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BARNEGAT BAY–LITTLE EGG HARBOR ESTUARY: CASE STUDY OF A HIGHLY EUTROPHIC COASTAL BAY SYSTEM

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Abstract. The Barnegat Bay–Little Egg Harbor Estuary is classified here as a highly eutrophic estuary based on application of the National Oceanic and Atmospheric Administration's National Estuarine Eutrophication Assessment model. Because it is shallow, poorly flushed, and bordered by highly developed watershed areas, the estuary is particularly susceptible to the effects of nutrient loading. Most of this load (~50%) is from surface water inflow, but substantial fractions also originate from atmospheric deposition (~39%), and direct groundwater discharges (~11%). No point source inputs of nutrients exist in the Barnegat Bay watershed. Since 1980, all treated wastewater from the Ocean County Utilities Authority's regional wastewater treatment system has been discharged 1.6 km offshore in the Atlantic Ocean. Eutrophy causes problems in this system, including excessive micro- and macroalgal growth, harmful algal blooms, altered benthic invertebrate communities, impacted harvestable fisheries, and loss of essential habitat (i.e., seagrass and shellfish beds). Similar problems are evident in other shallow lagoonal estuaries of the Mid-Atlantic and South Atlantic regions. To effectively address nutrient enrichment problems in the Barnegat Bay–Little Egg Harbor Estuary, it is important to determine the nutrient loading levels that produce observable impacts in the system. It is also vital to continually monitor and assess priority indicators of water quality change and estuarine health. In addition, the application of a new generation of innovative models using web-based tools (e.g., NLOAD) will enable researchers and decision-makers to more successfully manage nutrient loads from the watershed. Finally, the implementation of storm water retrofit projects should have beneficial effects on the system.

Key words: assessment; Barnegat Bay–Little Egg Harbor Estuary; eutrophication; indicators; nutrient loading; remediation.

Introduction

The Barnegat Bay–Little Egg Harbor Estuary is a nationally significant coastal system, having been designated the 28th National Estuary Program site by the U.S. Environmental Protection Agency on 10 July 1995. Little Egg Harbor is also included within the boundaries of the Jacques Cousteau National Estuarine Research Reserve, having been designated the 22nd program site of the National Oceanic and Atmospheric Administration (NOAA)-operated National Estuarine Research Reserve System on 20 October 1997. The ecological, commercial, and recreational importance of the Barnegat Bay–Little Egg Harbor Estuary has been the subject of two comprehensive volumes (Kennish and Lutz 1984, Kennish 2001*a*).

The Barnegat Bay–Little Egg Harbor Estuary is a shallow, lagoonal back-barrier system located along the central New Jersey coastline between 39°31′ N and 40°06′ N latitude and 74°02′ W and 74°20′ W longitude (Fig. 1) (Kennish 2001*b*). It is a highly eutrophic system susceptible to water quality degradation because of relatively low freshwater inflow, poor flushing, and highly developed coastal watershed areas. As such, it is representative of many other coastal bay systems in the United States affected by accelerated urban development, extensive construction activities (e.g., dredging, infilling, bulkheading, lagoon construction), industrial/

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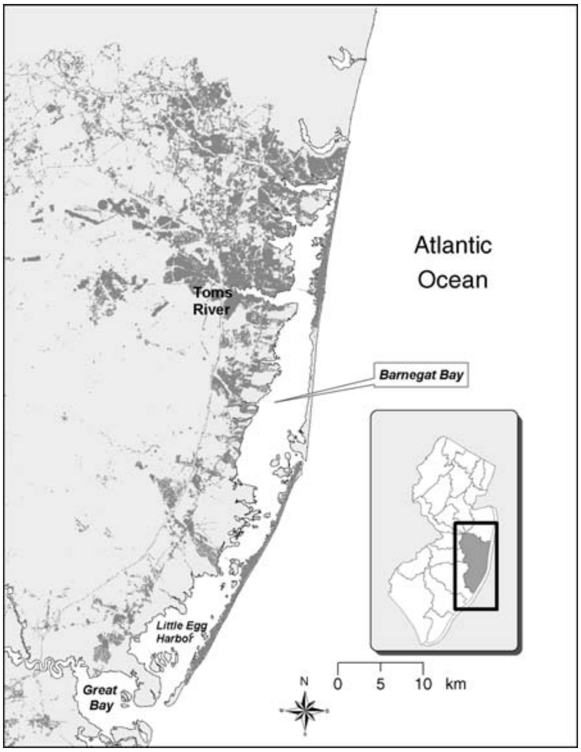

FIG. 1. Map of the Barnegat Bay–Little Egg Harbor Estuary. The inset shows the location of the estuary with respect to the state of New Jersey, USA. Data sources: New Jersey Department of Environmental Protection, New Jersey Department of Transportation, and Center for Remote Sensing and Spatial Analysis.

military operations, agricultural waste inputs, recreational pursuits (boating and associated marinas), and domestic water uses that contribute to nutrient loading problems (Kennish 1992, Bricker et al. 1999, Livingston 2002, 2005). Of greatest concern are nonpoint source nitrogen inputs that peak in waters of the northern estuary in closest proximity to the most heavily developed adjoining landmasses. Nutrient enrichment in the estuary has been linked to an array of cascading environmental problems, such as increased micro- and macroalgal growth, harmful algal blooms, bacterial pathogens, high turbidity, altered benthic invertebrate communities, impacted harvestable fisheries, and loss of essential habitat (e.g., seagrass and shellfish beds) (Kennish 2001*a*, *c*).

A science and management symposium ("Impacts to Coastal Systems") was held at Rutgers University on 7–8 April 2004 to assess in part the effects of nutrient enrichment in the Barnegat Bay–Little Egg Harbor Estuary, to examine the management strategies necessary for mitigating these effects, and to formulate recommendations for the revitalization/remediation of resulting degraded habitats in the system. Excessive amounts of inorganic nitrogen enter the estuary from the coastal watershed and airshed. Allocthonous organic carbon derived primarily from the watershed and in situ organic carbon production release additional nutrients to estuarine waters via bacterial decay, thereby exacerbating eutrophic conditions.

A specific challenge to scientists and managers attending the symposium was to formulate recommendations for an effective plan of action based on sound science to improve water quality and habitat conditions in the estuary. Although assessment of the Barnegat Bay–Little Egg Harbor Estuary was the central theme of the Rutgers symposium, other hydrologically and morphologically diverse lagoonal estuaries along the U.S. east coast were also investigated to provide a range of ecological and management comparisons for potential use in this system. Included here are the Great South Bay (New York), New Jersey inland bays, Delaware coastal bays, Maryland coastal bays, Virginia coastal bays, as well as Pamlico Sound and Albemarle Sound (North Carolina). Anthropogenic activities, nutrient and other pollutant inputs, and natural forcing factors affect all of these systems. Hence, similar environmental issues encountered in New Jersey coastal bays are faced by resource managers in coastal communities elsewhere along the U.S. east coast. This work focuses on eutrophication and ancillary water quality problems in the Barnegat Bay–Little Egg Harbor Estuary with reference to these other lagoonal systems.

