EXECUTIVE SUMMARY

Barnegat Bay-Little Egg Harbor (BB-LEH) Estuary is a shallow, poorly flushed coastal lagoon affected by multiple anthropogenic stressors and drivers of change from an expanding human population in the adjoining coastal watershed. These factors make it particularly susceptible to nutrient enrichment and other water quality problems. Land use-land cover in the BB-LEH Watershed has changed rapidly over the past three decades, and is currently more than 30% urban. Impervious cover in the BB-LEH Watershed is currently greater than 10%, and it will exceed 12% when all available land is developed. Such changes in land use have been shown to change hydrologic dynamics by increasing the percentage of impervious surface, resulting in decreases in recharge, increases in runoff, and more extreme hydrologic peaks and low-flow events in streams. Conversion of undeveloped land to urban land use is also associated with greater concentrations and loads of nutrients (nitrogen and phosphorus nutrient species) to area creeks, streams, rivers, and the main body of the estuary.

BB-LEH is a highly eutrophic estuary. Eutrophication is defined as the process of nutrient enrichment and increase in the rate of organic matter input in a waterbody leading to an array of cascading changes in ecosystem structure and function such as decreased dissolved oxygen levels, increased microalgal and macroalgal abundance, occurrence of harmful algal blooms (HABs), loss of seagrass habitat, reduced biodiversity, declining fisheries, imbalanced food webs, altered biogeochemical cycling, and diminished ecosystem services.

Nutrient loading from the watershed is an important driver of biotic change in the estuary. It can cause significant shifts in primary production and plant biomass, as well as changes in the composition of autotrophs, including microalgae, macroalgae, and rooted macrophyte assemblages that modulate higher-trophic-level dynamics. Thus, the effects of altered bottom-up controls on the biotic structure and function of the system can be far reaching. Nutrient enrichment and resulting eutrophic impacts pose serious threats to the estuary because they are leading to significant ecological decline of the estuary and affecting biotic resources, essential habitats (e.g., seagrass beds), ecosystem services, and human uses. These and other effects of urbanization will continue to increase with increasing development and alteration of the watershed, unless aggressive management actions and effective planning are implemented.

Regulatory protection and conservation of New Jersey's estuarine waters are based on dissolved oxygen (DO) measurements. Yet DO is only one indicator of ecological health, and must be monitored continuously in multiple locations for accurate assessments due to natural variations over the course of a day driven by natural processes such as changes in temperature or light, as well as community photosynthesis and respiration. Routine monitoring of DO over the years in BB-LEH, a coastal lagoon, has not been conducted frequently enough or at all necessary times and sampling stations over a 24-hour period, thereby biasing sampling results. For example, DO measurements must also be made between midnight and 6 a.m. Therefore, it is important to assess the ecological health of the estuary by examining a broader range of physicochemical and biotic indicators for effective ecosystem-based assessment and management. This project establishes appropriate biotic indicators and a framework for assessment using multiple biotic indices that will aid New Jersey in delineating environmental impacts using a broader, more relevant range of factors.

Previous assessments of BB-LEH designated the system as moderately eutrophic in the early 1990s, but later assessments reclassified it as highly eutrophic. Examples of assessments that have been applied to BB-LEH are NOAA's National Estuarine Eutrophication Assessment (NEEA) Model and Nixon's Trophic Classification. The current assessment of system eutrophication is based on degradation of eelgrass condition and other declining ecosystem measures that have continued in concert with nitrogen loading from the BB-LEH Watershed, as documented by the Index of Eutrophication developed for the estuary.

Nutrient loading has been repeatedly cited as a primary cause of ecosystem eutrophication of BB-LEH. The estimated range of annual total nitrogen loads from the watershed is 448,000 – 851,000 kg N yr-1, and the protracted water residence time in the estuary (74 days during the summer; Guo et al., 1997, 2004) facilitates nitrogen uptake by plants and nitrogen accumulation in estuarine bottom sediments which can be an important secondary nitrogen source for internal cycling. Highest nitrogen loading occurs in the north segment of the estuary due to greater development and altered land surface in northern watershed areas and the larger influent delivery systems (i.e., Toms River and Metedeconk River).

The assessment reported here documents multiple symptoms of eutrophication in the BB-LEH estuary. These include low dissolved oxygen concentrations, harmful algal blooms, heavy epiphytic loading, loss of essential habitat (eelgrass and shellfish beds), diminishing hard clam (*Mercenaria mercenaria*) abundance, and other ecosystem component shifts. Since 2004, the condition of eelgrass (*Zostera marina* L.) has declined significantly (in 2010 the lowest eelgrass biomass values were recorded for the estuary), and macroalgal blooms have occurred frequently with increased nitrogen loading from the BB-LEH Watershed. Light reductions have been linked to lower seagrass densities, slower growth rates, stunted morphology, and higher mortalities in the estuary. The loss of seagrass beds has a secondary impact on animal populations inhabiting them. The net result is diminishing ecological integrity of the system.

