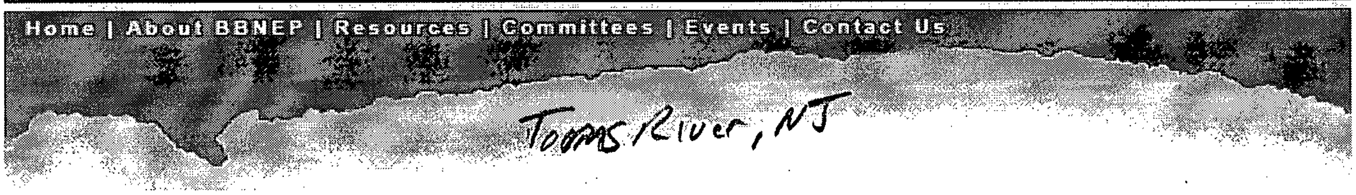
Barnegat Bay National Estuary Program



Toms River, NJ

The Barnegat Bay Estuary Program Characterization Report

Prepared by: Barnegat Bay National Estuary Program (Scientific and Technical Advisory Committee) January, 2001

Table of Contents

CH2 BBNEP 2001

I. PHYSICAL DESCRIPTION

The Barnegat Bay-Little Egg Harbor estuary, located along the central New Jersey coastline within the Atlantic Coastal Plain physiographic province, was designated as a National Estuary Program site on July 10, 1995 by the U.S. Environmental Protection Agency. Although long recognized for its great aesthetic, economic, and recreational value, this backbay system is now affected by an array of human impacts that potentially threaten its ecological integrity. The Barnegat Bay Estuary Program has focused on three priority areas of management concern for the Barnegat Bay-Little Egg Harbor estuary: (1) nonpoint source pollution/water quality degradation; (2) habitat loss and alteration; and (3) human activities and competing uses which are integrated into sections 1 and 2. A detailed assessment of these priority areas indicates that human activities in the watershed and estuary have led to substantial degradation of water quality, destruction of natural habitats, and reduction of living resources in the system.

The Barnegat Bay watershed, which covers an area of ~1,730 km2, lies almost entirely in Ocean County, one of the most rapidly growing counties in the United States. According to U.S. Census reports, the population in the watershed increased from nearly 40,000 people in 1940 to 108,000 in 1960, 208,000 in 1970, 346,000 in 1980, and 433,000 in 1990. The watershed now supports more than 450,000 people year-round, and more than 800,000 people during the summer tourist season. The population is concentrated in the northeastern and central portions of the watershed, as well as along the barrier island system. Land uses in the watershed include development (residential, commercial, industrial, and institutional), resource-based uses (agriculture and forestry), and open space (parks, refuges, and other natural areas). Since 1950, the Barnegat Bay watershed area has undergone dramatic development due to increasing population growth, with the land use changing from principally undeveloped and agricultural to suburban sprawl. The developed area of the bay watershed increased from 18% to 21% to 28% from 1972 to 1984 to 1995, respectively. In 1994/95, the distribution of land use in the watershed was as follows: forested, 45.9%; wetlands (both tidal and freshwater), 25.2%; urban/residential, 19.5%; agricultural land/grasslands, 6.6%; barren lands, 1.9%; and water bodies (lakes, impoundments, reservoirs), 0.9%.

Barnegat Bay, Manahawkin Bay, and Little Egg Harbor are three shallow microtidal bays which comprise the Barnegat Bay-Little Egg Harbor estuarine system. Together, these contiguous bays extend north-south for nearly 70 km along the central New Jersey coastline as a shallow, irregular tidal basin covering an area of 279 km2. The estuary is ~2 to 6 km wide and 1 to 7 m deep. Island Beach and Long Beach Island form a nearly continuous barrier island complex that separates the estuary from the Atlantic Ocean. Seawater enters the system through the Point Pleasant Canal, Barnegat Inlet, and Little Egg Inlet.

The Barnegat Bay-Little Egg Harbor estuary supports a thriving tourist industry, and its fisheries represent an invaluable recreational and commercial resource. For example, $1.71 billion tourist dollars were expended in Ocean County during 1995. At this time, ~45,000 tourist industry jobs were registered in the county, accounting for $631 million in payroll. In 1997, the total weight of finfish and shellfish harvested by vessels with a port landing in Ocean County (including that taken from ocean waters) amounted to 21,347,305 pounds (9,606,287 kg) and 19,724,768 pounds (8,876,146 kg), respectively. Clearly, people enjoy an array of recreational activities in the watershed and estuary, most notably boating, fishing, swimming, and hunting.

The estuary is an ecological treasure. An array of environmentally sensitive habitats exists here, such as sand beaches, bay islands, submerged aquatic vegetation, finfish nursery areas, shellfish beds, and waterfowl nesting grounds. Biotic communities are replete with rich assemblages of planktonic, benthonic, and nektonic organisms, some of which are of considerable recreational or commercial

importance (e.g., bluefish)

Pomatomus saltatrix; winter flounder, *Pseudopleuronectes americanus*; hard clams, *Mercenaria mercenaria*; and blue crabs, *Callinectes sapidus*). Most taxa are represented, including approximately 180 species of phytoplankton, nearly 100 species of benthic flora (algae and vascular plants), more than 200 species of benthic fauna, and about 110 species of fish.

The Barnegat Bay watershed contains a wide diversity of vegetation from coastal dune communities and low-lying estuarine and freshwater wetlands to uplands of pine/oak forests. The upland watershed consists, in part, of critically important Pinelands habitats which are protected by regulations and a myriad of local, state, and federal management programs. These Pinelands habitats support unique fish, amphibian, reptilian, mammalian, and avian populations.

II. WATERSHED WATER QUALITY

A. Freshwater Sources

Development in the watershed increases the probability of water quality degradation in bay tributaries. Nutrients and chemical contaminants enter these influent systems from point source discharges (e.g., outfalls regulated under the NJPDES permit program such as at the Oyster Creek Nuclear Generating Station, the largest point source discharger in the system) and nonpoint sources (e.g., stormwater runoff, ground water influx, and atmospheric deposition). While point sources of pollution are localized, nonpoint sources can extend throughout the watershed. Included in the latter category are pollutants originating from agricultural, residential, and commercial properties; atmospheric deposition; animal feedlots; and right-of-ways (e.g., highway and railway borders).

The freshwater supply in the region derives from four sources: (1) surface water flow; (2) ground water from the unconfined Kirkwood-Cohansey aquifer system; (3) ground water from deeper, confined aquifers; and (4) water transferred into the region from adjacent areas. Most freshwater inflow to the estuary is ground water that either discharges to streams that flow into the embayment or that seeps directly into the embayment. Surface water discharges (~28 m3/s) exceed direct ground water seepage (~4 m3/s) and incident precipitation. Freshwater discharge into the estuary from both surface water and ground water amounts to ~2.25 x 106 m3/d. Maximum stream flows occur during the winter and spring when evapotranspiration is lowest.

Freshwater inflow from surface water discharges and direct ground water input affects salinity and circulation in the estuary. Hence, it is important to determine the relative magnitude of the various freshwater sources. To this end, a hydrologic budget has been produced for the region which details the movement of freshwater through the system.

Ground water from the unconfined Kirkwood-Cohansey aquifer system is critical to surface water quality in the watershed. It is regarded as the largest source of freshwater for the estuary because most of the flow in local streams consists of base flow (i.e., discharge entering stream channels from ground water). For example, 63-73% of the total stream flow in the Metedeconk River between 1973 and 1989

was calculated as base flow. Similarly, 80-89% of the total stream flow in the Toms River between 1929 and 1989 was calculated as base flow. Virtually all of the flow in tributary streams during periods of little or no rainfall is comprised of base flow. The ratio of surface runoff to base flow increases during periods of precipitation.

Excessive water withdrawals from area aquifers is a concern because it can cause saltwater intrusion problems and reductions in stream flow. In 1990, estimated ground water withdrawals from private wells for residential use totaled ~3.16 x 10^{7} l/day, and average ground water withdrawals for public supply, as well as for commercial, industrial, and irrigation uses, totaled 1.71 x 10^{8} l/d. Ground water supplies have been lost in some areas of the watershed due to saltwater intrusion related to excessive withdrawal of well water. This has led to state-mandated reductions on withdrawals from affected aquifers. In an extreme case, drought conditions during the summer of 1999 culminated in statewide restrictions on nonessential ground water use.

B. Tributary Water Quality

Because of the quantitative significance of ground water inputs to tributary systems, the quality of ground water in the Kirkwood-Cohansey aquifer is a key determinant of the quality of freshwater inflow and water-quality constituent loadings to the estuary. Ground water in this aquifer system is generally acidic with low ionic strength and alkalinity. Its pH ranges from 4.4 to 6.7, and the total dissolved solids concentration is less than 100 mg/l. Nitrogen and phosphorus levels are generally low.

Tributary water quality is altered most greatly in developed areas of the watershed where higher concentrations of nitrogen, phosphorus, sulfate, and other inorganic constituents, as well as elevated values of pH and specific conductance have been observed. The in-stream concentrations of the inorganic constituents appear to be related to the intensity of development in areas which contribute drainage upstream of the surface water sites. The constituent loads transported by tributary systems to the estuary depend primarily on the size of the drainage basin and the type of land cover existing there. Urban centers and heavily developed residential areas with considerable impervious cover contribute greater constituent loads than rural areas with natural vegetative covers.

1. Nutrients

Nitrogen loads are of particular importance because of the tight coupling between nitrogen inputs to the estuary and primary production by autotrophs. The occurrence of phytoplankton blooms in the estuary is strongly related to nitrogen inputs. The estimated total nitrogen load to the system from the three major sources - surface water discharges (~50% of the total), atmospheric deposition (~39%), and direct ground water discharges (11%) - amounts to ~1.74 x 10^{6} lb/yr (7.9 x 10^{5} kg/yr). This value is considered to be an underestimate because it does not account for: (1) nitrogen in storm runoff that discharges directly to the estuary; (2) nitrogen released from bottom sediments of the estuary; and (3) nitrogen in ocean water entering the system on flood tides.

Of the three major sources of nitrogen for the estuary, surface water discharges contribute ~8.7 x 10^{5} lb/yr (3.9 x 10^{5} kg/yr) mainly in the form of nitrate. Much of this nitrate derives from base flow. The Wrangel Brook, Toms River, Mill Creek, and Tuckerton Creek Basins yield the highest total nitrogen loads to the estuary, and the Long Swamp Creek Basin, the lowest total nitrogen loads.

Direct atmospheric deposition (wet and dry) of nitrogen on the estuary water surface is estimated at ~6.7 x 105 lb/yr (3.0 x 105 kg/yr). This nitrogen originates principally from nitrous oxide emissions from fossil fuel combustion within the estuarine airshed. A portion of the nitrogen that is deposited on the watershed land mass enters the estuary via discharges from surface water and groundwater.

Direct ground water discharges deliver ~2 x 105 lb/yr (9.1 x 104 kg/yr) of nitrogen in the form of nitrate and nitrite. Although the concentrations of nitrogen species in shallow ground water exceed 10 mg/l in some areas of the watershed, median concentrations are < 0.2 mg/l. However, ground water in developed areas closest to the estuary may contain much higher levels of nitrogen. The total concentration of nitrogen in shallow ground water appears to represent a potentially significant reservoir of this nutrient for the estuary.

The concentrations of nitrate plus nitrite are highest in watershed areas characterized by moderate to high urban land cover. For example, the highest yields of nitrate plus nitrite occur in the Wrangel Brook and Toms River Basins. Much smaller yields are evident from the less impacted Westecunk and Cedar Creek Basins. Surface water discharges to the estuary account for an annual nitrate plus nitrite load of ~3.6 x 105 lb/yr (1.6 x 105 kg/yr).

Ammonia concentrations are low, with the median value in all flows amounting to 0.05 mg/l. Stormwater appears to be an important source of total ammonia plus organic nitrogen. In contrast, most streams have small total ammonia concentrations. Highest yields are recorded from the Mill Creek, Toms River, and Oyster Creek Basins. The Wrangel Brook Basin has the lowest yield. Surface waters discharge an annual ammonia load of ~1.1 x 105 lb/yr (5.0 x 105 kg/yr) to the estuary. The annual load of total ammonia plus organic nitrogen to the estuary from surface water inflow is ~4.6 x 105 lb/yr (2.1 x 105 kg/yr). The Mill Creek, Oyster Creek, and Toms River Basins are responsible for the largest yield of this constituent. The lowest yield is from the Long Swamp Creek Basin.

Surface water discharges transport ~2.3 x 105 lb/yr (1.0 x 105 kg/yr) of total phosphorus to the estuary. The Toms River, Wrangel Brook, and Oyster Creek Basins yield the largest fraction of total phosphorus. The Jakes Branch Basin yields the lowest fraction of this component.

2. Toxic Chemical Contaminants

Comprehensive monitoring of shallow ground water in the watershed reveals widely scattered occurrences of volatile organic compounds, mercury, and radium isotopes. When found, these contaminants generally exhibit low concentrations. However, there are some areas where the levels of volatile organic compounds, mercury, and radionuclides in ground water exceed the maximum permissible levels for public drinking water. The number of volatile organic compounds and the concentration of methyl tert-butyl ether (MTBE) in streams tend to increase with residential and industrial land use. The probability that chemical contaminants in ground water will reach the estuary depends on several major factors such as the chemical characteristics of the contaminants, the physical characteristics of the aquifer systems, and various processes taking place in the subsurface near the ground water and surface water interface that tend to reduce contaminant concentrations (e.g., adsorption, biodegradation, and denitrification). These processes remain essentially uncharacterized in the Barnegat Bay watershed.

3. Recommendations

It is necessary to establish a coordinated program of monitoring, research, and analysis in the watershed to understand more clearly the relative importance of specific pollutant sources and the transport mechanisms that can affect conditions in the estuary. The following information is needed: (1) more water quality data on the tributary streams; (2) determination of nutrient and chemical contaminant loads in these influent systems; (3) further assessment of nutrient and chemical contaminant transport processes in the watershed; and (4) estimates of atmospheric deposition in the immediate estuarine area. Additional research is also necessary to identify specific land uses and human activities that have contributed to elevated nitrogen yields in particular subbasins of the watershed.

III. ESTUARINE WATER QUALITY

Nutrient enrichment and pathogens are high priority management issues for this estuary program. Both can have a dramatic effect on water quality in the estuary. For example, high nutrient inputs (especially nitrogen) can lead to a variety of adverse conditions (e.g., increased algal biomass and production, toxic or nuisance algal blooms, elevated water column turbidity, loss of submerged aquatic vegetation, depleted dissolved oxygen levels, and a decline in biodiversity) that can severely impact the estuary. High fecal coliform bacteria counts, an indicator of the presence of pathogens, are responsible for the closure of bathing beaches and shellfish harvesting areas in the system.

A. Nutrients

Nutrient inputs to the Barnegat Bay-Little Egg Harbor estuary originate essentially from nonpoint sources, mainly stream and river discharges, atmospheric deposition, and ground water influx. Total nitrogen concentrations in the estuary range from ~20 to 80 µM. Organic nitrogen is by far the dominant form of nitrogen in the embayment, being ~10x greater than the concentration of dissolved inorganic nitrogen. Highest concentrations of organic nitrogen (~40 µM) have been reported during the summer. Mean seasonal ammonium and nitrate levels, based principally on sampling during the 1989 to 1996 period, amount to ~2.5 µM and < 4 µM, respectively. While the highest concentrations of ammonium occur in the summer, nitrate levels peak during the winter when biological assimilation is a minimum. Dissolved inorganic nitrogen levels are higher in the northern part of the estuary due to greater riverine nitrogen loading in this region. Phosphate concentrations, in contrast, do not exhibit any obvious spatial patterns. Mean annual phosphate concentrations are < 1 µM; highest phosphate levels arise during the summer, a seasonal pattern typical of other Mid-Atlantic estuaries.

The Barnegat Bay-Little Egg Harbor estuary is a moderately eutrophic estuary. Nutrient enrichment and excessive phytoplankton production can lead to a depression of dissolved oxygen levels, higher turbidity levels, a loss of submerged aquatic vegetation, and an increase in mortality of finfish, shellfish, and other organisms. Highest phytoplankton biomass values, as measured by chlorophyll *a*, occur in the northern estuary during the summer months in response to greater nutrient inputs from more developed areas of the watershed. During the late spring and summer period in recent years, the southern estuary has been the site of intense blooms of phytoplankton composed primarily of picoplanktonic green algae (*Nannochloris atomus*) and brown algae (*Aureococcus anophagefferens*). For example, blooms of *A. anophagefferens* exceeding 106 cells/ml were documented in Little Egg Harbor during 1995, 1997, and 1999. These blooms did not result in hypoxic or anoxic events, however. The New Jersey Department of Environmental Protection found biologically stressed conditions (dissolved oxygen concentrations < 5.0 mg/l) at five stations in the central part of the estuary between Toms River and Dipper Point during the

1990's.

High phytoplankton biomass and production (particularly in the northern estuary) during the warmer months of the year contribute to elevated turbidity readings. Annual phytoplankton biomass and production values in the estuary are ~10 mg chlorophyll *a*/m3 and nearly 500 g C/m2/yr, respectively. Secchi depth measurements are shallowest in the summer and fall, averaging < 1 m during these seasons. Phytoplankton, together with suspended sediments, detritus, and colored dissolved organic molecules, reduce water clarity and limit light penetration in the water column. This shading effect is detrimental to benthic flora. For example, benthic microalgal production is reduced by high summer turbidity, and SAV distribution may be restricted by this effect as well, especially in the northern estuary. A secchi disk model formulated for the system strongly suggests that light penetration is a major factor controlling the distribution of seagrasses, which appears to be more restricted today than during the past several decades (see below).

Aside from the potential impact of nutrient enrichment, toxic chemical contaminants may be locally important in the estuary (e.g., near marinas). The most extensive database on chemical contaminants in the estuary exists on trace metals and radionuclides. Other toxic chemical contaminants (e.g., halogenated hydrocarbons and polycyclic aromatic hydrocarbons) are not sufficiently characterized. Because of their potential carcinogenic, mutagenic, or teratogenic effects on estuarine organisms, additional study of these contaminants is warranted. The Barnegat Bay-Little Egg Harbor estuary may be more susceptible to toxic chemical contaminants than many other estuaries because of its limited dilution capacity and flushing rate.

B. Pathogens

New Jersey surface water quality standards support drinking water, recreational contact, and safe shellfish growing water uses. For the Barnegat Bay-Little Egg Harbor estuary, fecal coliform bacteria are used as an indicator of the potential occurrence of human and/or animal pathogens. These bacteria enter the system primarily via stormwater discharges, riverine inflow, overboard release of raw sewage from boats, malfunctioning septic systems, and direct waste input from animals. Highest concentrations are recorded during rain conditions. From 1988 to 1998, 834 beach closings were registered in the estuary as a result of elevated fecal coliform counts in water samples, with the highest number reported in 1989 (175), 1990 (186), and 1994 (127). Beachwood Beach in Beachwood, Windward in Brick, and Money Island in Dover had the greatest frequency of beach closings. In general, areas north of Barnegat Inlet exhibited the most degraded water quality conditions based on beach closings data (e.g., Lavellette, Seaside Heights, Seaside Park, Island Beach, Brick, Point Pleasant, Dover, Island Heights, Beachwood, Pine Beach, and Ocean Gate). However, water quality has improved in these areas in recent years. Since 1995, for example, there have been less than 50 beach closings reported each year throughout the estuary.

In regard to shellfish harvesting, the general trend in the estuary has been toward less restrictive shellfish growing classifications, although local areas of water quality degradation persist which is related to high inputs of coliform bacteria from nonpoint sources. The largest areas of shellfish harvesting restriction are found in Barnegat Bay tributaries from Toms River northward as well as in backbay locations along Island Beach. Shellfish harvesting is also prohibited from marinas and man-made lagoons.

The most dramatic improvement in water quality of the estuary occurred during the 1970's when the Ocean County Utilities Authority commenced operation of a state-of-the-art wastewater reclamation

system. Prior to operation of this system, wastewaters were discharged to the estuary, and fecal coliform levels were elevated. Pipeline outfalls now discharge wastewaters 1.6 km offshore in the Atlantic Ocean, thus bypassing the estuary.

C. Recommendations

Additional information must be obtained for a more complete understanding of water quality conditions in the estuary. First, more monitoring is needed at the appropriate spatial and temporal scales of relevant parameters to quantify changes in water quality as development in the watershed and airshed progresses. Second, experimental studies are required to further identify and quantify factors contributing to turbidity in the estuary. Third, investigations should be initiated to better clarify the sources and ecosystem effects of organic and inorganic nutrient forms entering the estuary.

IV. HABITAT LOSS AND ALTERATION

Human activities both in watershed areas and on open bay waters have impacted habitats and living resources of the system. Habitat fragmentation and human disturbance in the watershed adversely affect many plant and animal species. The construction of residential, commercial, and industrial structures as well as the building of roadways not only destroy natural habitat in the watershed but also can create pollution problems in receiving waters. These impervious surfaces facilitate surface runoff which promote the transport of pollutants (e.g., fertilizers, herbicides, pesticides, oil, metals, etc.) to waterways. Where development is most extensive, in the northern mainland watershed area and on the barrier island complex, nonpoint source pollution can degrade water quality and the health of living resources in the estuary. Along the estuarine perimeter, marsh filling and bulkheading, diking and ditching, and dredging and lagoon construction have disrupted salt marsh and shallow water habitats and altered biotic communities. The use of personal watercraft and boats has also disturbed some parts of the estuarine shoreline.