Physicochemical Characteristics

The Barnegat Bay–Little Egg Harbor Estuary is a long and narrow water body extending north-south for ~70 km along the central New Jersey coastline (Fig. 1). It is only ~2–6 km wide and 1.5 m deep at mean low

TABLE 1. Physicochemical characteristics of lagoonal estuaries in the Mid-Atlantic and South Atlantic regions.

Coastal embayment	Watershed area (km^2)	Population in watershed	Surface area (km^2)	Depth (m)
Barnegat Bay	1730	520 000	280	1.50
New Jersey inland bays	3431	330 178	278	1.11
Delaware inland bays	560	26 893	72	1.39
Maryland inland bays	283	15 166	54	1.92
Chincoteague Bay	487	5706	335	1.94
Great South Bay	1733	2 084 075	383	1.10
Albemarle Sound	45 036	1 274 559	2497	2.50
Pamlico Sound	26 841	1 380 000	5588	2.47

water, with a surface area of 280 km^2. Water temperature ranges from −1.5°C to 30°C, and salinity ranges from ~0.010 mg/kg to 0.032 mg/kg. Characterized by semidiurnal tides with a tidal range of <0.5–1.5 m, the estuary is well mixed. Current velocities are typically <0.5–1.5 m/s. Circulation is restricted by the extreme shallowness of the bay and a barrier island complex breached only at Barnegat Inlet and Little Egg Inlet. As a result, the flushing time exceeds 70 days in summer when nutrient enrichment occurs, which promotes eutrophication problems. Table 1 provides data comparing the physicochemical characteristics of the estuary to several other shallow lagoonal systems in the Mid-Atlantic and South Atlantic regions.

The Barnegat Bay watershed covers an area of 1730 km^2, with >500 km^2 of developed land. Small coastal-plain rivers and streams drain the watershed, and most of the freshwater discharge (>80%) derives from groundwater influx. The ratio of the watershed area to the estuarine surface area is ~6:1. The human population in the watershed has increased exponentially over the past 60 years to more than half a million year-round residents. Since 1972, the amount of developed land in the watershed has risen from 19% to >30% (Kennish 2001*a*).

Nutrient loading to the estuary has accelerated concomitantly with development in the watershed. Hunchak-Kariouk and Nicholson (2001) calculated a total nitrogen load to the estuary amounting to $\sim 7.9 \times 10^5$ kg N/yr. Of this total load, ~50% (3.9×10^5 kg N/yr) was derived from surface water inflow, ~39% (3.0×10^5 kg N/yr) from direct atmospheric deposition, and ~11% (9.1×10^4 kg N/yr) from direct groundwater discharges. The total nitrogen load from the watershed was based on the measure of both dissolved (ammonium and nitrate plus nitrite) and organic nitrogen species in major river basins. Because nitrogen inputs from storm water runoff, sediments, and tidal influx were not included in these calculations, the total nitrogen load was considered to be an underestimate. No point source inputs of nitrogen exist in the Barnegat Bay watershed. Since 1980, all treated wastewater from the Ocean County Utilities Authority's regional wastewater treatment system has been discharged 1.6 km offshore in the Atlantic Ocean.

Seitzinger et al. (2001) ascertained that nutrient levels are highest in the northern part of the estuary due to the effects of heavy coastal watershed development in upper Ocean County and Monmouth County. The mean concentrations of nitrate plus nitrite are typically <4 μmol/L in the estuary, with lowest levels observed in summer because of rapid biotic uptake. Highest levels of nitrate plus nitrite are evident in the winter when autotrophic production is lowest. Mean ammonium concentrations are usually <2.5 μmol/L, and peak levels exist in summer. Total nitrogen concentrations generally span ~20–80 μmol/L; most nitrogen in the estuary (87–90%) occurs in organic form. Phosphate concentrations are less than those of nitrate, nitrite, and ammonium, ranging within 0–1 μmol/L.

Kennish et al. (2005), conducting extensive nutrient sampling in Little Egg Harbor (39°35′ N, 74°14′ W) during 2004, found very low nitrate plus nitrite concentrations (0–0.8 μmol/L), as well as low ammonium levels (0–2.1 μmol/L). Total dissolved nitrogen amounted to 0–24.1 μmol/L. Phosphate levels were also low (0.03–1.21 μmol/L). Much higher concentrations of dissolved silica were commonly recorded (0–26.4 μmol/L). The nutrient concentrations documented by Kennish et al. (2005) are consistent with those of Seitzinger et al. (2001).

Eutrophic Indicators

Nutrient loading of Barnegat Bay–Little Egg Harbor estuarine waters has been linked to the initiation and proliferation of harmful algal blooms (HABs), alteration of benthic communities, the loss of essential habitat (e.g., seagrass and shellfish beds), and the decline of harvestable fisheries. Progressive eutrophication threatens the ecosystem structure and function. Its insidious effects can eventually lead to permanent alteration of biotic communities and essential habitat, nonproductive commercial and recreational fisheries, and declining human uses of the estuary.

Symptoms of eutrophication in the estuary have increased during the past decade (Kennish 2001*a*). Phytoplankton production in summer approaches 500 g $C \cdot m^{-2} \cdot yr^{-1}$, which exceeds that of many coastal bay systems worldwide (Fig. 2). Mean chlorophyll *a* values, in turn, range within ~15–20 μg/L during the warmer

Table 1. Extended.

Tide height (m)	Exchange time (d)	Average salinity (mg/kg)	Total suspended solids (kg/yr)	Total nitrogen (Gg/yr)	Total phosphorus (Gg/yr)
0.24	71	0.020	74.0	1.19	0.17
1.00	27	0.028	99.8	1.89	0.27
0.53	61	0.026	89.4	0.22	0.02
0.67	253	0.028	1.88	0.24	0.03
0.50	183	0.029	6.07	0.08	0.01
0.57	199	0.016	153.0	4.69	0.90
0.58	140	0.010	354.0	11.40	0.82
0.22	378	0.013	50.9	0.27	0.01

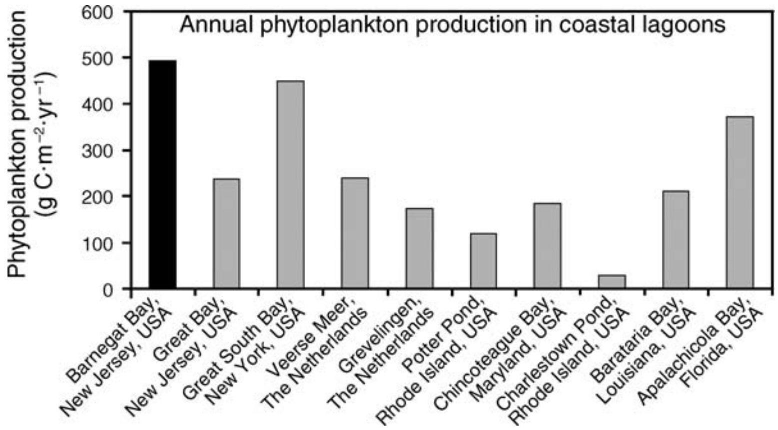

FIG. 2. Annual phytoplankton production in Barnegat Bay compared to several other coastal lagoons (from Styles et al. 1999). Data sources: Barnegat Bay, New Jersey, USA (Moser 1997); Great Bay, New Jersey, USA (MacDonald 1983); Great South Bay, New York, USA (Lively et al. 1983); Veerse Meer and Grevelingen, The Netherlands (Nienhuis 1993); Potter Pond, Rhode Island, USA (Nowicki and Nixon 1985); Chincoteague Bay, Maryland, USA (Boynton 1974); Charleston Pond, Rhode Island, USA (Nixon and Lee 1981); Barataria Bay, Louisiana, USA, and Apalachicola Bay, Florida, USA (Nixon and Pilson 1983).

months of the year when eutrophication impacts are manifested in the estuary (Kennish et al. 2005). Maximum phytoplankton production and biomass occur in the northern estuary where peak nitrogen levels have been recorded (Seitzinger et al. 2001). Highest turbidity also exists in this area of the estuary (Kennish 2001*a*).