BB-LEH is an estuary that has undergone significant ecological decline, as evidenced by the increasing eutrophication of the central and south segments since the 1990s ($P < 0.05$) and an even worse eutrophication condition documented for the north segment. An array of biotic indicator data collected over the past two decades reflects an impacted system.

This investigation is part of a multi-year, interdisciplinary effort by Rutgers University and the USGS that characterizes and quantifies the estuary with regard to watershed nutrient inputs, physical and water quality properties, and biological indicators and responses. Extensive databases collected over the 1989-2011 timeframe have been examined in this study. Component 1 of the study involves watershed nutrient loading quantification from existing (secondary) data. In Component 2, estuarine biotic responses to stressors and the current degree of eutrophication are quantified from new and secondary data. In Component 3, biotic indices are developed, and values of the indices are computed. The current extent and validation of eutrophication are determined in Component 4. Synthesis and management recommendations are developed in Component 5.

In this investigation, all available hydrologic, water-quality, meteorological, and land-use data were compiled and used in conjunction with a watershed loading model to determine nutrient loading on several spatial scales. Total nitrogen, total phosphorus, nitrate plus nitrite, ammonia, and organic nitrogen were quantified. PLOAD, a modeling tool for calculating concentrations, loads, and yields (area-normalized loads) of stream contaminants from water-quality, hydrologic, and meteorological data, was used to quantify nutrient loading in runoff. PLOAD runoff load and yield were calibrated to flow values from historic hydrologic records. Baseflow nutrient concentrations, loads, and yields were calculated for growing and non-growing seasons of 1989-2011.

Turf has been mapped in the watershed with an approximately 90% overall accuracy. The mapping was deemed of sufficiently high accuracy to be used as input to the USGS watershed-based nutrient runoff modeling. Turf coverage highly correlated with urban land cover and nutrient loading.

The term 'eutrophic condition' refers to eutrophication condition of the waterbody. The eutrophic condition of the estuary has been well documented (Seitzinger et al., 1992, 1993, 2001; Bricker et al., 1999, 2007; and Kennish et al., 2007a, 2010). Biotic response to nutrient loading and determination of overall eutrophic condition of BB-LEH requires the use of bioindicators and bioassessment protocols in conjunction with physicochemical water quality parameters (e.g., dissolved oxygen, nutrient concentrations, and Secchi depth). This investigation of condition and status of BB-LEH, therefore, also employs multiple plant biotic indicators. Multiple quantitative measures of benthic plant parameters must be obtained for accuracy because benthic microalgae, macroalgae, and seagrass play major roles in primary production of BB-LEH, as in other mid-Atlantic coastal lagoons. Eutrophication of this coastal lagoon is closely coupled to plant-mediated nutrient cycling, and thus accurate assessment of eutrophic condition must also focus on both key pelagic and benthic autotrophic indicators.

Prior to this report, no validated, quantitative biotic index existed to assess the ecosystem health of estuarine waters of New Jersey, most notably with respect to eutrophication. Through the development and application of a comprehensive Index of Eutrophication for the coastal bays of New Jersey, this project provides a measure of eutrophic impact in BB-LEH and a method to quantify the status and trends of the system. This index identifies the condition of, and relationships between, ecosystem pressures, ecosystem state, and biotic responses. The establishment of an appropriate Index of Eutrophication for BB-LEH will aid New Jersey in delineating environmental impacts. A long-term goal, though beyond the scope of this project, is to extend this type of ecosystem assessment of the BB-LEH system to all estuarine waters of New Jersey in order to protect biotic communities, recreational and commercial fisheries, water quality, and habitats. Therefore, this valuable research initiative has far reaching implications for coastal environmental protection and human use in New Jersey and other coastal states.

The Index of Eutrophication developed for this investigation for the BB-LEH Estuary builds on previous assessments, especially the National Estuarine Eutrophication Assessment (NEEA), which the Assessment of Estuarine Trophic Status (ASSETS) Model. The methodology for this project employs a quantitative, numeric scoring system (rather than qualitative) from 0 (degraded condition) to 100 (excellent condition) for ~20 indicators (rather than 5).

