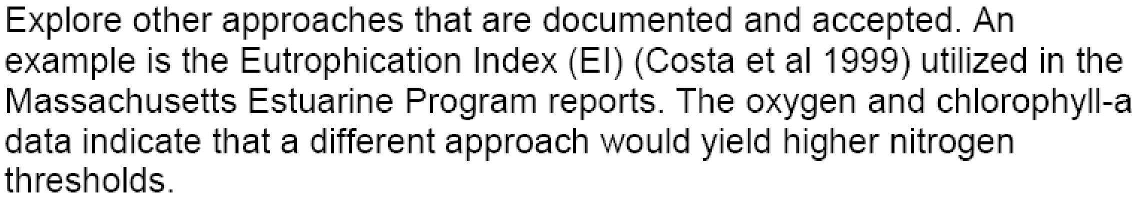
Coalition Communities

Comment #1 (ASA)

Identify the sources of nitrogen and phosphorus loads to the Great Bay Estuary.

Response: The nitrogen and phosphorus loads to the estuary are not necessary for setting water quality criteria. The nitrogen loads during 2006-2008 will be presented in the 2009 State of the Estuaries report being prepared by PREP.

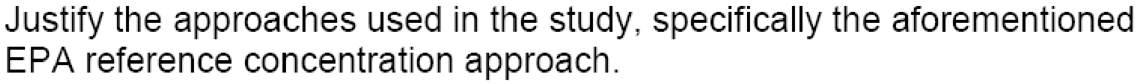
Comment #2 (ASA)



Explore other approaches that are documented and accepted. An example is the Eutrophication Index (EI) (Costa et al 1999) utilized in the Massachusetts Estuarine Program reports. The oxygen and chlorophyll-a data indicate that a different approach would yield higher nitrogen thresholds.

Response: EI appears to be useful as an indicator but it is not related to any existing water quality standard or biological requirement for benthic and aquatic community integrity (i.e., RSA 485-A:8, Env-Wq 1703.14). The EI does not include eelgrass loss and, therefore, is not relevant to setting criteria for the protection of eelgrass. Given that eelgrass is the most sensitive indicator of eutrophication, it is fully expected that the proposed nitrogen thresholds for eelgrass protection would be lower than those set for oxygen and chlorophyll-a.

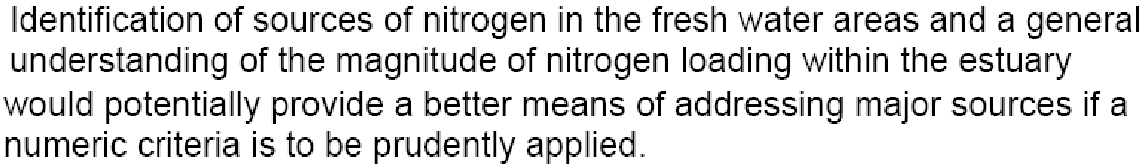
Comment #3 (ASA)



Justify the approaches used in the study, specifically the aforementioned EPA reference concentration approach.

Response: We assume that this comment is limited to the reference concentration approach used on page 66 of the report. It is correct to say that Portsmouth Harbor and Little Harbor do not exactly meet the definition of a reference site from EPA (2001). There are significant point and nonpoint sources and land cover has been heavily altered. However, the basic definition for reference conditions is: "In those cases where minimal biological resource uses are impaired by nutrient over-enrichment, then reference conditions for nutrients should be deemed to occur." The relatively stable and deep eelgrass beds that exist in Portsmouth Harbor and Little Harbor meet this definition. DES has added caveats to the discussion on page 66 acknowledging that, due to the less than pristine conditions and declining eelgrass cover, the reference concentration approach probably overestimates the appropriate criteria.

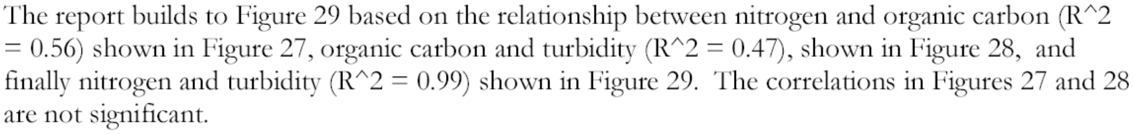
Comment #4 (ASA)



Identification of sources of nitrogen in the fresh water areas and a general understanding of the magnitude of nitrogen loading within the estuary would potentially provide a better means of addressing major sources if a numeric criteria is to be prudently applied.

See response to Comment #1

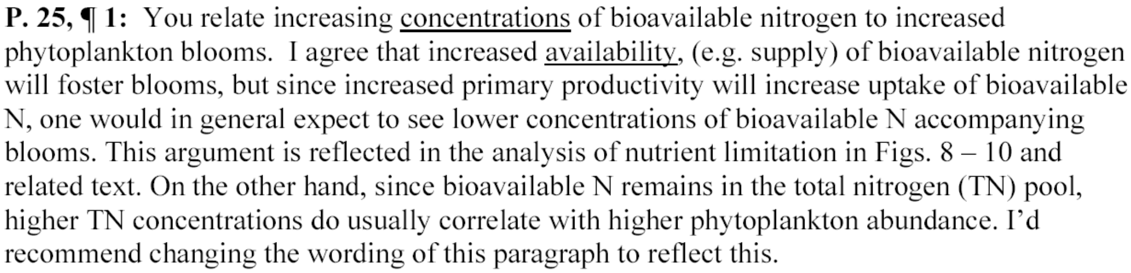
Comment #12 (Brown and Caldwell)



The report builds to Figure 29 based on the relationship between nitrogen and organic carbon (R^2 = 0.56) shown in Figure 27, organic carbon and turbidity (R^2 = 0.47), shown in Figure 28, and finally nitrogen and turbidity (R^2 = 0.99) shown in Figure 29. The correlations in Figures 27 and 28 are not significant.

Response: This comment was based on the November 12, 2008 draft of the report but similar graphs were included in the December 30, 2008 draft as well. Both regressions were statistically significant at the $p<0.05$ level, which was noted on the graph. Regardless, these two graphs were only used to illustrate relationships. They were not used to establish numeric criteria.

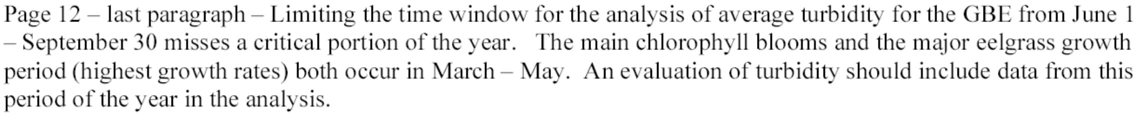
Ed Dettmann (USEPA)
Comment #10



**P. 25, ¶ 1:** You relate increasing concentrations of bioavailable nitrogen to increased phytoplankton blooms. I agree that increased availability, (e.g. supply) of bioavailable nitrogen will foster blooms, but since increased primary productivity will increase uptake of bioavailable N, one would in general expect to see lower concentrations of bioavailable N accompanying blooms. This argument is reflected in the analysis of nutrient limitation in Figs. 8 – 10 and related text. On the other hand, since bioavailable N remains in the total nitrogen (TN) pool, higher TN concentrations do usually correlate with higher phytoplankton abundance. I'd recommend changing the wording of this paragraph to reflect this.

Response: Li et al. (2009) demonstrated that the correlation between dissolved inorganic nitrogen and chlorophyll-a was negative for short time scales (less than weekly) but positive for long time scales (decadal). For this report, data were aggregated over multiple year time scales. Therefore, a positive correlation between dissolved inorganic nitrogen and chlorophyll-a is not unexpected.

