Barnegat Bay-Little Egg Harbor Estuary:

Ecosystem Condition and Recommendations

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Executive Summary: Recommendations

The Barnegat Bay-Little Egg Harbor Estuary is an impaired system both in respect to aquatic life support and human use. An array of biotic indicators, discussed below, clearly shows that the estuary has impairment problems. The principal cause of these problems is nitrogen over-enrichment mediated primarily by surface runoff from the Barnegat Bay watershed and atmospheric deposition from the overlying airshed.

The most immediate need for the Barnegat Bay-Little Egg Harbor estuarine system is the reduction of nitrogen loading. To this end, it is imperative to first establish nutrient criteria for the watershed and estuary. Long-term ecosystem improvement can only be achieved by reducing nitrogen inputs to the estuary.

Eutrophication (defined as a long-term increase in nutrient and organic matter input in a water body) is serious because it causes ecosystem-level impacts that reverberate through the structural and functional components of the estuary. Therefore, future studies must examine the responses of major biotic groups and essential habitat estuary-wide to accurately delineate the effects of nitrogen enrichment.

The following recommendations are proposed for biotic studies in the coastal bays of New Jersey:

- Seagrasses are key indicators of water quality and condition of the Barnegat Bay-Little Egg Harbor Estuary. Therefore, the monitoring of seagrass abundance and distribution in this system must be conducted consistently at regular intervals to establish a reliable bioassessment program. Quantitative measures of seagrass shoot density, biomass, and basal coverage are also extremely valuable for tracking the effects of nutrient enrichment and other impacts in the estuary.
- The development of a seagrass nutrient pollution indicator is strongly recommended to identify the early stages of eutrophication in the system. Because detailed surveys of SAV beds are labor intensive, costly, and time consuming, the development of an innovative nutrient pollution indicator based on assessment of nitrogen levels in seagrass tissues would be extremely useful for this system. By applying this indicator in the estuary, management mediated intervention could play a significant role in mitigating nutrient impacts on SAV beds. Such an indicator would also be valuable for determining when water quality conditions are degraded from year to year.
- There is an indication of significant loss of seagrass beds in the estuary since the mid-1970s, although differences in mapping methods make it difficult to unequivocally establish the occurrence of a major dieback and loss of eelgrass area. Results of a GIS spatial comparison analysis of SAV surveys reported by Lathrop et al. (1999) and Lathrop and Bognar (2001) showed that there has been loss of eelgrass in the deeper waters of the estuary culminating in the contraction

of the beds to shallower subtidal flats (< 2 m depth) during the period between the 1960s and 1990s. The loss appears to have been most severe in Barnegat Bay north of Toms River and in southern Little Egg Harbor.

- A two-pronged seagrass monitoring and assessment program is recommended. This entails the application of aerial photography, airborne digital scanning systems, or satellite-based remote sensing to map and monitor the seagrass beds, in conjunction with *in situ* sampling to corroborate the aerial observations. Airborne scanning systems yield high spatial resolution imagery, and analog aerial photography enables investigators to visually interpret and map expanses of the beds. Groundtruthing efforts in concert with this remote sensing work should consist of establishing a series of sampling transects, with an array of quadrat, core, and hand sampling sites. These field applications should be conducted at least every five years and preferably at greater frequency.
- Seagrasses are also excellent bioindicators of estuarine sediment quality, as well as overall ecosystem health. By monitoring the distribution and abundance of seagrasses in the Barnegat Bay-Little Egg Harbor Estuary and establishing quantitative measures of acceptable limits as biocriteria, effective bioassessment of estuarine condition can be conducted. A major goal is to establish nutrient criteria and TMDL's that will remediate the impacts of nutrient enrichment in the estuary. This can only be achieved through careful monitoring and assessment of seagrass habitat in the system. Delineating the distribution and abundance of seagrasses in this lagoon-type, coastal-bay system to track escalating eutrophic impacts is highly recommended. Since changes in seagrass distribution and

abundance can occur over periods as short as weeks or months, rapid and cost effective tools are needed to accurately determine seagrass condition within seasonal constraints and to quantify cause-and-effect relationships.

- Chlorophyll diagnostic photopigment analysis is needed for identifying and quantifying phytoplankton functional groups. Phytoplankton community composition is an effective indicator of phytoplankton activity/response, including blooms, that has been linked to nutrient enrichment and other environmental stressors.
- Regular surveys of algal blooms (both phytoplankton and macroalgae) must be conducted in the estuary to identify key autotrophic responses to nutrient stressors. Surveys for brown tide (*Aureococcus anophagefferens*) are a primary target of phytoplankton bloom surveys.
- Benthic community studies must be conducted to determine if significant changes have occurred over time. The last comprehensive investigation of the benthic community in the estuary was conducted by Robert Loveland and his students at Rutgers University from 1968 to 1974. By re-sampling the same areas of the estuary, it will be possible to compare the benthic community 40 years after the Loveland investigations. Data that must be collected to assess the benthic community include species composition, abundance, biomass, diversity, and evenness. Metrics recorded on the benthos will be used to document changes in the benthos over the period from low development to high development in the coastal watershed.

- The development of indices of benthic community condition is another valuable tool in bioassessment of estuarine ecosystems. In estuarine systems impacted by nutrient enrichment and bottom-up effects, such as the Barnegat Bay-Little Egg Harbor Estuary, the application of benthic index development for seagrass as well as other benthic habitats in the system is thus strongly recommended for effective biotic assessment. Metric measurements of targeted benthic assemblages will be used to effectively discriminate anthropogenically-stressed assemblages from non-stressed assemblages. These measurements can be used to generate numeric scores and indices of biotic integrity that can be important for developing biocriteria for this estuarine system. These data are necessary for accurate evaluation of ecosystem health useful for management decision making and resource protection. Benthic community sampling must be conducted at regular intervals (~five-year periods) to document changes in benthic condition through time.
- Shellfish stock assessment surveys must be conducted in the estuary, most notably targeting the hard clam (*Mercenaria mercenaria*) resource. The last hard clam stock surveys in Little Egg Harbor and Barnegat Bay were completed in 2001 and 1986, respectively.
- Population surveys are necessary to document the distribution and abundance of sea nettles (*Chrysaora quinquecirrha*) in the estuary. Population eruptions of sea nettles in the estuary have occurred in several years since 2000.

Abstract

New Jersey's coastal bays are subject to ongoing multiple anthropogenic impacts from an expanding population in adjoining coastal watersheds. Eutrophication poses the most serious threat to the long-term health and function of the bays, impacting essential habitats (e.g., seagrass and shellfish beds) as well as finfish nursery areas. Nutrient and organic carbon loading in these shallow, lagoon-type estuaries has been linked to an array of cascading environmental problems such as increased micro- and macroalgal growth, harmful algal blooms (HABs), bacterial and viral pathogens, high turbidity/benthic shading, altered benthic invertebrate communities, and impacted harvestable fisheries. These problems are causing the deterioration of sediment and water quality, loss of biodiversity, and disruption of ecosystem health and function. Human uses of estuarine resources are also being impaired. The net insidious effect of progressive eutrophication may be the permanent alteration of biotic communities and habitats in the system.