Candidate indicators were selected at the outset and organized into: 1) Ecosystem Pressures, 2) Water Quality, 3) Light Availability, 4) Seagrass, 5) Harmful Algal Blooms, and 6) Benthic Invertebrates. The Water Quality, Light Availability, and Seagrass indicators comprise the 'Index of Eutrophication'. Each component includes several key indicators. Data collection often occurred at different times and / or locations, therefore annual means (or medians) for the north, central, and south estuarine segments are utilized for all calculations regarding the Index of Eutrophication. These summary data are included as an appendix to the report. Data are analyzed separately for each segment of the bay, because they have been determined to be heterogeneous habitats.

The Index of Eutrophication compares observations at all sites directly to a spectrum of reference conditions that are termed 'thresholds'. Rescaling observations into scores accomplishes several tasks. First, it enables integration of multiple variables by bringing them into a common, unitless dimension. Second, it homogenizes the variances and standardizes their ranges, thereby not making one variable more dominant than another. This practice is common in the literature. Validation of the methodology is conducted both through comparison of multiple similar methods, and through the response in 2011, as data from that year were kept separate and out of the analyses.

Thresholds are defined values. They are not a mean and have no associated error. Thresholds were set at values of indicators that indicated a change in response values – such as changes in the slope or abrupt breaks in response indicators. Thresholds are defined according to values of indicators and their relevance to biological, physiological, and ecological condition. Thresholds were defined based on thorough examination of: (a) the literature review, (b) analysis of the assembled database for calibration to BB-LEH, (c) Best Professional Judgment (in cases where a, and/or b are unavailable), and (d) some combination of a-c, in that order of priority. Best Professional Judgment was used sparingly. Best Professional Judgment was not used to determine thresholds for an indicator if the literature or data analysis provided sufficient information.

One challenge of identifying and defining thresholds is that indicators' responses were rarely starkly or drastically step-wise in function. That is, the values of thresholds are not obvious nor do indicators respond in discrete manners. Rather, ecosystems respond to various levels of stressors through continuous linear or non-linear manners with interactive effects since multiple stressors generally contribute simultaneously, in conjunction with natural processes and variability. Furthermore, many variables act as both a response and a stressor. Because ecosystems respond to stressors in complex and interactive manners, it is unrealistic to expect obvious cusps or thresholds for any given individual stressors or response variable. Nevertheless, there is a high degree of confidence in the thresholds identified in this report based on general agreement of numerous literature studies and volume of data that were analyzed.

Raw Scores are calculated according to the mathematical relationship between an indicator's threshold values and the corresponding Raw Scores. The equations are used to calculate a Raw Score by inputting observations as x values, returning Raw Scores as y values. The rescaling equations for each indicator are provided. Raw scores range from 0 (bad) to 50 (excellent). Data are sorted and summarized by central tendency by Year and Segment. Descriptive, summery statistics of Raw Scores for each dataset are calculated for each segment during each year and stored as separate files. These files include means, medians, standard deviations, minimums, and maximums of each indicator's Raw Score. Where data were unavailable in a given segment during a given year, this was recorded as 'No Data' and was excluded from analysis. For Ecosystem Pressures, data were sorted by Year, Growing Season, and Segment before applying the rescaling equation to USGS modeled annual total nitrogen loading and annual total phosphorus loading. Rescaling equations were applied to each observation of Water Quality indicator (temperature, dissolved oxygen, total nitrogen concentration, total phosphorus concentration) during April to October (inclusive). These months were selected due to the importance of potential impacts on biological and human-use activities. Rescaling equations were applied to each observation of the six Light Availability indicators after excluding observations of each indicator where data was missing. Rescaling equations are applied to each observation of the five Seagrass indicators and the single HAB indicator.

Each indicator is weighted within its component according to a weighting that is calculated by principal component analysis (PCA). PCA was conducted using the covariance matrix of Raw Scores (not the correlation matrix) summarized by Year and Segment. Summarized data from all available years across the entire estuary (or as many segments as available) are used for PCA analysis to determine weightings. Up to three data points per year are thus plotted, and multiple years of data are required for this analysis to determine weightings for each indicator. A single weighting for each indicator is applied to data from each segment. Calculating unique weightings for each segment would be statistically inappropriate and would invalidate comparisons across segments. This method causes variables with large variances to be more strongly associated with components with large eigenvalues and causes variables with small variances to be more strongly associated with components with small eigenvalues and thus requires data with comparable units or standardized values (which is done by using the Raw Scores). Scree plots are examined to identify the cumulative explanatory power of each principal component. Generally, the first principal component explains ~50-75% of the variability, and the first two principal component axes explain ~80-90% of the variability. Principal component analysis and the comparison of the multivariate axes provide a flexible framework for objectively weighting multiple components and multiple variables within each component, especially when these variables are asynchronously available, either spatially or temporally. This technique – though tangential to the main project objectives – is an important contribution to BB-LEH, and ecosystem health assessment.