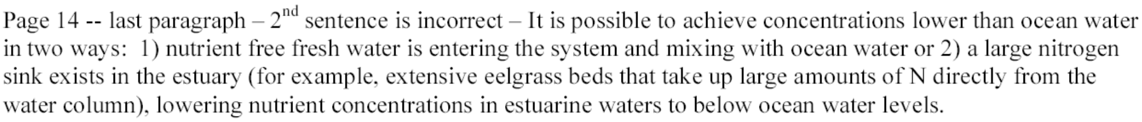
Fred Short (UNH)
Comment #2



Page 12 – last paragraph – Limiting the time window for the analysis of average turbidity for the GBE from June 1 – September 30 misses a critical portion of the year. The main chlorophyll blooms and the major eelgrass growth period (highest growth rates) both occur in March – May. An evaluation of turbidity should include data from this period of the year in the analysis.

Response: The turbidity analysis was expanded to cover all available data during the year.

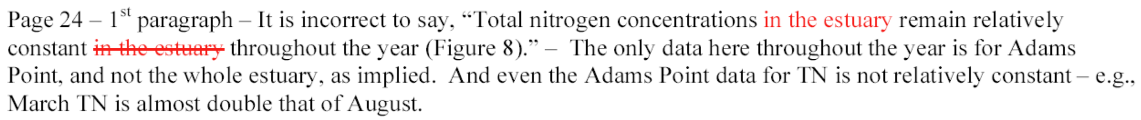
Comment #4



Page 14 -- last paragraph – 2nd sentence is incorrect – It is possible to achieve concentrations lower than ocean water in two ways: 1) nutrient free fresh water is entering the system and mixing with ocean water or 2) a large nitrogen sink exists in the estuary (for example, extensive eelgrass beds that take up large amounts of N directly from the water column), lowering nutrient concentrations in estuarine waters to below ocean water levels.

Response: DES does not feel that this scenario is feasible currently. See additional text added on page 17-18.

Comment #12

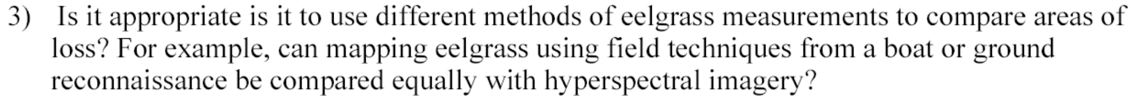


Page 24 – 1st paragraph – It is incorrect to say, "Total nitrogen concentrations in the estuary remain relatively constant ~~in the estuary~~ throughout the year (Figure 8)." – The only data here throughout the year is for Adams Point, and not the whole estuary, as implied. And even the Adams Point data for TN is not relatively constant – e.g., March TN is almost double that of August.

Response: The data for total nitrogen shows that the concentrations are, in fact, "relatively" constant. The minimum and maximum monthly concentrations of total nitrogen deviate from the annual median by only 30%. This is a small change compared to the 100% or greater changes in dissolved inorganic nitrogen concentrations, which can also be fully depleted during phytoplankton blooms. The point of the comparison between total and bioavailable nitrogen is to demonstrate that total nitrogen is a more stable indicator, and therefore a better candidate for a water quality criterion, than the bioavailable form. The data on Figure 7 show that total nitrogen concentrations are stable not just at Adams Point but also at endmember stations in the Squamscott River and in Portsmouth Harbor.

<u>Steve Clifton, Underwood Engineers</u>

Comment #3

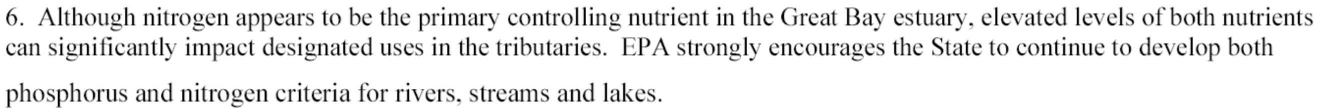


3) Is it appropriate is it to use different methods of eelgrass measurements to compare areas of loss? For example, can mapping eelgrass using field techniques from a boat or ground reconnaissance be compared equally with hyperspectral imagery?

Response: In Figure 18 eelgrass loss was calculated using eelgrass maps created using the same method of aerial photo interpretation. The hyperspectral imagery was only used to map the macroalgae cover.

<u>Steve Silva, EPA</u>

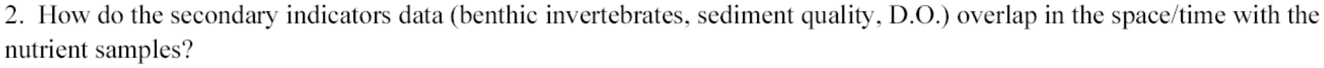
Comment #6



6. Although nitrogen appears to be the primary controlling nutrient in the Great Bay estuary, elevated levels of both nutrients can significantly impact designated uses in the tributaries. EPA strongly encourages the State to continue to develop both phosphorus and nitrogen criteria for rivers, streams and lakes.

Response: This comment is beyond the scope this report. DES is working on nutrient criteria for rivers and lakes as well.

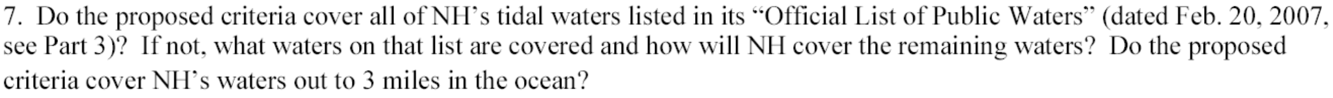
Comment #9



2. How do the secondary indicators data (benthic invertebrates, sediment quality, D.O.) overlap in the space/time with the nutrient samples?

Response: The overlap between nutrient concentrations and response variables is excellent. For regressions to set criteria, the data were limited to stations where both the nutrient and the response variable were measured during the same years. Sediment quality data from the National Coastal Assessment were collected in all assessment zones as shown on Figure 3.

Comment #14



7. Do the proposed criteria cover all of NH's tidal waters listed in its "Official List of Public Waters" (dated Feb. 20, 2007, see Part 3)? If not, what waters on that list are covered and how will NH cover the remaining waters? Do the proposed criteria cover NH's waters out to 3 miles in the ocean?

Response: The proposed criteria in this report apply to the Great Bay Estuary only (Figure 1). This estuary system includes all of the Great Bay, Little Bay, and Piscataqua

River. Tidal portions of the Winnicut, Squamscott (Exeter), Lamprey, Oyster, Bellamy, Cocheco, and Salmon Falls Rivers are also included. It is not clear whether the proposed criteria can be applied to the other two estuaries in New Hampshire (Hampton-Seabrook Harbor and Rye Harbor) or to coastal waters. Additional research is needed to establish criteria for these estuaries and the coastal waters.

# Appendix B: Responses to Comments on the Final Report

## Introduction

The DES recommendations for numeric nutrient criteria for the Great Bay Estuary were finalized and published on June 10, 2010. Prior to formal rulemaking, these criteria have been used as translators of the existing narrative standard for nutrients (Env-Wq 1703.14).

On May 12, 2010, DES received a letter from the municipalities of Portsmouth, Dover, Durham, Exeter, Newmarket, and Rochester that included a critique of the numeric nutrient criteria prepared by Hall & Associates, a consultancy from Washington DC. The major criticism raised by Hall & Associates was that the justification for the nutrient criteria did not contain a “mechanistic analysis” showing the cause-and-effect relationships between nitrogen and negative effects in the estuary.

DES contends that there is adequate justification in the final report for the proposed criteria. A conceptual model of nitrogen and its effects in estuaries was included. It was deemed unnecessary to provide rigorous proofs of the well-established relationships between nitrogen and eutrophication in estuaries. However, the comments from the municipalities indicate that it might be helpful to include such information in the report.