Recurring phytoplankton blooms have been reported, including a series of intense picoplanktonic events. For example, Olsen and Mahoney (2001) recorded blooms of the pelagophyte, *Aureococcus anophagefferens*, in Little Egg Harbor during late spring and summer in 1995, 1997, 1999, and 2000. Additional brown tide blooms were observed in 2001 and 2002 (M. Gastrich, *personal communication*). Cell counts of *A. anophagefferens* during these episodic blooms typically exceeded 10^6 cells/mL, with peak cell counts surpassing 2×10^6 cells/mL during 1999 (Table 2). Similar brown tide eruptions have been recorded in Maryland coastal bays and elsewhere (Glibert et al. 2001).

Negative effects of brown tide blooms may have contributed to the long-term decline of hard clams (*Mercenaria mercenaria*) and submerged aquatic vegetation (SAV) (*Zostera marina* and *Ruppia maritima*) in Little Egg Harbor. Brown tides cause a reduction of hard clam feeding and growth (Gastrich and Wazniak 2002), and may render the bivalve more susceptible to disease and predation (Kraeuter 2001). State surveys of hard clams in Little Egg Harbor revealed a 67% decrease in stock levels between 1985 and 2001 (NJDEP 2002). Bologna et al. (2000) showed that total SAV coverage in Little Egg Harbor declined by 62% between the mid-1970s and 1999. Coverage of SAV may have also decreased by ~2000–3000 ha in Barnegat Bay between the 1960s and 1990s; the most significant reduction of the beds appears to have occurred in the central and northern bay areas (Fig. 3), although different mapping techniques have confounded the results (Lathrop et al. 2001). The shading effects of frequent phytoplankton blooms, as well as increased growth of epiphytic algae and wasting disease (i.e., infestation by the slime mold, *Labyrinthula zosterae*), may have contributed to losses of SAV beds in the system (Bologna et al. 2000, Kennish 2001*d*). The effects of many of these stressors, even over a short-term period, can be significant. For example, in Chesapeake Bay, Moore et al. (1997) found that month long pulses in turbidity during the growing season can result in significant losses of *Z. marina*.

Olsen and Mahoney (2001) and Livingston (2002) noted the occurrence of other HAB species in the

TABLE 2. Number of *Aureococcus anophagefferans* recorded in the Barnegat Bay–Little Egg Harbor Estuary during the 2000–2004 period.

Year	No. samples	Mean concentration (no. cells/mL)	Standard deviation	Maximum concentration (no. cells/mL)
2000	248	190 488	423 637	2 155 000
2001	148	246 540	416 598	1 883 000
2002	128	281 922	316 737	1 561 000
2003	136	8987	8616	54 000
2004	155	15 686	10 194	49 000

Note: Data are from the New Jersey Department of Environmental Protection.

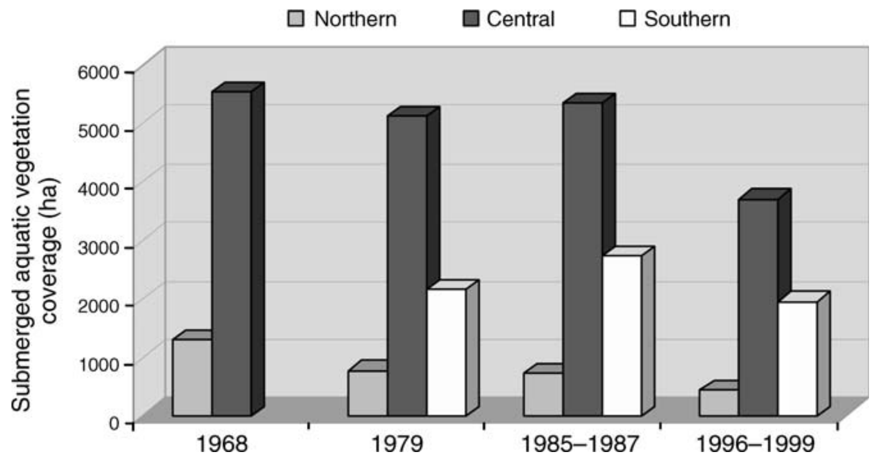

FIG. 3. Areal coverage of seagrass meadows in Barnegat Bay from the late 1960s to the late 1990s.

estuary, including the dinoflagellates *Dinophysis acuta, D. acumkinata, Prorocentrum lima, P. micans, P. minimum,* and *P. triestinum*, as well as *Scripsiella trochoidea* (=*Peridinium trochoideum*), *Protoperidinium brevipes,* and *Gymnodinium* spp. (now *Karlodonium*). The raphidophyte *Heterosigma* sp. is another toxic species also observed in the system. It is unknown if these species displaced natural phytoplankton assemblages during bloom events and if changes in phytoplankton community structure have affected secondary production in the system.

Blooms of benthic macroalgae are also becoming more frequent and problematic in the estuary (Bologna et al. 2000, 2001, Kennish et al. 2005). The filamentous or sheet-like forms (i.e., *Cladophora* spp., *Enteromorpha* spp., *Gracilaria tikvahia*, and *Ulva lactuca*) are particularly troubling because they grow as thick mats in nutrient-rich areas (Bologna et al. 2000, 2001, Kennish et al. 2005) and can significantly decrease or even preclude light transmission necessary for the growth of microphytobenthos and SAV (Valiela et al. 1997*a*, Hauxwell et al. 2001, 2003). When nutrient levels are high, these ephemeral macroalgal species grow rapidly and spread quickly over the estuarine floor. Large amounts of macroalgal biomass may not only reduce SAV photosynthetic potential, but also give rise to high biological oxygen demands through microbial respiration processes (Holmer 1999). The net effect is a decrease in oxygen levels and an increase in hydrogen sulfide of bottom sediments, both of which may be detrimental to SAV (Goodman et al. 1995). In extreme cases, benthic hypoxia/anoxia may develop and persist for an extended period of time. Altered sediment geochemistry, elevated turbidity, and diminished light availability associated with macroalgal blooms pose a serious threat to SAV survival, and beds of vascular plants are commonly lost under these conditions. The loss of SAV beds eliminates essential habitat for many finfish and benthic invertebrate populations (Kennish 2001*c*). The faunal communities are therefore less productive, and the absence of SAV promotes greater rates of erosion that further impact the benthic habitat.