The Barnegat Bay-Little Egg Harbor Estuary is classified as a highly eutrophic system based on application of NOAA's National Estuarine Eutrophication Assessment model (Kennish et al. in press). The inland coastal bays of New Jersey (lagoonal systems south of Great Bay) have also been recently classified as highly eutrophic (Suzanne Bricker, NOAA, personal communication, 2007). Because the Barnegat Bay-Little Egg Harbor Estuary is shallow, poorly flushed, and bordered by highly developed watershed areas, it is particularly susceptible to nutrient loading. Most of this load (~50%) derives from surface water inflow, but substantial fractions also originate from atmospheric deposition (~39%), and direct groundwater discharges (~11%) (Kennish, 2001). Other adverse effects on these bays include nonpoint source inputs of chemical contaminants,

as well as the physical alteration of habitat due to bulkheading, diking and ditching, dredging, and lagoon construction. Power-plant (Oyster Creek Nuclear Generating Station), point-source impacts (i.e., biocidal releases, thermal discharges, impingement, and entrainment) have increased mortality of estuarine and marine organisms in Barnegat Bay. Human activities in watershed areas, notably deforestation and infrastructure development, partition and disrupt habitats while also degrading water quality and altering biotic communities. Ongoing land development (~35% of the Barnegat Bay watershed is now developed) raises turbidity and siltation levels in tributaries of the estuary, creating benthic shading problems. Management actions, including the purchase of open space, improved stormwater controls, and smart development are being pursued to remediate some of the aforementioned insidious effects and restore vital estuary functions; however, evidence indicates that remediation efforts have not resulted in significant mitigation of ecosystem impacts. Ongoing conditions threaten the ecological integrity of the system.

Eutrophication

The Barnegat Bay-Little Egg Harbor Estuary is an impaired system both in respect to aquatic life support and human use. An array of biotic indicators, discussed below, clearly shows that the estuary has impairment problems. The principal cause of these problems is nitrogen over-enrichment mediated primarily by surface runoff from the Barnegat Bay watershed and atmospheric deposition from the overlying airshed.

It is important to examine the status and trends of submerged aquatic vegetation (SAV) in the context of eutrophication impacts. It is equally important to investigate the macroalgae and phytoplankton resident in the estuary, most notably in respect to the blooms of these autotrophic groups. This information is necessary to effectively assess the effects of nutrient loading and eutrophication in the bay.

The net insidious effect of progressive eutrophication is the potential for the permanent alteration of biotic communities and greater ecosystem-level impacts. The Department of Environmental Protection showed that hard clam (*Mercenaria mercenaria*) stocks in Little Egg Harbor decreased by two-thirds between 1986 and 2001. Recurring brown tide (*Aureococcus anophagefferans*) blooms occurred between 1995 and 2002 (Olsen and Mahoney, 2001; Gastrich et al., 2004). The biomass of seagrass beds in the Barnegat Bay-Little Egg Harbor Estuary in 2006 decreased by 50-88% compared to that of the 2004-2005 period (Kennish et al., 2007). Accelerated growth of drifting macroalgae (e.g., *Ulva lactuca*) has produced extensive organic mats that pose a danger to the seagrass beds. Rapid growth of other macroalgal species in the estuary, such as the rhodophytes *Agardhiella subulata*, *Ceramium* spp., and *Gracilaria tikvahiae*, can also be deterimental. In addition, the decomposition of thick macroalgal mats can promote sulfide accumulation and the development of hypoxic/anoxic conditions in bottom sediments that are devastating to benthic infaunal communities. Blooms of the sea nettle (*Chrysaora quinquecirrha*) have likewise developed in the estuary. These biotic problems are ascribed, in part, to increasing eutrophication. They are serious because they can lead to marked deterioration of water quality and habitat conditions, loss of biodiversity, and disruption of ecosystem health and function. Human uses of estuarine resources can also be seriously impaired by eutrophication, such as the harvesting of shellfish (due to diminished stock), use of bathing areas (due to sea nettles), and diminished water quality (due to brown tides).

Eutrophication (defined as a long-term increase in nutrient and organic matter input in a water body) is responsible for insidious degradation of estuarine systems worldwide (Nixon, 1995; Boesch et al., 2001). Generally linked to nutrient loading from adjoining coastal watersheds and local airsheds, eutrophication has been deemed a priority problem of the Barnegat Bay-Little Egg Harbor Estuary (Kennish, 2001). Nutrient enrichment is problematic because it can over-stimulate the growth of phytoplankton as well as benthic microphytes and macrophytes. The result is often recurring phytoplankton blooms and the excessive proliferation of epiphytic algae and benthic macroalgae that can be detrimental to benthic habitats such as SAV, which can be significantly compromised. Dissolved oxygen levels may be reduced as well, most notably in bottom sediments.

Symptoms of serious eutrophication problems have escalated in the Barnegat Bay-Little Egg Harbor Estuary over the past decade, manifested as frequent phytoplankton and macroalgal blooms, declining shellfisheries (hard clams, *Mercenaria mercenaria* and bay scallops, *Argopecten irradians*), and diminishing critical habitat (seagrass beds). Recurring phytoplankton blooms have been documented, including nuisance blooms (e.g., brown tides, *Aureococcus anophagefferans*) that occurred repeatedly between 1995 and 2002 (Olsen and Mahoney, 2001). Brown tides blooms were not monitored in 2006. Accelerated growth of drifting macroalgae (e.g., *Ulva lactuca*) has produced extensive organic mats that pose a potential danger to seagrass beds and other phanerogams serving as vital benthic habitat for various recreationally and commercially important species (e.g., blue crabs, *Callinectes sapidus*; bay scallops, *A. irradians*; and tautog, *Tautoga onitus*). Rapid growth of other macroalgal species in the estuary, such as the rhodophytes *Agardhiella subulata*, *Ceramium* spp., and *Gracilaria tikvahiae*, may also have been detrimental. In addition, the decomposition of thick macroalgal mats can promote sulfide accumulation and the development of hypoxic/anoxic conditions in bottom sediments that can be detrimental to benthic infaunal communities.

Frequent phytoplankton blooms can lead to shading effects and potentially dangerous oxygen depletion. Both may result in indirect impacts on seagrass beds and other vital habitat in the Barnegat Bay-Little Egg Harbor Estuary. Because excessive growth of benthic macroalgae has had direct impacts on seagrass beds, it is also critically important to assess the effects of this algal group on seagrasses (most notably *Zostera marina*) in the estuary.

Other significant biotic changes linked to nutrient enrichment of eutrophied estuaries in general are shifts from large to small phytoplankton species and from diatoms to dinoflagellates and microflagellates that can adversely affect shellfish species. Additional impacts include a shift from filter-feeding to deposit-feeding benthos, and a progressive change from larger, long-lived benthos to smaller, rapidly growing but shorter-lived species. The net effect is the potential for a permanent alteration of biotic communities of a system (Rabalais, 2002).

Schramm (1999) and Rabalais (2002) described a predictable series of changes in autotrophic components of estuarine and marine ecosystems in response to progressive eutrophication. For those systems that are uneutrophied, the predominant benthic macrophytes inhabiting soft bottoms typically include perennial seagrasses and other phanerogams, with long-lived seaweeds occupying hard substrates. As slight to moderate eutrophic conditions arise, bloom-forming phytoplankton species and fast-growing, short-lived epiphytic macroalgae gradually replace the longer lived macrophytes; hence, perennial macroalgal communities decline. Under greater eutrophic conditions, dense phytoplankton blooms occur along with drifting macroalgal species (e.g., *Enteromorpha* and *Ulva*), ultimately eliminating the perennial and slow-growing benthic macrophytes, a situation that appears to be taking place in the Barnegat Bay-Little Egg Harbor Estuary. With hypereutrophic conditions, benthic macrophytes become locally extinct, and phytoplankton overwhelmingly dominates the autotrophic communities.

Howarth et al. (2000a, b) and Livingston (2000) not only correlated hypereutrophication with proliferation of nuisance and toxic algal blooms but also with increased algal biomass, diminished seagrass habitat, increased biochemical oxygen demand, hypoxia/anoxia, degraded sediment quality, and loss of fisheries. Excessive nutrification problems are on the rise in U.S. waters and abroad, and they are impacting secondary production through altered food web interactions (Livingston, 2002). Some of these effects are occurring today in the Barnegat Bay-Little Egg Harbor Estuary.

Seagrasses

Seagrasses in the estuary have been impacted by declining water quality, brown tides, benthic algal infestation, boat scarring, and disease. To remain healthy, seagrasses are dependent on conditions of relatively low turbidity and high light transmission. As bay waters become more turbid due to algal blooms and suspended sediment, the light levels needed to sustain photosynthesis and seagrass productivity decrease. Nutrient enrichment of bay waters, whether from runoff, atmospheric deposition, or boat wastes, promotes algal blooms as well as infestations of epiphytic algae that coat the seagrass blades and threaten the longevity of the seagrass beds.