PCA on the covariance matrix was conducted on the median Raw Scores for temperature, dissolved oxygen, total nitrogen and total phosphorus, but this was done separately for 1989–1998 and 1999–2010 because total phosphorus data was unavailable during the first set of years. To test the effect of total phosphorus on the overall Water Quality, PCA on the covariance matrix was similarly conducted on the second set of years, but omitting the median Raw Scores for total phosphorus (see Validation below). Note that Raw Scores for Water Quality indicators are calculated on observations during April–October, inclusive. For the Light Availability indicators, PCA on the covariance matrix was conducted on median chlorophyll a Raw Scores, median TSS Raw Scores, average Secchi depth Raw Scores, average epiphyte to seagrass biomass ratio Raw Scores, and average percent light reaching seagrass leaves Raw Scores. PCA on the covariance matrix was conducted on median Raw Scores of Seagrass shoot density and mean Raw Scores for the other four Seagrass indicators. Note that PCA is not conducted for the Ecosystem Pressures because only a single number is provided for each segment in each year from the modeled nutrient loading provided by USGS. Therefore PCA cannot be conducted and total nitrogen loading and total phosphorus loading scores are averaged (each weighted 50%). PCA cannot be applied to the HAB component because there is only one indicator (weighted 100%). Each indicator's weighting is calculated as the square of the eigenvector of the first principal component for each variable.

Weighted scores are then calculated by multiplying the raw score by the weighting. Weighted scores also range from 0 (bad) to 50 (excellent). Thus, for example, the weighted score for any of the four Water Quality indicators contributes 0–50% of the score for the Water Quality Index (the weighting for each variable ranges 0–100%, * 50% = 0–50%). Note the important difference between the weighting and the Weighted Score. The weighting is the square of the eigenvector and represents the variability of the factor if data are available in a given segment in a given year. The Weighted Score is the Raw Score multiplied by the weighting and thus represents the consistency of the condition for that indicator. Weighted scores provide a measure of the consistency of the observations with respect to thresholds for the appropriate indicator.

The sum of the raw score and the weighted score equals the index score, and thus index scores range from 0 (bad) to 100 (excellent). An index for each of the six components is calculated by summing a Raw Score and Weighted Score, each of which contributes 50% to the component index score. Thus, for example, each of the indicators in the Water Quality component contributes 12.5-62.5% of the Water Quality Index. The Water Quality, Light Availability, and Seagrass Indices for each of components with sufficient data are then averaged together for the sets of years when data are available to calculate the overall Index of Eutrophication. While ideally each index would be used as input for another PCA to calculate a weighting for each index, there was an insufficient quantity of data to do so, and equal weighting (i.e. averaging) was considered justified as an alternative. Raw, weighted, and final scores for each component and the overall Index of Eutrophication condition are calculated for each segment of the estuary for each year (1989–2010), subject to data availability. Scores for the year 2011 are calculated independently for validation.

The purpose of adding the Raw Score and the Weighted Score to arrive at the Final Score for an indicator and each component index (e.g. Water Quality Index, Light Availability Index, Seagrass Response Index) is to assess both the condition and consistency of each indicator and each index. Consistency is important to include in an Index of Eutrophication because it highlights times and places when and where conditions of each indicator are changing (either positively or negatively) so that these indicators can be targeted for attention (e.g. for monitoring, management, or research). The implications for including both the condition and the consistency of eutrophication are that this tool can help prioritize decisions regarding limited resources available for various actions. For example, if an indicator is in flux, it may be worthy of more intense monitoring, research, or remediation action. If that same indicator consistently exhibited an extreme condition (e.g. 'Excellent' or 'Highly Degraded'), discussions regarding prioritization of resources may be efficiently directed towards another indicator.

This report documents that total nitrogen concentrations vary with location, year and season, and are largely determined by land-use patterns and precipitation. As shown in previous studies of BB-LEH and other locations, nutrient loading to the estuary has increased as watershed land has been developed, and total nitrogen concentrations in the estuary are proportional to the total nitrogen loading from the watershed. Total nitrogen concentrations are not exceptionally high (generally less than 2 mg L^{-1} as N) compared to other watersheds with large amounts of agricultural land cover and/or point sources from domestic waste-treatment plants. However, all data and results of nutrient loading calculations clearly show that urban land development is responsible for nutrient levels that are elevated above background levels. In addition, long water residence times promote the accumulation of nutrients within the estuarine system.