Bologna et al. (2001) chronicled the effects of a benthic macroalgal bloom in the Barnegat Bay–Little Egg Harbor Estuary during the summer of 1998. They initially recorded a macroalgal bloom in June that led to substantial algal-detrital loading to *Z. marina* beds throughout the summer and into the fall at rates >400 g ash free dry mass/m^2. The high detrital flux to the bay bottom smothered SAV in several locations, causing significant dieback of the beds. Hence, benthic macroalgal blooms appear to be directly responsible for the loss of seagrass habitat in the estuary, and they must be considered, together with nutrient loading and phytoplankton blooms, for effective management of coastal resources. To improve ecosystem functioning, it is vital to first reduce nutrient loading from surrounding coastal watersheds and airsheds.

The abundance of *Z. marina* populations in Chesapeake Bay and elsewhere has been strongly linked to water column light availability (Dennison et al. 1993, Moore et al. 2000, Moore 2001, Kemp et al. 2004). The correspondence between light availability and *Z. marina* depth of occurrence in U.S. east coast systems suggests that SAV distribution to 1 m depth can be expected when spring through fall illumination penetrates to ~1 m depth. Secchi readings for Barnegat Bay are typically ~1 m (Seitzinger and Styles 1999); therefore, in most areas, SAV growth to 1 m can be expected, given the absence of episodic phytoplankton blooms or other contributing factors (Lathrop et al. 2001). Recent surveys (Kennish et al. 2005) indicate that SAV extends to at least 1 m depth in the estuary. The declines observed in SAV populations in the bay, especially at deeper depths in the more northern regions of the estuary, suggest that there may be significant decreases in light that is available for SAV photosynthesis in more developed areas of the system. In addition, some of the

TABLE 3. Summary of the Assessment of Estuarine Trophic Status (ASSETS) application to the Barnegat Bay–Little Egg Harbor Estuary based on data from Hunchak-Kariouk and Nicholson (2001), Kennish 2001*b*, *c*, and Seitzinger et al. (2001). Overall ASSETS rating: "bad."

Parameter	Value
Pressure: overall human influence (OHI) index (high); ASSETS score 1	
Susceptibility method (ecosystem assessment rating: high)	
Dilution potential	low
Flushing potential	moderate
Nutrient inputs method (ecosystem assessment rating: high)	
Nutrient input	high
State: overall eutrophic condition (OEC) index (high); ASSETS score 1	
Primary symptom method (ecosystem assessment rating: high)	
Chlorophyll *a*	high
Macroalgae	high
Secondary symptom method (ecosystem assessment rating: high)	
Submerged aquatic vegetation	high
Nuisance and toxic blooms	high
Response: Determination of future outlook (DFO) index (improve, low); ASSETS score 4	
Future nutrient pressures	decreasing

Notes: Index categories appear in parentheses following index names, with ASSETS score appearing thereafter. Ecosystem assessment ratings appear in parentheses following method names.

SAV dieback appears to be attributable to smothering by macroalgal blooms or possibly to hypoxia resulting from macroalgal decomposition, although it is unclear which process predominates in this system.

EUTROPHICATION ASSESSMENT

The National Oceanic and Atmospheric Administration's National Estuarine Eutrophication Assessment (NEEA) model can be used to determine the magnitude, severity, and location of eutrophic conditions in estuarine systems (Bricker et al. 1999). The model employs a pressure–state–response framework to assess eutrophication in three component parts: *pressure*, overall human influence on development of conditions; *state*, overall eutrophic conditions within a water body; and *response*, determination of future outlook for conditions within the system. A full description of the original method as applied to estuarine systems can be found in Bricker et al. (1999). Details of modifications are provided by Bricker et al. (2003). Here, we apply the NEEA model to Barnegat Bay to assess eutrophic conditions (Table 3).

NEEA application to Barnegat Bay

Pressure, overall human influence (OHI).—Overall human influence for Barnegat Bay is "high" based on high susceptibility, because the bay has a low flushing rate (Kennish 2001*b*), moderate ability to dilute nutrients, and high loading based on loading susceptibility model results of 90% (high) (Table 3).

State, overall eutrophic condition (OEC).—The Barnegat Bay primary symptom rating is "high" based on high chlorophyll *a* (90th percentile is 22 g/L, spatial coverage is high, and frequency of occurrence is periodic) and observed macroalgal abundance problems (no data for epiphytes). Secondary symptoms are high, based on losses of SAV, although this may be partly from disease and problem occurrences of HABs (insufficient data for dissolved oxygen). These determinations give an OEC value of high (Table 3).

Response, determination of future outlook (DFO).—The DFO for Barnegat Bay, based on predicted population increase, planned management actions, and expected changes in watershed uses, is "improve low" given planned management actions to be implemented in the future (see *Impact remediation*).

Synthesis.—The determination for Barnegat Bay combines the OEC, OHI, and DFO values into a single overall rating. The high pressure and state conditions of the bay, despite expected improvements in future conditions, signify a highly impacted water body. Therefore, application of the NEEA model indicates that Barnegat Bay is now a highly eutrophic system, which is up from the moderate eutrophic rating of the bay during the early 1990s (Kennish 2001*a*). A highly eutrophic ranking is typical of many shallow lagoonal systems having long residence times (Bricker et al. 1999).

NITROGEN LOADS AND NITROGEN YIELDS

The human population within the Barnegat Bay watershed has increased exponentially over the past 60 years to more than half a million year-round residents (Fig. 4). Nearly a million people inhabit the watershed during the summer season, reflecting the importance of the region for tourism. Nutrient inputs to the estuary have increased concomitantly with the burgeoning watershed population (Kennish 2001*d*). Watershed-level nitrogen load estimates for Barnegat Bay have been developed by Moser et al. (1998), Alexander et al. (2000), and Hunchak-Kariouk and Nicholson (2001).

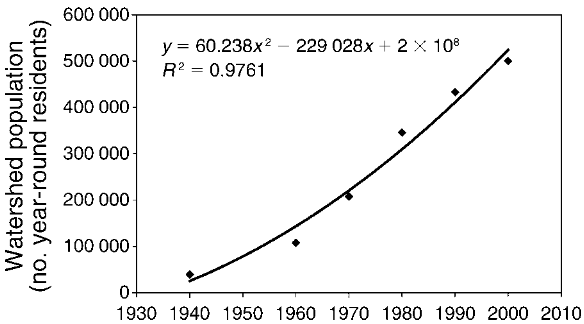

FIG. 4. Human population growth in the Barnegat Bay watershed over the 60-yr period 1940–2000.

Nutrient analysis of a long-term (USGS) gauging site on the Toms River near the town of Toms River clearly shows evidence of increased levels of inorganic nitrogen over the past 20 years (Hunchak-Kariouk and Nicholson 2001). Removing estimates of nitrogen loads associated with atmospheric deposition onto the open waters of Barnegat Bay, the loads associated with watershed-level runoff (which includes point source loads upstream of gauge locations) can be calculated. Watershed-level nitrogen load estimates for Barnegat Bay result in total nitrogen yield estimates of 4.1 kg $N \cdot ha^{-1} \cdot yr^{-1}$ (Moser et al. 1998), 8.6 kg $N \cdot ha^{-1} \cdot yr^{-1}$ (Alexander et al. 2000), and 3.5 kg $N \cdot ha^{-1} \cdot yr^{-1}$ (Hunchak-Kariouk and Nicholson 2001). The mean value of watershed-level nitrogen yield estimates for these three nutrient loading models is 5.4 kg $N \cdot ha^{-1} \cdot yr^{-1}$.