Seagrasses rank among the most sensitive indicators of long-term water quality in coastal bays and other estuarine systems (Dennison et al., 1993). Changes in the vitality and distribution of these vascular plants generally signal a decline in aquatic ecosystem health. During the last 30 years, significant declines in seagrass beds have occurred in New Jersey estuaries (Lathrop et al., 2001), resulting in the reduction of essential fish habitat and the potential loss of commercially and recreationally important species. Nutrient enrichment has promoted blooms of phytoplankton (e.g., *Aureococcus anophagefferens*) and benthic macroalgae (e.g., *Ulva*, *Gracilaria*, and *Codium*). Dinoflagellate and brown-tide blooms reduce light availability, adversely affecting eelgrass (*Zostera marina*) (Dennison et al., 1989) and causing negative impacts on other living resources such as shellfish populations (Bricelj and Lonsdale, 1997). Brown-tide blooms are now a recurring phenomenon in the coastal bays of New Jersey, New York, and Maryland. In response to shading stress, it appears that *Z. marina* may also be susceptible to infection by 'wasting disease' (*Labyrinthula zosterae*) (Bologna and Gastrich, unpublished data). This disease, which decimated *Z. marina* beds worldwide during the 1930's (den Hartog, 1987), may signal a significant decline in water quality. Aside from the impacts of 'wasting disease' on *Z. marina*, large-scale losses of the SAV habitat might occur due to the additional physiological stress associated with harmful algal blooms (HABs).

Seagrass Status and Trends

Lathrop

Richard Lathrop and his colleagues at Rutgers University conducted aerial imaging of the seagrass beds in the estuary using advanced digital camera equipment flown in an airplane along the entire length of the estuary. Color imagery was flown in the spring (May 4 and 5, 2003) before bay waters became too turbid, thereby enabling the researchers to visualize the bay bottom and determine the location of the seagrass beds. The aerial overflight was complemented with boat-based surveys up and down the bay to determine species type (i.e., eelgrass, *Zostera marina*, or widgeon grass, *Ruppia maritima*), percent cover, blade height, and sediment type. Advanced computer-aided interpretation techniques were used to map the location, areal extent, and percent cover of the seagrass beds in much greater detail than ever before possible. Seagrass beds were mapped at three levels of density: (1) dense (80-100% coverage); (2) moderate (40-80% coverage); and (3) sparse (10-40% coverage). Shallow sand/mud flats (< 10% seagrass) and benthic macroalgae (e.g., sea lettuce, *Ulva lactuca*) were also mapped. The resulting maps showed that 5,184 ha (12,804 acres) of seagrass beds existed in the estuary at the aforementioned levels of density.

Assessment of the overall condition of the indicator by Lathrop showed that the SAV distribution remained reasonably stable between 1998 and 2003. There did not appear to be any wholesale loss of beds when compared with maps of the 1990-2000 period. This stability was a positive outcome considering the continued development of the watershed as well as the severe brown-tide blooms that occurred in the bay during 2001 and 2002. However, the condition of the indicator appears to have changed substantially in previous years. Since 1968, for example, mapping surveys conducted periodically to monitor the extent and status of seagrass beds in the Barnegat Bay-Little Egg Harbor Estuary indicated significant shifts in distribution. Of particular note, earlier surveys showed evidence of a decline in the seagrass extent between the late 1970's and the mid-1990's, especially in the northern reaches of the bay.

Boat-based surveys conducted between 1996 and 1999 mapped 6,083 ha (15,025 acres) of seagrass. When comparing the 2003 and the late 1990's maps, a decline of approximately 900 ha (2,220 acres) or 15% of seagrass beds appears to be evident. Rather than representing a significant decline in seagrass, the difference in area figures is most likely due to a change in mapping techniques and the timing of the aerial imagery acquisition. The 1990's boat-based survey mapped SAV by following the exterior perimeter of seagrass beds and recording waypoints using a GPS. This technique tends to homogenize characteristics within a bed, creating a continuous SAV coverage where it may actually be discontinuous. Aerial photographic imagery and the image segmentation/classification techniques adopted in the 2003 study permitted a much finer delineation of exterior boundaries and internal bed discontinuities. In addition, the early May 2003 aerial imagery may have underestimated the spatial extent and cover of widgeon grass beds, which generally do not reach their peak density until later in the summer growing season.

There are major information gaps as to the relative importance of eutrophication vs brown-tide blooms on diminished water clarity and potential impacts on seagrass health. The significance of epiphytic algae, benthic macroalgae, wasting disease, and other disturbance factors on seagrass health and abundance is also uncertain.

The remote sensing based mapping has been complemented with *in situ* sampling to assess seagrass abundance and health and the impact of the aforementioned disturbance factors. Investigators conducted intensive sampling of seagrass beds during 2004, 2005, and 2006. Results of this work are described more thoroughly below.

Bologna

Paul Bologna and his colleagues at Montclair State University have been monitoring SAVs at five permanent sites in the Barnegat Bay-Little Egg Harbor Estuary, including Shelter Island, Marsh Elder, Ham Island, Barnegat Inlet, and Seaside Heights (Bologna et al., 2000, 2001; Bologna, 2006). Of these sites, the first four are eelgrass (*Zostera marina*) dominated sites, and the Seaside Heights is a widgeon grass (*Ruppia maritima*) habitat. At each of these sites, monthly core samples have been collected from May through September. Monitoring of some of these sites began as early as 1998, but all sites have been continuously monitored since 2001. Additionally, during the summer, baywide assessment of SAV has been conducted to answer various community level questions regarding the value of SAV as habitat for associated fauna.

While seagrass coverage has appeared to remain relatively stable over the last several years, greater fluctuations have occurred for seagrasses on a localized scale. For example, Bologna et al. (2001), investigating the relationship between *Zostera marina* and bay scallops (*Argopecten irradians*) in coastal New Jersey during 1998, found that a significant macroalgal bloom occurred. The initial high biomass of algae in June and subsequent algal-detrital fraction, created a significant algal-detrital loading to the *Z. marina* bed, which continued throughout the summer and into the fall. Loading rates exceeded 397 g ash free dry weight m^{-2}. This massive accumulation of algae and detrital matter smothered *Z. marina* and led to the elimination of both aboveground and belowground biomass from several locations in the bay (Bologna et al., 2001). Since that event, numerous brown-tides have impeded the recovery of these beds to pre-impact levels. Currently, these beds continue to be monitored to assess how their recovery is progressing.

One of the most important trends identified in these data is the relative relationship of brown-tide occurrence in the system and the development and spread of the 'wasting disease' in the populations of *Z. marina*. It appears that during brown-tide events, added light stress allows the spread of the disease among the populations. It is not clear yet how this occurs, and whether it is an immediate response or a delayed reaction in the plants. The other important trend is the lack of site stability. SAV is inherently variable in shoot density and plant biomass. As such, there is significant inter-annual variation in these parameters at the monitoring sites. It will be necessary, therefore, to monitor these sites in the future to detect any larger temporal cycle in the plant demographics.

The primary limiting environmental factor for SAV in New Jersey is adequate light. It is well recognized that significant reduction of light transmission negatively impacts seagrass growth and production. Additionally, it has been demonstrated that various sources of light attenuation components exist and include phytoplankton, epiphytes, and macroalgae, as well as land runoff causing general turbidity. Coastal bays that undergo eutrophication frequently experience some degree of light attenuation from all of these sources (Hauxwell et al., 2003). These supplemental stresses, while impacting the growth, production, and health of expansive beds, may also greatly affect seedlings (Bintz and Nixon, 2001) and patchy or low shoot density beds (Tamaki et al., 2002). Consequently, light attenuation may significantly impair the natural recovery of SAV in regions that have undergone losses and may reduce the effectiveness and survival of expansive beds. It is this light attenuation that is the most critical control of SAV in Barnegat Bay.