Therefore, as a response to these additional comments received, DES prepared a summary of the extensive scientific literature on nitrogen and its negative effects in estuaries, particularly depletion of dissolved oxygen and loss of eelgrass habitat. In addition, local data were used to illustrate that these cause and effect relationships are evident in the Great Bay Estuary.

## Cause and Effect Relationships for Nitrogen Documented in the Scientific Literature

The numeric nutrient criteria for nitrogen in the Great Bay Estuary were developed for two different endpoints: (1) To prevent occurrences of low dissolved oxygen; and (2) To protect eelgrass habitat. These endpoints were chosen because they are the two most common, and important, effects of elevated nitrogen in estuaries. The significance of dissolved oxygen and eelgrass in estuaries and the manner in which nitrogen causes or contributes to degradation of these endpoints is outlined in the following sections.

### *Dissolved Oxygen*

Low dissolved oxygen is a well established indicator of elevated nitrogen in estuaries (NRC, 2000; Cloern, 2001; Bricker et al., 2007; EPA, 2001; Diaz and Rosenberg, 2008). Fish and other species require sufficient concentrations of dissolved oxygen in the water to survive. In nitrogen-limited systems, such as estuaries (Howarth and Marino, 2006), increasing nitrogen inputs will increase primary productivity in the form of both pelagic phytoplankton and rooted or free-floating macroalgae. Respiration of the organic matter created by the primary productivity consumes oxygen from the water column and sediments. The resulting low oxygen conditions affect fish and benthic communities (Diaz and Rosenberg, 2008; Cloern, 2001; Bricker et al. 2007). Effects on species include death, compressed habitats, and shifts in species composition to opportunistic benthic species with short life spans and smaller body sizes (Diaz and Rosenberg, 2008; NRC, 2000).

### *Eelgrass*

Eelgrass (*Zostera marina*) is the base of the estuarine food web in the Great Bay Estuary. Healthy eelgrass beds filter water and stabilize sediments (Short and Short, 1984) and provide habitat for fish and shellfish (Duarte, 2001; Heck et al., 2003). While eelgrass is only one species in the estuarine community, the presence of eelgrass is critical for the survival of many species. Loss of eelgrass habitat would change the species composition of the estuary resulting in a detrimental difference in community structure and function. In particular, if eelgrass habitat were lost, the estuary would likely be colonized by macroalgae species which do not provide the same habitat functions as eelgrass (Short et al., 1995; Hauxwell et al., 2003; McGlathery et al, 2007).

Excess nitrogen effects eelgrass several ways, both directly and indirectly. For direct effects, elevated nitrogen (>0.05 mg N/L as nitrate) in the water can cause eelgrass to die. This effect has been explained by the fact that eelgrass evolved in an environment where bioavailable nitrogen (nitrate) was scarce. Therefore, eelgrass will process all available nitrate for protein synthesis, which depletes carbon reserves in the plant if nitrate is plentiful (Burkholder et al., 2007). Eelgrass that grows in high nitrogen areas is also more susceptible to wasting disease because too much of the available nitrogen and carbon is converted to proteins instead of anti-microbial compounds (Burkholder et al., 2007).

The most common indirect effect of nitrogen is decreased light availability because eelgrass requires a *minimum* of 22% of incident light for established plants to survive (EPA, 2003; Steward et al., 2005). Higher percentages of incident light are required for plant reproduction (Ochieng et al., 2010). Increasing nitrogen inputs to nitrogen-limited environments, such as estuaries (Howarth and Marino, 2006) stimulates primary productivity in the form of phytoplankton, epiphytes (algae that grows on plants), and rooted or free-floating macroalgae. The increased phytoplankton in the water column, epiphytes on eelgrass leaves, and mats of macroalgae in eelgrass beds result in too little light getting to the eelgrass plants, resulting in die off (Short et al., 1995; Hauxwell et al., 2001; Hauxwell et al., 2003; McGlathery et al., 2007, Burkholder et al. 2007). Macroalgae have lower light requirements for survival than eelgrass and thrive in high nitrogen environments (Fox et al., 2008). As eelgrass plants die, sediment from areas formerly stabilized by eelgrass is typically re-suspended by wave action or currents. The suspended sediments further decrease light availability and eliminate more eelgrass habitat in a negative feedback cycle (Burkholder et al., 2007).

## Cause and Effect Relationships for Nitrogen Documented in the Great Bay Estuary

### *Dissolved Oxygen*

Low dissolved oxygen has been measured in the Great Bay Estuary. In the tidal rivers where nitrogen concentrations are highest, dissolved oxygen concentrations are frequently lower than state water quality standards (PREP, 2009). Primary productivity in the estuary is the reason for the oxygen depletion because high frequency measurements of dissolved oxygen have documented diurnal swings from super-saturation to depletion which are indicative of *in-situ* photosynthesis and respiration (see Figure 1 for an example). Dissolved oxygen concentrations typically meet standards in the larger bays and harbors where nitrogen concentrations are lower.

### *Eelgrass*

In the Great Bay Estuary, eelgrass habitat has been declining since the mid-1990s. Slightly more than half of all the eelgrass present in 1996 still remains (DES, 2009b). The loss of eelgrass is the result of increased nitrogen through both direct and indirect effects. Average concentrations of dissolved inorganic nitrogen in the Great Bay have increased by 44% between 1974-1981 and 2001-2008 (PREP, 2009). In 2008, average nitrate concentrations in the estuary ranged from 0.069 mg N/L at the mouth of the estuary to 0.165 mg N/L in the tidal rivers. These concentrations were higher than the threshold for disruption of eelgrass protein synthesis (0.05 mg N/L of nitrate). Increased primary productivity in the estuary has been documented through rising phytoplankton populations (PREP, 2009) and the proliferation of macroalgae (Pe'eri et al., 2008). In fact, macroalgae has overgrown nearly 6% of the former eelgrass habitat in Great Bay (Pe'eri et al., 2008). When macroalgae forms dense mats on the sediment surface, it can prevent the re-establishment of eelgrass in these areas (Short and Burdick, 1996). Eelgrass has completely disappeared from the tidal rivers where nitrogen concentrations are the highest. The remaining eelgrass meadows in Great Bay, Little Harbor, and Portsmouth Harbor are all in decline (DES, 2009b).

As expected, suspended sediment concentrations in the estuary have increased as a result of the eelgrass loss. Figure 2 shows that suspended solids concentrations spiked in 1990-1992 following a period when eelgrass died off due to wasting disease. In the years following, the eelgrass population rebounded and the suspended solids concentrations returned to normal levels. Later, after the eelgrass populations in the Great Bay had been declining for several years, the suspended solids concentrations again became elevated. This pattern of increasing suspended solids concentrations following eelgrass loss is a negative feedback cycle that has been documented in the scientific literature (Burkholder et al., 2007). The increased turbidity from destabilized sediments further decreases light availability for the eelgrass.

Oysters are an important species for the estuary because of their ability to filter the water to remove solids. Oyster populations in the Great Bay Estuary in the 1990s were already a vestige of their former state (Jackson, 1944). Between 1993 and 2000, the adult oyster population fell by 95% (PREP, 2009). It has been hypothesized that the loss of the remaining oysters caused suspended solids concentrations to increase. However, the water quality data indicate that suspended solids concentrations did not change very much during the period when the remaining oysters died off (Figure 2). Therefore, it appears that the oyster populations present in the Great Bay Estuary in the 1990s were not large enough to have a significant impact on water quality.