We have applied the NLOAD model of Bowen et al. (2007) to calculate the land-derived nitrogen load from the Barnegat Bay watershed to the receiving estuary. Using this model, the total nitrogen load to Barnegat Bay, after accounting for losses within the watershed, is calculated to be 6.9×10^5 kg N/yr (3.9 kg $N \cdot ha^{-1} \cdot yr^{-1}$). This value is nearly equal to the estimate derived by Moser et al. (1998) (4.1 kg $N \cdot ha^{-1} \cdot yr^{-1}$). It does not account for internal loading or direct atmospheric deposition on the bay surface, although other models within NLOAD do account for these sources of nitrogen. Application of the NLOAD model indicates that 71% of the load originated from atmospheric sources, 29% from fertilizer sources, and 0% from wastewater sources (the entire Barnegat Bay watershed is now sewered and the outfall bypasses the estuary). The NLOAD model can be further used to estimate the nitrogen concentration in the estuary, to simulate build-out scenarios, or to determine the effects of various management options in the Barnegat Bay watershed.

Land use patterns and watershed-level nutrient loads for Barnegat Bay can be compared with those of four Florida estuaries (i.e., Tampa Bay, Sarasota Bay, Lemon Bay, and Charlotte Harbor), which appear to respond in a similar manner to patterns of land development (Tomasko et al. 2005). A strong relationship is evident among these systems between the degree of urbanization of their watersheds and the watershed-level nitrogen yields (Fig. 5). The present-day degree of urbanization in the Barnegat Bay watershed is higher than that of Tampa Bay in 1990 (24%), but lower than values for Lemon Bay and Sarasota Bay (43% and 48%, respectively; Tomasko et al. 2001). In southwest Florida, only Charlotte Harbor has a less-developed watershed than Barnegat Bay (7%; Squires et al. 1998). This technique can be used to derive an estimate of watershed-level nitrogen loads that might have occurred prior to large-scale human modifications of the watershed. From the above figures, the best-fit relationship between nitrogen yields and the degree of urbanization

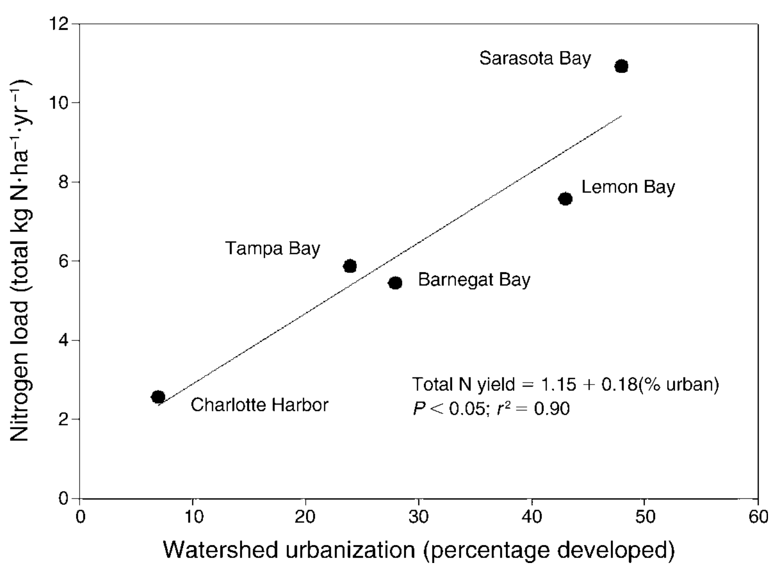

FIG. 5. Watershed-level total nitrogen load estimates for the Barnegat Bay–Little Egg Harbor Estuary relative to those of Charlotte Harbor, Tampa Bay, Lemon Bay, and Sarasota Bay, Florida, USA.

of the watershed calculates to the following:

$$y = 1.7x + 1.1 \quad (1)$$

where y represents watershed-level nitrogen yields (measured in kg $N \cdot ha^{-1} \cdot yr^{-1}$) and x is the degree of urbanization (development) of the watershed.

If the y-intercept of this relationship is used to denote the watershed-level nitrogen yield associated with a lack of human modification (i.e., the yield with zero percent development), then the "baseline" nitrogen yield estimate is 1.1 kg $N \cdot ha^{-1} \cdot yr^{-1}$. The mean total nitrogen yield estimate for Barnegat Bay (from the loading models of Moser et al. [1998], Alexander et al. [2000], and Hunchak-Kariouk and Nicholson [2001]) is 5.4 kg $N \cdot ha^{-1} \cdot yr^{-1}$. Consequently, if one omits impacts from direct atmospheric deposition, a preliminary conclusion would be that total nitrogen loads into Barnegat Bay from the watershed may be nearly five times higher than those that occurred prior to widespread development of the watershed.

Barnegat Bay and most estuaries in southwest Florida have experienced various forms of water quality and habitat degradation over the past few decades. At present, nonpoint source loads are the primary sources of nitrogen loads into Barnegat Bay and southwest Florida estuaries. If point source nitrogen loads are appropriately reduced, watershed-level nonpoint source nitrogen loads can be predicted based on the degree of urbanization of the individual watershed. From these relationships, specific numeric goals can be developed for controlling nonpoint source nitrogen loads. With adequate monitoring data, sub-basins within watersheds can be prioritized for their area-specific nitrogen loads. By targeting specific sub-basins, projects for storm water retrofits can be developed to implement an effective strategy for nonpoint source nitrogen load reduction.

Reduction of nutrient loading has been an effective management strategy for ameliorating eutrophication problems in some estuaries, and should be aggressively pursued for the Barnegat Bay–Little Egg Harbor estuarine system. For example, Hillsborough Bay, a subdivision of Tampa Bay, Florida, experienced a significant decrease in phytoplankton biomass and the rejuvenation of SAV beds as water transparency and dissolved oxygen concentrations increased in response to declining nutrient inputs following the implementation of advanced wastewater treatment in the watershed and tighter controls on fertilizer influx from watershed areas (Johansson 1991, Smith et al. 1999, Tomasko et al. 2005). Similarly, the application of improved wastewater treatment in cities and towns surrounding Long Island Sound has greatly reduced nutrient inputs to the system and contributed to a marked improvement in water quality (Kennish 2000). In upstream segments of the eutrophying Neuse River Estuary, phosphorus input controls via P-detergent bans and advanced wastewater treatment have eliminated nuisance cyanobacterial blooms and improved water quality (Paerl et al. 2006).

East Coast Lagoonal Estuaries: Comparative Analysis

Shallow coastal bays along the east coast of the United States have witnessed significant ecological changes in response to nutrient loading from coastal watersheds and airsheds. Lagoonal systems characterized by restricted water circulation, poor flushing, shallow depths, and heavily populated watersheds are particularly susceptible to nutrient enrichment impacts (Boynton et al. 1996, Kennish 2002). The Barnegat Bay–Little Egg Harbor Estuary and similar embayments, such as the Great South Bay (NewYork), Rehoboth Bay (Delaware), Newport and Sinepuxent Bays (Maryland), and Chincoteague Bay (Maryland and Virginia), provide examples. Even much larger lagoonal systems (e.g., Pamlico Sound) have experienced nutrient loading problems (Piehler et al. 2004, Paerl et al. 2006). These estuaries have also been impacted by natural stressors, including elevated hurricane and tropical storm activity, droughts, and large variations in tributary discharges and concomitant fluxes in nutrients and turbidity. Distinguishing and integrating the impacts of stochastic and human stressors in time and space are essential for understanding anthropogenically driven change of biodiversity and function, notably that attributable to eutrophication.