The major information gaps necessary to assess the resource include determining the relationships among brown-tide and macroalgal blooms and the health and biomass of SAV in Barnegat Bay. These two factors - brown-tide and macroalgal blooms - have been shown to negatively impact SAV and other living resources. To determine the future success of SAV in the bay, it will be necessary to understand how these variables impact seagrass beds. Perhaps the most critical data gap relates to the value of widgeon grass as a habitat. While studies have focused on eelgrass, there is little understanding of the role of widgeon grass in Barnegat Bay. Currently, Bologna is also investigating the community ecology of widgeon grass. It will be important to link the value of each seagrass species to the health of the bay.

Kennish

Submerged aquatic vegetation (SAV) is recognized as a critically important benthic habitat that receives special consideration in New Jersey. In 2004-2006, researchers at Rutgers University and the Jacques Cousteau National Estuarine Research

Reserve conducted detailed sampling of SAV in the Barnegat Bay-Little Egg Harbor to determine: (1) the demographic characteristics and spatial habitat change of SAV (*Zostera marina* and *Ruppia maritima*) in the system over an annual growing period; (2) the species composition, relative abundance, and potential impacts of benthic macroalgae on the SAV beds; and (3) the potential impacts of brown tide (*Aureococcus anophagefferans*) on the SAV (see Kennish et al., 2007). Results of this comprehensive three-year investigation of the seagrass beds revealed significant temporal and spatial variation in seagrass density (shoots m^{-2}), biomass, blade length, and percent cover of bay bottom. Quadrat, core, and water quality sampling at multiple transect sites in four disjunct seagrass beds of the estuary during the June-November period in 2004, 2005, and 2006 yielded more than 1000 abiotic and biotic measurements each year for assessment of seagrass dynamics in the system. The occurrence of brown tide and benthic macroalgal blooms and their potential impacts on seagrass beds in the estuary were also examined.

An array of physico-chemical data (i.e., temperature, salinity, pH, dissolved oxygen, turbidity, and depth) was collected at 120 sites along 12 transects on all sampling dates using either a handheld YSI 600 XL data sonde coupled with a handheld YSI 650 MDS display unit, an automated YSI 6600 unit (equipped with a turbidity probe), or a YSI 600 XLM automated datalogger. In addition, Secchi disk measurements were taken in the survey area along with several nutrient parameters (i.e., nitrate plus nitrite, ammonium, total dissolved nitrogen, phosphate, and silica). Seagrass demographic data collected at the sampling sites included the presence/absence of seagrass and macroalgae, aboveground and belowground biomass of seagrass, density of seagrass (except for

2004), percent cover of seagrass and macroalgae, and seagrass blade length. Sediment samples were also collected at all sampling sites and analyzed for percent sand, silt, and clay.

Metric measurements of seagrass beds in the estuary indicated a distinct seasonal pattern of density levels. For example, the density of *Zostera marina* (shoots m^{-2}) was significantly higher during the June-July period than during the August-September and October-November periods in both 2005 and 2006. The density of *Z. marina* shoots was significantly greater in June-July 2005 (479 shoots m^{-2}) than in June-July 2006 (378 shoots m^{-2}). Density measurements of *Z. marina* ranged from a mean of 163-479 shoots m^{-2} in 2005 and 171-378 shoots m^{-2} in 2006.

Biomass showed a greater decline over the study period. For example, between 2004 and 2006, the mean aboveground biomass of *Zostera marina* along six transects (1-6) in Little Egg Harbor decreased 87.7% from 59.62 g dry wt m^{-2} to 7.31 g dry wt m^{-2}, and the mean belowground biomass declined 59.4% from 75.60 g dry wt m^{-2} to 30.69 g dry wt m^{-2}. Similarly, along six transects (7-12) in Barnegat Bay between 2005 and 2006, the mean aboveground biomass of *Z. marina* declined 50% from 32.04 g dry wt m^{-2} to 16.03 g dry wt m^{-2}, and the mean belowground biomass decreased 52.4% from 84.59 g dry wt m^{-2} to 40.25 g dry wt m^{-2}. The decline in seagrass biomass was estuarywide. The mean biomass values of *Z. marina* in 2006 rank among the lowest mean annual biomass values ever recorded for this species in the estuary. They appear to be a consequence of increasing eutrophic impacts in the system associated with nuisance algal blooms, shading, and bottom disturbances.

The biomass of *Zostera marina* generally peaked during the June-July sampling period. For example, the maximum mean aboveground and belowground biomass of *Z. marina* in Little Egg Harbor in 2004 occurred during the June-July period, amounting to 106.05 g dry wt m^{-2} and 107.64 g dry wt m^{-2}, respectively. The biomass values subsequently declined during the ensuing August-September period (mean aboveground biomass = 54.61 g dry wt m^{-2}; mean belowground biomass = 68.69 g dry wt m^{-2}) and October-November period (mean aboveground biomass = 18.22 g dry wt m^{-2}; mean belowground biomass = 50.48 g dry wt m^{-2}).

In 2005, the maximum mean aboveground biomass (51.69 g dry wt m^{-2}) and belowground biomass (141.95 g dry wt m^{-2}) of *Zostera marina* in Barnegat Bay were also recorded during the June-July period. Lower mean aboveground and belowground biomass measurements were found during the August-September period, amounting to 28.79 g dry wt m^{-2} and 69.03 g dry wt m^{-2}, respectively. Even lower mean aboveground and belowground biomass measurements were recorded during the October-November period, equaling 15.66 g dry wt m^{-2} and 42.78 g dry wt m^{-2}, respectively. Over the 2005 study period, both the aboveground and belowground biomass values of *Z. marina* decreased by more than 69%.

The mean aboveground biomass of *Zostera marina* (eelgrass) in Barnegat Bay-Little Egg Harbor in 2006 peaked during the August-September period (mean = 13.77 g dry wt m^{-2}). In contrast, the mean belowground biomass was a maximum during the June-July period (51.54 g dry wt m^{-2}). A consistent seasonal decline in belowground biomass was evident in 2006 from a mean of 51.54 g dry wt m^{-2} in June-July, 36.08 g dry wt m^{-2} in August-September, and 24.23 g dry wt m^{-2} in October-November. The aboveground biomass did not exhibit a similar seasonal decline in 2006. During all years, both aboveground and belowground biomass values were highest at interior sampling sites along transects than at exterior sampling sites in closer proximity to seagrass bed margins.

The biomass of *Ruppia maritima* (widgeon grass) exhibited a decline in 2006, as did *Zostera marina*. The mean aboveground biomass of *R. maritima* ranged from 1.27-7.78 g dry wt m^{-2} in 2005 and 1.22-4.21 g dry wt m^{-2} in 2006. The mean belowground biomass of *R. maritima* ranged from 5.35-22.78 g dry wt m^{-2} in 2005 and 5.62-7.88 g dry wt m^{-2} in 2006.

The blade length of *Zostera marina* was relatively consistent during 2004 and 2005, but decreased greatly during 2006, which affected biomass values. The mean blade length of *Z. marina* in Little Egg Harbor during 2004 was 34.02 cm in June-July, 32.21 cm in August-September, and 31.83 cm in October-November. The mean blade length of *Z. marina* in Barnegat Bay during 2005 amounted to 32.71 cm in June-July, 25.89 cm in August-September, and 28.47 cm in October-November. In 2006, the mean blade length of *Z. marina* in the estuary was 19.37 cm in June-July, 18.65 cm in August-September, and 18.61 cm in October-November. The reduced growth during 2006 correlated with lower shoot density and biomass measurements at this time as well.