## Summary

Two of the most common, and important, effects of excess nitrogen on estuaries are low dissolved oxygen and loss of eelgrass habitat. The mechanistic pathways by which nitrogen causes or contributes to these endpoints have been well established in the scientific literature. Both of these effects have been observed in the Great Bay Estuary. All available data from the Great Bay Estuary are consistent with excess nitrogen as the primary cause of these effects.

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Figure 1: Example of diurnal swings of dissolved oxygen saturation measured in the tidal portion of the Squamscott Rivers using an in-situ datasonde

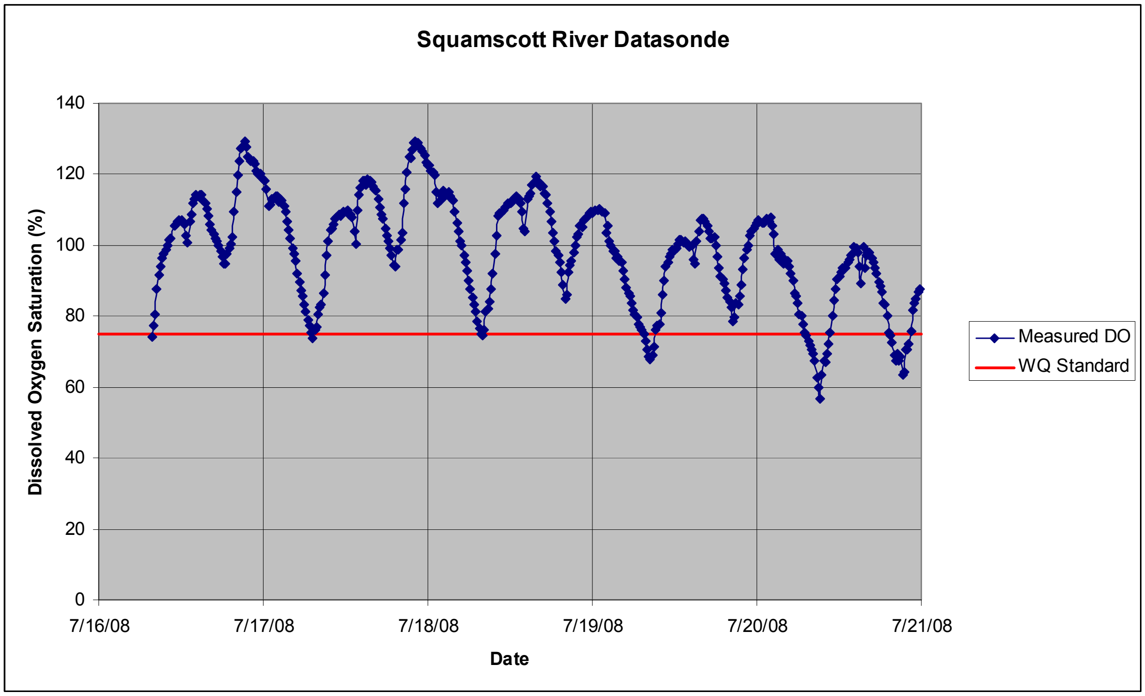
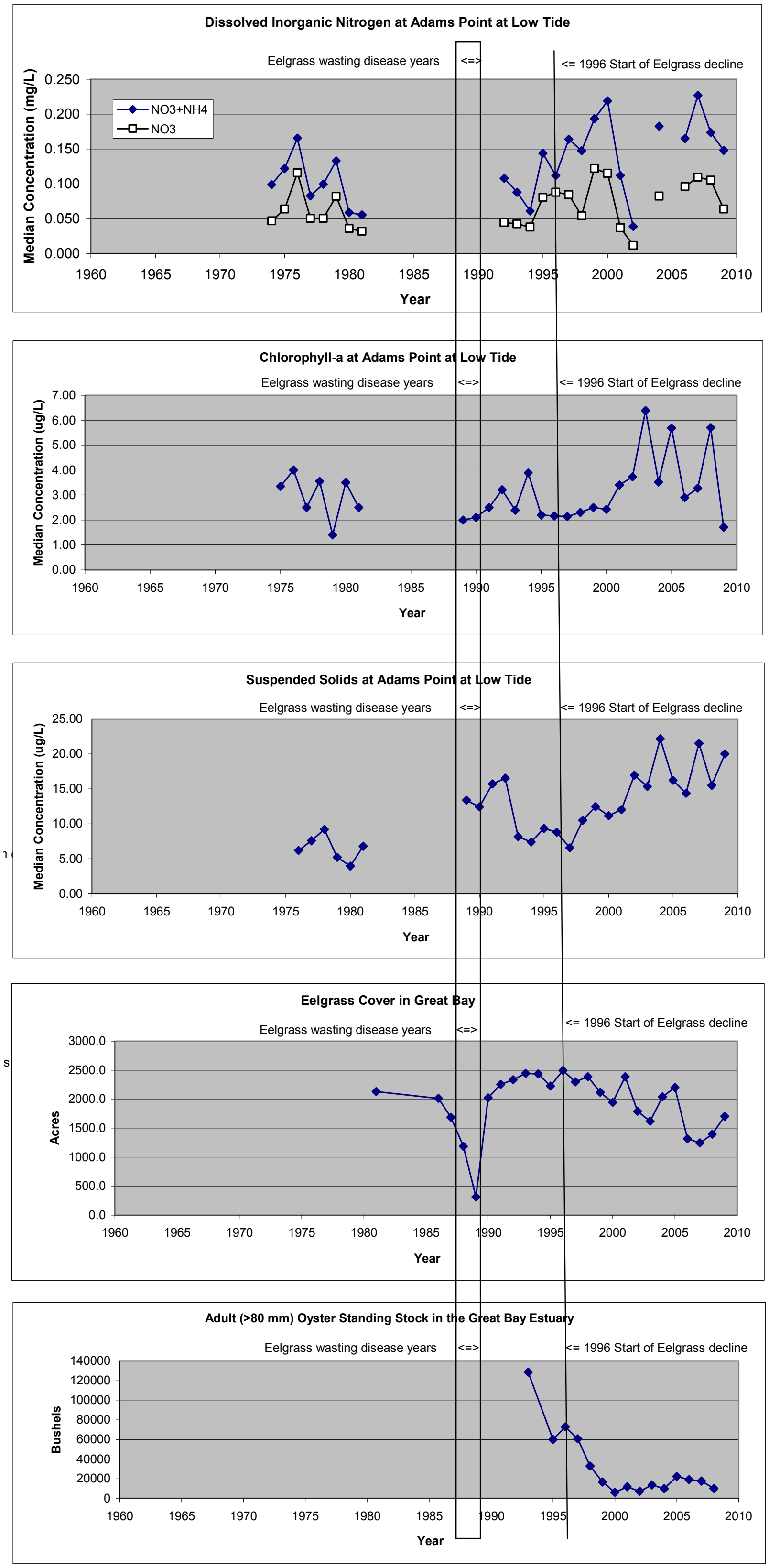


Figure 2: Long-term time series of water quality, eelgrass, and oysters in Great Bay.



Notes for Figure 2: Water quality is represented by annual median values measured at low tide at Adams Point. Annual median concentrations were only calculated for years with more than six measurements. Eelgrass cover is only for the Great Bay. Oyster standing stock includes all major beds in the Great Bay Estuary.

# Appendix C: Peer Review of Numeric Nutrient Criteria

## Introduction

In early 2010, DES initiated a technical peer review of the numeric nutrient criteria that have been proposed for the Great Bay Estuary. The purpose of the review was to provide independent technical assessment of the proposed criteria by national experts through the EPA's Nutrient Scientific Technical Exchange Partnership and Support (N-STEPS) program. The process was administered by the environmental engineering consulting firm Tetra Tech and the reviews were conducted by scientists at Cornell University and the University of Maryland.