Mid-Atlantic and South Atlantic regions

The lagoonal back-barrier systems in New York, New Jersey, Delaware, Maryland, and Virginia are coastal physiographic features characterized by shallow depths and shoals, minimal freshwater inputs, restricted basin circulation, poor flushing, and typically well-mixed water columns. These bar-built estuaries are beset by an array of similar anthropogenic problems across the region, with extensive nutrient enrichment, habitat loss and alteration, and turbidity-induced sediment inputs from adjoining watersheds. Symptoms of eutrophication are widespread, including massive algal blooms, epiphytic overgrowth, impaired habitats and harvestable fisheries, and altered trophic structure. Some of the most severe and pervasive eutrophic conditions are manifested in these enclosed bays.

Primary production derives from multiple plant subsystems in these shallow coastal bays, notably phytoplankton, benthic algae, and seagrasses that often contribute to elevated organic carbon loading. While seagrass communities have declined in a number of these bays since the 1970s due to nutrient enrichment, they have increased in abundance in others (e.g., Delmarva coastal bays). For example, Orth et al. (2006) reported an increase in the areal cover of eelgrass (*Zostera marina*) in the four northern bays of the Delmarva Peninsula amounting to 5190 ha between 1986 and 2003.

In the Mid-Atlantic region, the following coastal bay systems are compared to the Barnegat Bay–Little Egg Harbor Estuary: Great South Bay (New York); Southern inland bays to Cape May Inlet (New Jersey inland bays); Rehoboth, Indian River, and Little Assawoman bays (Delaware inland bays); Assawoman Bay, St. Martin River, Isle of Wight Bay, Sinepuxent Bay, Newport Bay, and northern Chincoteague Bay (Maryland coastal bays); Southern Chincoteague Bay (Virginia coastal bays); and Magothy, South, Cobb, Spider Crab, and Hog Island bays (Virginia coastal bays).

In the South Atlantic region, Pamlico Sound and Albemarle Sound are compared to the Barnegat Bay–Little Egg Harbor Estuary. Pamlico Sound is the largest lagoonal estuary in the United States. Its physicochemical characteristics are listed in Table 1 along with those of the Albemarle Sound and the aforementioned lagoonal systems of the Mid-Atlantic region.

Great South Bay (New York).—The watershed population surrounding Great South Bay is five times greater than that surrounding the Barnegat Bay–Little Egg Harbor Estuary, but high eutrophic conditions exist in both water bodies. The principal land use in the coastal watersheds is residential development. Nuisance algal blooms occur in the two bays, with moderate to high chlorophyll *a* concentrations (5 μg/L to >20 μg/L) being recorded (Bricker et al. 1997, 1999, Kennish et al. 2005). Epiphytic algal growth and moderate loss of submerged aquatic vegetation (SAV) have also been documented in these systems. Nitrogen concentrations are low to moderate (<0.1–1 mg/L) as are phosphorus concentrations (<0.01–1 mg/L) (Bricker et al. 1997, 1999, Kennish 2001*a*). Anoxic and hypoxic events periodically take place in Great South Bay, but not in the Barnegat Bay–Little Egg Harbor Estuary. Elevated nutrient inputs in summer, shallow depths, and low flushing rates promote eutrophic conditions.

New Jersey inland bays.—The moderate concentrations of nitrogen (0.1–1 mg/L) and moderate concentrations of chlorophyll *a* (5–20 μg/L) registered in the New Jersey inland bays are similar to those in the Barnegat Bay–Little Egg Harbor Estuary (Bricker et al. 1997, 1999). Turbidity levels are high in these inland systems. Nevertheless, they are categorized as having a low eutrophic condition because of the few nuisance or toxic algal blooms observed, low abundance of macroalgae, and absence of anoxic/hypoxic events. Little, if any, SAV cover has been delineated in the bays.

Delaware inland bays.—These shallow bays are highly eutrophic due to elevated concentrations of nitrogen (>1 mg/L) and phosphorus (>0.1 mg/L) (Bricker et al. 1997, 1999). The primary land use in the Delmarva coastal watersheds is agriculture, which accounts for much of the nutrient input. Chlorophyll *a* (>20 μg/L) and turbidity levels (Secchi disk depths, <1 m) are also high in these partially mixed estuaries (Bricker et al. 1997, 1999). In contrast to the Barnegat Bay–Little Egg Harbor Estuary, salinity stratification is common in spring. Flushing is very low in Rehoboth Bay (~80 d) and Indian River Bay (90–100 d), resulting in the retention of nutrients and significant phytoplankton blooms and high macroalgal abundance that have eliminated SAV beds. The symptoms of eutrophication observed in these stressed systems parallel those noted in the Barnegat Bay–Little Egg Harbor Estuary (Kennish 2001*a*).

Maryland coastal bays.—These complex systems comprise six interconnected water bodies that extend along most of the Maryland coastline. They are largely nonstratified and hence differ from the partially mixed condition of the Delaware inland bays. Freshwater delivery to the bays is low because the watershed areas are relatively small, particularly when compared to the river-dominated Chesapeake Bay system (Boynton et al. 1996). Water replacement times in the coastal bays, therefore, tend to be slow, as they are in the Barnegat Bay–Little Egg Harbor Estuary.

The principal watershed land use is agriculture, unlike the predominant residential development of the Barnegat Bay watershed, although there is increasing industrial-scale poultry production (Orth et al. 2006). Price (1997) noted that runoff accounts for 22% of the nitrogen and 34% of the phosphorus entering the coastal bays, with another 32% of the nitrogen and 16% of the phosphorus deriving from atmospheric deposition. Chicken and hog facilities are responsible for 32% of the nitrogen and 32% of the phosphorus inputs. The remaining nitrogen and phosphorus originate from groundwater. The total nitrogen load to the lower bays and upper bays is 2.4–3.1 g $N{\cdot}m^{-2}{\cdot}yr^{-1}$ and 4.1–6.5 g $N{\cdot}m^{-2}{\cdot}yr^{-1}$, respectively, which is considerably less than that of the Delaware inland bays (106 g $N{\cdot}m^{-2}{\cdot}yr^{-1}$) (Boynton et al. 1996). The watershed-to-water ratio for the Maryland coastal bays (~1:1) is also much lower than the ratio for the Delaware inland bays (~10:1) and a likely cause of the nitrogen loading differences between the systems.