As noted previously, the percentage of developed watershed area increased from 18% to 21% to 28% from 1972 to 1984 to 1995, respectively. A strong gradient of decreasing human development and subsequent habitat loss and alteration is evident when proceeding from the northern to southern sections of the watershed and estuary. The Barnegat Bay watershed currently is dominated by upland and wetland forests, which cover 37% and more than 25% of the watershed area, respectively. Development in the watershed has resulted in the following habitat losses: (1) 13,731 ha or 20% of upland forest between 1972 and 1995; (2) 1,875 ha or 6% of freshwater wetlands during the same period; and (3) 4,200 ha or 28% of tidal salt marshes during the past 100 years. Most of the tidal salt marsh losses occurred between 1940 and 1970. Passage of the Coastal Wetlands Law of 1970 and the Freshwater Wetlands Protection Act of 1986 have been particularly effective in curbing the loss of wetlands. Since passage of the Coastal Wetlands Law of 1970, the loss of tidal salt marsh area has decreased to <1.5%.

Apart from dredging and infilling, mosquito control measures (parallel grid ditching) have significantly altered salt marsh habitat. Approximately 5,890 ha of Barnegat Bay salt marshes have been ditched to reduce mosquito breeding habitat. This represents about two-thirds of the existing tidal salt marsh area. However, parallel grid ditching is no longer a desirable management technique of mosquito control in this system and is being replaced by alternative open marsh water management techniques.

More than 70% (4,224 ha) of the Barnegat Bay-Little Egg Harbor estuarine shoreline buffer zone is developed/altered, leaving only 29% (1,734 ha) in natural land covers. Approximately 45% of the estuarine shoreline is now bulkheaded (36% when tidal creeks are included). Bulkheading eliminates shoreline beach habitat important for shorebirds and terrapin turtles. It also deepens adjacent nearshore estuarine waters. The remaining undeveloped shoreline areas, including bay islands, should receive priority for protection as wildlife habitat and as open space buffer.

Additional open space acquisition must be pursued even though large expanses of upland and wetland habitats are presently protected as public open space. This acquisition is necessary to: (1) protect watershed areas in order to ensure high quality freshwater inflow to Barnegat Bay, Manahawkin Bay, and Little Egg Harbor; (2) protect habitat for commercially, recreationally, and ecologically important flora and fauna; and (3) maintain open space for human recreation and aesthetic enjoyment. Riparian corridors should be conserved to protect Barnegat Bay-Little Egg Harbor estuarine water quality from further degradation due to nonpoint source pollution associated with human development. The remaining tracts of interior contiguous forest should be considered for purchase to preserve the integrity of the pine barrens landscape from habitat fragmentation. Among the largely unprotected tracts in this regard are the Forked River Mountains, Berkeley Triangle, Heritage Minerals tract, and Maple Root Branch/Long Brook tract in Jackson Township.

Barrier island-coastal dune scrub/shrub and large contiguous areas of cultivated farmland/grassland are other critical wildlife habitat areas that should receive special consideration. The dune scrub/shrub and woodland communities of the barrier islands (excluding Island Beach State Park) have been substantially altered and in many locations completely destroyed. Contiguous areas of active or abandoned farmland and grassland habitat support several threatened species of birds and many other important terrestrial organisms. However, these areas are rather uncommon in the system; therefore, a concerted effort must be forged to protect them.

Approximately 50% of Barnegat Bay (~30,000 ha) has been mapped as open water habitat. About 32% of the benthic habitat has been mapped as potential submerged aquatic vegetation (SAV), and another 10% has been mapped as intertidal flat. Dredged lagoons account for only 3% of the benthic habitat.

SAV beds (mainly eelgrass, *Zostera marina*) serve several major functions in the estuary. They are important primary producers. Some animals graze on SAV (e.g., gastropods, fish, ducks, and muskrats). Perhaps most importantly, SAV provides critical habitat for numerous organisms in the estuary. More than 70% of New Jersey's total SAV acreage is located in the Barnegat Bay-Little Egg Harbor estuary.

There is some indication of the loss of SAV beds in the estuary in recent years, although differences in mapping methods make it difficult to unequivocally establish the occurrence of a major dieback and loss of eelgrass area. A GIS spatial comparison analysis of SAV surveys suggests that there has been loss of eelgrass in the deeper waters of the estuary resulting in the contraction of the beds to shallower subtidal flats (< 2 m depth) during the period between the 1960's and 1990's. The loss appears to have been most severe in Barnegat Bay north of Toms River but is also evident in southern Little Egg Harbor. Because of the uncertainty regarding the conclusions of this analysis, however, more investigations of SAV distribution in the estuary are recommended.

The wide array of habitats in the Barnegat Bay-Little Egg Harbor estuary and contiguous watershed areas supports a multitude of aquatic and terrestrial organisms. A list of animal and plant species of special emphasis has been developed for the system as a general indicator of estuarine biodiversity. Species of special emphasis that are either commercially/recreationally important, federal or state listed threatened or endangered or otherwise ecologically significant have been compiled and cross-referenced with the habitats to which they are affiliated. Based on this work, a Wildlife Habitat Map has been

generated which will serve as a useful reference for future studies of biotic communities and habitats in the system.

I. WATERSHED AND EMBAYMENT

An estuary is a coastal water body in which fresh water from rivers, streams, and ground water discharge mixes with seawater from the ocean. The Barnegat Bay estuarine ecosystem, located along the central New Jersey coast, consists of three shallow contiguous embayments: Barnegat Bay, Manahawkin Bay, and Little Egg Harbor. The estuary is situated between the mainland and a narrow barrier island complex, which includes Island Beach and Long Beach Island. The estuary extends north-south for nearly 70 km (43 mi) parallel to the mainland, between 39□40'N and 40□06' N latitude and 74□02'W and 74□20'W longitude. The 1,730 km2 (670 mi2) Barnegat Bay-Little Egg Harbor drainage area includes most of Ocean County, and parts of Monmouth and Burlington Counties, New Jersey (Figure 1). The estuary itself includes 279 km2 (108 mi2) of open estuarine water. It ranges from 2 to 6 km in width and 1 to 7 m in depth (Chizmadia et al., 1984).

Freshwater enters the estuary as surface discharge from numerous streams, as direct ground water discharge, and as incident precipitation. Seawater enters the estuary through Little Egg Inlet, Barnegat Inlet, and the Point Pleasant Canal. Salinity ranges from 11‰ to greater than 30‰. It is highest near inlets and the canal, and lowest near the mouths of the large surface water inflows (Moser, 1997).

The Barnegat Bay-Little Egg Harbor watershed area is situated entirely within the New Jersey Coastal Plain physiographic province, which is characterized by gentle slopes and low topographic relief. Human land uses dominate about 28‰ of the watershed (Lathrop and Bognar, 1996). Land-use patterns result in four distinguishable subareas: (1) The western watershed area; (2) the northeastern mainland watershed area; (3) the southeastern mainland watershed area; and (4) the barrier island complex. The sparsely-populated western watershed area lies within the environmentally sensitive Pinelands Area, in which development is controlled and managed through the Pinelands Comprehensive Management Plan. The northeastern mainland watershed area is extensively developed, and features major population centers such as Forked River, Toms River, and Lakewood. The southeastern watershed area is less extensively developed, and includes protected environmentally sensitive areas such as the Barnegat National Wildlife Refuge and the Manahawkin Fish and Wildlife Management Area. The barrier island complex at the eastern limit of the watershed area is heavily developed, except for Island Beach State Park. More than 450,000 people are year-round residents of the watershed. However, this population more than doubles during the summer tourist season.

II. CLIMATE AND RAINFALL

The Barnegat Bay estuary and its watershed are typified by a continental climate. However, the influence of the Atlantic Ocean results in a climate that is generally milder than areas farther inland. Wind or storms introduced into the region, especially from the northeast, result in more severe weather conditions.

Few facilities within the watershed regularly and continuously monitor meteorological conditions. The Oyster Creek Nuclear Generating Station (OCNGS), located in the central part of the watershed approximately 10-km northwest of Barnegat Inlet, is one facility that has collected local meteorological data since 1966. These data are presently being collected and electronically archived from various elevations on a meteorological tower that has been in operation since the mid-1970s. Other facilities that maintain local weather stations are the National Weather Service (NWS) in Pomona, New Jersey (~16 km west of Atlantic City), and the United States Coast Guard station located on Long Beach Island in Barnegat Light, New Jersey.

Seasonal variability of wind direction is evident in the region. Figure 2 depicts the frequency of

occurrence of winds from various directions averaged over a number of years. During the fall and winter seasons, winds are predominantly from the northwest to west direction. Cold and dry atmospheric conditions originating from the northwest U.S. and Canada characterize air masses from these directions. During the spring and summer, as the jet stream seasonally retreats northward, winds are predominantly from the south to the southwest. Under these conditions, warm and humid air prevails in the area. In the summer, a subtropical high-pressure system (a semi-permanent feature) settles over the southern half of the U.S, typically producing warm and humid southerly breezes in the Barnegat Bay region. Northeast winds, associated with Atlantic storms known as "northeasters," occur less frequently in this region. These storms generally form in the waters off the southeast U.S. coast and move north and northeast producing heavy surf, strong winds, and occasional tidal flooding.

Since the topography of the region surrounding Barnegat Bay is nearly flat, it is without many physical barriers which can significantly modify natural wind flow patterns. However, uneven heating between the land and water sometimes results in the development of a thermally induced "sea breeze," a common feature associated with large bodies of water. Sea breeze flow alters wind patterns in a relatively small area, which are usually confined to the immediate coast. The sea breeze phenomenon often produces a southerly or easterly wind circulation pattern near shore areas and over the barrier beach complex. Sea breezes can also penetrate several kilometers inland depending upon conditions such as, the percent of cloud cover, amount of solar insolation, or prevailing winds from opposing directions. Because Barnegat Bay is quite shallow (average depth ~1.5 m, ~4.9 ft), its waters respond relatively rapidly to temperature changes (as does a landmass) compared to larger bodies of water, such as the Atlantic Ocean. This limits the distance inland that sea breezes are able to penetrate. Approximately 85% to 90% of the time, sea breezes in the Barnegat Bay region do not reach farther than 11 km (6.6 mi) inland from the barrier island system. Sea breezes are primarily a daytime phenomenon because as evening progresses, the amount of solar insolation and resulting thermal differentials are reduced, diminishing sea breeze circulation.

Daily high temperatures in the Barnegat Bay watershed range from an average of ~1.6°C (~35°F) during the winter to ~23.9°C (~75°F) during the summer (Figure 3). At night, the ground typically cools off more rapidly than the overriding air, which results in a nocturnal temperature inversion. For example, temperature differentials of 10°F over a 100 m (328 ft) vertical distance are occasionally observed at the OCNGS meteorological tower. Formation of such an inversion can limit atmospheric mixing and produce air stagnation.

Precipitation can occur throughout the year in the region due to various climatic conditions (Figure 4). The average annual precipitation totals 117 cm (~46 in). During the late spring and summer, maritime tropical air originating from the south can cause hazy, warm, and humid conditions and air masses. This can bring either widespread showers, heavy thunderstorms caused by localized convection, or both. Precipitation resulting from these conditions has a generally short duration and is high in intensity. These conditions can result in flash floods, which cause extensive soil erosion and structural damage. In July 1991, in an extremely intense convective precipitation, the area experienced over 22.9 cm (9 in) of rain in a six-hour period, resulting in widespread flash flooding, as well as damage to several highway bridges. Harvey Cedars, located on Long Beach Island, received over 27.9 cm (11 in) of rain from the same storm.

During the fall, winter, and early spring, precipitation is generally from storm events associated with the passage of low pressure systems and frontal boundaries. Such low pressure areas are associated with the upper atmosphere jet stream, which often passes over the region during these seasons. One type of such storm, termed "northeasters," produces steady, copious rainfall over an extended period of time (generally 24 to 36 hours). Northeasters form near the Atlantic coast, primarily due to the influence of the Gulf Stream, a warm-water current that parallels the eastern seaboard. The Gulf Stream warms the air overlying it, creating a front along the east coast. When jet stream disturbances move over this temperature gradient, surface low pressure systems can form. Because of the abundant moisture from the ocean and the temperature gradient of the coastal front, these storms occasionally develop explosively into severe storm systems. During the storm period, constant winds from the east and northeast produce flooding along the back bays of the estuary and cause beach erosion along the barrier islands. Sustained winds at these times can exceed 80 kmph (50 mph) with wind gusts exceeding 96 kmph (60 mph). Typically, three to five coastal storms occur during any given calendar year. The most severe storms generally occur during the fall, when temperature differences between the air and the ocean are greatest (Figure 5).

Another source of precipitation is from tropical systems such as hurricanes. Although tropical storm systems are not common at these latitudes due to the relatively cool ocean temperatures, the remnants of tropical systems can produce large amounts of rainfall (e.g., 10 or more centimeters; 5 or more inches) in a relatively short period of time. Hurricanes occurring at these latitudes most often pass to the east of the estuary, which reduces the probability of major damage to the area because the most destructive winds and rain associated with a hurricane are found to the storm's north and east.

III. GEOLOGY

The Barnegat Bay-Little Egg Harbor watershed is located in the Atlantic Coastal Plain which forms the largest of the four physiographic provinces in New Jersey, covering ~10,500 km2 (~4,200 mi2). The coastal plain in New Jersey is characterized by a seaward thickening wedge of unconsolidated sediments that starts as a featheredge at the Fall Line and reaches ~1,981 m (~6,500 ft) thick in southern Cape May County (Zapecza, 1989). The sediments consist of alternating layers of clay, silt, sand, and gravel dipping gently 10-60 feet per mile (Zapecza, 1989). The layers of sand and gravel form productive aquifers and the layers predominated by silts and clays form confining units. These layers of sediments outcrop in irregular bands that trend northeast-southwest (New Jersey Geological Survey, 1996).

Most of the sediments of the New Jersey Coastal Plain range in age from Cretaceous to Miocene (135 to 5.3 million years old) and were deposited in deltaic and marine environments as sea level fluctuated during Cretaceous and Tertiary times (New Jersey Geological Survey, 1996). Layers of sand and gravel were deposited during the slow retreat of the sea, forming aquifers. Intervening layers of silt and clay were deposited with the advancing sea, forming confining units. The period of marine deposition ended in the Miocene with the Cohansey Sand (Zapecza, 1989). Continental deposits then covered the area during the late Tertiary and Quaternary times. Fluvial sands and gravels, such as the Beacon Hill Gravel, were deposited at this time. Figure 6 shows the surficial geology of the watershed area.

Unconsolidated coastal plain sediments form five principal aquifers that are present in the watershed area. From shallowest to deepest, these aquifers are: (1) the Kirkwood-Cohansey aquifer system; (2) the

Atlantic City 800-Foot Sand; (3) the Wenonah-Mount Laurel aquifer; (4) the Englishtown aquifer system; and (5) the Potomac-Raritan-Magothy aquifer system (Figure 7). The Kirkwood-Cohansey aquifer system is the only unconfined aquifer in the watershed area. The confined aquifers are unconfined outside the watershed area where they outcrop or are overlain by permeable surficial deposits. The Potomac-Raritan-Magothy aquifer system is the most productive aquifer and the most heavily used confined aquifer in the coastal plain (U.S. Geological Survey, 1985). Withdrawals rates from individual wells can be as high as 7,692 l/min (2,000 gal/min). The aquifer system is divided into upper, middle, and lower units. The upper and middle units of the Potomac-Raritan-Magothy are the most heavily used in the Barnegat Bay-Little Egg Harbor watershed area. The Englishtown aquifer is an important source of water in Ocean and Monmouth Counties and has excellent water quality. Wells tapping this aquifer may yield up to 3,846 l/min (1,000 gal/min) (U.S. Geological Survey, 1985). The Wenonah-Mount Laurel aquifer and the Atlantic City 800-Foot Sand are important confined aquifers in the coastal plain, but are not heavily utilized in the Barnegat Bay-Little Egg Harbor watershed area. The Atlantic City 800-Foot Sand is used along the barrier islands in southern Ocean County and Atlantic and Cape May Counties. The Kirkwood-Cohansey aquifer system is unconfined and is becoming an increasingly important source of water supply as the confined aquifers become depleted. This aquifer exceeds 107 m (350 ft) in thickness in some places and yields ~1,892.5 l/min (~500 gal/min) (U.S. Geological Survey, 1985). Ground water from the Kirkwood-Cohansey aquifer system provides the principal source of freshwater to the Barnegat Bay-Little Egg Harbor estuary through either direct discharge or through discharge to tributary streams.

IV. SOILS

Soils are the result of earthen parental material, landscape, climate, and biological feedback interacting through time. Within the estuarine watershed, parent material and landscape position are the dominant influences determining the nature of soil. The watershed lies completely in the area recognized as the outer coastal plain and consists primarily of two types of mineral materials, Cohansey Formation sands and Beacon Hill gravels. Soils form predominantly from either one of the two parent materials or a mix of both. Landscape primarily refers to whether the land shape is concave and converging or convex and diverging. Concave is usually low and wet, whereas convex is high and dry.

Approximately six million years ago, the watershed was a broad plain covered with marine sand, several river channels with braided gravel bars across the floodplain, and a few oxbows accumulating organic matter. The Hudson River flowed across central New Jersey and made a turn to the east in what today is know as southwestern Monmouth County. The deposit, known as the Beacon Hill Formation, was a gravel point bar laid into the channel of the Hudson River. The highest elevations in the watershed were above 107 m (330 ft), and they declined in a series of marine terraces to the coast. The lowest elevations of the Beacon Hill were less than 30.5 m (100 ft) to the eastern portion of the mainland. Over time, the river migrated southward by eroding the southern outside bank of the river's massive curve and leaving the more gravelly material, known as the Beacon Hill Formation, on the northern inside turn. Three million years later, the river had continued to down cut the main channel through the central part of the state, and followed a path that would eventually become the Delaware River. From that time forward, deposition stopped, and a gravel layer covered the entire watershed.

Over time, sea levels rose and fell, and new streams formed on top of the gravel deposits. The stream headwaters were probably much nearer to the down cutting Hudson channel. The slopes extending to the east were shallow and the soils were porous, which acted to reduce erosion. The streams to the west flowed over finer soils and steeper grades back to the main channel causing erosion. This moved the divide to the east until the fine textured soils dipped below the sandy deposits of the Cohansey Formation and slowed the erosion. Today, that great gravel deposit exists only on high and wide ridges and isolated mounts lying beyond the end of the ridges. In the sloping valleys of the watershed, streams

have down cut through the gravel exposing the underlying sandy Cohansey Formation. The Beacon Hill Formation is more dissected to the east, with only a few isolated remnant hilltops as the only evidence that the deposit extended to the east. Although the landscape is stable today, during the last ice age when the landscape was frozen tundra, tremendous amounts of erosion resulted when rain fell upon the thawed surface overlying permafrost. In the past six million years, the entire topography of the landscape has inverted through erosion.

A. Soils Derived from Beacon Hill Materials

The feldspathic Beacon Hill gravels weather to clay. As these soils weathered in place for approximately six million years, they developed thick horizons, high clay contents, and reddish brown colors similar to soils in the southeastern U.S. The soils belonging to this group developed color and textural B horizons.

Erosion has thinned the Beacon Hill deposit. When its original thickness exceeds 1.5 m (5 ft), the soil is found completely within the weathered material and is called the Aura series. The upper 61 cm (24 in) is usually yellowish brown in color, reflecting weathering from the last period of severe erosion, which occurred during the close of the most recent glaciation in northern New Jersey. The subsoil is a reddish-brown sandy loam that is usually more than 1.2 m (4 ft) thick. Runoff has eroded the deposit at its edges, causing it to thin. When the soil is about 0.9 m (3 ft) thick, it is yellowish-brown sandy loam in the subsoil and is called Sassafras.

Moving still closer to the eroded edge of the Beacon Hill cap, the layer becomes thinner and the soil is called Downer. Slightly higher and thicker to the center of the Beacon Hill is the Downer sandy loam phase, and on the lower elevation is the loamy and surface texture phase. The difference in the two soils is more than just the surface texture. The loamy sand phase has slightly less clay at all depths within the profile. However, the difference is not enough to identify a new series. The Downer sandy loam not only contains more clay in the surface, but also differs in the thickness and percent clay in the subsoil. In the sandy loam, the percentage of sand in the B horizon of the two Downer soils varies from 16-17% in the subsoil and is typically 76.2 cm (30 in) thick, whereas the loamy sand subsoil has 12-14% and extends to only a depth of 61 cm (24 in). The profile often has gravel. The slightly increased water holding capacity of the sandy loam phase has an effect upon plant communities by increasing the percentage of white oaks and increasing the diversity of the understory, which mark the end of common Mountain Laurel thickets.

In places, the layers of the Cohansey sand that were directly beneath the clay forming Beacon Hill materials received downward translocated clay. When this setting is exposed to soil forming processes, it also gives rise to the Downer soil.

B. Soils Derived from the Cohansey Formation

The Cohansey sand gives rise to a very different set of soil conditions. Its extremely coarse quartzose sand produces no clay upon weathering. These soils develop strong color differences in the subsoil, but there is minimal textural change. Soils that form from this quartz dominated material are droughty, have little organic matter, low cation exchange capacity, and thus exhibit a poor capacity to attenuate nutrients. When water tables are deep, the soil is considered excessively drained and is called the Lakewood series. These soils are extremely acidic. The pitch pine-oak forest dominates these areas. As the landscape setting moves closer to the stream and to a lower elevation and the water table moves closer to the surface, the soil is called the moderately well-drained Lakehurst. Moving still closer and into very low flat wood pitch pine forest, the soil is termed the Atsion series. If the site is sufficiently low and the water table either reaches the surface or is above the mineral surface, the soil is called the

Berryland series. If the water is above the surface for a period long enough that organic matter accumulates on the surface to a depth of more than 41 cm (16 in), the soil is called the Manahawkin series.

C. Mixed Parent Materials

Although a glacier did not cover this area, its close proximity resulted in a frozen barren area. As the surface layers thawed, a thick soup-like mixture of water and loose soil flowed down the side slopes leaving a layer of pedisediment or foot slope sediments and causing the more cohesive weathered edge to retreat. The finer textures capping all the ridges acted like a pedestal effect protecting the underlying sands from erosion.