## Peer Review Results

EPA transmitted the results of the review to DES on June 29, 2010. The reviewers found that the numeric nutrient criteria were clearly explained and well supported by the scientific literature and reasoning. They noted that there is a large amount of water quality data that for the Great Bay Estuary and these data were well used in the report. Finally, the reviewers praised the use of multiple lines of evidence to develop the criteria as a way to enhance confidence in the results.

The reviews concluded with assessments of the nutrient criteria in terms of transparency, defensibility, reproducibility, and protectiveness of the resource. Transparency refers to how clearly and completely the data and analyses in the report were explained. Defensibility relates to how well the conclusions of the report were justified by data and the scientific literature. Reproducibility describes whether someone else could re-create the analyses and graphs and come to the same conclusion. Finally, the reviewers were asked to remark on whether the numeric nutrient criteria were likely to be protective of natural resources in the Great Bay Estuary. For all four subjects, the reviewers gave the DES report favorable reviews. In summary, the reviewers validated the scientific methods and decision-making used by DES to develop the numeric nutrient criteria.

While the reviewers supported the report, they also offered detailed comments on additional analyses that could be used to strengthen the conclusions. The most important comments related to the need to develop numeric criteria for phosphorus for the estuary and the need to develop watershed nitrogen loading models. DES is actively working on watershed nitrogen loading models and will consider developing phosphorus criteria in the future.

The full text of the reviewers comments are provided on the following pages.

**UNITED STATES ENVIRONMENTAL PROTECTION AGENCY**
**Region 1**
**5 Post Office Square, Suite 100**
**Boston, MA 02109-3912**

June 29, 2010

Harry T. Stewart, Director
NHDES Water Division
29 Hazen Drive
PO Box 95
Concord, NH 03302-0095

RE: Transmittal of Independent Peer Review of Nutrient Criteria Proposal for Great Bay Estuary

Dear Mr. Stewart:

In March 2010, the Environmental Protection Agency (EPA) initiated an independent peer review of a nutrient criteria proposal for Great Bay Estuary (Great Bay) developed by the State of New Hampshire Department of Environmental Services (NHDES). The peer review process was administered by the environmental engineering consulting firm Tetra Tech through the Nutrient Scientific Technical Exchange Partnership and Support (N-Steps) program. N-Steps is a partnership among academic, state and federal agencies to provide technical support to state and tribal agencies for the development of nutrient criteria. On June 2, 2010, the peer review process was completed. Attachments A and B to this letter are the final peer reviews from the N-Steps expert reviewers.

EPA considers this a significant step, among many underway, toward addressing cultural eutrophication in Great Bay. Nationally, excess nutrients are a major source of impaired waters which adversely impact both human health and aquatic life. The development and adoption of numeric nutrient criteria is a key step toward restoring and protecting water quality in the United States. The peer reviewed nutrient criteria proposal is among the materials EPA will consider when developing controls to limit the discharge of nutrients into Great Bay.

Among other things, the reviewers found that the Great Bay nutrient criteria proposal is well explained and well supported by appropriate literature and reasoning. They also noted that there is a large amount of water quality data pertaining to Great Bay and it was well used in the report. Finally, the reviewers noted the multiple analyses used in this work provides enhanced confidence in the results, which is a good approach in systems as complicated and variable as estuaries.

The purpose of the peer review was to support the state by providing advice from national experts on how to improve the technical and scientific soundness of the document as a basis for future development of numeric nutrient water quality criteria. It was not intended to finally or comprehensively resolve the many complex issues concerning the development of nutrient criteria and the implementation of nutrient controls for Great Bay. There will be additional opportunities to submit scientific, technical, legal, and policy comment on all dimensions of the proposed nutrient criteria, and any future nutrient controls based on these criteria, in other regulatory forums (e.g., the State's criteria development/approval process and the National Pollution Discharge Elimination System permit issuance process). EPA expects this engagement with the regulated community and other stakeholders to be productive and to ultimately improve the quality of its decision making. In the interim, EPA appreciates the effort by N-Steps to provide a detailed review of New Hampshire's nutrient criteria proposal for Great Bay and welcomes their recommendations for deriving numeric nutrient criteria with a sound scientific basis.

We commend you and your staff for providing excellent leadership in the area of estuarine nutrient criteria development. Please contact Stephen Silva (617-918-1561) or Ellen Weitzler (617-918-1582) if you have any questions.

Sincerely,

Stephen S. Perkins, Director
Office of Ecosystem Protection

cc: Paul Currier, NHDES
Phil Trowbridge, NHDES

# ATTACHMENT A

# Review of "Numeric Nutrient Criteria for the Great Bay Estuary"

Robert W. Howarth
Cornell University, Ithaca, New York

June 2, 2010

# Review of "Numeric Nutrient Criteria for the Great Bay Estuary"

Robert W. Howarth
Cornell University, Ithaca, NY 14853

June 2, 2010

The Great Bay nutrient criteria report was a joy to read and provides an excellent basis for protecting this estuarine ecosystem from nutrient pollution. While many states have narrative nutrient criteria, very few have addressed the difficult challenge of establishing numeric criteria. I applaud the State of New Hampshire for providing some excellent leadership in this area.

The reliance on a weight-of-evidence approach, using several approaches and sources of information, is a strong point of the report. Of the approaches analyzed, some worked better than others. For example, the use of the health of the benthic invertebrate community proved problematic, while relating eelgrass habitat suitability to nitrogen through a relationship to water clarity and penetration worked very well. Similarly, the use of continuous oxygen data proved much more useful for setting nitrogen criteria than did the use of spot sampling for oxygen. The Great Bay report did a beautiful job of explaining the rationale behind each of the approaches tested, as well as in explaining the reasons for using some over others in setting numeric nitrogen criteria. I agree with the report's use of low dissolved oxygen and loss of eelgrass habitat as the two most sensitive and appropriate approaches for setting numeric criteria.

Assumptions in the Great Bay report are well explained and generally well supported by appropriate literature and reasoning. The Great Bay estuary is surprisingly rich in data on nutrient concentrations, dissolved oxygen concentrations, chlorophyll levels, and distribution of seagrasses and macro-algae, and these data were well used in this report.

The Great Bay report takes the approach of setting concentration-based criteria for nutrients rather than using a load-based approach. I found this surprising, as much of the effort in many other estuaries and coastal systems (Chesapeake Bay, Long Island Sound, the Northern Gulf of Mexico hypoxic zone) use a load-based approach (although as noted in the report, the State of Massachusetts has developed a concentration-based approach for protecting estuaries). The NRC (2000) Clean Coastal Waters report stressed the use of loading-based approaches, and specifically warned against using approaches based on inorganic nutrient concentrations; we did this because of inorganic nitrogen concentrations are often low in the most nitrogen-impaired coastal ecosystems, due to the high level of uptake by phytoplankton and other primary producers. The NRC (2000) Clean Coastal Waters report did not consider the use of concentration-based criteria based on total nitrogen, in part because we were aware of no locations where such an approach had been developed and tested.

The Great Bay report has convinced me that the concentration-based approach for setting criteria based on total nitrogen can be powerful and protective. Still, I would have liked to have seen some analysis of how a load-based approach might work in the Great Bay ecosystem. Had the load-based approach also been tested, the authors of the Great Bay report may well have demonstrated that the total-nitrogen concentration approach was more powerful and protective (given the demonstrated strength of that approach, as developed in the report). But we cannot be sure without having seen the load-based approach as well. I would caution other states against using the concentration-based approach without also considering load-based approaches.