Water quality differences exist between the northern coastal lagoons (i.e., Assawoman Bay, Isle of Wight Bay, Sinepuxent Bay, and Newport Bay) and Chincoteague Bay. For example, nutrient-loading rates are generally higher in the northern inland bays and tributary creeks than in Chincoteague Bay (Orth et al. 2006). Boynton et al. (1996) reported annual loading rates ranging from 2.4 g $N{\cdot}m^{-2}{\cdot}yr^{-1}$ (Sinepuxent Bay) to 39.7 g $N{\cdot}m^{-2}{\cdot}yr^{-1}$ (St. Martin River). Loading rates were low for Chincoteague Bay (3.1 g $N{\cdot}m^{-2}{\cdot}yr^{-1}$), Assawoman Bay (4.1 g $N{\cdot}m^{-2}{\cdot}yr^{-1}$), and Isle of Wight Bay (6.5 g $N{\cdot}m^{-2}{\cdot}yr^{-1}$), with intermediate loading rates for Newport Bay (17.5 g $N{\cdot}m^{-2}{\cdot}yr^{-1}$). At loading rates of 2–6 g $N{\cdot}m^{-2}{\cdot}yr^{-1}$, chlorophyll *a* levels were calculated to be ~15–20 μg/L.

Bricker et al. (1997, 1999) documented high (>20 μg/L) to hypereutrophic (>60 μg/L) chlorophyll *a* concentrations in the Maryland inland bays. Nitrogen concentrations were reported as moderate to high (0.1 mg/L to >1 mg/L) and phosphorus concentrations as high (>0.1 mg/L). Turbidity was also high (Secchi disk depth, <1 m) in these bays. In Chincoteague Bay, elevated turbidity levels were likewise recorded (Secchi disk depth, <1 m), but only moderate nitrogen (0.1–1 mg/L) and phosphorus (0.01–0.1 mg/L) levels were found. Chlorophyll *a* concentrations were moderate (5–20 μg/L). No anoxic or hypoxic events were observed. Harmful algal blooms and biological resource impacts have been chronicled in the Maryland inland bays. Based on these data, Bricker et al. (1999) determined that the Maryland inland bays were moderately eutrophic, and Chincoteague Bay had a low eutrophic condition.

Glibert et al. (2007) showed that the mean chlorophyll *a* levels in the Maryland coastal bays during summer amount to ~15–20 μg/L. In summer, the average nitrate plus nitrite concentrations are <2.0 μmol/L. The mean concentrations of dissolved organic nitrogen (DON), in turn, typically range 5–10 μmol/L. They noted that the total nitrogen concentrations in the coastal bays have increased significantly since the mid-1990s, mainly attributable to the rise in DON. An increase in intensity and duration of HABs has occurred concurrently with the increase in total nitrogen in the bays during the decade since the mid-1990s.

In summary, the lagoonal systems with the highest eutrophic conditions in the Mid-Atlantic region include Great South Bay, Barnegat Bay–Little Egg Harbor Estuary, and the Delaware inland bays. They tend to be the most heavily affected by nutrient loading, nuisance algal blooms, and HABs. In addition, the loss of SAV has been most acute in these enclosed water bodies. Ongoing coastal development and accelerated urban and agricultural runoff are largely responsible for the eutrophication problems encountered in the lagoonal estuaries of New York, New Jersey, Delaware, and Maryland. Human activities in surrounding coastal watersheds have facilitated the transport of nutrients and sediments to the bays, leading to the observed degradation of the water and habitat quality, as well as the biotic communities, over the past several decades. Their extreme enclosure, shallow depths, and poor flushing have promoted more widespread eutrophication as evidenced by generally high levels of chlorophyll *a*, epiphytes, macroalgal abundance, nuisance algal blooms, HABs, and SAV loss.

Virginia coastal bays.—Lower Chincoteague Bay and the southern Delmarva coastal bays (i.e., Magothy, South, Cobb, Spider, Crab, and Hog Island bays) constitute the Virginia coastal bay systems. Nixon et al. (2001) examined the responses of shallow coastal bays including Chincoteague Bay to nutrient enrichment. With a mean depth <2 m, a residence time of 76 d, and a total nitrogen input rate of 0.6 $\mathrm{mmol \cdot m^{-2} \cdot d^{-1}}$ (Nixon et al. 2001), the bay has exhibited some SAV losses and moderately elevated chlorophyll *a* levels, eutrophic responses that are less acute than in the Barnegat Bay–Little Egg Harbor Estuary (Kennish 2001*a*).

The southern Delmarva coastal bays generally have much shorter flushing times than the Delmarva and northern Maryland coastal bay systems. For example, Hog Island Bay, with a mean depth of 2.1 m (Oertel 2001), has a flushing time of only two days (Orth et al. 2006). Nevertheless, the bay has been subject to effects of seasonal inorganic nitrogen inputs and related hypoxic events (Fugate et al. 2005:67). Most nutrient inputs to the coastal bays occur via small tributary creeks, groundwater discharges, and atmospheric deposition, similar to the Barnegat Bay–Little Egg Harbor Estuary. Efforts to restore SAV have proven to be successful in the decade since the mid-1990s in the Delmarva coastal bays, with SAV beds expanding at a rate of more than 305 ha/yr in these systems (Orth et al. 2006).

Pamlico Sound.—Pamlico Sound has a surface area of 4350 km^2, which is more than 15 times that of the Barnegat Bay–Little Egg Harbor Estuary. The expansion of agricultural, industrial, and urban development in tributary watersheds of Pamlico Sound in the three decades since the mid-1970s has resulted in a substantial increase in nitrogen loading to influent systems, notably the Neuse and Tar-Pamlico Rivers (Piehler et al. 2004). These systems have experienced increasing eutrophic conditions manifested by more frequent algal blooms, decreased water clarity, expanded hypoxia, periodic anoxia, fish kills, and trophic disruption (Twomey et al. 2005, Paerl et al. 2006). They are not only affected by nutrient and other pollutant inputs, but also by hydrologic alterations (water supply diversions) and manifestations of climate change (droughts, hurricanes, and floods).

The more frequent occurrence of hurricanes and tropical storms since the mid-1990s has had a biostimulatory effect on the phytoplankton community in Pamlico Sound, attributable to pulses of dissolved inorganic nitrogen inputs (Paerl et al. 2000, 2001). Seasonal and/or storm-induced variations in river discharges, and the resulting changes in flushing rates and hence estuarine residence times, have differentially affected phytoplankton taxonomic groups as a function of their contrasting growth characteristics. The net effect has been the alteration of the phytoplankton community composition in conjunction with acute hydrologic and nutrient changes. Decreases in the occurrence of winter–spring dinoflagellate blooms and increases in the abundance of chlorophytes have coincided with the greater frequency and magnitude of tropical storms and hurricanes since 1996. Such stochastic, hydrologic-induced effects have not been observed in the Barnegat Bay–Little Egg Harbor Estuary, where nutrient enrichment and associated impacts more closely parallel those observed in the Delaware, Maryland, and Virginia coastal bays (Bricker et al. 1999, Kennish 2001*a*).

Because of the bounding effect of the Outer Banks, Pamlico Sound has a relatively long residence time, which plays a major role in determining the availability and utilization of nutrients by phytoplankton and other autotrophs in the system (Paerl et al. 2006). A similar effect of the barrier island complex (i.e., Island Beach and Long Beach Island) along the central New Jersey coastline is observed in the Barnegat Bay–Little Egg Harbor Estuary. Monthly water quality measurements have been made in Pamlico Sound since fall 1999 (Peierls et al. 2003). Piehler et al. (2004) reported the following dissolved inorganic nitrogen concentrations and chlorophyll *a* concentrations in the sound during the 2000–2001 period: nitrate (<1 μmol/L), ammonium (~0.5–1.5 μmol/L) and chlorophyll *a* (3–15 μg/L). These values are very close to those recorded in the Barnegat Bay–Little Egg Harbor Estuary (Kennish 2001*a*, Kennish et al. 2005). While Pamlico Sound has exhibited a highly stratified water column with periodic stratification-mediated hypoxia (dissolved oxygen ~1.5 mg/L) in summer (Piehler et al. 2004), the Barnegat Bay–Little Egg Harbor Estuary rarely exhibits dissolved oxygen problems because of its well-mixed water column.