Many areas have a mixture of the two types of parent material. During the last several thousand years, there have been periods when extreme heat, fire, drought, and cold in the area have caused denudation of vegetation. When this happens, wind blows sand across the surface. This is especially true of sands that were carried in water channels. The prevailing winds are from the northwest causing much sand to blow to the south side of east-west streams and to the east side of north-south streams. The deposited sands closest to streams are thicker and coarser. Enclosed depressions on the landscape are a clear indicator of eolian deposition as depressions result only from deposition processes or the dissolution of parent material, of which there is none within the watershed. When the entire soil forms in a relatively recent deposit, the soil will be within the watershed and termed the Evesboro or Klej. As the layer covers the Beacon Hill pedisediment, another set of soils is established to cover the stratification of parent material that is reversed from the order in which the water laid deposits exist. A Woodsmansie series is windblown sand over what would have formed an Aura. The soil forming processes actually occur in the overlying sand instead of the gravel layers. When the windblown sand is over a thin layer of pedisediment over sand, the soil may be mapped as Lakewood or Lakehurst depending on depth to water. The A and E horizons form in the windblown materials. The soils are classified the same because the small amounts of pedisediment will not change the use and interpretation of the soil.

In all cases, except the soils that are periodically saturated in the spring, there is no direct overland flow to the streams. Soils predominantly derived from Beacon Hill materials have moderate permeability and have some capacity for filtering the percolating water. Areas dominated by the coarse sand have maximum leaching with minimum filtering, even if they have thin layers of lag sediment.

The improvised soils of the Barnegat Bay watershed offer little buffering against additions or depletions. Calcium is nonexistent. The low pH causes nutrient availability problems and aluminum toxicity in plants. The sandy soils would be best characterized as a dry, sterile, acid environment. Sandy textures dominate this environment. Few organisms live in the soil, and the food chain is characterized by slow growth under austere conditions. The low cation exchange capacity does little to attenuate additions. The low nutrient holding capacity results from the effect of the organic matter and the presence of cation exchange capacity of the clay fraction of the soil. Cation exchange capacity from the organic fraction of the soil is largely pH dependent. Most of the nutrients reside within the vegetative state rather than within the soil. The nutrient status of all the soils is very low. The waters that flow from these soils are clean, not because of how the soil treats the water, but because the land use is native vegetation without the addition of lime, fertilizers, or pesticides.

D. Soils Derived from Organic Soil Material

Important organic soils occur at the edges of the bay and in the mouths of streams that empty into the bay. Sea-level rise submerges the mineral materials over time. Organic soils also form in broad flooded

reaches of streams.

E. Landscape

The New Jersey Coastal Plain consists of a series of marine terraces. The highest terrace is the most dissected by streams. Because there are no confining beds, maximum infiltration occurs in the highest elevations and most distant interfluves. Infiltration in the highlands maintains the ground water and provides the base flow during the summer. Rainfall falls on the lower terrace where the streams are less incised; wetter areas occur in the interfluve position. The lowest terrace with most of the organic soil materials either in or on the surface has the greatest filtering capacity. These soils and especially the wet soils of the lowest terrace provide important filtering of surface water before it enters the bay. The carbon and the anaerobic conditions can dispose of nitrogen compounds harmlessly as nitrogen gas is released into the atmosphere. Wetlands become more critical as a greater percentage of the total water flowing in the streams with increased surface flows (resulting from land conversion away from forests) must be cleaned. The deepening, widening, or straightening of stream channels reduce the effectiveness of the wetlands to perform this function. Due to the high infiltration rates in forests, most soils not in the wetlands will only produce a significant response in peak flows during the most extreme rainfall events.

F. Soils and Hydrology

The watershed of the Barnegat Bay-Little Egg Harbor estuary is best characterized as a bed of sand overlying an aquifer that outcrops into the embayment. A full exchange of water occurs between the stream channels and the adjacent wetland soils through most of their length. In contrast to upland streams, which have a retreating nick-point segment that erodes a through-flow section and deposition segment, streams in the coastal plain gradually receive ground water as they flow seaward. The riverine wetland parallels the watercourse continuously on at least one bank except in areas that have been filled. There are no naturally occurring lakes. The lowest reaches, as the streams approach the estuary, are constantly flooded by rising sea level.

V. HYDROLOGY

Freshwater within the watershed not only influences the character of the estuary but also provides a source of water supply for the region. The characterization of freshwater flows in the watershed is based on measurements and analysis of flow in different parts, or compartments, of the hydrologic system. Most of the freshwater flowing into the estuary enters as discharge from numerous streams. Stream flow measurements are available for U.S. Geological Survey gaging stations at 19 sites within the Barnegat Bay-Little Egg Harbor watershed area (Figure 7). The total drainage area above the downstream-most gaged sites is 865 km2 (335 mi2), or 60% of the total land area within the watershed.

A. Surface Water Hydrology

The source of stream flow is an important consideration in the evaluation of contaminant loadings to the estuarine ecosystem. Stream flow has two components: direct runoff and base flow. Direct runoff is stream flow that results from surface runoff and precipitation that falls directly on the stream. Base flow is generally stream flow that results from the discharge of ground water to the stream. On an annual basis, most of the stream flow to the Barnegat Bay is base flow. For example, annual base flow for the Toms River during the years 1929-89 ranged from 80% to 89% of the total stream flow. The base flow for the Metedeconk River during the years 1973-89 was 63% to 79% of the total stream flow (Watt et al., 1994). During high-flow periods immediately following rainfall events, more of the flow is surface runoff and less is base flow. During periods of little or no rainfall, virtually all flow in the streams is

base flow.

Stream flow fluctuates in response to a variety of hydrologic conditions, although a cyclic seasonal pattern of variability is common, as illustrated by the stream flow hydrograph for the Toms River during 1976-98 (Figure 7). Highest stream flows typically occur during winter and early spring when evapotranspiration is lowest. The lowest stream flows usually occur during late summer and fall, near the end of an extended period of high evapotranspiration. For example, during the period 1929-89, the mean monthly discharge of the Toms River near the town of Toms River for the month of April was 160% of the mean annual discharge, whereas the mean monthly flow for September was 52% of the mean annual discharge (Hickman, 1995).

The stability of the freshwater flow regime during extreme hydrologic events is an important consideration in the maintenance of the estuarine ecosystem. A flow duration curve provides an indication of this stability. This curve is a cumulative-frequency curve showing the percentage of time that any specific discharge is equaled or exceeded (Lanbein and Iseri, 1960). The flow duration curve for the Toms River, for example, shows that the median discharge (50% exceedance) at the Toms River stream flow gaging station is 5.3 m3/s (~187 ft3/s), the 99% exceedance is 1.9 m3/s (67 ft3/s), and the 1% exceedance is 18.3 m3/s (640 ft3/s) (Watt et al., 1994). This means that the stream flow at this site is nearly always more than 1.9 m3/s (67 ft3/s) and less than 18.3 m3/s (640 ft3/s). Table 1 lists discharge statistics for the six continuous stream flow gaging stations in the watershed area.

Results of trend tests on stream flow of the North Branch of the Metedeconk River near Lakewood (station number 01408120) and the Toms River near the town of Toms River (station number 01408500) indicate that the lowest annual discharge decreased during water years 1970-89. Climatic variations may have caused or contributed to these trends (Hickman, 1995).

B. Ground Water Hydrology

Ground water discharge from the unconfined Kirkwood-Cohansey aquifer system to streams within the watershed area is the largest source of freshwater to the Barnegat Bay-Little Egg Harbor estuary. The altitude of the water table in the watershed area is shown in Figure 8. The water table is generally a subdued replica of land surface. Shallow ground water flows perpendicular to water table contours, in directions similar to that of the surface drainage. The regional pattern of ground water flow trends from northwest to southeast. Most of the ground water in the unconfined aquifer system follows short flow paths and discharges locally to surface water bodies or follows longer, deeper flow paths and discharges to distant streams at lower elevations, to the estuary, or to the Atlantic Ocean. Some flow leaks into deeper aquifers. Most water within the unconfined aquifer system discharges to local streams as base flow. The aquifer system is generally in good hydraulic connection with surface water bodies, and streams generally gain flow from the aquifer system throughout the year (Nicholson and Watt, 1996).

The distribution of direct ground water discharge to the estuary can affect salinity and circulation. It can be restricted locally by the presence of silt and clay beds beneath the estuary (Lennon et al., 1997). The total amount of direct ground water discharge to the estuary is less than the amount of stream base flow entering the system (Nicholson and Watt, 1996; Guo, et al., 1996).

The deeper, confined aquifers underlying the watershed area have different subsurface extents, but most include areas to the north in northern Monmouth County and parts of Middlesex County. Figure 9, a generalized hydrogeologic section, shows the position of each of the major aquifers in the watershed. As a result of excessive ground water withdrawals, water levels in the confined aquifers have declined to well below sea level, and saltwater intrusion has resulted in the loss of ground water supplies in some

areas. In response to these problems, the New Jersey Department of Environmental Protection (NJDEP) mandated reductions in withdrawals from affected aquifers, and costly alternative sources of water supply have become necessary. Saltwater intrusion remains a major, long-term concern for water supplies in the region.

C. Hydrologic Budget

The relative magnitude of the various sources of freshwater to the estuary is best summarized by a hydrologic budget for the region. Precipitation and water imported for water supply are the only freshwater inflows to the land surface of the watershed area. Freshwater outflows from the land surface of the watershed area include direct runoff, evapotranspiration, ground water recharge, and surface withdrawals for water supply. Figure 10 exhibits the relative magnitude of each of these components. Water entering the shallow aquifer system as recharge is discharged to streams as base flow, discharged directly to the estuary, withdrawn for water supply, or leaked downward to deeper, confined aquifers. Figure 10 also displays the relative magnitude of each of these components.

1. Freshwater Inflows

Freshwater inflows to the estuary include incident precipitation (precipitation that falls directly on open estuarine waters), surface water discharge to the estuary, and direct ground water discharge to the estuary. Annual precipitation in the watershed area is 1.17 m (3.8 ft). Over the estuary surface of 279 km^2 (108 mi^2), incident precipitation averages ~840 million m^3 (~222 billion gal) annually, which is equivalent to ~2.3 million m^3/d (~940 ft^3/s). The total of all surface water discharges to the estuary is ~2 million m^3/d (~800 ft^3/s). Direct ground water discharge to the estuary is ~0.3 million m^3/d (~110 ft^3/s). Figure 11 summarizes the annual freshwater inflows to the embayment.

During unusually dry periods, the combined total of all freshwater inflows is approximately one-third of the annual average rate of inflow. It is sustained almost entirely by ground water discharge to tributary streams and direct ground water discharge. Under such low-flow conditions, less freshwater is available to mix with influent saltwater and to dilute contaminant loadings, thus affecting the water quality regime of the estuary.

2. Water Use, Drinking Water Wells, Intakes, and Other Diversions

The sources of water supply in the region fall into four general categories: (1) ground water from the shallow, unconfined aquifer system; (2) ground water from the deeper, confined aquifers; (3) surface water; and (4) water transferred into the region from adjacent areas. If a water supply becomes unavailable for present or anticipated future use, as a result of saltwater intrusion or some other source of contamination, then alternatives to that supply must be implemented. There is concern that a greater reliance on the unconfined aquifer system and surface water withdrawals would result in less freshwater flowing into the estuary, thus magnifying the effects of low-flow conditions.

Ground water from the shallow, unconfined aquifer system for public supply, as well as for commercial, industrial, and irrigation uses in 1994 averaged ~114 MLD (~30 MGD). Withdrawals for these uses from the deep, confined aquifers averaged ~64 MLD (~17 MGD). Total withdrawals from private wells for domestic use in 1990 were estimated at ~33 MLD (~8.8 MGD) (CH2M HILL, 1994). These withdrawals are likely to have increased in recent years. One surface water intake, located on the Metedeconk River, withdrew an average of 23 MLD (6.1 MGD) in 1997 (A. Lechich, Brick Utilities, personal communication, 1998). In 1990, net water transfers into the three state-designated Regional Water Resource Planning Areas within the watershed were estimated at a total of 9 MLD (2.4 MGD)

(NJDEP, 1996), although this net rate is likely to have increased in recent years.

3. Water Supply Characterization

Growing communities in the Toms River, Atlantic Coastal, and Metedeconk River watersheds share numerous sources of water supply, including ground water from confined and unconfined aquifers, surface water, and water transferred in from adjacent areas. These watersheds likewise share a variety of factors and issues that act to limit water availability. Many of the sources of water supply are also the sources of freshwater flows to Barnegat Bay, resulting in both competition for this vital resource and a common need for its protection.

> Historical increases in population, water demand, and other human activities in the region have resulted in substantial water supply problems, including excessive water level declines, saltwater intrusion, stream flow reduction, and water quality degradation. As population and water demand increase, these stresses could become more severe. Water use in the region is principally depletive. Most water used in the homes and businesses of the region is ultimately discharged to the ocean following treatment, or is otherwise used consumptively, without opportunity for beneficial reuse.

Withdrawals from the unconfined Kirkwood-Cohansey aquifer system have lowered ground water levels and caused reductions in stream flow. Freshwater flows are needed to support natural riverine and estuarine ecosystems and to assimilate pollutant loadings. Reductions in freshwater flows to Barnegat Bay are expected to affect estuarine water quality, habitats, and other ecological resources. The unconfined Kirkwood-Cohansey aquifer system is particularly vulnerable to contamination. If a water supply drawing on a particular source in a particular area becomes unavailable for present or anticipated future use, then alternatives to that water supply must be considered and implemented.

It is essential that potential water supply solutions are evaluated through a watershed-based approach. Efforts to protect surface and ground water supplies must be integrated with a broader effort in watershed-based, water resource management, which seeks to synthesize land-use planning, water-supply planning, wastewater management, and ecosystem protection. Prior to developing and implementing a final watershed plan that meets this objective, water availability, as well as water resource problems in the region must be characterized and quantified more precisely. In particular, watershed stakeholders should determine, within tolerable limits, the amount of surface water needed (locally and regionally) to support freshwater ecosystems on the mainland, and the amount of freshwater necessary to maintain the ecosystem components of the estuary. Existing and projected point and nonpoint source pollutant loadings should be integrated into these estimates to ensure that water quality and water quantity issues are properly integrated.

While minimum stream flows are being estimated, the optimal, sustainable rates of withdrawal from the region's confined aquifers should also be determined. In order to adequately characterize stream flow needs and confined aquifer vulnerability to saltwater intrusion, additional hydrogeologic monitoring and investigation will be necessary.

Once the water resource problems are better defined, then a determination can be made of the short-term and long-term strategies that need to be implemented. Strategies could be implemented when specific hydrologic "triggers" (identifiable events or conditions that indicate the need for action) occur and are documented through established monitoring networks. Four possible implementation strategies are described which relate to the management of saltwater intrusion. Each of these strategies includes the

development of alternative regional water supply alternatives to confined aquifer supplies.

Water conservation measures should be implemented for water supply management (such as reducing water losses from distribution system leaks) and for water demand management (such as reducing demand for turf irrigation by use of indigenous vegetation for landscaping). Several potential water supply alternatives should be considered to meet growing demand, while simultaneously reducing environmental stress to the region's ecosystems. Among these alternatives is the utilization of unallocated Manasquan Reservoir water. This alternative should include measures to supplement the yield of the reservoir system, such as transferring water from adjacent areas, and the conjunctive use of the confined aquifers regulated by Critical Water Supply Area #1 during drought. Plans are currently underway for an off-line reservoir to store water from the Metedeconk River.

Another water supply alternative that should be evaluated is seasonal conjunctive use of water from different sources. In this alternative, unconfined aquifers (or other surface water) would be primarily used during periods of high stream flow, and the confined aquifers would be used during periods of low stream flow. This alternative provides the benefit of reducing stress on stream base flow during natural low-flow periods, while allowing for recharge of the confined aquifers when the unconfined aquifers are being used. New interconnections between water systems can help provide an overall increase in system yield by facilitating conjunctive use of different sources.

Other possible alternatives include flood skimming of surface water, and artificial recharge of surface waters to the region's confined aquifers. Strategic location of supply wells can reduce the effects of stream flow reduction from pumpage of the unconfined aquifers and saltwater intrusion from pumpage of the confined aquifers. Stormwater can also be used to artificially recharge unconfined aquifers through the use of recharge basins.

Depletive effects of unconfined aquifer withdrawals could be alleviated by the implementation of wastewater reuse, whereby water is withdrawn from unconfined aquifers, used, treated locally under regional authority, and then discharged locally to streams or land-applied in the general vicinity of the withdrawal, allowing for beneficial reuse. The use of domestic wells that withdraw their supplies from the water table aquifer, in combination with properly designed and maintained individual septic systems on adequately sized lots, achieves this wastewater reuse objective at a local scale.

Desalination may become a viable alternative if future demand approaches the sustainable yield of the other alternatives. However, desalination is an expensive alternative and will be pursued only under the most extreme conditions.

Several strategies should be emphasized in order to protect water quality. These strategies include: source water assessment and protection, well head protection, aquifer recharge area protection, nonpoint source pollution prevention, and depletive water use management. Active stakeholder participation in each of these strategies will be critical to their success, and therefore public outreach on water supply issues and guidance on implementation of Best Management Practices (BMPs) should be emphasized and encouraged.

VI. WATER AVAILABILITY AND DEMAND

Presented below is a summary of water availability, recent (1990) water demand, and projected water demand for each watershed, as described in the 1996 New Jersey Water Supply Plan. Water supply availability is defined as the safe yield for surface water supplies, combined with the dependable yield of

> ground water supplies. The safe yield of a surface water supply is the amount of water from a reservoir or surface water intake that would be continuously maintainable throughout a repetition of the most severe drought of record, after compliance with minimum stream passing flows.

For ground water, the NJDEP currently employs "planning thresholds" where a percentage of ground water recharge is considered available for depletive water uses without resulting in harmful impacts such as saltwater intrusion, intolerable stream flow diminishment and impairment of the designated uses of water resources. Depletive withdrawals refer to water that is not returned to a water resource from which the water was originally withdrawn. The most common depletive water use is water that is withdrawn, used, collected in a sewerage system, and discharged at a distant location.

For planning purposes, unconfined aquifer recharge was determined using a stream base flow separation analysis of the northern part of the outer coastal plain (James Boyle, New Jersey Geological Survey, personal communication, October 15, 1998). In the coastal region, the NJDEP assumes that a maximum of 10% of recharge is available for depletive water uses. The 10% of recharge value was selected after evaluating several regions that have undergone comprehensive geohydrologic investigations in an effort to estimate the threshold at which ground water supplies experience significant and acceptable stresses. This 10% of recharge value is used for planning purposes; more comprehensive, area-specific geohydrologic evaluations are generally employed to revise the planning thresholds. Depletive ground water use in two of the three Barnegat Bay watersheds (i.e., Toms River and Metedeconk River) currently exceeds the planning threshold.

The NJDEP is presently reconsidering the use of the above-described planning thresholds. It is evaluating the use of separate thresholds for unconfined aquifers and confined aquifers. For unconfined aquifers (that are not near coastal waters), the NJDEP is considering the use of thresholds that are based on a percentage of low stream flow as a means of precluding intolerable reductions in stream discharge during drought. For confined aquifers, the NJDEP is considering the use of saltwater intrusion rate as the "yardstick" for ground water withdrawals from these resources. If these thresholds are adopted, the planning surpluses and deficits described below could be subject to change.

It should be noted that population and water demand projections in the 1996 New Jersey Statewide Water Supply Plan reflect those for the period of 1990 to 2040. Future water supply planning should employ population and water demand projections for the period 2000 to 2050, or at buildout (buildout refers to the maximum extent of land development permissible under local zoning and land-use ordinances) should that be anticipated to occur prior to the end of the planning horizon. It should also be noted that estimating population and consequent water supply needs are just that -- estimates. The development of such projections is not an exact science, especially in a complex state like New Jersey. There are many factors - demographic, economic, sociopolitical, climatic and technological - that influence future populations and water demand. It is for these reasons that it is important to employ "triggers" to initiate water supply alternatives versus the total reliance on estimates. Caution must be exercised, however, to allow adequate "lead time" to implement the alternatives.

> The Manasquan River, Metedeconk River, Toms River, and Atlantic Coastal watersheds have experienced significant growth over the past several decades. The population of Ocean County has grown eight-fold from 1950 to 1990 (56,622 to 471,100) (Donald J. Bergman and Associates, 1990). Ocean County's population is projected to grow to 772,988 by the year 2040 (CH2M Hill, 1994). During the period between 1950 and 1990, water demand increased ten-fold (Bergman and Associates, 1990). Water demand in 1990 has been estimated at 276 MLD (72.9 MGD), with peak water use at 416 MLD (109.9

MGD). Water demand in the county is projected to increase to 447 MLD (118 MGD) (peak demand 685 MLD, 181 MGD) by the year 2040.

As shown in Table 2, the population in the four watersheds is projected to increase 71% during this period, while water demand is projected to increase by the same percentage. The overall state population is projected to grow by only 16% during this period. The populations of the Manasquan River and Metedeconk River watersheds are projected to increase the least (26% and 38%, respectively), while the watersheds to the south - the Toms River and Atlantic Coastal watersheds - are projected to increase the most (80% and 150%, respectively).

A. Metedeconk River Watershed

The estimated ground water availability in the Metedeconk River watershed is 42.4 MLD (11.2 MGD) (10% of total recharge). Surface water availability in the watershed is 49.2 MLD (13 MGD) (Brick Township MUA), resulting in 91.6 MLD (24.2 MGD) in total available water. However, since 0.76 MLD (0.2 MGD) is transferred (1990) out of the watershed, a net water supply of 90.8 MLD (24 MGD) exists for planning purposes. Since the estimated ground water withdrawals are 51.9 MLD (13.7 MGD) (1990), and the estimated surface water withdrawals are 5.3 MLD (1.4 MGD) (1990), the watershed has been assigned a "planning" surplus of 33.7 MLD (8.9 MGD). In addition, since 1990 ground water withdrawals exceed the (10% of recharge) threshold, there is a ground water deficit of 9.5 MLD (2.5 MGD). The overall surplus is expected to decrease to 30.7 MLD (8.1 MGD) by the year 2040 based on population projections. As discussed below, the above values reflect 1990 figures and need to be updated. Because the planning surplus is likely to be lower, Brick Township has contracted more water during the past decade.