A progressive seasonal decrease in the percent cover of seagrass in the estuary was evident during each year of the study and correlated well with the seasonal decline of eelgrass biomass. For example, the percent cover of seagrass in the study area over the June-November period dropped from 45% to 21% in 2004, 43% to 16% in 2005, and 32% and 19% in 2006. By comparison, the percent cover of macroalgae was less consistent than that of seagrass. The percent cover of macroalgae in Little Egg Harbor in 2004 increased from 13% to 21% from June to September and then decreased to 14% in November. In Barnegat Bay during 2005, macroalgal areal coverage dropped from 14% in June-July to 2% in October-November. In 2006, the percent cover of macroalgae in the estuary increased from 2% during the June-July period to 7% during the October-November period. Macroalgae completely covered extensive areas of the bay bottom during blooms, particularly when comprised of sheet-like forms such as *Ulva lactuca*, as was the case in Little Egg Harbor in 2004. These blooms appear to cause significant dieback of seagrass in some areas of the estuary.

The macroalgae in the estuary belong to a drift community. In 2004, 32 macroalgal species were collected in Little Egg Harbor, with most being red algae (n = 19), which comprised 59% of all the species in the samples. Green algae (n = 11) and brown algae (n = 6) accounted for 34% and 6% of the algal species collected, respectively. *Ulva lactuca*, a green alga, was the most common species found, being recorded in 59% of the samples. Fewer macroalgal species (n = 21) were identified in samples collected in Barnegat Bay in 2005. Red algae once again dominated the collections, constituting 16 species. The most abundant forms were *Gracilaria tikvahiae* (present in 70% of samples), *Bonnemaisonia hamifera* (56%), *Spyridia filamentosa* (46%), and *Champia parvula* (19%).

No brown tide blooms were recorded in the estuary based on samples collected during 2004 and 2005. Peak counts of *Aureococcus anophagefferans* amounted to 4.9×10^4 cells ml^{-1} in 2004 and 4.7×10^4 cells ml^{-1} in 2005, respectively. No samples were collected in 2006.

Infestation of wasting disease did not appear to be significant based on field observations of seagrass samples. Only a fraction of eelgrass samples appeared to have wasting disease. However, a more detailed investigation of wasting disease infestation is recommended in the future.

A high-resolution videographic digital camera and recording unit was deployed to collect detailed images of seagrass habitat in the study area to augment the database collected via *in-situ* sampling. Coupled to a differential global positioning system (GPS), this *in-situ* imaging tool yielded valuable fine-detailed data for characterizing seagrass habitat in spatially restricted locations. More than 300 images of seagrass habitat have been archived for later data analysis, such as quantification of the basal area of seagrass cover, local distribution of seagrass, abundance of macroalgae, and presence of epifauna, to delineate biotic conditions over well-defined temporal and spatial scales. Underwater videography provided an effective means of investigating seagrass beds without compromising the integrity of the habitat via destructive invasive sampling.

The following recommendations are proposed based on the conclusions of this comprehensive three-year study and other recent investigations:

- Seagrasses are key indicators of water quality and condition of the Barnegat Bay-Little Egg Harbor Estuary. Therefore, the monitoring of submerged aquatic vegetation in this system must be conducted consistently at regular periods to establish a reliable bioassessment program. Quantitative measures of seagrass distribution, shoot density, biomass, and basal coverage are extremely valuable for tracking the effects of nutrient enrichment and other impacts in the estuary.

- The development of a seagrass nutrient pollution indicator is strongly recommended to identify the early stages of eutrophication in the system. Because detailed surveys of SAV beds are labor intensive, costly and time consuming, the development of an innovative nutrient pollution indicator based on assessment of nitrogen levels in seagrass tissues would be extremely useful for this system. By applying this indicator in the estuary, management mediated intervention could play a significant role in mitigating nutrient impacts on SAV beds. Such an indicator would also be valuable for determining when water quality conditions are degraded from year to year.
- There is some indication of significant loss of seagrass beds in the estuary since the mid-1970s, although differences in mapping methods make it difficult to unequivocally establish the occurrence of a major dieback and loss of eelgrass area. Results of a GIS spatial comparison analysis of SAV surveys reported by Lathrop et al. (1999) and Lathrop and Bognar (2001) suggest that there has been loss of eelgrass in the deeper waters of the estuary culminating in the contraction of the beds to shallower subtidal flats (< 2 m depth) during the period between the 1960s and 1990s. The loss appears to have been most severe in Barnegat Bay north of Toms River and in southern Little Egg Harbor. Because of some uncertainty surrounding the conclusions of this analysis, however, periodic investigations of seagrass beds in the estuary are recommended.
- A two-pronged seagrass monitoring and assessment program is also recommended. This entails the application of aerial photography, airborne digital scanning systems, or satellite-based remote sensing to map and monitor the

seagrass beds, in conjunction with *in situ* sampling to corroborate the aerial observations. Airborne scanning systems yield high spatial resolution imagery, and analog aerial photography enables investigators to visually interpret and map expanses of the beds. Groundtruthing efforts in concert with this remote sensing work should consist of establishing a series of sampling transects, with an array of quadrat, core, and hand sampling sites. These field applications should be conducted at five-year intervals and preferably at greater frequency.

- Regular surveys of algal blooms (both phytoplankton and macroalgae) must be conducted in the estuary to identify key autotrophic responses to nutrient stressors. Surveys for brown tide (*Aureococcus anophagefferens*) are a primary target of phytoplankton bloom surveys.
- The development of indices of benthic community condition is another valuable tool in bioassessment of estuarine ecosystems. In estuarine systems impacted by nutrient enrichment and bottom-up effects, such as the Barnegat Bay-Little Egg Harbor Estuary, the application of benthic index development for seagrass as well as other benthic habitats in the system is thus strongly recommended for effective biotic assessment. Metric measurements of targeted benthic assemblages leading to numeric scores and indices of biotic integrity can be subsequently incorporated into development of biocriteria for this estuarine system. The result will be an accurate evaluation of ecosystem health useful for management decision making and resource protection. Benthic community sampling must be conducted at regular intervals (~five-year periods) to document changes in benthic condition through time.

Seagrasses are excellent bioindicators of estuarine sediment quality, as well as overall ecosystem health. By monitoring the distribution and abundance of seagrasses in the Barnegat Bay-Little Egg Harbor Estuary and establishing quantitative measures of acceptable limits as biocriteria, effective bioassessment of estuarine condition can be conducted. A major goal is to establish nutrient criteria and TMDLs that will remediate the impacts of nutrient enrichment in the estuary. This can only be achieved through careful monitoring and assessment of seagrass habitat in the system. Delineating the distribution and abundance of seagrasses in this lagoon-type, coastal-bay system to track escalating eutrophic impacts is highly recommended. Since changes in seagrass distribution and abundance can occur over periods as short as weeks or months, rapid and cost effective tools are needed to accurately determine seagrass condition within seasonal constraints and to quantify cause-and-effect relationships.

Algal Blooms

Causes

Nutrient enrichment of estuarine waters is closely linked to a series of cascading environmental problems, notably increased growth of phytoplankton and macroalgae (including both harmful and nuisance forms) and associated loss of SAV and reduced dissolved oxygen levels as noted above. These problems can then lead to a deterioration of sediment and water quality, loss of biodiversity, and disruption of ecosystem functions. Human uses of estuarine resources can also be seriously impaired.

Nutrient loading, particularly nitrogen, is generally correlated with the occurrence of algal blooms. Severe toxic and noxious phytoplankton blooms are on the rise worldwide due to accelerated coastal development and associated nutrient loading to receiving waters. These blooms are typically characterized by the explosive growth of a single phytoplankton species, which is responsible for an array of negative impacts. Excessive growth of some phytoplankton species generates HABs, which variously encompass brown tides, yellow tides, red tides, and other types. The toxic forms are particularly dangerous to numerous organisms such as shellfish, finfish, as well as humans. Secondary impacts include shading effects, altered grazing patterns, and changes in trophic dynamics that are detrimental to estuarine function. A number of HAB-forming species have been recorded in the Barnegat Bay-Little Egg Harbor Estuary, including *Dinophysis* spp., *Gymnodinium* (*Karlodonium*) spp., *Heterosigma* sp., and *Prorocentrum* spp.) (Olsen and Mahoney, 2001).