Albemarle Sound.—Although Albemarle Sound has a surface area less than half of Pamlico Sound, its watershed area is nearly twice as great (Table 1). The mean water depth in Albemarle Sound is approximately the same as in Pamlico Sound (~2.5 m). However, the nitrogen inputs are much higher. Bricker et al. (1999) indicated that insufficient data exist to accurately determine the eutrophic condition of Albemarle and Pamlico sounds. Only moderate nitrogen inputs and overall human influence have been noted in both water bodies, suggesting that high eutrophic conditions are unlikely in either system.

Impact Remediation

One of the major goals of the "Impacts to Coastal Systems" symposium was to develop a management strategy to mitigate eutrophication impacts in the Barnegat Bay–Little Egg Harbor Estuary based on research findings and management programs applied in other coastal bay systems of the Mid-Atlantic and South Atlantic regions. To this end, symposium participants formulated a series of recommendations designed to improve water quality, restore impaired habitats, and revitalize living resources associated with these impacts by focusing on more stringent controls of nonpoint source nutrient inputs to the estuary. The scientific literature is clear regarding remediation of eutrophication impacts: reduce nutrient loading to the estuarine water body.

A four-component management strategy was devised at the symposium to improve environmental conditions in the Barnegat Bay–Little Egg Harbor Estuary, namely the implementation of low-impact (smart) development in the Barnegat Bay watershed, the upgrade of storm water controls, the pursuit of open space preservation, and the determination of total maximum daily loads (TMDLs) for nutrients entering the estuary. The application of best management practices (BMPs) in the watershed was deemed to be vital to achieving the reduction of nutrient loading necessary to remediate the array of eutrophication problems that have arisen in the estuary in the three decades since the mid-1970s despite the tighter government regulations on point source pollutant discharges, the activation of a centralized wastewater treatment system with ocean discharge, and more aggressive efforts to monitor water quality. Symposium participants recommended the following BMPs for effective development of the watershed: (1) construction practices minimizing soil compaction that facilitates land runoff; (2) maintenance of natural vegetation on residential lots; (3) use of vegetated infiltration basins, pervious driveways and roads, and bioretention gardens; and (4) implementation of conservation zones. These BMPs, together with comprehensive outreach and education programs that urge homeowners to adopt controlled fertilizer, pesticide, and pet waste management practices, have proven effective in reducing nonpoint source nutrient inputs to other estuarine systems (e.g., Long Island Sound) (P. E. Stacey, *personal communication*). Some of these measures have been applied in other Mid-Atlantic coastal watersheds with various degrees of success. When the management process has involved everyone (i.e., scientists, decision makers, stakeholders, and the public) and consisted of a balanced set of management tools, greater success has been achieved on nutrient reduction goals in targeted systems.

An integrated watershed and airshed management strategy with set nutrient limits for the estuarine waters is stressed. For this strategy to be effective, enforcement of violations for noncompliance must be supported. Realistic restoration efforts on damaged habitat, such as submerged aquatic vegetation (SAV), should be undertaken concomitantly with nutrient reduction programs.

To prevent Barnegat Bay and Little Egg Harbor from experiencing further deterioration of both water quality and natural resources (e.g., hard clam beds and SAV meadows), advanced storm water retrofit systems that substantially reduce nutrient loads are needed. If estimates of population growth, projected shifts in land use, and potential changes in nutrient loads are simultaneously developed, it would then be possible to determine the amount of nitrogen load that would have to be offset to "hold the line" on nitrogen loads in the estuary. When combined with tributary-level ranking efforts focused on identifying "hot spots" of nitrogen loading (e.g., Hunchak-Kariouk and Nicholson 2001), priority storm water retrofit projects can be developed and hopefully implemented. These retrofit projects should have beneficial effects on the estuary.

Because of the rapid rate of watershed development in the coastal zone of New Jersey, ocean space preservation is also recommended to reduce future water quality impacts in the estuary. Continued development in the Barnegat Bay watershed will lead to greater susceptibility to elevated eutrophic conditions. By limiting the amount of developable land area in the watershed, the effectiveness of new controls on nonpoint source inputs of nutrients to the estuary should be markedly increased.

It is essential to conduct a long-term water quality monitoring program in the estuary to determine the effectiveness of the aforementioned management strategies to limit nutrient inputs. Determinations of species-specific phytoplankton, SAV, and benthic micro- and macroalgal responses to anthropogenic nutrient loading, with particular application to seasonal and interannual changes of the system, are strongly emphasized as well. In addition, the study of long-term changes of trophic organization in areas affected by nutrient-induced algal blooms should be pursued, along with integrated analyses of higher-trophic-level indices based on the responses of SAV, infaunal and epibenthic invertebrates, and fishes to altered algal communities.

Conclusions

The Barnegat Bay–Little Egg Harbor Estuary is classified as a highly eutrophic system based on application of the National Oceanic and Atmospheric Administration's National Estuarine Eutrophication Assessment model. Eutrophic conditions have worsened during the decade since the mid-1990s with recurring phytoplankton and macroalgal blooms, HABs (brown tide blooms), epiphytic growth, loss of essential habitat (submerged aquatic vegetation) and harvestable fisheries (shellfish), and altered benthic communities. The most severe effects of eutrophication occur in the estuary during the summer months when nutrient loading (i.e., nitrogen compounds) from surrounding watershed areas increases, and the photoperiod is favorable for autotrophic uptake. Various nuisance and harmful algal species have the ability to obtain nutrients and carbon via assimilation of dissolved organic compounds. For some species, particularly those with mixotrophic tendencies, the organic component of the nutrient pool may be more important to the development of harmful bloom species than the inorganic component. In the Barnegat Bay–Little Egg Harbor Estuary, the organic nitrogen concentrations are about 10 times greater than the dissolved inorganic nitrogen concentrations, and they may play a significant role in the occurrence of eutrophication.

Accelerated development in the Barnegat Bay watershed during the 30 years since the mid-1970s has contributed greatly to progressive eutrophication of the estuary. Low freshwater inflow, shallow depths, poor flushing, and high residence times promote eutrophy. Watershed development and associated water quality impacts are greatest in the northern estuary. Eutrophic conditions also exist in a number of other shallow lagoonal estuaries of the Mid-Atlantic and South Atlantic regions, with the most serious conditions observed in Great South Bay and the Delaware inland bays.

A management strategy has been proposed to mitigate nutrient enrichment impacts in the Barnegat Bay–Little Egg Harbor Estuary. This strategy involves the implementation of four principal measures: (1) low-impact (smart) development and best management practices (BMPs) in the Barnegat Bay watershed; (2) upgrade of storm water controls; (3) open space preservation; and (4) total maximum daily loads (TMDLs) for nutrient limitation in the estuary. The use of BMPs in the watershed is critical to the long-term improvement of water quality and habitat conditions in the system.

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