B. Toms River Watershed

The estimated ground water availability in the Toms River watershed is 20 MGD (10% of total recharge). There are no public surface water supplies in the watershed. Approximately 37.9 MLD (10 MGD) are diverted for commercial/agricultural use. Because 7.2 MLD (1.9 MGD) are transferred (1990) into the watershed, a net available water supply of 82.9 MLD (21.9 MGD) exists for planning purposes. However, the watershed has been assigned a "planning" deficit of 62.5 MLD (16.2 MGD) because ground water withdrawals are estimated at 106.4 MLD (28.1 MGD) (1990), and surface water withdrawals are estimated at 37.9 MLD (10 MGD) (1990). This deficit is projected to increase to 153 MLD (40.4 MGD) by the year 2040. The 1990 planning deficit is probably lower because Ciba Geigy ceased withdrawing surface water for operations during that year. Since 1990 ground water withdrawals exceed the planning threshold, there is a ground water deficit of 30.7 MLD (8.1 MGD). As discussed below, the figures presented above reflect 1990 statistics; they need to be updated with more recent data.

C. Atlantic Coastal Watershed

The estimated ground water availability in the Atlantic Coastal watershed is 94.6 MLD (25 MGD) (10% of total recharge). There are no public surface water supplies in the watershed. A net water supply of 95.8 MLD (25.3 MGD) exists for planning purposes because 1.1 MLD (0.3 MGD) are transferred (1990) into the watershed. Since ground water withdrawals are estimated at 45.0 MLD (11.9 MGD) (1990) and surface water withdrawals (likely agricultural) are estimated at 1.1 MLD (0.3 MGD) (1990), the watershed has been assigned a "planning" surplus of 45.8 MLD (12.1 MGD). Due to relatively large projected increases in population growth, the watershed is expected to have a deficit of 7.2 MLD (1.9 MGD) by the year 2040. There is a ground water surplus of 49.6 MLD (13.1 MGD).

D. Manasquan River Watershed

As mentioned previously, the Manasquan River watershed is discussed in this document because some of the surface water supplies from the Manasquan Reservoir may be available to "augment" water supplies in the Barnegat Bay watershed. The estimated ground water availability in the Manasquan River watershed is 34.4 MLD (9.1 MGD) (10% of total recharge). Surface water availability in the watershed is 113.6 MLD (30 MGD) (Manasquan Reservoir), resulting in 148 MLD (39.1 MGD) in total available water. However, there is a net available supply of only 98.4 MLD (26.1 MGD) because 49.2 MLD (13.0 MGD) is transferred out of the watershed. Because ground water withdrawals are estimated at 40.9 MLD (10.8 MGD) (1990) and surface water withdrawals are estimated at 7.2 MLD (1.9 MGD) (1990), the watershed has been assigned a "planning" surplus of 50.7 MLD (13.4 MGD). In addition, because current ground water withdrawals exceed the (10% of recharge) threshold, there is a current ground water deficit of nearly 7.6 MLD (2.0 MGD). Based on population projections, the overall surplus is expected to decrease to 30.7 MLD (8.1 MGD) by the year 2040. The Manasquan Reservoir has contracted more water (a total of about 60.6 MLD, 16 MGD) since 1990. The 1990 planning surplus is likely much lower.

E. Water Availability in All Four Watersheds

For all four watersheds, the estimated ground water availability is 247 MLD (65.3 MGD). Surface water availability in the watershed is 163 MLD (43 MGD) (Manasquan Reservoir and Brick Township MUA), resulting in 410 MLD (108.3 MGD) in total available water. Because most of the interbasin transfers are between the four watersheds, the net water supply is unaffected by these activities. The region as a whole is in a slight planning ground water deficit because ground water withdrawals are estimated at 248 MLD (65.5 MGD) (1990). Surface water withdrawals are estimated at 51.5 MLD (13.6 MGD) (1990); thus, a surface water planning surplus of 112.4 MLD (29.7 MGD) exists for planning purposes. Overall, this translates to the watershed being assigned a "planning" surplus of 111.7 MLD (29.5 MGD). The planning surplus is likely much lower because the Manasquan Reservoir and Brick Township MUA have contracted more water since that date.

F. Assumptions and Uncertainties

The reliability of estimates of water availability is subject to the validity of numerous assumptions derived from current knowledge of rates and locations of withdrawals and transfers, and knowledge of the regional and local hydrologic systems and subsystems. As noted above, withdrawals and interbasin transfers reflect 1990 estimates; consequently, if they have substantially increased since 1990, then the applicable "planning" surpluses or deficits may need to be adjusted. Further, ground water availability from confined aquifers within the watershed should represent the amount of water permitted pursuant to the critical water supply area regulations. As suggested above, more comprehensive geohydrologic investigation may result in a revision of the 10% of recharge planning threshold for estimating ground water availability.

For withdrawals from the unconfined Kirkwood-Cohansey aquifer system, the amount of water that may be withdrawn is dependent on stream flow reduction that results from these activities. As discussed below, reductions to stream base flow are rather significant as a result of current depletive withdrawals in some of the watersheds and subwatersheds. The current use of ground water thresholds by the NJDEP is applied to a watershed as a whole. If ground water withdrawals are concentrated in a subwatershed (e.g., Kettle Creek), those withdrawals could possibly have a detrimental impact on stream flow in that

subwatershed. Thus, the "masking" of local conditions by the regional scale of analysis is an issue. The NJDEP is in the process of adopting regulations that deal with depletive withdrawals from unconfined aquifers. If adopted, it is anticipated that the region as a whole will have a substantial ground water deficit.

Peak seasonal water use in the Barnegat Bay watershed is significant and may further reduce the amount of available water. Since peak water use typically occurs at approximately the time of year when stream flow is naturally low (during summer and early fall), it could have a significant effect on stream flow diminishment. Peak demand in Ocean County is about 160% of average demand; Ocean County has the third largest ratio of peak-to-average demand (peaking factor) of all the counties in the state. Only Cape May and Monmouth counties have larger peaking factors. The state average is about 130%. It is thought that this high peak demand represents a combination of the use of summer homes along the coast and high irrigation demands. In addition, the safe yield of the existing Brick Township MUA surface water intake may possibly be lower than presently thought due to substantial depletive ground water withdrawals from the Kirkwood-Cohansey aquifer system upstream of the intake. If proven to be accurate, the surface water planning surplus may need to be adjusted downward. Further, considerable growth is projected upstream of the Brick Township MUA's intake. Should future development use the Kirkwood-Cohansey aquifer system, stream flow depletion can be further accelerated.

Lastly, as growth continues in the region, there will likely be additional withdrawals from the confined aquifers outside of the critical water supply areas. More geohydrological investigations will be needed to determine if the confined aquifers can support this growth without accelerating additional saltwater intrusion along the central part of the coast.

Regarding water quality, experience suggests that extensive growth can impair both surface and ground water quality. If substantial impairment of the Kirkwood-Cohansey aquifer or surface water sources occurs in the future and major supplies are lost, the water supply deficit will be exacerbated.

VII. IMPACTS OF EXCESSIVE WATER DEMAND ON WATER RESOURCES

The historical increases in population and water demand in the Middlesex-Monmouth-Ocean region have resulted in substantial water supply problems. Below is a discussion of those impacts to the confined and unconfined aquifers.

A. Confined Aquifers

Prior to the development of regional water supplies, water pressure levels in all confined aquifers in the New Jersey Coastal Plain were above sea level (see Appendix A-1). Withdrawals from confined aquifer supply wells located within and outside the project area (see Appendix A-2) have produced cones of depression that are extensive (see Appendix A-3). These withdrawals have caused the migration of saltwater into two productive aquifers outside the project area in northern Monmouth County and in Middlesex County (USGS, 1989).

These deep cones of depression are the result of withdrawals in areas where relatively low rates of ground water flow from adjacent areas and overlying aquifers are available to replace the water withdrawn. By 1983, confined aquifer withdrawals in response to high water demand had caused ground water pressure levels to decline below 67.1 m (220 ft) below sea level in the Englishtown aquifer system in the Lakewood and Brielle/Spring Lake areas. In the Wenonah-Mount Laurel aquifer, the pressure levels declined to below 56.4 m (185 ft) below sea level in the Manasquan-Belmar area. In the middle aquifer of the Potomac-Raritan-Magothy aquifer system, the levels declined to below 9.1 m (30 ft)

below sea level in the Lakewood area. In the upper aquifer of the Potomac-Raritan-Magothy aquifer system, levels declined to below 12.2 m (40 ft) below sea level in the Freehold area. The U.S. Geological Survey estimated that if withdrawals had been left unrestricted, ground water levels would have declined further.

Saltwater intrusion caused by excessive confined aquifer withdrawals has resulted in elevated chloride concentrations in supply wells in the upper and middle aquifers of the Potomac-Raritan-Magothy aquifer system to the north of the project area. Specific locations where the upper aquifer is affected by saltwater are the South Amboy, Keyport, Union Beach, and Keansburg areas. Specific locations where the middle aquifer is affected are the Sayreville, South Amboy, Keyport, and Union Beach areas (USGS, 1993). The potential for saltwater intrusion into these aquifers in the project area is not well understood, but is a concern.

In response to this situation and a similar situation in another part of the New Jersey Coastal Plain, the NJDEP designated Water Supply Critical Areas #1 and #2, and mandated reductions in confined aquifer withdrawals in these areas. Since reductions were initiated in 1990, ground water levels in Critical Area # 1 have substantially recovered (Figure 12). However, the threat of saltwater intrusion remains.

Some supply wells which tap major confined aquifers within the project area are considered potentially threatened by saltwater intrusion over the long term (O. Zapecza, USGS, written communication, July 6, 1994). These are located in the following areas:

- Long Beach Island (Atlantic City 800-Foot Sand aquifer);

- Barnegat Light, Seaside Heights, and Seaside Park (Piney Point aquifer);

- Spring Lake, Belmar, and Neptune (Wenonah-Mount Laurel aquifer);

- Point Pleasant, Lavalette, other Monmouth County locations (Englishtown aquifer system);

- Point Pleasant, Chadwick, and Lavallette (upper aquifer of the Potomac-Raritan-Magothy aquifer system); and

- Lavallette, Toms River, and other locations in northern Ocean County (middle aquifer of the Potomac-Raritan-Magothy aquifer system.)

B. Unconfined Aquifers (Kirkwood-Cohansey Aquifer System)

Many municipalities and public purveyors use the unconfined Kirkwood-Cohansey aquifer system in the watershed. Because of the potential threat of saltwater intrusion in the confined aquifers of the region, it is anticipated that demands for additional withdrawals from the Kirkwood-Cohansey aquifer system will increase.

> Historical ground water withdrawals have caused shifting flow patterns in parts of the Kirkwood-Cohansey aquifer system, reducing ground water discharge to streams and wetlands of significant ecological value. Recent hydrogeologic

investigations indicate that withdrawals from the Kirkwood-Cohansey have lowered ground water levels and have caused average reductions in stream flow up to 11% (USGS, 1997). In some streams, stream flow during natural low-flow periods could decrease by ~26% if water allocations are fully utilized. Kettle Creek, in particular, could be most affected. Withdrawals have caused average ground water levels to decline by up to 6.1 m (20 ft) near pumping centers. At full allocation, it is estimated that water levels will decline further by up to ~6.1 m (~20 ft). These impacts can potentially damage riverine ecosystems and reduce the yields of the surface water supplies of the Metedeconk River (and the Toms River if it is used for water supply purposes in the future).

A recent investigation of trends in stream discharge over time concluded that stream flow measured at gaging stations on the North Branch of the Metedeconk River and Toms River decreased during low-flow periods between 1970 and 1989 (USGS, 1995). However, the cause(s) of these declines has not yet been determined, nor has there been a determination of whether ecological resources or shellfish have been affected. Nevertheless, the NJDEP is presently evaluating actions to be taken to minimize possible impacts.

There are two areas in the region where saltwater intrusion has affected wells withdrawing water from the Kirkwood-Cohansey aquifer system. Saltwater has adversely affected public-supply wells located in Seaside Heights and Point Pleasant Beach. There are numerous other public and private wells that are located near brackish water along the coast. Consideration should be given to additional monitoring, where applicable, especially if higher allocations are proposed.

Domestic wells in Berkeley, Dover, Eagleswood, Lakewood, and Stafford produce water with high levels of sodium (Donald J. Bergman and Associates, 1990). It is unknown if this phenomenon is caused by saltwater intrusion, road salting, or septic systems.

Present and future withdrawals from the region's confined aquifers can also shift ground water flow patterns and result in stream flow diminishment. These effects should be quantified so that the cumulative effects of all pumpage can be understood.

Ocean County has the largest number of domestic wells of any county in New Jersey. It is thought that large numbers of these wells are used for lawn irrigation. When there are large numbers of domestic wells that are used for this purpose in close proximity to each other, the effects can be similar to a large public well that serves homes and businesses that are in a sewer service area. Much irrigation water is subject to evapotranspiration and is not "recycled" into the aquifer system. It was estimated that domestic wells in Ocean County used 40.5 MLD (10.7 MGD) in 1990 (Donald J. Bergman and Associates, 1990). Most of these wells are in the Kirkwood-Cohansey aquifer system.

When large areas are developed, impervious cover can reduce ground water recharge. These effects can have stream flow depletion effects that are similar to the effects of large pumping centers. In regard to the magnitude of development projected in the Barnegat Bay watershed, increases in impervious cover could have significant effects on ground water levels and stream base flow. In addition, large amounts of impervious cover (10% or more) could greatly affect the overall quality of watersheds/subwatersheds through the introduction of significant nonpoint sources of pollution, habitat loss, and other impacts associated with human intervention.

VIII. ESTUARINE CIRCULATION

Winds, tides, salinity gradients, and the geomorphology of the Barnegat Bay-Little Egg Harbor estuary strongly control hydrological conditions. Because of the extreme enclosure and shallowness of the system, winds significantly influence circulation patterns, and tidal forces are of secondary importance. Episodic meteorological events (i.e., hurricanes, northeasters, and other major storms) can dramatically alter circulation in the estuary. Under normal conditions, Barnegat Bay is vertically homogeneous, although a tendency toward two-layered flow occurs in deeper waters of the Intracoastal Waterway and larger river tributaries (Carpenter, 1963; Chizmadia et al., 1984). Lateral circulation is greatest at Barnegat Inlet, Little Egg Inlet, and the Intracoastal Waterway.

A. Tidal Effects

The Manasquan Inlet, which is the entrance to the Intracoastal Waterway in New Jersey, provides a conduit for the input of seawater into northern Barnegat Bay via the Point Pleasant Canal. Ocean water not only enters the estuarine system from the Point Pleasant Canal in the northern perimeter, but also from Barnegat Inlet near the center and from Little Egg Inlet at the southern border. The Point Pleasant Canal is a narrow (30-40 m wide; 98-131 m wide), 3-km-long (1.8 mi-long) waterway connecting the Manasquan River and the Intracoastal Waterway. The Manasquan River to the head of tide is included in the estuarine system by virtue of this connection through the Point Pleasant Canal.

Located ~35 km (~21 mi) south of Manasquan Inlet, Barnegat Inlet forms a major conduit for waters flowing from the Intracoastal Waterway and Oyster Creek Channel to the Atlantic Ocean. Between 1839 and 1939, the inlet migrated more than 1,200 m (3,960 ft) to the south. The construction of arrowhead jetties in 1939-1940 prevented continued migration. The inlet has been restructured and dredged repeatedly since the 1930s to provide a navigable channel from the bay to the ocean. Apart from the arrowhead jetties, inlet structures employed during the past 60 years to stabilize the system have included shoreline revetments, a sand dike to better align interior channel flow, a raised impermeable jetty, and, most recently, near-parallel jetties. All of these structural changes have influenced inlet hydraulics and sediment input, ultimately affecting the channel location (Seabergh et al., 1996). Despite inlet stabilization efforts in the 1930s, which resulted in a significant increase (~50%) in the tidal prism (i.e., the volume of water moving through the inlet during the flood portion or the ebb portion of the tidal cycle, exclusive of freshwater) from 22.9 x 106 m3 (802 x 106 ft3) in 1932 to 32.1 x 106 m3 (1124 x 106 ft3) in 1940, subsequent sedimentation in the intra-jetty area caused the tidal prism to decrease significantly between 1940 and 1987 (Fields, 1984; Ashley, 1988). By 1987, the tidal prism had declined to 11.6 x 106 m3 (406 x 106 ft3), representing more than a 60% reduction since 1940 (Table 3, Figure 13). Between 1987 and 1991, the U.S. Army Corps of Engineers realigned the south jetty, constructing a 1,300-m-long (4,290-ft-long) impermeable rock structure to an elevation of 2.4 m (7.9 ft), and extending it nearly parallel to the existing north jetty. Subsequent to the reconfiguration and dredging of the inlet, the maximum tidal prism increased once again to levels comparable to those observed in the 1930s. Long-term velocity measurements (34 days) made by the U.S. Army Corps of Engineers with Acoustic Doppler Current Profilers indicate a wide range of tidal prism magnitudes since the inlet reconstruction. Ebb tidal prisms now vary between 12.5 and 33.0 x 106 m3 (438 and 1,155 x 106 ft3), and flood tidal prisms, between 8.9 and 41.3 x 106 m3 (312 and 1,446 x 106 ft3) (Seabergh et al., 1998). Strong winds directed along the channel axis (northwest-southeast) contribute to maximum extremes in the tidal prism.

The flushing time for Barnegat Bay (i.e., the time required for replacement of all bay water) appears to differ significantly on a seasonal basis. For example, Guo et al. (1997) calculated a flushing time of 27 days for the month of January 1995 and 71 days for June/July 1995. However, some degree of uncertainty regarding salinity values during the June/July period bring into question the absolute value of the summer flushing time.

The tidal range at Barnegat Inlet now amounts to 1.4-1.5 m (4.6-5.0 ft) (Seabergh et al., 1998). Prior to initiation of inlet reconstruction in 1987, the mean and spring tidal ranges at Barnegat Inlet were 0.94 and 1.2 m (3.1 and 4.0 ft), respectively. The spring tide range in the bay at Mantoloking, Waretown, and Harvey Cedars amounted to 0.18 m (0.6 ft), 0.21 m (7.0 ft), and 0.30 m (1 ft), respectively (Rogers et al., 1990). However, comparing tidal gauge data collected at Waretown in 1976 to that in 1998, the spring tidal range has increased by 6-7 cm (2.4-2.8 in) (Table 4, Figure 14). This increase is attributed to the greater tidal flow resulting from the restructuring of Barnegat Inlet.

The Barnegat Bay-Little Egg Harbor estuary has semidiurnal tides. Strong tidal currents occur at both Barnegat Inlet (> 1 m/s, > 3.3 ft) and Little Egg Inlet (> 2 m/s, > 6.6 ft). At Barnegat Inlet, the mean flood tide current velocity exceeds the mean ebb tide current velocity by ~0.3 m/s (~1 ft/s). Flood tide current velocities are much greater than ebb tide current velocities during spring tide (Seabergh et al., 1998).

The shallowness of the estuary, as well as extensive shoals and marsh islands near the inlets, restrict tidal flow and attenuate tidal energy. While significant tidal flow takes place at Barnegat Inlet, the largest tidal exchange volume in the system occurs through Little Egg Inlet. The tidal range in Little Egg Harbor is slightly greater (~0.5-1 m, ~1.7-3.3 ft) than in Manahawkin Bay (~0.5 m, ~1.7 ft). Because Little Egg Inlet is relatively wide (~2.5 km, 1.5 mi), and some areas in close proximity to the inlet are deeper (> 10 m, > 33 ft) than those near Barnegat Inlet, it is responsible for much of the exchange of ocean water between Little Egg Harbor and Manahawkin Bay. Chant (2000) notes that coastal pumping and the inlet-bay configuration strongly influence water exchange within the system.

Some tidal exchange occurs at the Point Pleasant Canal in the northern reach, although it is small relative to that at Barnegat Inlet and Little Egg Inlet. Tidal wave propagation is significantly retarded through the canal such that in the northern bay, it is about 5 hours behind the tide stage in the nearby ocean. In addition, the track of the wave reduces the tidal amplitude by a factor of 10 in the northern reach of the bay (Starosta et al., 1981).

Barnegat Inlet, Oyster Creek Channel, and the Intracoastal Waterway greatly influence water circulation in Barnegat Bay. Oyster Creek Channel trends east-west, connecting Barnegat Inlet and the Intracoastal Waterway. This channel and the Intracoastal Waterway, which trends north-south, facilitate the movement of tidal currents through the estuary. Tidal currents traverse the length of the Oyster Creek Channel, which is ~2.5-3.5 m (~8.3-11.6 ft) deep; they intercept the Intracoastal Waterway, and then spread north and south within the bay. The Intracoastal Waterway channel ranges from 1.5-3.7 m (5.0-12.2 ft) in depth at mean low water. The channel width, in turn, varies from ~10-60 m (~33-198 ft), and averages ~30 m (~100 ft).

Chant et al. (1997, manuscript submitted) observed strong semidiurnal tidal motion distorted by overtides and strong residual motion in the Intracoastal Waterway channel just inside of Little Egg Inlet. They showed that estuarine water tends to be trapped in coves near the inlet by tidal vortices during rising tide. As in Barnegat Bay, the progressive tidal wave is strongly influenced by frictional effects of the estuarine floor. Consequently, the tide rises faster than it drops. Relative to the tidal height, tidal currents are phase-advanced, with maximum velocities preceding high and low water by several hours. Minimum salinity is noted at the end of ebb, and maximum salinity, at the end of flood.