More recently, emphasis has been placed on macroalgal blooms in shallow eutrophic estuaries. Green-tide forming taxa (e.g., *Enteromorpha* and *Ulva*) may be particularly problematic. When exposed to elevated nutrient levels, these plants can grow very rapidly to form sheet-like masses that drift along the estuarine floor. Such high biomasses of macroalgae can severely degrade benthic habitats and communities.

HABs, however, comprise the most serious algal blooms in estuaries, with blue-green algae, diatoms, dinoflagellates, pyrmnesiophytes, and raphidophytes well represented. They exist in three general forms (Hallegreaff, 1995; Livingston, 2000):

1. Nontoxic bloom populations reaching concentrations that eventually affect important environmental factors such as dissolved oxygen, with resulting hypoxia/anoxia ending in debilitation and/or extirpation of other populations.

2. Toxic bloom species that introduce toxic agents into associated food webs to the extent that upper trophic levels (including humans) are adversely affected.
3. Toxic bloom species that produce and release substances having direct and/or indirect effects on associated populations. These species are usually not harmful to humans, but are known to adversely affect other aquatic plant and animal species.

Although there is general correlation of HABs with elevated nutrient levels, the blooms cannot always be linked to nutrient over-enrichment. It is also unclear if dissolved organic nitrogen forms play a more significant role in their generation in some systems.

Brown-Tide Blooms

Brown-tide blooms, caused by the pelagophyte, *Aureococcus anophagefferens*, have continued to plague Barnegat Bay since 1995, the coastal bays in New York since the mid-1980's, and the Maryland coastal bays since 1998. These algal blooms can discolor the water brown and may cause negative impacts on shellfish, notably the ecologically and commercially important hard clam and scallop, as well as on seagrasses. During 2000-2002, the levels of brown-tide blooms in the Barnegat Bay-Little Egg Harbor Estuary were elevated as compared to levels in other estuaries that exhibited negative impacts on natural resources (Gastrich et al., 2004, 2005). Gastrich and Wazniak (2002) showed that elevated levels of brown tide may cause negative biotic impacts, such as a reduction in the growth of juvenile and adult shellfish (e.g., hard clams and mussels), reduced feeding rates in adult hard clams and other shellfish, recruitment failures, and even mortality of shellfish. The dense shading of these blooms may also contribute to the loss of seagrass beds, which serve as important habitat for fish and shellfish.

Abundances of *Aureococcus anophagefferens* in the estuary have been classified using the Brown Tide Bloom Index (Gastrich and Wazniak 2002) and mapped, along with salinity and temperature parameters, to their geo-referenced location using the ArcView GIS. The highest *A. anophagefferens* abundances (>10^6 cells/ml), Category 3 blooms (≥ 200,000 cells ml^{-1}), and Category 2 blooms (≥ 35,000 to ≤ 200,000 cells ml^{-1}), recurred during the 2000-20002 period of sampling and covered significant geographic areas of the estuary, especially in Little Egg Harbor. While Category 3 blooms were generally associated with warmer water temperatures (> 16^{o}C) and higher salinities (> 25-26 ppt), these factors were not sufficient alone to explain the timing or distribution of *A. anophagefferens* blooms. There was no significant relationship between brown-tide abundances and dissolved organic nitrogen measured in 2002, which was consistent with results of other studies.

Extended drought conditions, with corresponding low freshwater inputs and elevated bay salinity that occurred during the 2000-2004 period, were conducive to blooms. Abundances of *Aureococcus anophagefferens* were well above those reported to cause negative impacts on shellfish. Category 3 blooms generally occurred at water temperatures above 13-17 ^{o}C and within a salinity range between 25 and 31 ppt. An assessment of the risk of SAV habitat to brown-tide bloom categories indicates that 35% of the SAV habitat located in Barnegat Bay-Little Egg Harbor Estuary had a high frequency of Category 2 or 3 blooms for all three years of study. This is important considering that over 70% of the New Jersey's eelgrass beds are located in this system (Lathrop et al., 2001), and brown tides may pose a risk to these seagrass resources.

Although the presence of *Aureococcus anophagefferens* was first reported in New Jersey coastal bays in 1988, with blooms documented in 1995, 1997 and 1999, there were insufficient data to develop trends. A monitoring program of NJDEP has shown a trend in elevated abundances of brown tide from 2000-2002. Since there was no significant bloom in 2003 and 2004, brown-tide blooms do not occur every year in the estuary. While GIS analysis has shown that seagrass habitat areas are located in the High-Risk Category 3 bloom 'hotspot' areas that have occurred, no direct causal link has yet been established between brown-tide blooms and seagrass decline in the Barnegat Bay-Little Egg Harbor Estuary.

Managers would like to know more about the causes of brown-tide blooms and how to control them. The usual factors in algal removal are not effective for brown tides. While numerous studies have addressed some factors that may promote blooms (e.g., high salinity, warmer temperatures, organic nutrients), infection by viruses may aid in the demise of brown tide. For example, a virus specific to *Aureococcus anophagefferens* isolated during brown-tide blooms in New Jersey and New York coastal bays has the ability to lyse healthy brown-tide cells (Gastrich et al., 2002, 2004). The percent of brown-tide cells infected by the virus appears highest at the end of the blooms (Gastrich et al., 2004). These results support the hypothesis that viruses may be a major source of mortality for brown-tide blooms in regional coastal bays.

Major information gaps on brown tide that must be addressed by future investigations in the estuary are the following:

- Continuous and long-term monitoring data on the spatial and temporal occurrence of brown tides in all coastal bays.
- Environmental factors that promote, maintain, and terminate brown-tide blooms.
- More frequent shellfish stock assessments along with studies that distinguish the potential negative impacts of brown-tide blooms, as opposed to other causes of shellfish decline in these areas.
- Assessments that provide a greater understanding of the relative importance of maximum brown-tide bloom abundance vs. bloom duration, as well as specific levels of blooms on seagrass health and productivity.

Frequent phytoplankton blooms can lead to shading effects and light attenuation on seagrass beds. Both appear to impact seagrass habitat and other vital habitat in the Barnegat Bay-Little Egg Harbor Estuary. While investigations and data collection are underway on brown tides in the estuary, no studies have been initiated on the interaction of benthic macroalgae and seagrasses as well as other bottom-dwelling organisms and habitats in the system. Because excessive growth of benthic macroalgae may have greater direct impacts on seagrass beds, it is also critically important to assess the effects of this algal group on seagrasses (notably *Zostera marina*) in the estuary.

Sea Nettles

Sea nettles (*Chrysaora quinquecirrha*) have only recently become a serious problem for human use of New Jersey's coastal bays. Prior to 2000, sea nettles were not present in the coastal bays in elevated numbers. However, between 2000 and 2006 periodic blooms of the jellyfish occurred in various areas, most notably the lower salinity waters of the Barnegat Bay-Little Egg Harbor Estuary. The summer of 2004 was particularly problematic. Mid-summer abundance maxima were recorded then, with highest concentrations found north of the Toms River in embayments from Silverton to the Metedeconk River. Population eruptions of sea nettles adversely affected human use of the estuary for bathing in various areas of the Barnegat Bay.

Research scientists at the University of Maryland, who have studied sea nettle problems in Chesapeake Bay, indicate that the jellyfish blooms are coupled to elevated nutrient levels associated with fertilizer runoff and other watershed waste inputs. Therefore, the co-occurrence of sea nettle blooms and high nutrient inputs (>1 million kilograms per year of nitrogen to Barnegat Bay) infers a direct link to human activities in coastal watershed areas. A similar relationship has been established in Chesapeake Bay and its watersheds.

Global warming may be another factor in the northward expansion of jellyfish blooms in U.S. estuaries. Sea nettles thrive at temperatures above 25 ºC, and the warmer summer temperatures during the past two decades have probably fostered this expansion. Increasing nitrification of bay waters, together with rising water temperatures, spells trouble for susceptible estuarine environments.