BB-LEH is particularly sensitive, even to small amounts of nutrient loading, because of its small estuarine surface area and volume relative to the expanse of the watershed and because of its extreme enclosure by a barrier island complex. Hence, the effects of development and resulting nutrient loading to BB-LEH are much more significant than they would be for a deeper and more open estuary. An important observation is that loads and yields of nutrients from the BB-LEH Watershed are to a large degree controlled by precipitation totals. Although nutrient concentrations are somewhat diluted by large amounts of water during major runoff events, the variability in runoff volumes is more dynamic, and the effect is higher loading rates during wetter seasons and years. This holds true for runoff and base-flow loading, because the streams in the BB-LEH Watershed are largely groundwater fed, and the discharge levels are strongly tied to precipitation totals for these highly responsive streams.

It is also stressed here that nitrogen and phosphorus occur in three principal media of the estuary: the water column, biotic tissue, and bottom sediments. Bottom sediments are typically the major repository of nutrients in coastal lagoons, exceeding the concentrations in the water column and biotic tissue. In fact, far greater concentrations of nitrogen are typically stored in bottom sediments of coastal lagoons (often 10-fold to 100-fold higher in bottom sediments than in the water column; Sand-Jensen and Borum, 1991; Burkholder et al., 2007). Internal nutrient loading via nutrient fluxes from bottom sediments to the overlying water may be a significant driver of biotic change for this estuary.

The concentrations of nutrients in the water column are highly variable, particularly the dissolved inorganic components which are rapidly assimilated by autotrophs. Thus, low dissolved nitrogen concentrations in the water column may occur concurrently with algal blooms in the system due to rapid autotrophic uptake.

The amount of nutrients bound in plant tissue must also be considered when assessing eutrophication of estuarine systems; hence, the concern regarding nuisance and toxic algal blooms in these systems. In a separate study, we measured nitrogen concentrations in *Zostera marina* leaves along transects of 10 sampling stations in all three segments of the estuary. Mean leaf nitrogen concentrations ranged from 1.05 to 3.94%, reflecting a considerable amount of nitrogen assimilated from the water column and sediment pools and sequestered in plant tissue. This is a substantial amount of nitrogen when considering all seagrass leaves in the estuary. In addition, it does not consider the large amount of nitrogen concurrently bound up in the tissues of macroalgae and microalgae along the estuarine floor, which would be assimilated even faster than that taken up by seagrass.

Because of the shallow depths of BB-LEH, there is a tight benthic-pelagic coupling, as has been demonstrated in other coastal lagoons as well. In these systems, water quality monitoring of nitrogen concentrations provides only a part of the database necessary to completely assess ecosystem condition – or source of nitrogen. It also does not reflect biogeochemical processing in bottom sediments, how much nitrogen is sequestered in the sediments that may vary from year to year (and may be released to the water column), and the role of benthic microalgae in removing nitrogen released from the sediments before it reenters the pelagic domain. These processes, again, affect nitrogen levels in the water column. If nutrient measurements are not made on biotic tissue and bottom sediments, they constitute important data gaps that need to be addressed by future research and monitoring programs.

Other studies (e.g., Touchette and Burkholder, 2000) reported that phosphate in the water column of seagrass habitats typically ranges from ~0.1 to 1.7 μM compared to higher concentrations in sediment pore water ~0.3 to 20 μM. Ammonium levels in the water column were reported at 0 to 3.2 μM in the water column compared to ~1 to 180 μM in sediment pore water. Finally, nitrate + nitrite concentrations were reported at ~0.05 to 8 μM in the water column compared to ~2 to 10 μM sediment pore water.

Eutrophic condition is closely tied to indicators of light availability, and these indicators are also closely coupled to seagrass success or failure. Macroalgal blooms occurred relatively frequently and impacted seagrass beds in BB-LEH by attenuating or blocking light transmission to the beds, leaving many unvegeted bay bottom areas. From 2004 to 2010, Pre-Bloom conditions (60-70% macroalgae cover) occurred 10 times (0.45 blooms m^{-2}), Early Bloom conditions (70-80%) occurred 19 times (0.67 blooms m^{-2}), and Full Bloom conditions (80-100%) occurred 36 times (1.57 blooms m^{-2}). Blooms were more frequent during June-July (27 occurrences, 1.10 blooms m^{-2}), and August-

September (22 occurrences, 0.95 blooms m^{-2}), than October-November (16 occurrences, 0.63 blooms m^{-2}). The majority of the blooms occurred during the 2008-2010 period, signaling an increase in recent years.