Water circulation in lower Little Egg Harbor is greatly affected by proximity to Little Egg Inlet, deep channels (> 10 m, >33 ft) landward of the inlet, and a cluster of marsh islands in the southern perimeter (Carriker, 1961). During flood tide, tidal currents moving northward from the inlet diverge into northwestward- and northeastward-flowing components (Figure 15a). Chant et al. (1997) indicated that flooding currents are strongest on the western side of the lower bay. The northwestward currents flow

through narrow channels between the marsh islands toward Tuckerton Creek, and then proceed northward along the western shore. The diverging flood tidal flow creates complex circulation patterns in the central basin of lower Little Egg Harbor. The current velocities dissipate rapidly northward. Maximum velocities decrease from ~0.5 m/s (1.7 ft) in the southern reach to < 0.05 m/s (< 0.17 ft) in upper Little Egg Harbor. Current patterns are reversed during ebb tide (Figure 15b). Figure 16 shows the magnitude of flood and ebb tidal currents in lower Little Egg Harbor as recorded by Chant et al. (1997).

Carriker (1961) demonstrated that the aforementioned complex circulation patterns, together with wind action, high evaporation rates, and the small volume of freshwater input to the system in summer, generate relatively uniform high salinities throughout lower Little Egg Harbor. As a result, vertical salinity and thermal stratification is weak. Lower Little Egg Harbor functions as a retaining vessel of essentially homogeneous seawater. The uniform salinities suggest rapid and complete mixing of the water.

B. Freshwater Inflow

A significant source of freshwater for Barnegat Bay, Manahawkin Bay, and Little Egg Harbor derives from tributaries that drain the New Jersey Pine Barrens along the western shore. From the headwaters of the streams, pristine freshwater flows eastward through predominantly forested areas along the gentle slope of the coastal plain to the bayshore area. The largest tributaries lie north of Barnegat Inlet and drain about 70% of the 878 km2 (351 ft2)watershed area surrounding Barnegat Bay (Moser, 1997). Drainages north of Cedar Creek contribute a combined average freshwater flow of ~12 m3/s (~420 ft3/s). Among the most important influent systems in the northern region are Toms River (6 m3/s, 210 ft3/s) and Cedar Creek (3.1 m3/s, 109 ft3/s) (Bauersfeld et al., 1991). Toms River alone drains nearly one-half of the contributing drainage area (= 116,550 ha, 291,375 ac) to Barnegat Bay (Hunchak-Kariouk, 1997). Other notable tributaries include the Metedeconk River, Kettle Creek, Stouts Creek, Forked River, Oyster Creek, and Manahawkin Creek. Forked River and Oyster Creek are connected by the intake and discharge canals of the Oyster Creek Nuclear Generating Station. Total surface inflow of freshwater into Barnegat Bay typically represents only about 2-3% of the tidal prism. However, an additional freshwater component, which appears to be substantial, originates from direct groundwater seepage, (Carpenter, 1963; Chizmadia et al., 1984). Groundwater discharge from the unconfined Kirkwood-Cohansey aquifer system to the Toms River, Kettle Creek, and Metedeconk River is the largest source of freshwater inflow to northern Barnegat Bay (Nicholson and Watt, 1997).

Smaller coastal streams drain into Little Egg Harbor. Mill Creek, Cedar Run, Westecunk Creek, and Tuckerton Creek are the largest influent systems in this area. Other meandering tidal creeks terminate near the upland-saltmarsh boundary (e.g., Thompson Creek, Ezras Creek, Dinner Point Creek, and Parker Run). Except during periods of heavy precipitation, these streams transport limited volumes of freshwater. Overall, Manahawkin Bay and Little Egg Harbor receive significantly less stream inflow than Barnegat Bay..

C. Circulation Patterns

Coastal pumping drives 70% of subtidal motion in the estuary (Chant, 2000). It is remotely forced by coastal sea level. This process plays a significant role in the movement of seawater from Little Egg Harbor into Barnegat Bay. Tidal magnitude in the estuary diminishes north and south of Barnegat Inlet and north of Little Egg Inlet. Several interactive factors - wind, tide, hydraulic head, density differences, bathymetry, and basin morphology - contribute to complex circulation patterns within the estuary. Wind velocity and direction strongly influence water movements in the system. Southerly winds (south-southwest) predominate in the summer, and westerly winds (west-northwest), in the spring, fall, and winter at a mean velocity of less than 15 km/hr (Chizmadia et al., 1984). Although summer seabreezes

can be considerable during afternoon hours, wind velocities during the summer months are generally less than in other seasons of the year. The reduced meteorological forcing contributes to greater occurrences of horizontal and vertical stratification in summer (Starosta et al., 1981). Because of the shallowness of the bay, the location of the barrier beach complex, and the attenuation of tides, winds can completely dominate circulation patterns for protracted periods. This is most evident in shoals along the eastern perimeter of Barnegat Bay and the shallows of Manahawkin Bay and upper Little Egg Harbor.

Southerly winds during the summer months, together with hydraulic head from water accumulation in the northern portion of Manahawkin Bay, cause a northward flow of water into Barnegat Bay. The movement of this water through Clam Island Channel flushes the southern portions of Barnegat Bay. North of Barnegat Inlet, however, the enclosure and shallowness of the bay restrict local wind-driven currents. Water accumulating at the northern end of the bay should result in a return (upwind) current at some depth below the surface as a result of a pressure gradient. However, the extreme shallowness of the bay and significant bottom friction retard the return flow. The net effect is a pressure gradient which balances the wind stress. Carpenter (1963) proposes that a return current may develop along the shore of the bay, but this is difficult to delineate from density currents arising from runoff accumulation in the northern basin.

About 70% of the Barnegat Bay-Little Egg Harbor watershed area is drained by mainland tributaries located north of Barnegat Inlet as noted previously (Moser, 1997). Freshwater entering along the western shore from these influent systems creates a mean density gradient across the bay from west to east. A south flowing current arises from the resultant pressure gradient in combination with Coriolis force. This flow augments that developing from hydraulic head associated with runoff accumulation in the northern reach.

The aforementioned flow pattern is accentuated during the winter months when winds predominate from the west-northwest. The wind stress produces an eastward flow, thereby accumulating water along the eastern shore and Island Beach. This water subsequently flows southward in association with density currents and is ultimately discharged through Barnegat Inlet.

The rate of horizontal turbulent diffusion is low in Barnegat Bay (Carpenter, 1963). This explains, in part, why the bay is not well mixed in a horizontal plane (Guo et al., 1997). In contrast, the bay is vertically well-mixed, under average conditions, as evidenced by relatively uniform salinity measurements in the water column in most areas. Exceptions include the Intracoastal Waterway, where there is a tendency toward two-layered circulation in waters deeper than 1.5 m (4.9 ft) (net seaward drift of lower salinity water in the surface layer and net upestuary drift of higher salinity water in the bottom layer), and in larger river tributaries (Carpenter, 1963; Starosta et al., 1981; Moser, 1997).

Human activities have significantly affected water circulation both locally and regionally in the estuary. The construction of the Point Pleasant Canal, reconfiguration of Barnegat Inlet, and implementation of maintenance dredging operations have all influenced the general water movements in the system. More locally, the construction and operation of the Oyster Creek Nuclear Generating Station (OCNGS) caused the reversal of water flow in Forked River and altered the discharge of Oyster Creek. In addition, water temperatures in Oyster Creek and contiguous bay waters have increased due to thermal discharges from the OCNGS (Kennish and Olsson, 1975; Kennish, 1978; Kennish et al., 1984).

Literature Cited

Ashley, G. M. 1988. Tidal prism study, Barnegat Inlet, New Jersey. Final Report to the U.S.

Army Corps of Engineers, Rutgers University, New Brunswick, New Jersey.

Bauersfeld, W.R., E. W. Moshinsky, E. A. Pustay, and F. L. Schaefer. 1984. Water Resources Data for New Jersey Water Year 1984, Volume 1. Atlantic Slope Basins Hudson River to Cape May. U.S. Geological Survey Water-Data Report NJ-84-1, U.S. Geological Survey, West Trenton, New Jersey. 327 p.

Bauersfeld, W.R., E. W. Moshinsky, E. A. Pustay, and W. D. Jones. 1988. Water Resources Data New Jersey Water Year 1988, Volume 1. Atlantic Slope Basins Hudson River to Cape May. U.S. Geological Survey Water-Data Report NJ-88-1, U.S. Geological Survey, West Trenton, New Jersey. 359 p.

Carpenter, J. H. 1963. Concentration distribution for material discharged into Barnegat Bay. Technical Report, Pritchard-Carpenter, Consultants and the Johns Hopkins University.

Carriker, M. R. 1961. Interrelation of functional morphology, behavior, and autecology in early stages of the bivalve *Mercenaria mercenaria*. J. Elisha Mitch. Sci. Soc., 77:168-241.

Chant, R. J., M. C. Curran, K. Able, and S. Glenn. 1997. Circulation patterns in Little Egg Harbor

and its role in larval winter flounder distribution: preliminary results. Pp. 109-121 *in:* Flimlin, G. E and M. J. Kennish (eds.), *Proceedings of the Barnegat Bay Ecosystem Workshop*. Rutgers Cooperative Extension of Ocean County, Toms River, New Jersey.

Chant, R. J.; Curran, M. C., Able, K., and Glenn, S., submitted. Delivery of winter flounder larvae

to settlement habitats in coves near tidal inlets. Est. Coastal. Shelf Sci.

Chant, R. J., 2000. Tidal and subtidal motion in a multiple inlet/bay system, the Barnegat Bay-Little

Egg Harbor estuary. J. Coastal Res. (the volume).

Chizmadia, P. A., M. J. Kennish, and V. L. Ohori. 1984. Physical description of Barnegat Bay. Pp. 1-28 *in* Kennish, M. J. and R. A. Lutz (eds.), *Ecology of Barnegat Bay, New Jersey*. Springer-Verlag, New York. pp. 1-28.

CH2M Hill, Metcalf & Eddy and New Jersey First, Inc. 1994. New Jersey Statewide Water Supply Master Plan - Water Supply Database. Technical Report, New Jersey Department of Environmental Protection, Trenton, New Jersey.

Donald J. Bergman and Associates, Inc. 1990. Ocean County Water Supply Study - Projection of Water Demands and Populations. New Jersey Department of Environmental Protection, Trenton, New Jersey.

Fields, M. L. 1984. Physical processes and sedimentation in an intra-jetty area, Barnegat Inlet,

New Jersey. M.S. Thesis, Rutgers University, New Brunswick, New Jersey.

Guo, Q., N. P. Psuty, G. Lordi, and C-S. Tsai. 1997. Circulation studies in Barnegat Bay. Pp. 17-29 *in*: Flimlin, G. E and M. J. Kennish (eds.), *Proceedings of the Barnegat Bay Ecosystem Workshop.* Rutgers Cooperative Extension of Ocean County, Toms River, New Jersey

Hickman, R. E. 1995. Statistical characteristics of stream discharge in tributaries of selected estuaries in southern New Jersey. U.S. Geological Survey Water Resources Investigations Report 91- 4141, U. S. Geological Survey, West Trenton, New Jersey.

53 p.

Hunchak-Kariouk, K. 1997. Relation of loads of ammonia, nitrate, and bacteria to land use during base flow and stormflow in three tributaries to the Toms River, New Jersey, 1994-95. Pp. 49-61 *in*: Flimlin, G. E and M. J. Kennish (eds.), *Proceedings of the Barnegat Bay Ecosystem Workshop.* Rutgers Cooperative Extension of Ocean County, Toms River, New Jersey.

Langbein, W. B. and K. T. Iseri. 1960. General introduction and hydrologic definitions: U.S. Geological Survey Water-Supply Paper 1541-A, U.S. Geological Survey, Washington, D. C. 29 p.

Lathrop, R. G. and J. A. Bognar. 1997. Monitoring habitat loss and alteration in the Barnegat Bay region. Pp. 243-251 *in*: Flimlin, G.E. and M. J. Kennish (eds.), *Proceedings of the Barnegat Bay Ecosystem Workshop.* Rutgers Cooperative Extension of Ocean County, Toms River, New Jersey.

Lennon, G. P., D. C. Allen, and B. Carson. 1997. Groundwater recharge distribution to a small embayment, New Jersey. Pp. 84-94 *in*: Flimlin, G.E. and M. J. Kennish (eds.), Proceedings of the Barnegat Bay Ecosystem Workshop. Rutgers Cooperative Extension of Ocean County, Toms River, New Jersey.

Moser, F. C. 1997. Sources and sinks of nitrogen and trace metals, and benthic macrofauna assemblages in Barnegat Bay, New Jersey. Ph.D. Thesis, Rutgers University, New Brunswick, New Jersey.

New Jersey Geological Survey. 1993. A method for Evaluating Ground-Water Recharge Areas in New Jersey. NJGS Geological Survey Report GSR-32, New Jersey Department of Environmental Protection, Trenton, New Jersey. 95 p.

New Jersey Department of Environmental Protection. 1994. Depletive Water Use Project for Regional Water Resource Planning Areas of New Jersey. New Jersey Department of Environmental Protection, Trenton, New Jersey.

New Jersey Department of Environmental Protection. 1996. New Jersey Statewide Water Supply Plan. New Jersey Department of Environmental Protection, Trenton, New Jersey. 173 p.

New Jersey Department of Environmental Protection 1996. New Jersey Statewide Water Supply Plan: The Vital Resource -- Water for the 21st Century. New Jersey Department of Environmental Protection, Trenton, New Jersey.

New Jersey Geological Survey. 1996. Geologic Map of New Jersey, New Jersey Department of Environmental Protection, Trenton, New Jersey. 2 p.

New Jersey Department of Environmental Protection 1998. Recommended implementation plan for the Atlantic County Water Supply Study and Nearby Environs. Draft Report, New Jersey Department of Environmental Protection, Trenton, New Jersey.

Nicholson, R.S., and M. K. Watt. 1997, Ground water flow in the unconfined aquifer system of the Toms River, Metedeconk River, and Kettle Creek Basins, New Jersey. U.S. Geological Survey Water Resources Investigations Report 96-4066, U. S. Geological Survey, West Trenton, New Jersey. 100 p.

Nicholson, R.S. and M. K. Watt. 1997. Groundwater Flow in the Unconfined Aquifer of the Northern Barnegat Bay Watershed, New Jersey. Pp. 31-47 *in*: Flimlin, G.E. and M. J. Kennish, (eds.), *Proceedings of the Barnegat Bay Ecosystem Workshop*. Rutgers Cooperative Extension of Ocean County, Toms River, New Jersey.

Reed, T. J., G. L. Centinaro, M. J. DeLuca, J. T. Hutchinson, and J. Scudder. 1997. Water Resources Data New Jersey Water Year 1996, Volume 1. Surface Water Data. U.S. Geological Survey Water-Data Report NJ-96-1, U.S. Geological Survey, West Trenton, New Jersey. 562 p.

Reed, T. J., G. L. Centinaro, M. J. DeLuca, and J. T. Hutchinson. 1997. Water Resources Data New Jersey Water Year 1997, Volume 1. Surface Water Data. U.S. Geological Survey Water-Data Report NJ-97-1, U.S. Geological Survey, West Trenton, New Jersey. 608 p.

Rogers, Golden, and Halpern. 1990. Profile of the Barnegat Bay. Final Report for the Barnegat Bay Study Group, New Jersey Department of Environmental Protection, Trenton, New Jersey.

Rosman, R., P. J. Lacombe, and D. A. Storck. 1993. Water Levels in Major Artesian Aquifers of the New Jersey Coastal Plain. (USGS WRI Report 95-4060), U.S. Geological Survey, West Trenton, New Jersey.

Rutgers Cooperative Extension. 1998. Home*A*Syst for the Barnegat Bay Watershed. An Environmental Risk-Assessment Guide for the Home. Rutgers Cooperative Extension of Ocean County, Toms River, New Jersey. 124 p.

Seabergh, W. C., M. A. Cialone, and D. K. Stauble. 1996. Impacts of inlet structures on channel

location. Proceedings of the International Conference on Coastal Engineering, Vicksburg, Mississippi, pp. 4,531-4,544.

Seabergh, W. C. M. A. Cialone, and J. W. McCormick. 1998. Effects of inlet modifications at Barnegat Inlet, New Jersey. Technical Report, U.S. Army Corps of Engineers, Vicksburg, Mississippi.

Starosta, T. P., M. B. Roche, D. W. Ballengee, and V. L. Ohori. 1981.

Hydrographic study of Barnegat Bay, New Jersey, 1981. Technical Report, GPU Nuclear Corporation, Parsippany, New Jersey.

U.S. Geological Survey. 1971. Water Resources Data for New Jersey, Part 1. Surface Water Records, 1971. U.S. Geological Survey, West Trenton, New Jersey.

U.S. Geological Survey. 1985. National Water Summary 1984--Hydrologic Events Selected Water-Quality Trends and Ground-Water Resources: U.S. Geological Survey Water-Supply Paper 2275, U.S. Geological Survey, Reston, Virginia.

U.S. Geological Survey. 1989. Simulated Effects of Future Withdrawals in the Northeastern Coastal Plain Aquifers of New Jersey (USGS WRI Report 88-4199), U.S. Geological Survey, West Trenton, New Jersey.

Watt, M. K., M. L. Johnson, and P. J. Lacombe. 1994. Hydrology of the unconfined aquifer system, Toms River, Metedeconk River, and Kettle Creek Basins, New Jersey, 1987-90. U.S. Geological Survey Water-Resources Investigations Report 93-4110, U.S. Geological Survey, West Trenton, New Jersey. 5 p.

Zapecza, O. S. 1989 Hydrogeologic Framework of the New Jersey Coastal Plain. U.S. Geological Survey Professional Paper 1404-B, U.S. Geological Survey, Reston, Virginia. 49 p., 24 pl.

Table 1

GPU Nuclear, Inc.

Oyster Creek Nuclear Generating Station

Meteorological Monitoring Locations and Measurements

Height (feet)	Parameter	Primary Sensors	Secondary Sensors
380	Wind Speed	X	X
	Wind Direction	X	X

	Temperature	X	X
	Delta Temperature	X	X
150	Wind Speed	X	
	Wind Direction	X	
	Temperature	X	
	Delta Temperature	X	
33	Wind Speed	X	X
	Wind Direction	X	X
	Temperature	X	X
	Delta Temperature	X	

Summary of availability and demand

On a watershed basis, water availability, population and consequent water demand for projections for each watershed are as follows (CH2M Hill, 1994):

Watershed	Net Water Availability (MGD)	1990 Population	1990 Water Demand (MGD)	2040 Population	2040 Water Demand (MGD)
Manasquan River	39.1	90,788	12.8	115,074	18.0
Metedeconk Creek	24.0	135,923	15.0	187,533	25.6
Toms River	21.9	204,672	38.2	368,948	62.4
Atlantic Coastal	25.3	81,491	12.2	203,530	27.2
REGIONAL TOTAL	110.0	512,874	78.2	875,085	133.2

Table 1. Summary of water availability, population, and water demand, by watershed.

APPENDIX A

Figure A-1. map showing water levels in confined aquifers prior to development:

1. Atlantic City 800-foot sand

2. Piney Point aquifer

3. Wenonah-Mount Laurel aquifer

4. Englishtown aquifer

5. Middle Potomac-Raritan-Magothy aquifer

Figure A-2. Map showing water withdrawals from confined aquifers:

1. Atlantic City 800-foot sand

2. Piney Point aquifer

3. Wenonah-Mount Laurel aquifer

4. Englishtown aquifer

5. Upper Potomac-Raritan-Magothy aquifer

6. Middle Potomac-Raritan-Magothy aquifer

Figure A-3. Map showing water levels during 1988 in confined aquifers:

1. Atlantic City 800-foot sand

2. Piney Point aquifer

3. Wenonah-Mount Laurel aquifer

4. Englishtown aquifer

5. Upper Potomac-Raritan-Magothy aquifer

6. Middle Potomac-Raritan-Magothy aquifer

Figure 1. Location of the Manasquan River, Metedeconk River, Toms River, and Atlantic Coastal watersheds.

Figure 2. Generalized hydrogeologic section showing principal aquifers in the region.

Figure 3. Diagram illustrating saltwater encroachment concepts.

Figure 4. Location of Water-Supply Critical Areas 1 and 2.

Figure 5. Diagram illustrating the effects of a well pumping from an unconfined aquifer on ground-water discharge to a stream.

Figure 6. Water-level hydrographs for wells screened in the middle aquifer of the Potomac-Raritan-Magothy aquifer in northern counties of the New Jersey Coastal Plain, 1978-94.

Figure A-1.1 Water levels in the Atlantic City 800-foor Sand prior to development.

Figure A-1.2 Water levels in the Piney Point aquifer prior to development.

Figure A-1.3 Water levels in the Wenonah-Mount Laurel aquifer prior to development.

Figure A-1.4 Water levels in the Englishtown aquifer prior to development.

Figure A-1.5 Water levels in the Middle Potomac-Raritan-Magothy aquifer prior to development.

Figure A-2.1 Withdrawals from the Atlantic-City 800-Foot Sand, 1993.

Figure A-2.2 Withdrawals from the Piney Point aquifer , 1993.

Figure A-2.3 Withdrawals from the Wenonah-Mount Laurel aquifer, 1993.

Figure A-2.4 Withdrawals from the Englishtown aquifer, 1993.

Figure A-2.5 Withdrawals from the Upper Potomac-Raritan-Magothy aquifer, 1993.

Figure A-2.6 Withdrawals from the Middle Potomac-Raritan-Magothy aquifer, 1993.

Figure A-3.1 Water levels in the Atlantic City 800-foor Sand, 1988.

Figure A-3.2 Water levels in the Piney Point aquifer, 1988.

Figure A-3.3 Water levels in the Wenonah-Mount Laurel aquifer, 1988.

Figure A-3.4 Water levels in the Englishtown aquifer, 1988.

Figure A-3.5 Water levels in the Upper Potomac-Raritan-Magothy aquifer, 1988.

Figure A-3.6 Water levels in the Middle Potomac-Raritan-Magothy aquifer, 1988.

I. GROUND WATER

Most of the freshwater inflow to the Barnegat Bay-Little Egg Harbor estuary is ground water that either discharges to streams that flow to the estuary or that seeps directly to the estuary. Consequently, the quality of shallow ground water is a potentially important determinant of the quality of freshwater inflow and water quality constituent loadings. The unconfined Kirkwood-Cohansey aquifer system is present throughout nearly all of the watershed area, and most of the ground water that flows to the streams and the estuary passes through this aquifer system. As a result, the quality of ground water in the Kirkwood-Cohansey aquifer system is most relevant to surface water quality in the watershed and the estuary.