Research scientists Jennifer Purcell (Western Washington University) and Robert Ulanowicz (University of Maryland) stress the potential dangers of sea nettle blooms on estuarine food chains. Most importantly, much of the energy flow in food chains dominated by sea nettles does not pass upward to upper trophic level organisms, thereby reducing biotic production of the system. The result is substantially altered biotic communities.

There are no quick solutions. Remedial actions that involve physical removal of sea nettles from estuarine waters are rarely successful once the jellyfish take up residence. As noted previously, attempts to net and remove jellyfish may actually increase their distribution and abundance. Probably the best approach is to reduce pollution inputs and eutrophic conditions in the estuarine waterbody. Water quality alteration must also be minimized by improving pollution controls at the watershed source and by instituting best-available stormwater controls. In addition, greater enforcement of environmental regulations is necessary, as is the establishment of nutrient criteria (which currently do not exist) for coastal waters. Therefore, the long-term solution to the sea nettle problems in New Jersey' coastal bays requires more effective administrative/management intervention.

Shellfish (Hard Clams and Scallops)

Because of its wide distribution in relation to temperature, salinity, and sediment type, as well as its long life, the hard clam, *Mercenaria mercenaria*, can serve as a primary indicator of the overall health of the Barnegat Bay-Little Egg Harbor estuary. Prior stock assessments and other studies can provide a basis for comparison. However, the lack of stock surveys of hard clams in the estuary since at least 2001 limits the decision-making capacity on shellfish resources of the estuary.

The public can easily relate to the importance of the hard clam as an indicator of estuarine health because of its value as a resource species. The Classification of New Jersey's Shellfish Waters, in accordance with the National Shellfish Sanitation Program, has been selected as a water quality indicator. This readily available information base directly relates the hard clam and its availability for harvest directly to human health and ecosystem health.

The major focus of this signature species is as an indicator of the ecological health of the estuary. For example, stock assessment information on the hard clam would provide a direct assessment of the level of abundance of the dominant filter feeder in the estuary, the level of abundance of a harvestable resource, and the identification of places where this resource may need restoration. In addition, if size-frequency distributions, box counts, and size-at-age are added to the basic population survey information, long-term trends in populations of this resource are easily determined. Thus, a record of ecosystem performance can be elucidated. It is critical, therefore, to conduct periodic surveys of hard clam stocks in the estuary.

Newly set hard clams have been shown to be more sensitive to some environmental contaminants than many standard test organisms. In standard bioassay tests, for example, newly set clams were shown to be more sensitive than *Ampelisca abdita, Ampelisca verrilli, Palaemonetes pugio, Rhepoxynius abronius,* and *Amphiiascus tenuiremis* to the heavy metal cadmium and the hydrocarbon fluoranthene. A physiological based model of hard clam population dynamics is currently being developed for Great South Bay, New York, because of the drop in clam populations in that system. This model will have the clam's responses to brown tide (an important phenomenon in the Barnegat Bay-Little Egg Harbor system) incorporated. If the base environmental data are available, it could be run to compare the responses of the hard clam in the New Jersey system to that in New York.

Chlorophyll *a*

Biocriteria should be established in the Barnegat Bay-Little Egg Harbor Estuary using chlorophyll *a* quantitative measures. Such measures are particularly important for identifying and assessing impairment of altered systems, and many states currently monitor chlorophyll *a* routinely. Historical databases can be used to characterize the reference conditions, and the chlorophyll *a* criteria can be defined by consensus of expert opinion based on analysis of the databases and thresholds levels of impacts.

Chlorophyll diagnostic photopigments are commonly used for identifying and quantifying phytoplankton functional groups and are effective indicators of phytoplankton community activity/response, including blooms, that has been linked to nutrient enrichment and other environmental stressors (Paerl et al., 2003, 2005). Phytoplankton community composition is an indicator of ecological condition and change. Diatoms, dinoflagellates, chlorophytes, cyanobacteria, and cryptomonads each have unique diagnostic photopigment signatures that are useful for identifying phytoplankton community composition. Chorophyll, therefore, is strongly recommended as a key criterion for bioassessment in the Barnegat Bay-Little Egg Harbor Estuary from which total maximum daily loads (TMDLs) can be designated.

In Chesapeake Bay, water quality criteria (i.e., water clarity and dissolved oxygen) have been developed for specific designated uses that have been defined for a variety of habitats (USEPA 2003a). As an example, Moore and his colleagues have developed water clarity criteria for the Chesapeake Bay that are protective of SAV designated use of shallow waters (Moore and Wetzel, 2000). Exceedences of these criteria are measured as a cumulative frequency distribution (CFD) over both space and time within specific designated use areas (USEPA, 2003b). Shallow water, SAV designated use areas are quantified as the single best year of SAV distribution mapped across the available 1930-2000 historical, photographic data record out to the 2-m depth contour. Attainment of the SAV designated use can be met in two ways: (1) attainment of Chesapeake Bay segment-specific SAV acreages that are based on the historical single best year composite distribution; or (2) attainment of segment-specific water clarity levels (22% of surface irradiance throughout the SAV growing season) which are applied out to the historical limits of SAV growth. Application of this approach for coastal bay systems in New Jersey will require the improvement of monitoring of SAV abundances as well as integrated measurements of water clarity, especially in shallow water areas where conditions may be different than in deeper, mid-bay areas. Since changes in the distribution and abundance of SAV can be important indicators of water quality changes over space and time, SAV can provide an important tool for understanding the cause/effect relationships necessary for management of bay eutrophication. However, this requires biotic assessment of the SAV beds in the impacted waterbody. Biocriteria can be developed from long-term quantitative measures of SAV abundance and distribution through biomonitoring programs, such as those conducted in Chesapeake Bay and Virginia coastal bays by the Virginia Institute of Marine Science.

Benthic Indices

The development of indices of benthic community condition would be another valuable tool in bioassessment of the Barnegat Bay-Little Egg Harbor Estuary. During the past decade, benthic assemblages have been used to assess water quality and environmental status and trends in regional areas (Van Dolah et al., 1999; Paul et al., 2001; Borja et al., 2003; Muniz et al., 2005). Indices that have been developed have proven valuable in delineating overall environmental health of estuarine ecosystems (Dauer, 1993; Diaz and Rosenberg, 1995; Weisberg et al., 1997; Rosenberg et al., 2004). This is so because benthic species are largely sedentary, highly responsive to habitat disturbances, and many of them have long life spans. They are more reliable indicators than drift macroalgae, plankton, and fish, and provide *in situ* measures of relative biotic integrity and habitat quality (Gibson et al., 2000). In addition, they integrate water and sediment quality conditions and play an important role in biogeochemical cycling of nutrients and other substances (Dauer, 1993; Diaz et al., 2004). Furthermore, benthic assemblages respond predictably to many natural and anthropogenic stressors, and thus have been utilized to document the effects of specific stressors including organic enrichment, hypoxia, chemical contaminants, and other factors (Weisberg et al., 1997; Rosenberg et al., 2003). Such disturbances in the benthos are typically manifested by changes in species composition, abundance, biomass, and diversity signaling successional shifts in benthic community structure (Rosenberg et al., 2004). These data will also shed light on changes in trophic structure and function, which could reflect bottom-up or top down effects. Several studies have demonstrated the value of benthic communities as indicators of ecosystem health (Dauer, 1993; Weisberg et al., 1997; Diaz et al., 2004). These studies have examined various univariate and multivariate methods or biotic coefficients for assessment of estuarine environmental status. Benthic indices employing species abundance, dominance, diversity, and other parameters are useful measures of community composition and function, and they serve as indicators of estuarine condition.

Because of their sensitivity to stress-induced changes in benthic communities, benthic indices also have utility in assessing anthropogenic impacts. The development of benthic indices reduces large biotic datasets to values which permit more meaningful statistical assessments.