The criteria approach developed in the Great Bay report lends itself well to adaptive management. That is, the State of New Hampshire can monitor over time both the concentrations of total nitrogen and the identified sensitive response variables (oxygen concentrations, chlorophyll levels, water clarity and light transmission, and seagrass distribution.), and re-assess the protectiveness of the nutrient criteria periodically into the future. I strongly urge the State to develop a strategy to implement such an adaptive management program for the Great Bay estuary.

While the Great Bay report is well written and extremely well argued, I believe the report would benefit from a stronger executive summary. The lead author of the report, Philip Trowbridge, gave an excellent summary of the report in an oral presentation at the biennial meeting of the Coastal & Estuarine Research Federation in Portland, Oregon, last fall. Perhaps he could use the outline of that talk in revising the executive summary of the report.

## Specific Comments on the Report:

1.) When below the limit of detection, data were reported as being at the level of detection, and used in averaging, etc. (page 4). This introduces a slight bias towards higher average concentrations estimated for both total nitrogen and dissolved oxygen, and is therefore not the most conservative approach. I suggest reporting these data as a range, using both zero and the limit of detection. I suspect this assumption is unlikely to affect conclusions in any significant manner, though.

2.) The report assumes that phytoplankton biomass is composed of 50% carbon by weight and 6% nitrogen (page 5). This gives a molar C:N ratio of 9.7, which is fairly high. I think using a lower value for carbon might be more reasonable, perhaps 42 to 45%. I would also suggest a higher value for nitrogen, perhaps 7.5%. This would give a molar C:N ratio that is consistent with the Redfield ratio (approximately 6.8 for C:N). Using total particulate matter concentrations of nitrogen to infer the nitrogen content in living phytoplankton (as the report does) is problematic, as much of the particulate matter is non-living detritus, probably derived from terrestrial sources and seagrasses as well as from phytoplankton. The conclusions of the report are undoubtedly very insensitive to these assumptions, however.

3.) Similarly, the report assumes a phosphorus content of 1.3% of the weight of phytoplankton, based on measurements of phosphorus in the total particulate matter in the estuary (page 6). This is not justified, and I would suggest using a value more in line with the Redfield ratio (15:1 by moles, so 1.1% phosphorus by weight if one assumes 7.5% nitrogen by weight).

4.) The report uses the molar N:P ratio both for total nitrogen and phosphorus and for inorganic nitrogen and phosphorus to make inferences about nitrogen vs. phosphorus limitation (pages 6 and 28). For justification, the report cites NRC (2000) and Howarth & Marino (2006). These two sources refer specifically to the N:P ratio of biologically available nitrogen and phosphorus, indicating that the ratio of dissolved inorganic nutrients often reflects this availability. NRC (2000) and Howarth & Marino (2006) did not recommend using the N:P ratio of <u>total</u> nitrogen and phosphorus, in part because coastal ecosystems often have relatively high concentrations of recalcitrant organic nitrogen (compared to organic phosphorus, which is recycled more rapidly). I suggest emphasizing the inorganic N:P ratio in the Great Bay report. See Figure 11 on page 29.

5.) The report assumes that total nitrogen in the Gulf of Maine is not changing much over time (page 18). I believe this is assumption is fine, and the report need not worry overly or be defensive about the increased nitrogen load from land having a major influence on the Gulf of Maine in that regard. In general, the inputs and concentration of total nitrogen on the continental shelf off the northeastern US are dominated by inputs of deep North Atlantic water (Boyer, E. W., and R. W. Howarth. 2008. Nitrogen fluxes from rivers to the coastal oceans. Pages 1565-1587 in D. Capone, D. A. Bronk, M. R. Mulholland & E. J. Carpenter (eds.), Nitrogen in the Marine Environment, 2nd Edition, Elsevier, Oxford.). This would probably be particularly true in the Gulf of Maine.

6.) The relationship between total nitrogen and chlorophyll is very strong (page 30), and provides a robust approach for setting a total nitrogen criteria. The report is correct in arguing that the relationship between inorganic nitrogen and chlorophyll should be less strong, due to the large amount of inorganic nitrogen taken up by primary producers. The relationship is nonetheless strong.

7.) The report makes a convincing case that eelgrass has declined significantly in Great Bay since 1996, with some of the area that formerly supported eelgrass now dominated by nuisance macro-algae (page 37). This is a very disturbing trend, and points to the need to better control loss of eelgrass. The development of a total nitrogen criteria level of 0.34 to 0.38 mg N/l, based on proliferation of nuisance algae in Great Bay, seems justified (page 38). The report correctly points out the need to separately assess nitrogen criteria for eelgrass protection based on water clarity.

8.) The report concludes that benthic invertebrate data are dominated by salinity rather than by nitrogen per se (although nitrogen and salinity are correlated). This is a reasonable interpretation.

9.) The regressions between chlorophyll or nitrogen and low dissolved oxygen concentrations are striking, and as the report states, somewhat surprising for grab samples of oxygen taken at one point in time since dissolved oxygen can change dramatically over the course of a day (pages 45-50). Despite the noise in these relationships, it would be tempting to use them to set a nitrogen criteria level, if the more robust continuous oxygen data from the sonde deployments were not available. I agree with the report's use of these datasonde data to set the standard, which seems robust (pages 51-52).

10.) The section on light transmisivity and eelgrasses is very well done, and the correlation between total nitrogen and turbidity (page 65) is very striking. The nitrogen thresholds presented on page 66 appear justified.

## Charge Questions:

In writing this review, I was charged with four specific questions on the transparency, defensibility, and reproducibility of the Great Bay report, as well as an assessment as to whether or not the recommended criteria will be adequately protective. I address each of these briefly below.

*Transparency:* The Great Bay report does an excellent job of stating their assumptions and explaining their analytical approaches, and the limitations of these approaches. The data behind the report are also available on line. This is among the most transparent assessment reports I have seen, and I applaud the authors for this.

*Defensibility:* The report uses data from a variety of sampling studies, and uses a weight of evidence approach in the assessment of these data. For the most part, the sampling and analytical methods behind these data seem straightforward and are consistent with commonly used and accepted approaches. Importantly, the report does a nice job of stating how the nutrient data were used (ie, in estimating total nitrogen and specific nitrogen pools). As most of the data come from government monitoring programs, it seems likely that QA/QC processes were used. However, the report does not document this. A brief discussion on QA/QC issues, perhaps with reference to appropriate web sites where more information is available, would be very useful.

The report did an excellent job of stating the designated uses of Great Bay and in explaining how those uses could be protected from the nutrient criteria proposed.

*Reproducibility:* I did not attempt to independently verify the many analyses that are included in the report. However, for the most part these analyses are straightforward, and appear reasonable and well done. Further, the data behind the analyses are available on line, allowing any one to further test the analyses, including making changes in assumptions and approaches. This is very important, and adds greatly to the credibility of the Great Bay nutrient criteria report.

*Protective:* The proposed nutrient criteria seem quite protective of the designated uses of the Great Bay estuarine system. The criteria could be made even more protective if they are used in the context of adaptive management. The State of New Hampshire should be encouraged to continue to monitor both total nitrogen concentrations and the response of sensitive indicators (dissolved oxygen, chlorophyll, light penetration, water clarity, and eelgrass and macro-algal distributions). These monitoring data should feed into a periodic re-assessment of the nutrient criteria, and the criteria adjusted downward if necessary to protect designated uses of the Great Bay estuary.