The unconfined aquifer system generally is much more vulnerable to contamination than underlying confined aquifers. The quality of ground water in deeper, confined aquifers is important to water supplies that draw on them, but the quality of this water does not directly relate to surface water quality in the watershed or the estuary. The quality of ground water in the confined aquifers is less variable than water from the unconfined aquifer system (Harriman and Voronin, 1984).

Changes in land use, such as the conversion of farmland to residential housing development, can have major effects on ground water quality, because different substances are used in association with different types of land use. Chemicals and other substances used at the land surface can move to the ground water system through recharge from precipitation. These substances may eventually move into the estuary from ground water flows that enter streams and rivers, and then discharge into the estuary at the shoreline. Thus, an agricultural area that has been contributing nitrogen to the water system from fertilizers may at some later time after land conversion contribute residential fertilizers and pesticides and/or chemicals associated with gas stations or dry-cleaning operations prevalent in areas of residential development.

Many studies have been conducted to investigate the effects of land use on water quality in the Kirkwood-Cohansey aquifer system, the ground water resource directly beneath the Barnegat Bay watershed. These include studies of nitrates, pesticides, and volatile organic compounds in ground water of New Jersey Coastal Plain aquifer systems (Vowinkel, 1991), and an investigation of the relation of radium, nitrate, and pesticide occurrence in ground water to agricultural land use and depth in the Kirkwood-Cohansey aquifer system (Szabo et al., 1997). Major findings for select constituents and their relation to land use are summarized below.

A. Data Sources

Data sources include various data reports and interpretive reports, as well as databases maintained by the U. S. Geological Survey (USGS) and the Ocean County Health Department (OCHD). The USGS has conducted a number of studies of ground water quality of the Kirkwood-Cohansey aquifer system in recent years, resulting in a substantial database, which is part of the National Water Information System (NWIS) maintained by the USGS. Data contained in this database were used in the preparation of numerous interpretive reports that provide the basis for much of the summary of ground water quality presented here.

An evaluation of ground water quality in much of the Barnegat Bay watershed was conducted by the U.

S. Geological Survey during the early 1980's, resulting in two summary reports. Harriman and Sargent (1985) evaluated inorganic chemistry using results of analysis of ground water samples from 209 wells screened in the Kirkwood-Cohansey aquifer system, in an area that closely approximates the Barnegat Bay watershed. Thirty chemical constituents, as well as physical characteristics, were statistically analyzed. A report by Harriman and Voronin (1984) includes results of analyses for selected volatile organic compounds. More recent studies of ground water quality in the Kirkwood-Cohansey aquifer system have focused on the relations between water quality and land use and on particular constituents, particularly pesticides, nitrate, mercury, and radionuclides (Vowinkel et al., 1994; Kozinski et al., 1995; Barringer et al., 1997; Szabo and DePaul, 1998).

In 1996, 22 shallow wells located close to streams within the Barnegat Bay watershed were sampled as part of a watershed-oriented monitoring network. Wells located near streams were selected so that the samples collected would be more representative of ground water discharging to the respective nearby streams than would be samples collected from wells selected randomly. Results of the analysis of these samples are included below.

Ocean County implemented a private well testing ordinance in 1986 to ensure that residents using private wells were receiving safe, potable water. The ensuing well testing program has resulted in tens of thousands of well tests and the accumulation of an extensive well-test database that is maintained by the OCHD. Analytical results from over 25,000 private (domestic) well tests conducted between 1986 and 1991 were statistically analyzed by Camp et al. (1993) and the U. S. Geological Survey. Results of these statistical analyses provide a basis for evaluating the frequency with which elevated levels of contaminants occur in shallow ground water in the watershed.

B. Summary of Ground Water Quality Conditions

The following discussion describes the water-quality conditions in the Kirkwood-Cohansey aquifer system within the Barnegat Bay watershed. Figures 1-3 show nitrate plus nitrite, pH, and specific conductance, respectively, in samples of ground water from 22 shallow wells located near streams throughout the watershed. Table 1 shows the statistical summary of water analyses presented by Harriman and Sargent (1985).

1. Nutrients

Both human activities and natural resources contribute to increased nitrate in ground water. Some atmospheric deposition and organic matter in the soil are natural sources of nitrates, whereas sources from human activities vary by land-use type. Lawn fertilizers, septic system wastes, leaky sewer pipes, and industrial wastes contribute to increased nitrogen in ground water in urban/residential areas. Sources of nitrogen in agricultural areas include crop fertilizers, animal manure, and septic system wastes. Increased nitrogen can be attributed also to atmospheric deposition from automobile exhausts and industrial emissions (Clawges et al., 1999).

Nitrate is a common form of nitrogen that is mobile in the ground water system and usually exists at shallow depth. Results of studies show a strong relation between land use and nitrate concentrations in

the unconfined Kirkwood-Cohansey aquifer system (Vowinkel and Siwiec, 1991; Stackelberg et al., 1997; Szabo et al., 1997; Clawges et al., 1999). Analysis of data from these studies indicates that concentrations of nitrate were significantly higher in water samples from wells in agricultural areas (where nitrogen fertilizer use is high) than in samples from wells in residential/urban or undeveloped areas. Szabo et al. (1997) reported that the greatest concentrations of nitrate occurred at shallow to medium depth (5 to 45 ft) below the water table. A study conducted in the coastal plain of Long Island, New York, showed that sewering practices, as well as land use, affect concentrations of nitrate in ground water (Leamond et al., 1992).

The concentrations of nitrogen and phosphorus are low in most shallow ground water areas within the Barnegat Bay watershed compared to levels observed in surface water. However, there are many potentially important exceptions. In summarizing ground water quality characteristics for the Kirkwood-Cohansey aquifer system in the area, Harriman and Sargent (1985) reported median concentrations of < 0.05, < 0.01, 0.14, and 0.08 mg/l for ammonia, nitrite, organic nitrogen and nitrite plus nitrate (all as nitrogen), respectively, and < 0.01 mg/l for both phosphorus and orthophosphate as P. The median concentration of organic carbon was 0.5 mg/l. Nitrate concentrations were as high as 10.5 mg/l, and ammonia concentrations were as high as 5.6 mg/l. Nitrate is a major constituent in ground water sampled in some residential areas (Watt et al., 1994), and a small percentage of analysis results contained in the OCHD Well Test database (51 tests out of 22,791, or 0.2%) revealed nitrate concentrations in excess of the 10 mg/l drinking water standard (Camp et al., 1993). Ground water sampled in 1996 from 22 wells located near streams in some areas contained elevated nitrate concentrations as high as 4.9 mg/l (Jones and DeLuca, 1996), but ammonia concentrations were less than 0.2 mg/l in samples from all but one of these wells. The distribution of nitrite plus nitrate concentrations in these 22 wells is shown in Figure 2. Orthophosphorus concentrations in samples from all but one of these wells were ≤ 0.02mg/l.

2. Other Inorganic Constituents

Ground water in the unconfined aquifer system is generally acidic with low ionic strength and alkalinity; pH typically ranges from 4.4 to 6.7. The total dissolved solids usually are less than 100 mg/l. Consequently, the water is highly corrosive in many areas and can leach trace elements and asbestos fibers from plumbing materials. The temperature of ground water samples reported by Harriman and Sargent (1985) ranged from 5.5$_o$C to 17.0$_o$C. Specific conductance (a measure of the ability of water to conduct electricity) ranged from below 20 to more than 1,000 microsiemens per cm. Specific conductance in samples collected in 1996 from shallow wells near streams were less than 300 microsiemens per cm (Jones and DeLuca, 1997). The predominant cations in shallow ground water are sodium and potassium, and the major anion is chloride. Sea salts from wind-blown marine aerosols or saltwater intrusion, and the effects of human activities, such as roadway deicing, waste disposal, and leachate from fertilized land, all contribute to the concentrations of predominant ions. High bicarbonate concentrations are also found in some areas, which can be the result of the oxidation of organic matter and the dissolution of carbonaceous shell material.

Unstable radioactive elements are found in a wide range of concentrations in all rocks, soil, and water. In parts of the Kirkwood-Cohansey aquifer system, concentrations of total radium (the sum of radium-226 and radium-228) exceed the U. S. Environmental Protection Agency (USEPA) maximum contaminant level of 5 pCi/l (picocuries per liter). Of the 15 wells in the Barnegat Bay watershed

sampled during 1988-96 period, concentrations of total radium in water samples from two wells in one area exceeded the MCL. Leaching of nitrogen, calcium, and magnesium from agricultural chemicals applied to croplands may increase the mobility of radium in ground water. Investigations are currently underway to evaluate the distribution of other radioisotopes in the Kirkwood-Cohansey aquifer system and their contribution to the gross alpha-particle activity in water supplies (Szabo and DePaul, 1998). The incidence of radium in surface water of the Atlantic slope basins of New Jersey has not been investigated.

3. Volatile Organic Compounds

Volatile Organic Compounds (VOCs) are commonly used for household and industrial purposes, and are components of such materials as cleaning agents, solvent degreasers, refrigerants, and fumigants. VOCs are also components of gasoline, oil, and heating fuels. Ground water has been and continues to be contaminated by VOCs from sources such as industrial discharges, landfills, municipal wastewater discharges, leaks and spills from storage tanks, and domestic septic system effluent. Because VOCs are most often associated with urban land use, they are more frequently detected in aquifers beneath urban areas than in aquifers beneath non-urban areas.

Results presented by Harriman and Voronin (1984) indicated that 5% of the well-water samples (7 out of 142) from the Kirkwood-Cohansey aquifer system in the Barnegat Bay watershed had detectable concentrations of compounds that were included in limited scans for volatile organics. The detected compounds included xylenes, benzene, and toluene. Results from the statistical analysis of the OCHD Well Test database confirmed a widely scattered presence of VOCs at low levels (Camp et al., 1993). Two percent of the tests included in the analysis had concentrations above an established drinking water standard. This result suggests that, in areas where private wells are utilized, a small fraction of shallow ground water is contaminated by VOCs at levels of concern for human health.

In cases where well water analysis indicated that a standard (or standards) had been exceeded, water treatment or well replacement and/or retesting assured that results met drinking water standards. Statistical analysis of the OCHD Well Test database should not be construed to indicate that water delivered by private domestic water supplies was contaminated in excess of drinking water standards.

The frequency of occurrence provides a rough indication of the prevalence of a particular compound in shallow ground water. However, the OCHD data set includes retests in which not all compounds were evaluated; therefore, the true meaning of calculated frequencies is uncertain and must be evaluated with caution. The most frequently detected compound (7%) was methylene chloride, a compound commonly used in commercial and industrial applications as a solvent and aerosol propellant. This particular compound also can be introduced accidentally to water samples through laboratory contamination because it is a common laboratory solvent. The quality assurance information that would be needed in order to evaluate the likelihood of laboratory contamination is unavailable, and thus the meaning of the relatively high frequency of occurrence of methylene chloride is uncertain. The next most frequently detected compound (2%) was 1,1,1 trichloroethane, which is also used in industrial applications as a solvent. The third most frequently detected compound (1%) was tetrachloroethylene. The frequency of detection of the other 14 compounds was less than 1%.

4. Pesticides

Pesticides are substances or a mixture of substances used to control pests, such as insects (insecticide), weeds (herbicides), and molds and fungi (fungicides). Synthetic organic pesticides were introduced in the 1940's, and since then the manufacture and use of these pesticides have steadily increased (Barbash and Resek, 1996). Pesticides have long been used on agricultural crops; however, in the last few decades use in urban and undeveloped areas has increased. Pesticides have been used in residential areas to control insects, weeds and fungi on lawns, golf courses, cemeteries and parks, private and public gardens. They are also used and to control weeds on railroad, transmission-line, and roadway right-of-ways.

The potential of individual pesticides to contaminate ground water is controlled by the chemical characteristics of the compound, and the characteristics of the soil and aquifer material they penetrate. The chemical characteristics include, water solubility, soil adsorption, and persistence. Soil characteristics include texture, amount of organic matter, number and size of soil pores, and the depth to water from land surface. For example, sandy soil and low organic matter (characteristic of the Barnegat Bay watershed) will allow pesticides to move easily from land surface to the water table. A shallow depth to water from the land surface increases the probability that pesticides will reach the ground water.

The USGS began studies in 1992 to investigate the vulnerability of public supply wells to contamination by pesticides. The methods for determining vulnerability of a well are described by Vowinkel et al. (1994) and Vowinkel et al. (1996). Wells were rated as low, medium, and high vulnerability to pesticide contamination. Pesticide vulnerability ratings were determined for 115 public supply wells screened in the Kirkwood-Cohansey aquifer system in Ocean County, and six of these wells, or about 5%, were assigned a high rating. The remaining 95% of the wells were assigned a medium vulnerability rating, primarily because all public supply wells screened in the Kirkwood-Cohansey aquifer system are considered at least somewhat susceptible to pesticide contamination. Among 32 of the wells for which additional water quality information was available, the concentration of nitrite plus nitrate as nitrogen increased with increasing pesticide vulnerability rating (Eric Vowinkel, U.S. Geological Survey, personal communication, 1999). Pesticides were not detected in water samples drawn from 7 public supply wells screened in the Kirkwood-Cohansey aquifer system in Ocean County (Clawges et al., 1998). These data and pesticide vulnerability ratings provide some indication of the frequency with which pesticides may be present at detectable levels in shallow ground water in the Barnegat Bay watershed.

5. Pathogens

Although ground water is not considered a primary pathway for the transport of pathogenic organisms to surface water in the watershed, the available data on bacteria in ground water were evaluated. The possible presence of pathogenic organisms in water is indicated by the presence of indicator coliform bacteria. A statistical analysis of the OCHD Well Test database indicated that coliform bacteria were present in less than 2% of analyzed samples (Camp et al., 1993).

6. Metals

A statistical summary of the concentrations of various metals in shallow ground water in the watershed is reported by Harriman and Sargent (1985). Median concentrations of barium, beryllium, cadmium, chromium, lead, and silver were all below the respective detection limits. Median concentrations of

manganese, strontium, and zinc were 0.014, 0.016, and 0.02 mg/l, respectively. The median iron concentration was 0.29 mg/l. Iron and manganese concentrations exceeded drinking water standards in some areas. Some slightly elevated concentrations in some of samples were possibly attributable to the leaching of metals from well-construction materials.

Among metals present in water, mercury is a primary health concern for both human and aquatic life. There is no single source, land use, or mode of transport that is responsible for the occurrence of elevated concentrations of mercury in ground water in the Kirkwood-Cohansey aquifer system (Barringer et al., 1997). Mercury concentrations in sediments of the Kirkwood-Cohansey aquifer system are low (~10 ng Hg/g). Elevated mercury levels (> 10 ng Hg/g) in area aquifers are probably ascribable to anthropogenic sources (Dooley, 1992).

Mercury attributable to human activities is largely derived from point sources of contamination such as landfills, industrial sites, military installations, and cemeteries, as well as from waste discharged from schools, hospitals, laboratories and dental offices. However, Barringer et al. (1997) could not conclusively link any of these sources with elevated concentrations of mercury in ground water found at 34 sites investigated in the Kirkwood-Cohansey aquifer system. Mercuric chloride (a form of mercury that is highly soluble in water) and phenyl mercuric acetate have been historically used as pesticides on agricultural crops in the New Jersey Coastal Plain. These pesticides have also been used in lawn care to control the growth of crabgrass and snow mold. Of the 34 sites in the study, 26 are located in or near past or present agricultural land (Barringer et al., 1997). In general, elevated mercury concentrations in ground water occur when there is a source and a chemical or physical process conducive to mercury mobilization and transport.

Concentrations of total mercury that exceed the Maximum Contaminant Level (MCL) of 2 µg/l have been reported in ground water samples from the Kirkwood-Cohansey aquifer system, including samples from the Barnegat Bay watershed. Elevated mercury concentrations in sampled ground water in the Kirkwood-Cohansey aquifer system appear to be spatially clustered, although this spatial pattern could be related, at least in part, to the non-random manner in which incidences of mercury contamination are typically investigated (Barringer et al., 1997). A statistical analysis of the OCHD Well Test database by the U. G. Geological Survey revealed that of the more than 12,000 samples analyzed for mercury, 106 (less than 1%) were found to contain mercury in concentrations in excess of the MCL (M. Ayers, U.S. Geological Survey, written communication, 1995). Investigations are currently underway to better understand the sources, transport, and fate of mercury in the Kirkwood-Cohansey aquifer system.

II. Surface Water

The main rivers and streams draining the Barnegat Bay-Little Egg Harbor watershed are the Metedeconk River, Kettle Creek, Toms River, Cedar Creek, Forked River, as well as Oyster, Mill, Westecunk, and Tuckerton Creeks. A part of Manasquan River flow enters the northern perimeter of Barnegat Bay through the Point Pleasant Canal Additional water discharge contributions to the bay are from islands and small basins via direct groundwater inputs. The relative contributions of nonpoint sources of contamination to streams in the coastal plain are likely influenced by ground water in this region of the state.

Much of the estuarine watershed lies within the state-designated Pinelands Area. The streams and

shallow ground water in the Pinelands are acidic, with low alkalinities and generally low buffering capacities (Lord et al., 1990). Yuretich et al. (1981) describe the waters of the Pinelands as being atmospheric-controlled; that is, they receive a large part of their composition from precipitation. Such waters are also susceptible to changes in chemical composition due to nonpoint source contributions from various land-use activities .

The estuary receives constituents from point and nonpoint sources within the contributing drainage basin. Point sources are discrete, identifiable origins of constituents, such as permitted discharges from municipal and industrial wastewater treatment facilities that contribute water to a stream at a constant rate, independent of stream flow conditions. Constituents from more diffuse, nonpoint sources are transported to a stream or river by storm runoff from agricultural, residential, and urban areas including impervious surfaces (highways and parking lots), as well as ground water that percolates through soil, and effluent from leaking underground storage tanks, septic systems, and landfills. Ground water discharge to a stream is almost constant, varying slightly with season and precipitation rate. Storm runoff, composed of overland runoff and interflow, contributes to a stream intermittently, depending on storm intensity and frequency, and only during high flows at which time the ground water contributions to the stream are diluted (Chow, 1964; Novotny and Chesters, 1981). Instream concentrations of constituents are a summation of the contributions from constant (point sources and ground water discharge) and intermittent (storm runoff) sources.

The main contributors of water quality constituents to the estuary are nonpoint sources in the basin because there are few major permitted point source discharges to the major rivers draining the watershed. Nonpoint source contributions to a surface water body are greatly affected by the type and intensity of development and historical land use in the contributing drainage area. Concentrations of some constituents are typically associated with certain human activities, such as sediment from construction sites and nutrients from agricultural runoff and intensive lawn maintenance. Increased amounts of impervious surfaces reduce the infiltration rate of rainfall and enhance storm runoff. Soil compaction during building construction also reduces infiltration. Land cover consisting of forest and wetlands has greater water retention and less storm runoff than other land-use covers as a result of ponding and dense vegetation. The presence of some constituents in ground water can be attributed to historical land uses. For example, before the residential development of the early 1970's, several poultry farms were located within the Wrangel Brook basin. Nutrients from agricultural runoff, which infiltrated soils and deeper sediments may still be present in ground water. Because of the slow movement of ground water, the concentrations of these constituents in receiving streams may remain high for many years.

II. A. Data Sources

Available data on water and sediment quality data during water years 1960-98 at stream sites located within the Atlantic Coastal Plain were compiled for this Characterization Report. Most of the streams drain into the estuary; however, data from a few sites that drain into other estuaries and bays of the Atlantic Coastal Plain and the lower Delaware River basins were also included. This additional information was included because the streams drain areas with similar hydrology, geology, and water chemistry as streams within the Barnegat Bay watershed, and the information from these sites is transferable to streams located within the bay watershed.

The minimum criteria for data inclusion were as follows: (1) the data were for samples collected and analyzed with methods comparable to and consistent with those used by the U. S. Geological Survey (USGS); (2) the data were for samples collected and analyzed between October 1, 1959 and September 30, 1998; (3) the samples were collected throughout any consecutive three years; and (4) the data were available in digital format. If available, instantaneous stream flow - the stream discharge at the time of

sampling - was retrieved and associated with each individual water quality sample. Remark codes pertaining to specific sample qualifiers are stored with the water quality data.

Steps were taken to ensure consistent data quality because of the long time period over which the data were collected. Water quality data for the period of record from each data source were reviewed separately to identify any obvious inconsistencies (i.e., extreme data outliers), because of changes in laboratory remark codes, reporting levels, analytical methods, project data entry protocols, project data quality review protocols, sample preservation, and sample processing. Breidt et al. (1991) found similar anomalies in USGS water quality data from this period of record. Some data sets had considerable data-quality concerns and are summarized separately and only qualitatively for this characterization. Extreme values were retained unless they were known to be errors of data entry.

On the basis of laboratory analytical procedure, constituent concentrations for total ammonia, total nitrite, and total nitrite plus nitrate at the USGS National Water Quality Laboratory were considered to be dissolved, regardless of how they were reported in the database. Data considered for this analysis were those collected for: (1) USGS cooperative programs and investigations; (2) USGS National Water Quality Assessment (NAQWA) Programs; (3) the Pinelands Commission; and (4) the Brick Township Municipal Utilities Authority.

USGS cooperative programs (i.e., USGS, with cooperating federal, state, and local agencies) maintain a network of water quality stations throughout New Jersey. The data are used to assess the water quality throughout the state and constitute a valuable database for developing an improved understanding of its water resources. Records of surface water quality ordinarily are obtained at or near stream gaging stations because the interpretation of records of surface water quality nearly always requires corresponding discharge data. Samples are collected and measurements are made at these sites, usually five times a year. In addition to the statewide routine network, smaller networks of water quality stations are established to provide data for specific studies. These sites are maintained for short durations, usually less than five years. Data collected by the USGS and cooperating agencies in New Jersey are maintained in the National Water Information System (NWIS) database. The NWIS is maintained by the USGS. Data maintained in NWIS are for samples collected and analyzed by methods of the USGS, which are consistent with nationally recognized standards. These data are collected as part of ongoing water quality monitoring and special investigations of New Jersey streams.