Eutrophication of BB-LEH is also indicated by extensive epiphytic biomass and coverage of seagrass leaves observed in 2009, 2010, and 2011 that correlate with large-scale concurrent reduction in eelgrass biomass. Epiphytes can attenuate up to 90% of the light incident on seagrass leaves. Epiphyte biomass in 2009 peaked during June-July (mean = 121.8 mg dry wt m^{-2}). In 2010, peak epiphyte biomass occurred during August-September (mean = 67.7 mg dry wt m^{-2}). In 2011, the highest epiphyte biomass was also recorded in August-September (mean = 144.0 mg dry wt m^{-2}). Maximum biomass of epiphytes also occurred at the time of peak epiphyte areal cover on eelgrass leaves. The mean percent cover of epiphytes during all sampling periods in 2009 ranged from 19.2 to 38.3% for upper leaf surfaces and 18.4 to 38.3% for lower leaf surfaces. This is significant areal coverage. In 2010, the mean percent cover of epiphytes was generally lower than in 2009, with the values ranging from 11.3 to 25.7% for upper leaf surfaces and 10.7 to 24.4% for lower leaf surfaces. However, higher values of epiphyte percent cover were found during the October-November sampling period in 2010 than in 2009, with the mean upper leaf and lower leaf percent cover values ranging from 20 to 21% in October-November 2010 compared to mean values ranging from 18.4 to 19.2% in October-November 2009. The highest epiphyte percent cover on seagrass leaves was recorded during the August-September sampling period in 2011 when the mean upper leaf and lower leaf percent cover values were 48.1% and 48%, respectively.

Brown tide, hazardous algal blooms (HABs) caused by the pelagophyte *Aureococcus anophagefferens* were most pronounced in BB-LEH between 1995 and 2002, but they have not been monitored since 2004. Monitoring for *A. anophagefferens* must be conducted with the proper technique and cannot be accurately measured by chlorophyll *a* concentrations since the species does not fluoresce with this pigment (Anderson et al. 1989, 1993). However, one brown tide bloom occurred in 2010, and others may have occurred after 2004 as well. The highest *A. anophagefferens* abundances ($>10^6$ cells mL^{-1}), Category 3 blooms ($\geq$ 200,000 cells mL^{-1}) and Category 2 blooms ($\geq$ 35,000 to $\leq$ 200,000 cells mL^{-1}), occurred in 1997 and 1999 and then again during the 2000-2002 period. Brown tides also attenuate light, and thus impact seagrass beds. In addition, hard clams cease to grow above a brown tide threshold level of 400,000 cells mL^{-1}. This picoplanktonic alga can cause deleterious effects on hard clam populations at levels an order of magnitude below those that cause discoloration of the water.

A hard clam (*Mercenaria mercenaria*) stock assessment conducted in 2001 revealed more than a 67% reduction in hard clam abundance when compared with an earlier stock assessment conducted in 1986-87. The loss of such large numbers of hard clams appears to reflect a shift or transition in the system away from one of top-down control exerted by filter feeders consuming and regulating phytoplankton populations to one of bottom-up control limited by nutrient inputs (see Heck and Valentine, 2007). Aside from elevated densities of brown tide, high abundances of *Nannochloris atomus* and *Synechococcus* sp. have occurred in the estuary as well. Shifts in the food web structure of the estuary (e.g. phytoplankton size structure and species composition; picoplankton blooms) due to nutrient enrichment could have impacted the hard clam population.

Only 7 hard clams were found at 120 quadrat sampling stations in the estuary in 2010 for primary biotic data. In 2011, only 9 hard clams were found at these 120 quadrat sampling stations. Only 2 bay scallops (*Argopecten irradians*) were found at these sampling stations in 2010, and none in 2011. While hard clam and bay scallop data were evaluated to determine their appropriateness for potential inclusion as an indicator for the Index of Eutrophication, there were too few data points to be able to identify threshold values and conduct assessment. Hence, these data were not included in the Index of Eutrophication.

For other light influencing factors, the mean total suspended solids (TSS) values generally ranged from 5-40 TSS units. Maximum TSS values exceeded 200 TSS units. Secchi depths generally exceeded 2 m in all estuary segments. Minimum mean Secchi depths were ~1 m. From 1997-2010, the mean chlorophyll *a* measurements generally ranged from ~1-12 mg L^{-1}. Maximum chlorophyll *a* values exceeded 40 mg L^{-1}.

Seagrass conditions documented in this report clearly show substantial degradation over time that is not isolated to one bed, but rather is geographically extensive estuary. Such widespread response signals a broad-scale stressor. We attribute this response to eutrophication resulting from nutrient loading to the estuary and associated light attenuation due to microalgal and macroalgal blooms that directly impact seagrass beds. Eelgrass biomass declined consistently over the 2004-2006 and 2008-2010 periods and overall from 2004-2010. Furthermore, the rate of decline of eelgrass biomass during 2008-2010 was slower than that of 2004-2006. This change in the rate of decline is related to nutrient loading and associated symptoms of eutrophication, and occurred perhaps because there was less biomass left to be lost. Though long-term monitoring of seagrass was not started early enough to observe the beginning of the initial decline prior to 2004, the pattern of biomass decline with increasing nutrient concentrations is similar to load-decline relationships described in the literature.