# ATTACHMENT B

## Review of "Numeric Nutrient Criteria for the Great Bay Estuary"

Walter R. Boynton

University of Maryland, Solomons, Maryland

May 29, 2010

Dr. Michael Paul
Senior Scientist
Center for Ecological Sciences
Tetra Tech, Complex World, Clear Solutions
400 Red Brook Blvd.
Owings Mills, MD 21117

29 May, 2010

Dear Dr. Paul,

I have completed a review of the document entitled "Numeric Nutrient Criteria for the Great Bay Estuary" produced by Phillip Trowbridge, P. E. of the New Hampshire Department of Environmental Services. I apologize for being a few days late in completing this task.

My review consists of three parts and these include a series of overview comments, page by page questions/comments and summary responses to the questions posed in your letter of instruction to me (transparency, defensibility, reproducibility and protective).

***Overview Comments***:

The author makes clear at the start that the development of the TN criteria uses a weight of evidence approach. Given the "state of the art" in estuarine science I think this is a very reasonable approach. In addition, the author used multiple analyses in many portions of this work and that provides enhanced confidence in the results. Simply said, this is a good approach to use in systems as complicated and variable as estuaries.

The analysis is very empirical. That is, it is based on local measurements…quite a pile of local measurements made at many sites during a 9 year period. In addition, there is good reference to the appropriate scientific literature and to adjacent estuarine areas. I think this was a well-grounded analysis.

No complex model was used in this analysis and this adds to the transparency and reproducibility of this work. The approach adopted in this work is far less expensive, less time consuming, easier to verify, easier for the informed public to understand and more readily adjusted as understanding improves. Having said all that, we need to remember that water quality models can do some things that regression analysis can not do or is very limited in capability (e.g., forecasting, exploring for temporal and spatial sensitivities, coping with co-correlated variables).

I was very pleased to see that a conceptual model was used to guide the development of these analyses. What I mean here is that there was a mechanistic basis for the variables used in these analyses. The author used many water quality measurements to develop regression models between TN and chlorophyll-a, DO and water clarity. In addition, continuous monitors were used to estimate DO impairments and finally, relationships between water quality and water clarity were quantified based on light attenuation measurements via in-situ sensors and hyperspectral imagery. All solid approaches.

Specific water quality thresholds were developed for DO (>5 mg/l or > 75% saturation) annual median TN =< 0.45 mg/l and the 90th percentile chlorophyll-a =< 10 ug/l. For protection of SAV annual median TN =< 0.25-0.30 mg/l. There was detailed discussion supporting each of these conclusions.

There is a strong conclusion that N was the limiting nutrient and the only one of consequence. I think they should do a bit more on this issue. I think they are correct but they do not have definitive evidence and they do indicate (correctly I think) that P is important in lakes and rivers. Using N:P ratios really only indicate the potential for nutrient limitation. A single nutrient strategy could be a risk road to take. I do note the author indicated nutrient criteria will be developed for NH rivers and lakes and P will likely be prominent in those analyses. I made a few detailed comments regarding this later in my review. Finally, a word about a risk of a single nutrient strategy. There have been several instances now recorded where P was controlled in the rivers or freshwater portions of estuarine systems (Neuse River, NC and in a Swedish fjord…there may be others). Following P reductions there was a positive response in the freshwater zone but deterioration in the more saline zones. It seems like a portion of the N that had been sequestered in the river now passed through to the estuary and caused increased issues in the N-limited zone. So, as we all know, these systems are linked and thus a duel nutrient strategy is worth thinking about. I should note that it is clear the author is thinking about this issue.

***Detailed Questions/Comments:***

Pg 2 indicate that nutrient thresholds developed for DO, SAV and benthic invertebrates. Bentos not mentioned in Exec Summary and it should be mentioned if a threshold was developed. Are there no bacterial issues in this estuarine complex? If so, indicate this and any other issues that did not need threshold development

Pg 3. I had expected to see an effort to relate TN concentrations to TN loads to the estuary from the surrounding basin. But, that was not the case. I was surprised and immediately wondered how they will regulate TN concentrations. All this is explained later but it would have been helpful to get this straight at the beginning of the document

Pg 3 I think there needs to be more discussion about the use of median values in assessment zones. I know the authors cited the work of Li et al (2008) but I still feel that the justification was not as strong as it could be…I basically think it opens a strong assessment to attack. In other estuaries (e.g., Ches Bay and others) investigators have found strong relationships using seasonal or annual average values. I think the authors would be well-served by beefing up this section (or doing so in some other section of this report).

Pg 4 Use of a 9 year data set is a strong point in this work as such a temporal record is more likely to capture scales of variability typical of estuarine systems. However, in tables presented later it is also clear that any statements about a nine year effort with monthly sampling is somewhat misleading. If all months were sampled then there would be 108 observations at each sampling site. There are of course many good reasons for not getting a sample for ALL months. But, some sites were not sampled very frequently. This is just a word of caution from a reviewer.

Pg 5 …"some aspects of nutrient cycling". The grab samples of concentrations tell us very little about nutrient cycling. Generally, rate measurements are needed to get serious insights concerning nutrient cycling…just re-write this sentence.

Pg 5 Is there a Table showing nutrient (and other variable) detection limits?

Pg 5 last para. Clarify the 5%, 50% and 6% sentence. What biomass is being referred to here? Is this water column POC? I'm not at all sure doing this (despite EPA guidance) is worthwhile. These ratios really vary widely in my experience. Whatever is decided, this is a weak approach and not much should be inferred from these results.

Pg 6. I have several comments regarding the use of nutrient ratios for determining nutrient limitation. The main point is that these really just indicate POTENTIAL for limitation. For example, a molar-based N:P ratio of 5 would indicate the potential for N limitation. However, if N concentrations were high ( much greater than Ks values) then there would not be much in the way of N limitation at all. So, I'm suggesting a word of caution here. Nothing has been strongly demonstrated with nutrient rations (although I think the author is correct). If they have the ability and resources I'd suggest a bioassay approach as reported by Fisher et al a few years back in Estuaries. That strengthens conclusions. To go another step, large-scale mesocosms can be used as reported by D'Elia et al some years ago, also in Estuaries I think. I'd also recommend the author examine papers by Walter Dodds(or Dodd) who examined this concept in some detail and generated some practical suggestions about the use and abuse of the N:P ratio concept.

Pg.7 There are 22 assessment zones but there are only 14 labeled in Figure 1. Clarify this.

Pg 9. Critical for what? Clarify

Pg 10. I know very little about the use of hyperspectral imagery so I have no comment. But, the tone of this section indicates there is some debate about this approach and the data generated. So, I trust someone who is better equiped than I am to provide some useful comment.

Pg. 11. ..."not likely to have changed during a matter of weeks" Are you sure? That has not been my experience. I think days to weeks (as in two weeks) is a safe statement. How many weeks are you really indicating? Be more specific here.

Pgs 11-12. well done...no comment

Pg. 14 Why compute the daily average % saturation when the sondes provide the actual extent of DO variability, including a minimum?

Pg 15. Re-write last 5 sentences in last paragraph on Pg 15...not clear to me what you are doing here.

Pg. 16. Excellent summary of the "weight of evidence" approach. Nice!

Pg. 17 Adams Point not identified in Fig 1. Note also that the seasonal pattern of nutrient concentrations seen here are also observed in many other estuarine systems.

Pg 18. Very good discussion of off-shore TN concentration. A clear and reasonable discussion.

Pg 19. Why not use Box and Whisker plots. They are not difficult to construct and contain a lot more information.

Pg. 20. Nice visual diagram. However, it does indicate that sampling was not as intense as generally suggested. There are lots of sites where < 10 measurements were made during a 9 year period.

Pg. 23. Suggest that Ks values (nutrient concentration when growth rate is half of the max) be added to this graph or at least to the text. There are plenty of Ks values in the literature so a range of values could be presented for NH4, NO3 and PO4.