Data on surface water quality and bottom sediment quality for the period of record water years 1960-97 were retrieved from NWIS for 53 stations located within the estuarine watershed; 28 of these stations, including the USGS water quality station on the Toms River near the town of Toms River, had three or more years of surface water quality data. These stations are located within the Metedeconk River, Kettle Creek, Toms River (including Union and Ridgeway Branches, Wrangel Brook, and Jakes Branch), Cedar Creek, Forked River, Oyster Creek, Mill Creek, Cedar Run, Westecunk Creek, and Tuckerton Creek basins. Data were also retrieved for the McDonalds Branch in Lebanon State Forest, the hydrologic benchmark station located in the Delaware River drainage basin. Data for selected field parameters, major ions, nutrients, bacteria, sediment, and metals were available for these stations.

Since 1994, the water quality in several tributaries to the Toms River has been monitored as part of a cooperative study between the USGS and the New Jersey Department of Environmental Protection (NJDEP) to investigate nonpoint sources to the estuary. The sites are located on Long Swamp Creek, Wrangel Brook, Davenport Branch, and Jakes Branch; the drainage areas upstream from the sites are characterized as either highly, moderately, or slightly developed. Data for selected field parameters, nutrients, bacteria, and sediment were available for samples collected during a variety of seasonal and flow conditions.

USGS-NAWQA program studies are designed to assess the status of the nation's water quality, describe status and trends in water quality, and provide a sound scientific understanding of the primary natural and human factors that affect the quality of the nation's water reserves. As part of the Long Island-New Jersey (LINJ) coastal drainages investigations, intensive surface water monitoring at Great Egg Harbor River near Sicklerville occurred during 1996-98. In addition, synoptic sampling for VOCs, pesticides, and nutrients from 18 surface water sites within the New Jersey Atlantic Coastal Plain (including sites on the Toms, Great Egg Harbor, and Maurice Rivers) was conducted in 1997 and 1998.

The Pinelands Commission, in cooperation with the OCHD, monitored the water quality at 20 sites on 15 streams within the Barnegat Bay watershed from 1987 to 1996. Data for selected field parameters, major ions, and nutrients were available for these stations. A total of 13 Pinelands Commission sites and historic USGS water quality stations were co-located.

The Brick Township Municipal Utilities Authority (BTMUA) monitors water quality on a daily basis throughout the Metedeconk River Basin, upstream of the main intake near Forge Pond. Data for selected field parameters and bacteria have been collected since 1989 at a network of stations located throughout the watershed. Data for selected field parameters and bacteria were available for six sites on both the South and North Branches of the Metedeconk River for the time period 1989 to 1998. In 1996 the network was expanded to 30 sites, and samples were co-located for analysis of VOCs.

B. Data Organization

Data from the USGS, Pinelands Commission, and NJDEP sites were commingled and divided into three groups (water years 1959-72, 1973-86, and 1987-97) that correspond to available land cover data for 1972, 1984, and 1994/5, respectively. For the purposes of describing surface water quality within the bay watershed, the distribution of land cover in the area of contributing drainage to each water quality site was determined from 1972, 1986, and 1994/5 land cover data obtained from Rutgers University. These land-use percentages were determined, in part, by the use of a geographic information system and categories defined by Fegas et al. (1983).

The percentage of urban land ranged from 0 to 49% in the drainage basins of the 14 sites with water quality between water years 1959-72. In the drainage basins of the 18 sites with water quality between water years 1973-86, the percentage of urban land ranged from 0 to 39%. The percentage of urban land ranged from 0 to 55% in the drainage basins of the 25 sites with water quality between water years 1987-97.

From the 1994/5 data, sites draining more developed areas (that is, areas where the urban/residential and agricultural land plus grasslands land cover were greater than 10%) were located on the Metedeconk and Toms Rivers, the downstream reach of Ridgeway Branch, Wrangel Brook, Davenport Branch, Long Swamp Creek, and Mill Creek and its tributary Four Mile Branch. Sites draining less developed areas (i.e., areas where the urban/residential and agricultural land plus grasslands land cover were less than 10%) were located on tributaries to the upper reach of Toms River (Mapleroot, Union, and Old Hurricane Branches), the upstream reach of Ridgeway Branch, Jakes Branch, Cedar Creek and its tributary Factory Branch, North Branch of Forked River, and Oyster and Westecunk Creeks.

Table 2 lists the 43 stations with 3 years or more of surface water quality data during these time periods, and Figure 4 shows their locations. Data are available for selected field parameters and major ions at 14 USGS stations during the water years 1960-72. Data are available for selected field parameters, major

ions, nutrients, bacteria, and metals at 19 USGS stations during the water years 1973-86. Surface water quality data for selected field parameters, major ions, and nutrients collected during the time period 1987-97 are available for 25 sites (2 USGS, 20 Pinelands Commission, and 4 NJDEP sites). A NJDEP and a Pinelands Commission site were co-located, and available data for both sites were commingled. Data from the BTMUA for selected field parameters, ammonia, bacteria, total organic carbon, and VOCs at 30 sites on the North and South Branches of the Metedeconk River for water years 1989-98 were analyzed separately. The sites of the BTMUA network are described in Table 3; the location of these sites is shown in Figure 5.

Table 4 gives the median values of surface water quality data for 43 sites within the bay watershed for the three aforementioned time periods. Figures 6-8 present box plots of the number of observations and distribution of the data in each of the time periods. Sites are arranged from left to right in order of increasing percentage of urban land cover. Box plots are used to indicate the range of data values and show a center line (median or 50th percentile) splitting a rectangle defined by the 25th and 75th percentiles. Whiskers are lines drawn from the ends of the box to the 10th and 90th percentiles. Box plots are not shown in cases where there are less than 9 data values. Comparisons between the sites during a time period and at an individual site over time are difficult to interpret for many reasons. The number of observations at individual sites during each time period varies greatly. At some sites, less than three measurements were made of some water quality characteristics, whereas at other sites, such as the long-term USGS water quality monitoring sites on Toms River and McDonalds Branch, data were collected several times a year, sometimes monthly, for decades. No concurrent flow data were available for the Pinelands Commission data. Data compiled for this analysis were not collected uniformly throughout the year/seasons or hydrologic conditions. For example, some data were collected specifically during summer low-flow conditions. For a more thorough interpretation of these data, the purpose of the data collection and the hydrologic conditions at the time of sample collection must be examined.

1. Water Quality Trends

Because many factors (e.g., stream flow, season, sampling frequency) can affect observations of water quality, several years of data are needed to determine a trend in water quality at a station. Therefore, water quality trends can only be determined at sites where long-term records exist. Several USGS studies examined trends in selected water quality constituents in streams of the New Jersey Coastal Plain during various time periods and flow conditions. The results are summarized below. Trends were determined at the USGS water quality station on the Toms River near the town of Toms River during water years 1976-86 (Hay and Campbell, 1990) and 1986-95 (Hickman and Barringer, 1999) for all flow conditions. During water years 1976-86, the trends were positive for dissolved chloride and total nitrogen, and negative for dissolved magnesium, potassium, lead, chromium, and iron. The trends for specific conductance, pH, dissolved sodium, calcium, total ammonia, total phosphorus, were insignificant. During the same time period, the trend was insignificant for instantaneous stream flow. Robinson et al. (1996) reported on associations between water quality trends determined for water years 1976-86 and several drainage basin characteristics (i.e., population, effluent discharge, road-salt application, and agricultural activities). No statistically significant associations between water quality trends and drainage basin characteristics were determined at Toms River near the town of Toms River. During water years 1986-95, the trends were positive for pH, specific conductance, and total nitrite plus nitrate, ammonia, and negative for total organic nitrogen. The trends were insignificant for dissolved solids, sodium, potassium, calcium, and magnesium; total, hardness, alkalinity, nitrogen, and

phosphorus; and fecal coliform bacteria. During the same time period, the trend for instantaneous stream flow was also negative. In another study by the NJDEP, Carter (1996) reported no significant trend in summertime fecal coliform levels in the Toms River during the period of 1975-94.

Available pH, specific conductance, nitrite plus nitrate, and ammonia data for the long-term USGS water quality station on the Toms River near the town of Toms River are plotted versus time in Figures 9-12. Long-term trends are indicated by a computer generated smoothed line. The apparent trends from this large data set are similar to the combined findings of Hay and Campbell (1990) and Hickman and Barringer (1999) which show that pH, specific conductance, and nitrite plus nitrate appear to be increasing at this site.

Variations in concentration over time can indicate changes in certain drainage basin characteristics. Trends during high flows (stream flows greater than the 25th flow duration value) and low flows (stream flows less than the 75th flow duration value) were determined for selected constituents during water years 1976-93 at sites within the New Jersey Coastal Plain (Hunchak-Kariouk et al., 1999). Comparisons of trends in constituent concentrations during high and low flows can indicate changes over time in the contributions from constant (ground water and point sources) and intermittent (storm runoff) sources. Positive trends during low flows indicate an increase in the contributions from point sources and ground water or both over time, whereas negative trends indicate a decrease in the contributions from point sources and ground water. Positive trends during high flows indicate an increase in the storm runoff contributions, whereas negative trends indicate a decrease in the storm runoff contributions. Figures 9-15 provide examples of trends. During low flows, water years 1976-93, trends were positive for dissolved sodium and chloride, indicating an increase in the contributions from point sources and ground water over time. At this time, trends were negative for total phosphorus, indicating a decrease in the contributions from point sources and ground water over time. Trends were insignificant for dissolved solids, total hardness, total suspended solids, total nitrogen, dissolved nitrite plus nitrate, and total ammonia plus organic nitrogen. During high flows, the trend was positive for dissolved chloride, indicating an increase in the contribution of dissolved chloride from storm runoff over time, and negative for total hardness and phosphorus, indicating a decrease in the contributions of these constituents from storm runoff over time. Trends were insignificant for total suspended solids, dissolved solids and sodium, total nitrogen, dissolved nitrite plus nitrate, and total ammonia plus organic nitrogen.

Specific conductance and pH data were available for all three time periods (water years 1960-72, 1973-86, and 1987-97) at sites on the Toms River, Oyster Creek, Mill Creek, and McDonalds Branch. Figures 13 and 14 illustrate the median concentration values for the three time periods plotted as bar charts on a map of the watershed. Table 2 lists the site names, and Table 4, the median concentration values. The median concentration values are listed in Table 4; site names are listed in Table 2. The median values of pH and specific conductance are similar during each time period. Statistical significance was not determined because the number of observations during each time period varied greatly. The median pH at the Mill Creek site was larger than at any other site during each time period. The median specific conductance at the Toms River site was larger than at any other site during each time period.

Nitrite plus nitrate data were available for two time periods (water years 1973-86 and 1987-97) at 8 sites (5 sites in the Toms River watershed and one site on the Oyster Creek, Mill Creek, and McDonalds Branch.) Figure 15 shows the median concentration values for the two time periods plotted as bar charts on a map of the watershed. Table 2 lists the site names, and Table 4, the median concentration values. The median concentrations are higher at the 3 sites on the Toms River than at the other sites. In addition, the median concentration increased over time at each of these 3 sites. The median concentrations are low, and they did not vary much over time at sites on the Jakes Branch, Oyster Creek, Mill Creek, and McDonalds Branch.

2. Nutrients

Table 4 presents the median values of available nutrient data (total phosphorus, nitrogen, nitrite plus nitrate, ammonia plus organic nitrogen, and ammonia) for water years 1973-86 at 17 stream sites within the watershed and at a site on McDonalds Branch. Figure 7b shows the distributions of these data. Table 4 lists the median values of available nutrient data for water years 1987-97 at 24 stream sites and at the site on McDonalds Branch. Figure 8a and 8b illustrate the distributions of these data. Table 5 contains summary statistics for ammonia measurements at 30 sites on the North and South Branches of the Metedeconk River. The following paragraphs compare the concentrations for each of five nutrient species. Data from the Metedeconk River are discussed separately. The data were not suitable for rigorous statistical analysis because they originated from various sources (collecting agencies). The purpose of data collection was different for each site (i.e., frequency of sample collection, season of collection, hydrologic conditions, etc.), and the number of observations varied greatly between sites.

Concentrations of total phosphorus during water years 1987-97 were low in streams of the watershed. Concentrations were somewhat higher in streams draining more developed areas, although a direct increase in concentrations with increasing development (that is, increasing percentages of urban and agricultural plus grasslands land cover in the area of contributing drainage) is not obvious (Figure 8a). Median concentration values ranged from 0.01 to 0.07 mg/l, and the median value for all sites was 0.01 mg/l (Table 4 and Figure 16).

Concentrations of total nitrogen during water years 1987-97 were higher in streams draining more developed areas (Figure 8b). Median concentration values ranged from 0.18 to 0.99 mg/l, and the median value for all sites was 0.49 mg/l (Table 4 and Figure 17). Total nitrogen is a measure of several nitrogen species that can be dissolved (ammonia and nitrate plus nitrite) or associated with particles (organic nitrogen). Instream concentrations are dependent on the relative abundance of the dissolved and particulate species, contributions from groundwater and storm runoff, and modifications by instream biological and chemical processes.

Concentrations of total nitrite and nitrate plus nitrite during water years 1987-97 were strongly related to the amount of development in the area of contributing drainage to the specific stream (Figure 8b). Median concentration values ranged from 0.01 to 0.64 mg/l, and the median value for all sites was 0.07 mg/l (Table 4 and Figure 18). Median concentrations were 0.15 mg/l or greater at sites draining more developed areas except at one site on each the Davenport Branch and Mill Creek. Median values were 0.07 mg/l or less in streams draining less developed areas. Median concentrations increased in the downstream direction on the Toms River and were the highest (greater than 0.5 mg/l) at all three sites on Wrangel Brook.

Concentrations of total ammonia plus organic nitrogen during water years 1987-97 were somewhat related to the amount of development in the area of contributing drainage. Sites draining more developed areas had greater concentrations. The median concentration values ranged from 0.20 to 0.74 mg/l, and the median value for all sites was 0.30 mg/l. The median concentrations were less than 0.50 mg/l at all but one site with less than 10% development, and 0.50 mg/l or larger at five sites with greater than 10% development.

Values of total ammonia at the 25 sites not located on the Metedeconk River during water years 1987-97

were low. The median concentration values ranged from 0.02 to 0.39 mg/l and were 0.05 mg/l or less at all but four sites (Table 4 and Figure 19). The median value was 0.10 mg/l or greater at the two most downstream sites on the Toms River and the sites on Long Swamp Creek and Mill Creek. Concentrations were high on Mill Creek. The 25th percentile value was 0.30 mg/l. Concentrations of ammonia were fairly similar at the 30 sites on the Metedeconk River; median concentration values ranged from 0.10 to 0.30 mg/l, and the median value for all sites was 0.20 mg/l (Table 5). Ammonia concentrations were slightly lower at sites on the upper reaches of both branches, especially in the South Branch.

In-stream concentrations of nutrients appear to be related to the intensity of development (i.e., the percentages of urban/residential and agricultural plus grasslands land cover) in the areas of contributing drainage upstream of the surface water sites. Streams draining more developed areas have higher concentrations of nitrogen and phosphorus, although phosphorus concentrations throughout the bay watershed were small. Ammonia concentrations throughout the watershed were somewhat related to the intensity of development, but were also small. Ammonia concentrations in both branches of the Metedeconk River were similar to those measured in the Toms River. Mill Creek had very high ammonia concentrations (median value = 0.39 mg/). In most streams, especially those draining less developed areas such as the Mapleroot, Union, and Ridgeway Branches, and Old Hurricane Brook, the predominant nitrogen species was organic nitrogen. In more developed areas (i.e., Toms River, Davenport Branch, Long Swamp Creek, and Four Mile Branch), the median concentrations of nitrite plus nitrate and ammonia plus organic nitrogen were nearly equal. Nitrite plus nitrate was the predominant nitrogen species at all three sites on Wrangel Brook.

3. Other Inorganic Constituents

Figure 8a summarizes pH, specific conductance, and sulfate data measured at 24 stream sites within the bay watershed and a site on the McDonalds Branch during water years 1987-97. Table 4 lists the median values. Table 5 provides statistics for pH and specific conductance data measured at 30 sites on the North and South Branches of the Metedeconk River.

Values of pH were higher in streams draining more developed areas. Median values at the 25 sites not located on the Metedeconk River ranged from 3.9 to 5.7, and the median value for these sites was 4.5 (Table 4 and Figure 20). Median pH values were greater than 5.0 at three sites with 10% or greater development. Median values at the 30 sites on the South and North Branches of the Metedeconk River ranged from 4.4 to 6.6 (Table 5). Development is greater in the lower portions of the Metedeconk River watershed, and the pH was greater in the downstream than the upstream reaches of both branches. Median pH values at all downstream sites were 6.5 and 6.4 and at all upstream sites were 5.8 and 5.7 on the North and South Branches, respectively.

Values of specific conductance were slightly higher in streams draining more developed areas. Median values at the 25 sites not located on the Metedeconk River were generally low, ranging from 27 to 145 ms/cm. The median value for these sites was 52 ms/cm (Table 4 and Figure 21). Median specific conductance values increased in the downstream direction along the Toms River. Values were largest at the site on Long Swamp Creek, which drains an area with the greatest amount of development (greater than 50% urban land cover). Median specific conductance values at the 30 sites on the South and North Branches of the Metedeconk River ranged from 44 to 113 ms/cm (Table 5). Specific conductance was

greater at sites on the North Branch than the South Branch Metedeconk River (median values = 94 ms/cm and 79 ms/cm, respectively) and greater in the downstream than the upstream reaches of both branches. Median specific conductance values at all downstream sites on the North and South Branches were 95 ms/cm and 83 ms/cm, respectively. At all upstream sites on these influent systems the specific conductance values were 62 ms/cm and 60 ms/cm, respectively.

Sulfate concentrations in surface water can be an indicator of the extent of acid deposition which is of great concern because much of the watershed lies within the Pinelands where the waters are acidic and have low alkalinity and buffering capacity. Sulfate concentrations were somewhat related to the amount of development in the area of contributing drainage. Sites draining more developed areas had slightly higher concentrations than sites draining less developed areas. Median concentration values of sulfate during water years 1987-97 ranged from 1.0 to 13.0 mg/l, and the median value for all sites was 6.0 mg/l (Table 4).

The 24 stream sites within the bay watershed were grouped into two major categories based on their water quality during water years 1987-97, in a manner similar to that reported by Windisch and Zampella (1989). These investigators summarized water quality data collected between 1983 and 1988 at over 40 sampling sites on Pinelands streams within Ocean County. Data from 20 of these sites were included in this data synthesis. The first group includes sites located on tributaries to the upper reach of the Toms River (i.e., Mapleroot, Union, and Old Hurricane Branches), the upstream reach of Ridgeway Branch, Jakes Branch, Cedar Creek and its tributary Factory Branch, North Branch Forked River, and Oyster and Westecunk Creeks, all of which drain less developed areas. Water quality at these sites is generally characterized by low nitrite plus nitrate, pH, specific conductance, and sulfate concentrations. Several of the sites on tributaries to the Toms River have somewhat lower pH and ammonia values compared to the other sites of this group.

The second major group of stream sites is comprised of sites located on the Metedeconk and Toms Rivers, the downstream reach of Ridgeway Branch, Wrangel Brook, Davenport Branch, Long Swamp Creek, and Mill Creek and its tributary Four Mile Branch, all of which drain more developed areas. At these sites, nitrite plus nitrate, pH, and specific conductance concentrations are higher than at the other sites. Nitrite plus nitrate concentrations are the highest at sites on Wrangel Brook, and ammonia concentrations are highest at the site on Mill Creek. Specific conductance, pH, and phosphorus, in turn, are highest at the site on Long Swamp Creek.

4. Volatile Organic Compounds

VOCs are not routinely measured in samples collected as part of the USGS/NJDEP water quality network. Few investigations of VOCs in surface waters of New Jersey have been conducted. However, since 1996, several reconnaissance and synoptic studies have been conducted in New Jersey as part of the USGS Long Island-New Jersey (LINJ) National Water Quality Assessment (NAQWA) coastal drainage program. The objective of this program is to understand the effects of toxic compounds in surface water and bed sediment on aquatic communities. While these studies have focused on northern New Jersey, some sampling has occurred at sites on Great Egg Harbor River and South Branch Big Timber and Mantua Creeks (tributaries to the Delaware River) in the coastal plain, and the results are transferable to the bay watershed. Land use within the area of contributing drainage to the Great Egg Harbor River at Sicklerville is similar to the land-use distribution within the bay watershed. Conditions

at this Great Egg Harbor River site are most likely indicative of the more developed areas of the bay watershed.

Terracciano and O'Brien (1997) examined the occurrence of VOCs in streams on Long Island, New York, and New Jersey. Their work included data from a reconnaissance sampling in the winter and early spring of 1996 at nine streams located in a variety of land-use settings across New Jersey. The six most frequently detected compounds in samples collected from the New Jersey streams were (in order of decreasing detection frequency) MTBE, chloroform, cis-1,2, dichloroethene, tetrachloroethene, methylene chloride, and toluene - all by-products of and compounds used in gasoline, commercial and industrial processes, and the chlorination of drinking water.

In a study of the spatial variability of VOCs in streams on Long Island, New York, and in New Jersey, the number of VOCs detected and the concentration of MTBE were related to the land-use composition in the area of contributing drainage (O'Brien et al., 1997). Sites with higher percentages of residential and industrial land use had greater numbers of VOCs and higher concentrations of MTBE than sites with higher percentages of forests and wetlands. Generally, detection frequencies and concentrations were less in samples collected from the Great Egg Harbor River than in samples collected in other streams of New Jersey (Reiser and O'Brien, 1998). In this same study, greater detection frequencies were reported for this site during cooler months (October-March) than warmer months (April-September) for the six most frequently detected VOCs.