Eelgrass areal cover also generally decreased through 2010, but the decline in plant biomass, a key water quality indicator, was most marked. A general decline in plant parameters (except blade length) was evident from 2008 to 2010 corresponding with temporal separation (yearly and seasonally of environmental parameters suggests their importance to seagrass condition). Eelgrass biomass had yet to recover by 2010 from the decline of plant abundance and biomass observed in 2006. Eelgrass biomass values for 2010 were the lowest on record for BB-LEH. Eelgrass biomass measurements in 2011 showed no improvement over those of the 2008-2010 period. Thus, biomass may be reaching a new, lower, steady state in the estuary. A return to previous levels of eelgrass biomass therefore may be difficult to attain.

The condition of *Ruppia maritima* in the estuary also does not appear to be strong, although only one year of data (2011) has been collected on widgeon grass in the north segment since 2004. There is no way to validate the condition of widgeon grass in the north segment without additional years of sampling there. Previous years of sampling in the central and south segments, however, show conclusively that widgeon grass is depauparate in these areas, with mean biomass values ≤ 1.6 g dry wt m^{-2} during all sampling periods in 2005 and 2010, when the only widgeon grass was found. Somewhat higher aboveground and belowground biomass values of widgeon grass were recorded in 2011, especially in the more favorable environment of the north segment. However, no widgeon grass samples were found in the south segment during 2011. These data demonstrate that widgeon grass dominates seagrass beds only in the north segment, while eelgrass dominates the beds in all other areas. In addition, the north segment does not appear to be a major habitat for either species.

The detrimental impact of nutrient loading on the ecosystem health of BB-LEH is clearly evident in the comparison of the values of the overall Index of Eutrophication vs. total nitrogen loading and total phosphorus loading. As nutrient loading increases, eutrophication condition plummets from a score of almost 70 to below 40, and in some cases even lower. The initial rapid response of the decline underscores how sensitive BB-LEH is to even small increases in nutrient loading, especially at lower levels of loading. The system responds differently after reaching a threshold of nutrient loading. In excess of nutrient loads amounting to ~2,000 kg TN km^{-2} yr^{-1} or ~100 kg TP km^{-2} yr^{-1}, the Eutrophication Index values no longer decline as rapidly and level off, though with a great amount of variability, ranging between 2 and 50. Therefore, in excess of ~2,000 kg TN km^{-2} yr^{-1} or ~100 kg TP km^{-2} yr^{-1} another factor or set of factors may explain the variability of the eutrophication condition. However, what remains clear is that throughout the entire system, nutrient loading – both total nitrogen loading and total phosphorus loading – clearly results in substantial degradation and eutrophication of BB-LEH.

The data also indicate that different portions of BB-LEH are in different stages of degradation and eutrophication. The north segment, which experienced the highest levels of nutrient loading, has already undergone severe degradation and eutrophication, as evidenced by the lowest values of the Index of Eutrophication for this segment as compared to the central or south segments. The central and south segments are similar to each other, and over the years 1989-2010, both have undergone significant decline in condition associated with increasing eutrophication.

There are significant and overt biotic responses to nitrogen enrichment of the estuary. The characterization of biotic response indicators in the estuary to nutrient loading entails the use of existing datasets collected between 1989 and 2010. Data collected on the indicators in 2011 are employed as a validation dataset.

In some years, the estuary has shifted to different community states. For example, from 1999-2002, BB-LEH experienced severe brown tide (> 1.8 x 10^6 cells mL^{-1}) events, but in 1998, 2004, and 2005, extensive macroalgal blooms were recorded and have persisted through ensuing years (2008-2010). Both types of bloom events are detrimental to seagrass habitat.

BB-LEH Estuary is an impaired system as documented by low dissolved oxygen (DO) levels. There were 82 occurrences of DO levels $\leq$ 4 mg L^{-1} (the surface water quality criterion for DO is 4 mg L^{-1}) in the estuary and tributary systems determined from grab samples taken at multiple sampling sites between 1989 and 2010. Dissolved oxygen concentrations at and below 4 mg L^{-1} are important ecologically as low oxygen stresses commercially and recreationally important species of fish, invertebrates, and other organisms. Most of the low DO values observed occurred in the south segment (N = 63), with far fewer in the central segment (N = 13) and north segment (N = 6). These values represent DO measurements taken quarterly, mainly during the morning and afternoon (daylight) hours. Hence, the number of observations of DO below 4 mg L^{-1} is quite likely to be a significant underestimate of the number of DO violations that actually occurred during this time period because nighttime measurements were not made. While the estuary is designated as impaired in the north segment due to low DO, the data presented here indicate that the estuary is also likely to be impaired in the south segment due to DO levels below 4 mg L^{-1}.