Pg 25. One issue missing in this report is any indication of inter-annual variability in key variables. For example, what is the concentration difference in NO3 between wet and dry years? How do wet year concentrations compare to the threshold values? Are dry year values much lower or only slightly lower? It seems like there are enough sites sampled frequently enough for an analysis of this issue. And, this wet dry issue does play into TMDLs in general.

Pg. 28. First paragraph. I agree in general. But, P can and does play a role in some estuaries. See for example work by Fisher mentioned earlier for Chesapeake Bay. His findings (and those of others) helped the Bay Program to adopt a duel nutrient strategy. In the northern GoM, very high N additions have apparently induced P-limitation in portions of the Mississippi River plume (see Ammerman's work). Again, author should use the term "potential for nutrient limitation" in this paragraph. Finally, if TN:TP ratios cluster about 16 (like phytoplankton) why do the other ratio techniques discussed earlier indicate that phytoplankton constitute such a small fraction of the POC? Something wrong here I think.

Pg. 30. 1st Para. Adequate water clarity…add also sufficiently long water residence time and modest grazing pressure

3rd para add the p values as well as r2 values

4th para Is there any other line of evidence that indicates phytoplankton are such a small fraction of TN. This seems to me to be a very small percentage. There seemed to be some large diel swings in DO and that would indicate a substantial autotrophic component…very little of this is phytoplankton? Heck, there are phytoplankton blooms!

Pg 31 last para delete word "proves". In this game we "prove" nothing! Pick a different word (strongly suggests….clearly indicates)

Pg 32. Relative to many estuaries these are low concentrations. My eyeball estimate is that an area-weighted system wide average would be about 2.5 ug/l…not much chlorophyll. You might make a stronger point of this because there is not much further reduction reasonably possible. There are estuaries with chlorophyll concentrations >200 ug/l and in those cases huge reductions are possible and warranted. Also, why not box and whisker plots for fig 13. Finally, why are the median chlorophyll values in Fig 16 much higher than the 90th percentile values in Fig. 13? Please get this clarified.

Pg 34 First, nice figure! Is the water residence time also longer (along with proximity to nutrient loads) in the upper tributaries….that's where the problem areas seem to be located? Please make this point if that is the case.

Pg 35. General comment. The figure and table legends are very brief. It would have been helpful to have more detailed legends. For example, in Fig 15, what are the time and space scales included in this regression model set? Its really helpful to have the figure + legend tell a story without having to go back into the text. Of course, you can't put the whole text in each legend but these legends are very brief…too brief in my opinion.

Pg 36. Has any analysis been done on the residuals in the regression model shown in Figure 17. Such an approach has been useful to many other researchers. The residuals themselves might suggest another important variable. This is a very central analysis presented in this figure and explanations for the remaining variability would be useful (water residence time, water clarity, depth, all may play a role). Finally, have these sites really been used for trends…or are they really sentinel or long-term stations?

Pg 37 Might be useful to cite a few more Valiella papers to support this contention…I see there is one.

Pg 38. Why was a margin of safety of 10-20% selected? Why not 5% or 25%. Preventing the loss of SAV and preventing the proliferation of macroalgae is of prime importance. This statement deserves a bit more discussion and justification. Here the issue of wet and dry years and the effect this has on TN loads and concentrations comes into play.

Pg 39. This is a great visual diagram. Several comments: 1) there has been a very large reduction in eelgrass in a single decade. The text does not seem to make this point strongly enough…this system is really changing; 2) can depth contours be shown so it is clearer just where eelgtass can and can not grow; 3) can any indication of SAV density be shown (using shades of red, for example)?

Pg 40. 130 station visits…does this mean 130 sediment samples were collected? Be clear on this.

Pg 41. Dump the "proved" stuff. Use another word.

Pg 42 Both analyses seem reasonable. Why not test B-IBI relationships to DO, SAV or some other variables that make sense. Even if such analyses do not directly relate to N criteria they do show some significant understanding of how the system operates.

Pg 43. Fig 21. Is the very low values (strong departure from the pattern) a hack or is there something else going on. If something else, explain in the legend.

Pg 45 Third paragraph…good discussion. This is observed elsewhere as well.

Pg 45 last paragraph. Not much certainty here. But, good idea. Can more data be brought to this analysis?

Pg 46 last sentence. I agree. Lots of samples help and a big range in conditions certainly helps. They used a within system comparative approach which was very useful and surely helped in seeing these relationship emerge.

Pg 49 Same comment as for Fig 16…examine the residuals. Or, would it be useful to "scale" the x variable as done in the Vollenweider regression analyses (perhaps for water residence time or depth). Stronger relationships certainly give managers and politicos more guts to do what needs to be done.

Pg 50. All relationships are weak…I agree with the text.

Pg 51. Last paragraph…I agree…good point.

Pg 52 last paragraph. SOD is exerted in all sediments, not just in the Lamprey River. A basin prone to stratification probably should be treated as a special circumstance and not representative of the system. There are, for example, deep portions of Chesapeake Bay that will likely remain hypoxic even if (a big if) all proposed nutrient reductions are successful. Figure 31 shows there are some significant DO issues in the tributary rivers.

Pg 55-67. This is a good discussion/analysis of a difficult issue. I liked the approach which came at the problem from several different angles. Is it useful to use the Chesapeake Bay 22% light transmission value in a more northern estuary with far cooler water temperature? Is there guidance from a more similar system (Narragansett Bay?).

***Basic Review Questions:*** I was favorably impressed by this analysis and should appropriate actions be taken to meet these nutrient criteria, good things are likely to happen.

***Transparency:*** I think they did a solid job on this. The methods section seems complete. They walked the reader through the conceptual model, made it clear that this was a weight of evidence approach (versus some other approach), used a variety of methods to reach conclusions and were frank about the lower limits of TN concentrations (i.e., not reasonable to get lower than the inflowing ocean water). I have made a few suggestions for increased clarity

***Defensibility:*** We all know that just about any analysis can be challenged and criticized and this one is no different. However, I find the approach, methods and analyses used to reach conclusions solid. This was an empirical analysis and there is a lot to say for that approach since the values reported were actually measured (repeatedly) in the estuary in question. Analytical methods seemed fine. I caught some defensiveness regarding the hyperspectral work and indicated that someone other than me needs to examine that aspect of this work.

The designated uses were clear to me. I did indicate that I saw no bacterial work and I was a bit surprised at that. I assume the data are there to indicate there are no bacterial issues related to contact uses.

I thought the logic related to numeric criteria development was especially clear. I favor the multiple approaches used in this analysis and I thought the author did a solid job of relating results from one analysis to other analyses and eventually to numeric TN criteria. I had expected to see a good deal of attention paid to nutrient load estimates but there were none. However, it was clear that this is the next step (or one of the next steps) in this process.

***Reproducibility:*** I believe this is true. From what I can see, someone could re-do these analyses and I think they would reach (or could reach) the same conclusions. Because a conceptual model linked to empirical analyses approach was used it is far easier to "re-run" some or all of these analyses or to update the analyses. Programs relying on coupled land-use, circulation and water quality models face a far more complex and expensive and time consuming task in this area. Some would argue that the latter approaches are never reproduced because of these issues.

***Protective:*** The basic answer to this question at this time is "who knows?" In any fundamental way, we can't be sure. But, in a practical fashion, there are strong arguments here that the suggested levels will be protective and, as I read the document, if achieved would favor improved habitat conditions relative to the benthos, eelgrass communities and DO conditions. Furthermore, the author took the point of view that if these criteria are achieved and the system does not fully respond as expected, then additional steps for further reductions in TN concentrations will be taken. He makes the same argument for phosphorus (i.e., if P appears to be a player in all this then P controls in tidal waters will need to be developed).