Benthic indices employing species abundance, dominance, diversity, evenness, richness, and other parameters are very useful measures of community composition and function, and they serve as indicators of estuarine condition. Because of their sensitivity to stress-induced changes in benthic communities, benthic indices also have utility in assessing anthropogenic impacts. The development of benthic indices reduces large biotic datasets to values which permit more meaningful statistical assessments. Four major classes of indices are: (1) the index of biotic integrity (IBI) - multimetric; and (2) multivariate index; (3) species tolerance index; and (4) observed/expected index. The multimetric indices are habitat specific. All have in common species richness, abundance/biomass, presence of sensitive and tolerant species, and many other parameters. One potential problem is that the expectations are habitat specific and many indices are needed for a region.

The disadvantage of the multivariate index is that it is not intuitive, and it is highly dependent on the particular test dataset. The index components change when additional data become available. The species tolerance index is easy to describe, and it is habitat independent. The presence/absence of species is a sensitive metric. A major disadvantage of this index, however, is that the baseline data on species tolerances are limited. The observed/expected index identifies taxa that are expected to be present at specific types of habitats. It quantifies the presence and dominance of these species.

This index is habitat independent, readily explained, and easy to calculate. A major disadvantage, however, is that it requires a large amount of data from clean sites along habitat gradients to establish expected species along numerous habitat gradients. A few years of data should also be obtained before application.

Benthic indicators of ecological condition also target elements that characterize benthic macroinvertebrate community structure and identify opportunistic (e.g., *Mulinia lateralis*), pollution sensitive (e.g., *Ampelisca* spp.), and pollution tolerant species (e.g., *Capitella capitata*) that occupy disturbed habitats. A benthic index of biotic integrity will differentiate impaired habitats and bottom communities from those pristine or little impacted by development and anthropogenic activities. Carefully designed investigations utilizing appropriate measures of benthic condition (metrics) have proven to be useful in assessing estuarine and nearshore marine environmental status and trends.

In estuarine systems impacted by nutrient enrichment and bottom-up effects, such as the Barnegat Bay-Little Egg Harbor Estuary, the application of benthic index development is strongly recommended for biotic assessment. Metric measurements of targeted benthic assemblages leading to numeric scores and indices of biotic integrity can be subsequently incorporated into development of biocriteria for an estuarine system. Biological assessment in this case will entail a comparison of monitoring scores of the assemblages to the biocriteria that have been developed (Gibson et al., 2000). The result will be an accurate evaluation of ecosystem health useful for management decision making.

Seagrasses as Indicators

Seagrasses are also excellent bioindicators of estuarine water and sediment quality, as well as overall ecosystem health (Hemminga, 1998; Duarte, 1999; Corbett et al., 2005; Lamote and Dunton, 2006). By monitoring the distribution and abundance of seagrasses in the Barnegat Bay-Little Egg Harbor Estuary and establishing quantitative measures of acceptable limits as biocriteria, effective bioassessment of estuarine condition can be conducted. Assessing the distribution and abundance of seagrasses in lagoon-type, coastal-bay systems to track escalating eutrophication impacts is highly recommended. Since changes in seagrass distribution and abundance can occur over periods as short as weeks or months, rapid and cost effective tools are needed to determine seagrass condition and to quantify cause and effect relationships.

A two-pronged seagrass monitoring and assessment program is recommended for this estuary entailing the application of aerial photography, airborne digital scanning systems, or satellite-based remote sensing to map and monitor the seagrass beds, in conjunction with *in situ* sampling to corroborate the aerial observations (Ward et al., 1997; Moore et al., 2000; Short et al., 2002; Garono et al., 2004). Of the remote sensing methods employed, aerial photography and the acquisition of airborne imagery have been the most widely adopted. Airborne scanning systems yield high spatial resolution imagery and analog aerial photography enable investigators to visually interpret and map expanses of the beds (Lathrop et al., 2006). Groundtruthing efforts in concert with remote sensing work can consist of establishing a series of sampling transects, with an array of quadrat, core, and hand sampling sites (Short et al., 2002).

Seagrass coverage has been on the decline in many estuaries due in large part to anthropogenic activities. According to Lamote and Dunton (2006), more than 70% of the large-scale declines in seagrasses reported in a number of recent studies have been ascribed to eutrophication problems. Increased nutrient loading from surrounding watersheds and airsheds have stimulated phytoplankton and benthic macroalgal growth leading to blooms and associated shading and reduction of light availability and intensity (Brush and Nixon, 2002; Campbell, 2003). Epiphytic accumulation on seagrass blades can also cause a significant decrease in seagrass abundance (Irlandi et al., 2004). Large mats of drift macroalgae overlying seagrasses often increase sulfide production along with anoxic conditions that damage seagrass beds (Carlson et al., 1994).

More recently, high resolution, underwater videographic imaging coupled to a differential global positioning system (GIS) database has also proven to be effective for assessing the distribution, abundance, and coverage of seagrass beds (Norris et al., 1997). This approach has recently been applied to investigations of seagrass demographics in the Barnegat Bay-Little Egg Harbor, a lagoonal estuary in New Jersey (Kennish et al., 2006, 2007). High quality underwater video images of bottom habitats can be obtained using a digital video camera and recording unit. This package can generate thematic maps and the quantification of the basal area of seagrass cover for effective comparison of population data over well-defined temporal scales. This *in-situ* imaging tool offers several advantages over high-resolution, remote sensing techniques (i.e., aerial photography and satellite imaging), which yield broad spatial coverage of an estuarine system, but are not effective for assessing fine detail in spatially restricted habitat areas. In addition, remote sensing platforms are usually limited by local weather and astronomical factors (e.g., cloud cover, sun angle, and wind), estuarine surface conditions, water depth, and water clarity. Remote sensing surveys are normally limited to one imaging mission as well due to cost constraints, which may or may not miss the peak biomass period for the targeted seagrass species. Single-snapshot remote sensing missions, therefore, provide no information on the yearly temporal variability of seagrass habitat.

Quantitative measures of seagrass coverage and abundance are extremely valuable for assessing the effects of nutrient enrichment in estuaries. Historical data on seagrass distribution can be compared to results from current monitoring efforts to establish reliable biocriteria for the endemic beds. Biomonitoring of the submerged aquatic vegetation must be conducted at consistent and regular periods to establish a reliable bioassessment program.

Conclusions

The Barnegat Bay-Little Egg Harbor Estuary is an impaired system both in respect to aquatic life support and human use. An array of biotic indicators clearly shows that the estuary has impairment problems. The principal cause of these problems is nitrogen over-enrichment mediated primarily by surface runoff from the Barnegat Bay watershed and atmospheric deposition from the overlying airshed.

Nutrient enrichment of the Barnegat Bay-Little Egg Harbor Estuary is closely linked to a series of cascading environmental problems, notably increased growth of phytoplankton and benthic macroalgae (including both harmful and nuisance forms), loss of SAV, and declining shellfish resources. These problems have also led to deterioration of sediment and water quality, loss of biodiversity, and disruption of ecosystem health and function. Human uses of estuarine resources have also been impaired. The Barnegat Bay-Little Egg Harbor Estuary is a highly eutrophic system typified by algal blooms (both phytoplankton and benthic macroalgae) that can be detrimental to seagrass growth. It is important to examine the status and trends of SAV. It is equally important to investigate the macroalgae and phytoplankton resident in the estuary, most notably in respect to the blooms of these autotrophic groups. A detailed study of the structure and function of the benthic faunal community is also needed. In addition, shellfish surveys must be conducted. This information is vital for tracking biotic responses in the estuary to nutrient loading and eutrophication.

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Ecology and Oceanography of Harmful Algal Blooms:

http://www.redtide.whoi.edu/hab/nationplan/ECOHAB/ECOHABhtml.html

Bigelow Laboratory for Ocean Sciences (West Boothbay Harbor, ME):

http://www.bigelow.org/hab/

NOAA Harmful Algal Bloom Project: http://www.csc.noaa.gov/crs/habf/