Based on application of the assessment model, estuarine waters in BB-LEH are worse off in terms of nitrogen than phosphorus. In addition, based on nutrient concentrations, the north segment is in much worse condition than the central or south segments which are undergoing eutrophication. The central segment is slightly better than the south segment, but not by much. Since 1992, the condition of BB-LEH has progressively worsened over time for both nitrogen and phosphorus. Periods of improvement (1989-1992, 1996-2002, and 2006-2008) have not outpaced shorter but more detrimental periods of degradation, thus leading to the overall poorer condition regarding nutrient loading.

The occurrence of sea nettle blooms in the north segment has posed a hazard to human use of some waters in the estuary. Lower salinity waters north of Toms River have had the greatest numbers of sea nettles. Blooms of sea nettles have increased in the past decade. Increasing eutrophic condition and hardened shorelines may have contributed to this problem. Currently, approximately 40-45% of the estuarine shoreline is bulkheaded. Most of the north segment of the estuary is now bulkheaded, which provides ideal overwintering habitat for sea nettles.

The bioindicators examined and the Index of Eutrophication developed and applied in this study can support nutrient management planning. The report documents the extent and limitations of available data and provides a framework for holistic ecosystem monitoring for the future that can serve as a basis for future assessments of eutrophication condition. Currently, BB-LEH is highly eutrophic and is susceptible to nutrient loading. Total nitrogen and phosphorus are highest in areas with the highest percentages of urban and agricultural land, and with the lowest percentages of forested and undeveloped land. Nitrogen loads from areas covered with turf are about twice those of non-turf urban areas. Phosphorus loads from turf areas are more than eight times those from non-turf areas. Phosphorus concentrations, loads and yields are generally higher in areas with more development, and higher during runoff than in baseflow. Index of Eutrophication values declined in the central and south segments, indicating these segments are currently undergoing eutrophication. Eutrophication condition was worst in the north segment despite modest improvements, in contrast to stages and trends in the south and central segments.

From 1989 to 2010, BB-LEH experienced low dissolved oxygen (82 times ≤4 mg L^{-1}), high total suspended solids (max >200 mg L-1) and chlorophyll *a* (max >40 μg L^{-1}), harmful algal blooms (≥200,000 cells mL^{-1}), epiphytic loading (mean values up to 38.3% cover of seagrass), macroalgae blooms (80-100% cover 36 times, 70-80% cover 19 times, 60-70% cover 10 times), habitat loss, >67% fewer clams, and degraded seagrass biomass (to 2.7±8.0 g m^{-2} aboveground; 17.9±37.5 g m^{-2} belowground). Index of Eutrophication values declined 34% and 36% in the central and south segments, from 73 and 71 in the 1990s to 48 and 45 in 2010, respectively, indicating these segments are currently undergoing eutrophication. The north segment has already undergone eutrophication and remains highly eutrophic. The Index of Eutrophication values for the northern segment decreased markedly from 2009 to 2010.

Nutrient loading severely degraded BB-LEH and initial rapid declines highlight sensitivity of the estuary to loading and that a 'tipping point' may have been crossed beyond ~2,000 kg total nitrogen km^{-2} yr^{-1} or ~100 kg total phosphorus km^{-2} yr^{-1}. Collectively, the direct relationship between nutrient loading from the watershed and estuarine nutrient concentrations, the degradation of an array of biotic indicators, and the relationship between nutrient loading and the Index of Eutrophication supports the conclusion that BB-LEH is a highly impacted estuarine system.

A holistic management approach must be accelerated to remediate environmental problems in BB-LEH associated with nutrient enrichment due to ongoing development and land use-land cover changes in the watershed. Multiple corrective strategies should be applied concurrently, such as improved stormwater control systems, implementation of best management practices in the watershed, open space preservation, fertilizer controls, soil restoration, and education programs that explain to the public how and why these strategies are important and necessary for the protection of BB-LEH. Management of the watershed must also examine ways to minimize the creation of impervious surfaces, compacted soils, and sprawl, while concurrently preserving natural vegetation and landscapes. A total maximum daily load (TMDL) for nitrogen and phosphorus is also a necessary element to effectively mitigate the eutrophic condition of the estuary. Application of a TMDL should be pursued concomitantly with the other management approaches noted above. It is necessary to respond aggressively at this time to nutrient loading from the watershed because of the severity of the eutrophication problems in the estuary, which may become intractable if they are not remediated in the short term. A well-coordinated and holistic management plan is critical to improving the ecological condition and resources of the estuary. This is a long-term approach to remediate the eutrophication problems in the estuary.