Since 1996, the Brick Township Municipal Utilities Authority (BTMUA) has measured VOCs in samples from its water quality network of 30 sites on the North and South Branches of the Metedeconk River. VOC data from these 30 sites and trip blanks collected between January and October, 1998, were suitable for this analysis after extensive data manipulation. Available data for trip blanks show considerable contamination, making the assessment of site data highly tenuous. These data quality concerns prevent a thorough assessment of the data, which can only be qualitatively summarized for this data synthesis.

Thirteen VOCs were detected in samples collected by BTMUA from the 30 river sites and in trip blanks. Four additional compounds were detected only in trip blanks (Table 6). Eleven of these 13 VOCs were detected at sites throughout New Jersey in a VOC synoptic study by the LINJ NAWQA (O'Brien et al., 1997). The four most frequently detected compounds in samples collected from the Metedeconk River were methyl tert-butyl ether (MTBE), tetrachloroethene (PCE), napthalene, and 1,1-dichloroethene. MTBE was detected at all sites and most frequently (50% or more of the time) at 10 sites. However, MTBE was also detected in 60% of the trip blanks, and the median concentration in the trip blanks was higher than that at all but two sites. 1,1-dichloroethene was detected at 4 sites on each of the North and South Branches. Six chlorinated compounds and toluene were detected only in samples collected at river sites and not in trip blanks.

5. Pesticides

In a synoptic investigation as part of the USGS National Water Quality Assessment Program during June 9-18, 1997, pesticides were detected in water samples collected from 50 New Jersey streams, including the Toms River. Six of 47 analyzed pesticide compounds were detected in samples from the Toms River near the town of Toms River, at concentrations of less than 0.05 mg/l (Reiser, 1999). These

compounds included malathion, metalochlor, desethyl atrazine, DCPA, chlorpyrifos, and tebuthiuron. The concentrations of these detected compounds were within established criteria for both human health and aquatic life (Reiser and O'Brien, 1998). Additional short-term synoptic studies of pesticides are planned.

Concentrations of a narrower spectrum of 21 pesticides in base flow and storm flow of the adjacent Manasquan River were measured in 1990, and five of these pesticides were detected at concentrations of 0.05 mg/l or less (Ivahnenko and Buxton, 1994). As described earlier, reported pesticide application rates on agricultural lands of the Manasquan River and Metedeconk River basins are similar. However, the percentage of agricultural land in the Manasquan River basin above the sampling site is 30.7%, which is considerably higher than that of any Barnegat Bay tributary stream. Therefore, it is concluded that agricultural practices are unlikely to result in high pesticide concentrations in Barnegat Bay tributary streams. Because the percentage of developed land is higher than the percentage of agricultural land in the Barnegat Bay watershed, pesticides applied to residential lawns, other turfed areas, and along transportation and utility corridors may be a greater concern.

6. Pathogens

Fecal coliform bacteria data collected in the Toms River near the town of Toms River as part of the USGS/NJDEP water quality network are assessed every two years by the NJDEP. Examination of the water quality index values reported in 1988 and 1992 show an improvement in the water quality of the Toms River (New Jersey Department of Environmental Protection, 1995). Fecal coliform counts exceeded the state criterion of 200 MPN/100ml in 38% of the samples summarized in 1988 (N.J. Department of Environmental Protection, 1990) and in 14% of the samples summarized in 1992 (New Jersey Department of Environmental Protection, 1995).

Fecal coliform bacteria were measured as part of a nonpoint storm runoff study in the Toms River drainage basin (Hunchak-Kariouk, 1999). Concentrations were highest in those samples collected just before or at peak stream flow. Concentrations during the growing season were higher during storm flow than during base flow at all sites monitored. During base flow in the growing season, concentrations were highest at a site on Long Swamp Creek draining a highly developed area, and lowest at sites on Wrangel Brook draining moderately developed areas. During storm flow, concentrations in the growing season were similar to those at sites on Long Swamp Creek and Wrangel Brook and higher than those at a site on Davenport Branch draining a slightly developed area. During the nongrowing season, concentrations were highest at the site on Long Swamp Creek and lowest at the site on Davenport Branch. At sites on all three streams, concentrations were greater during the growing season than during the nongrowing season.

7. Metals

Metals can be transported from the watershed to the estuary in stream flow as dissolved species and associated with suspended sediment and colloids (insoluble chemical solids) in the water column.

Metals readily form complexes with manganese and iron oxides and hydroxides, which are dissolved and associated with particulate surfaces. Metals associated with sediment in the stream bed can enter the water column as the sediment is resuspended during high stream flows. Metals can also enter the estuary from the atmosphere in the form of dry and wet deposition of metal-containing particulates. The concentration, predominant species, bioavailability, and toxicity of each metal depend on the chemical properties of the metal, water chemistry (as controlled by water acidity and the type and concentration of the major inorganic and organic compounds), and seasonal conditions such as temperature and stream flow (Meade, 1995).

Water column and bottom sediment data were collected on six toxic trace metals (arsenic, chromium, copper, lead, nickel, and zinc), manganese, and iron at 28 sites throughout the bay watershed and at the McDonalds Branch in Lebanon State Forest during water years 1960-97. Although manganese and iron are not trace elements, they aid in the interpretation of trace element data because their concentrations reflect weathering, sedimentation, and the ambient chemistry in the water column. In addition, iron is an important agent in the onset of brown tide blooms (Cosper et al., 1996). Except at the long-term water quality sites on the Toms River near the town of Toms River and McDonalds Branch in Lebanon State Forest (a national benchmark site), samples for metal analysis were collected very infrequently (five or fewer samples during the sampling period). For analysis, the sites were grouped by amount of urban development into five groups: (A) McDonalds Branch in Lebanon State Forest; (B) all sites in the Forked River, Mill Branch, and Cedar, Oyster, Westecunk, and Tuckerton Creek Basins; (C) all sites in the Toms River Basin, excluding the Toms River at the town of Toms River site; (D) the Toms River at the town of Toms River; and (E) all sites in the Metedeconk River and Kettle Creek Basins (Table 7). Water column (total concentration) data for unfiltered, whole water samples were available for stations in all groups. Bottom sediment data, in turn, were available for stations in groups B, D, and E only. For this characterization, the total water metal concentration was used, which is the sum of the concentrations of the dissolved, colloidal, and suspended sediment metals.

Figure 22 shows the distributions of water column and bed sediment concentrations among the site groups for each metal. Table 8 provides a summary of these data. The site groups are arranged from left to right in order of increasing intensity of land development in the contributing drainage area of the sites in each site group. These data can only be compared qualitatively because of varying data available for each station and reporting limits, which differed for each medium and which changed over time. For the purpose of this characterization, censored values (data with less than remark codes) were considered equivalent to the reporting level at the time of sample analysis. The actual values are known to be less, but the exact value is indeterminate (Reed et al., 1998). The reporting limit is the minimum value for reporting a concentration measured by some standardized technique. The reporting limit for some metals changed during water years 1960-97 due to differences in sample collection and laboratory procedures.

Median concentrations of arsenic and chromium were low and similar among the site groups and between the water column and bed sediment for each site group. Many concentrations were reported as less than censored values (Table 10). The general pattern of differences in the water column concentrations of copper, nickel, zinc, manganese, and iron among the site groups was: $A \simeq B \leq C \leq D \leq E$; the median concentrations and variance (spread between the 25th and 75th percentile values) increase with increasing urban development in the basins. The pattern of differences in the water column concentrations of lead among the site groups was: $B < A \simeq C \simeq E < D$. Stream bed sediment concentrations of zinc, chromium, and copper were less than the concentrations in bay sediments reported by Moser and Bopp (1996), whereas some lead concentrations in bed sediments of site groups B and E were similar to or higher than those of bay sediments.

The concentrations of metals in the water column and bed sediments of influent systems in the watershed are qualitatively related to the amount of development (urban/residential and

agriculture/grasslands) in the sampled basin. The basins of the Metedeconk River and Toms River are more developed than the remainder of the bay watershed and the McDonalds Branch basin. The highest maximum and median concentrations of metals were at sites in either the Metedeconk River basin or at the Toms River at the town of Toms River. The lowest median concentrations were in the McDonalds Branch and in rivers other than the Metedeconk River and Toms River.

The utility of the data comparisons (e.g., the median concentrations) reported in this characterization to water quality regulations is uncertain for a several reasons. The purpose of the data collection and the hydrologic conditions at the time of sampling were not investigated for the characterization. The values reported here are for the total concentration of substances composited from several sites over very long time periods during which sampling and laboratory methods varied.

8. Bed Sediment and Suspended Sediment Quality

Stream bed sediments can be a source or sink of toxic chemicals such as trace elements and chlorinated organic chemicals depending on the physiochemical conditions in the water column and bottom sediments. Many trace elements in aquatic systems are strongly associated with iron and manganese oxide coatings on sediments. Chlorinated organic chemicals are extremely hydrophobic and therefore tend to sorb to organic matter, which is either dissolved in the water or associated with suspended and bottom sediments. As a result, sediments can provide a mechanism for these toxic chemicals to remain in surface water systems for many years after their input. When bed sediments are disturbed and transported downstream, re-equilibration with surrounding waters may release the chemicals to the water column.

The presence and distribution of trace elements and chlorinated organic compounds in stream bed sediments were determined for selected rivers of New Jersey (O'Brien, 1997; Stackelberg, 1997). The distribution of toxic chemicals was examined with respect to both physiographic province and major drainage areas with varying percentages of different land use. Bed sediment concentrations of toxic chemicals within the Barnegat Bay watershed were not analyzed in these studies; however, concentrations in other major drainage basins in the New Jersey Coastal Plain were examined. Land use in the Big Timber Creek and Cooper River (BTCR) basins is mostly urban. In the Salem River and Raccoon Creek (SRRC) basins, land use is mainly agriculture. Land use in the Great Egg Harbor and Mullica River (GEMU) basins is principally forest and wetland and that in the Toms River and elsewhere in the Barnegat Bay watershed is predominantly forest and wetland (similar to the GEMR basins). Results of these analyses are generally transferable to the Barnegat Bay watershed, although many river segments in the inner coastal plain that cross confining-unit outcrop areas may have different bed sediment compositions with correspondingly different adsorptive characteristics than those of the outer coastal plain.

Concentrations of arsenic and nickel in bed sediments are similar throughout the New Jersey Coastal Plain and do not appear to be related to land use because concentrations are similar among the urban (BTCR), agricultural (SRRC), and less-developed (GEMU) basins. Concentrations of copper and lead are higher in urban (BTCR) basins than in agricultural (SRRC) and less-developed (GEMU) basins, and concentrations of chromium, zinc, and iron are higher in urban (BTCR) and agricultural (SRRC) basins than in less-developed areas (GEMU) areas. Manganese concentrations are higher in agricultural (SRRC) basins than in urban (BTCR) and less-developed (GEMU) basins. Therefore, if the Barnegat

Bay watershed is comparable to the GEMU basins with respect to factors affecting trace metals in bed sediments, then concentrations of trace metals in bed sediments of the Barnegat Bay watershed are likely to be low in relation to other, more developed basins in New Jersey.

Concentrations of DDT and DDE in bed sediments are similar throughout the New Jersey Coastal Plain and do not appear to be related to land use because the concentrations are similar among the urban (BTCR), agricultural (SRRC), and undeveloped (GEMU) basins. Concentrations of DDD, chlordane, dieldrin, and PCBs are higher in urban (BTCR) basins than in agricultural (SRRC) and undeveloped (GEMU) basins. Therefore, concentrations of chlorinated organic chemicals in bed sediments of the Barnegat Bay watershed are probably low.

Suspended sediment can be a transport mechanism for nutrients, organic chemicals, and metals to the estuary. Some hydrophobic organic chemicals and charged inorganic species such as phosphates, ammonium and organic nitrogen, as well as metals become associated with particle surfaces and are mobilized in the stream. Data on suspended sediment (quantity and quality) in streams of the bay watershed are limited. Historical data (prior to 1986) are available for sites on the North Branch of the Metedeconk River, Oyster Creek, and Westecunk Creek, and recent data (since 1994) are available for sites on the Wrangel Brook, Davenport Branch, and Long Swamp Creek. Suspended sediment has been measured at the long-term water quality stations on the McDonalds Branch in Lebanon State Forest and Toms River near the town of Toms River since 1969 and 1972, respectively. Table 9 lists sites where suspended sediment data have been collected.

Figure 23 shows the concentrations of suspended sediment, total phosphorus, ammonia plus organic nitrogen, and total organic carbon at sites within the bay watershed. Concentrations of total phosphorus, ammonia plus organic nitrogen, and total organic carbon are whole water measurements and represent the sum of the concentrations associated with suspended sediment and dissolved in the water column. The magnitude of these total water column concentrations is a qualitative measure of the amount of these nutrients associated with suspended sediment.

Concentrations of suspended sediment measured in streams of the bay watershed were low. Median values were less than 20 mg/l at all sampled sites (where data were available). Concentrations at sites on the North Branch of the Metedeconk River, Toms River, Wrangel Brook, and Long Swamp Creek were similar and higher than concentrations in Oyster Creek, Westecunk Creek, and McDonalds Branch, which were very low. Concentrations of phosphorus and total ammonia plus organic nitrogen were somewhat higher at sites on the North Branch of the Metedeconk River, Toms River, and Long Swamp Creek, where the concentrations of suspended sediment were also higher than at other sites in the watershed. Total concentrations of nutrients were lower at sites on Oyster Creek, Westecunk Creek, and McDonalds Branch, where the concentrations of suspended sediment were sampled than at other sites in the watershed.

III. ATMOSPHERIC DEPOSITION

Although human activities that directly affect water quality are usually assumed to be the dominant sources of estuarine pollutants, atmospheric deposition also can be a significant source of various contaminants to coastal waterways. Results of local studies of atmospheric deposition in the Barnegat Bay watershed are not yet available (Y. Gao, Rutgers University, written communication, 1999).

However, investigations of other areas in, and adjacent to, New Jersey provide a reasonable indication of the likely magnitude of atmospheric deposition of various constituents.

Systematic investigations of the atmospheric deposition of toxics, such as mercury, pesticides, and volatile organic compounds have been initiated recently, and some results are available. These investigations generally show that the potential for significant atmospheric contributions of toxic chemicals to the Barnegat Bay watershed, in comparison with potential contributions from local sources, is probably relatively small. Notable exceptions are mercury, lead, and the gasoline oxygenate methyl tert-butyl ether (MTBE). In 1995, the National Air Deposition program (NADP) initiated the NADP Mercury Deposition Network (NADP/MDN), which includes monitoring stations at Lewes, Delaware, and Wye, Maryland. The concentration of mercury measured nationwide in this monitoring program between February 1995 and February 1997 typically ranged from 5 to 15 ng/l. The highest concentration (50 ng/l) was recorded at the Lewes, Delaware station (NADP, 1999, The NADP/MDN Transition Phase Report, unpublished data accessed July 13, 1999, on the World Wide Web at URL http://nadp.sws.uiuc.edu/mdn/mdn_trandata_rpt.html). Numerous studies are presently underway to further assess the threats, sources, and transport of mercury contamination. In addition, Moser (1997) concluded from a literature review and an analysis of estuary sediment cores that atmospheric deposition is an important source of lead (Pb) to the estuary.

In urban areas nationwide, atmospheric deposition generally is a less important source of VOCs than urban land surfaces (Lopes and Bender, 1998). Baehr et al. (1999) evaluated the atmosphere as a source of VOCs in shallow ground water in the Glassboro region of southern New Jersey and frequently found low-level concentrations of chloroform, methyl-tert butyl ether (MTBE), 1,1,1-trichloroethane, tetrachloroethylene (PCE), and carbon disulfide (not a VOC) in shallow ground water of the Kirkwood-Cohansey aquifer system. Atmospheric concentrations of MTBE (but not the other compounds) were found to be high enough (as high as 43.8 ug/l) to potentially explain its frequent detection in shallow ground water. In the Barnegat Bay watershed, the presence of MTBE in shallow ground water has not been investigated systematically, but this contaminant was the most frequently detected VOC in surface water samples from the Metedeconk River by the Brick Township Municipal Utilities Authority.

Pesticides can be transported into the atmosphere by various processes, dispersed by air currents, and then re-deposited on land and water surfaces. More than 24 agricultural pesticides have been reported in fog and rainfall in the United States, Canada, and Europe. Although atrazine and alachlor concentrations of 0.2-0.4 ug/l were typically measured in precipitation sampled in midwestern cornbelt states during 1990-91, concentrations of these compounds measured in precipitation across the northeastern United States at this time were generally less than 0.05 ug/l (Goolsby et al., 1997). In the Glassboro area in southern New Jersey, pesticide concentrations in precipitation were less than 0.05 ug/l during most of the year, but were higher during the spring application period (A. Baehr, U. S. Geological Survey, written communication, 1999).

Atmospheric deposition of nitrogen is generally recognized by east coast estuarine programs as either a significant factor in eutrophication or a mechanism of possible concern (Valigura et al., 1996). A strong linkage between increasing rates of nitrogen oxide emissions and increasing cultural eutrophication of coastal waters of the northeast United States has been suggested (Jaworski et al., 1997). However, trends in nitrate ion concentration in precipitation sampled nationwide during 1983-94 did not exhibit a consistent spatial pattern, and trends in the coastal mid-Atlantic region during this period were not statistically significant ($p > 0.05$) (Lynch et al., 1996). Johnsson and Barringer (1993) described inorganic precipitation chemistry in the McDonalds Branch subwatershed, situated close to the Barnegat Bay watershed. They showed that ammonium and nitrate were substantial carriers of ionic charge in precipitation sampled during 1984-88, and that concentrations of most major ions, including nitrate, were higher in throughfall (sampled under the forest canopy) than in precipitation. This finding suggests

that dry deposition of nitrogen on vegetative surfaces in the Barnegat Bay watershed could be significant, as suggested by Wang (1984).

Atmospheric deposition can increase the nitrogen load of streams if nitrogen inputs to a watershed exceeds vegetative uptake or if soils are particularly permeable and unable to retain nitrogen. Jaworski et al. (1997) observed that for large watersheds in the northeastern U. S., riverine nitrogen fluxes were highly correlated with nitrogen deposition onto their landscapes and also with nitrogen oxide emissions from fossil fuel combustion into their airsheds.

For the purposes of relating precipitation chemistry with that of surface and ground water in the Barnegat Bay watershed, and estimating the contribution of nitrogen load from atmospheric deposition, inorganic chemical data for precipitation sampled at selected sites as part of the National Atmospheric Deposition Program (NADP), were examined. Two NADP sites proximal to the Barnegat Bay watershed for which data are available for the past 10 years are located at Washington Crossing, New Jersey, and on the eastern shore of Maryland at Wye. NADP summary reports indicate that inorganic precipitation chemistry is similar at these and surrounding sites (NADP, 1995, 1997), and similar to that observed in the McDonalds Branch basin by Johnsson and Barringer (1993). Therefore, these two NADP sites provide a reasonable indication of the chemistry of precipitation occurring over the Barnegat Bay watershed. A factor that may possibly limit the applicability of these sites is their relatively inland location with respect to sources of marine aerosols. Monthly mean values for nitrate-N, ammonia-N, sulfate, specific conductance, and pH for these two sites were analyzed for the 1987-97 period. Figure 24 shows statistical distributions of these values for the two respective sites. These distributions can be used to summarize the recent history of precipitation chemistry for the Barnegat Bay watershed.

Concentrations of the five inorganic constituents in shallow ground water located near streams were similarly analyzed. Water from 22 shallow wells located near surface water was sampled during September and October of 1996, and respective constituent values for the wells were commingled and statistically analyzed (Jones and DeLuca, 1997). These synoptic data can be thought of as a "snapshot" in time with fairly wide spatial coverage.

The 25 surface water sampling sites with constituent data for the 1987-97 period were selected, and respective constituent medians for these sites were commingled and statistically analyzed. Some streams were sampled more frequently than others; therefore, an uneven statistical reliability is present among the median values analyzed. Whereas ground water samples provide an indication of the chemistry along discrete flow paths that intersect a small fraction of the aquifer system resource, the samples from the 22-25 surface water sites integrate all surface water inputs upstream (covering most of the watershed land mass). In this sense, the available surface water quality data set represents the surface water resource more completely than the available ground water data set represents the ground water resource.

In spite of fundamental differences between the data sets for these hydrologic compartments (spatial coverage vs. temporal coverage), a qualitative comparison of statistical distributions can provide a meaningful first step in understanding the relations between precipitation, ground water, and surface water. Relative distributions provide some indication of the extent to which precipitation can be expected to represent a potential source of these constituents in ground water and surface water.

The inner quartile range (IQR) was used to measure the variability in constituent concentrations. The IQR measures the range of the central 50% of the data values and is defined as the 75th percentile minus the 25th percentile. IQRs of sulfate concentrations, specific conductance, and pH in precipitation are small when compared to those for the shallow ground water and surface water sampling sites. This finding suggests that factors other than precipitation may be affecting sulfate concentrations, specific

conductance, and pH of shallow ground water near streams and in surface water. Nitrate-N concentrations in precipitation fall within a narrow range, whereas the nitrate-N concentrations in ground water span a wider range. Ammonia-N concentrations in precipitation are generally higher than, and span a wider range than, those of either ground water or surface water samples. The ground water quality data set exhibits greater variability than the surface water quality data set, possibly as a result of the discrete nature of ground water sampling relative to the integrative nature of surface water sampling. In general, a qualitative comparison of the relative ranges of water quality constituent values indicates that precipitation could represent a potential source of ammonia-N and nitrate-N to both ground water and surface water, and that ground water could represent a potential source of, or influence on, all five of these constituents in surface water.

Literature Cited

Baehr, A., P. E. Stackelberg, and R. J. Baker. 1999. Evaluation of the atmosphere as a source of volatile organic compounds in shallow ground water. Water Resour. Res., 35:127-136.

Barbash, J. E. and E. A. Resek. 1996. Pesticides and Ground Water Distribution: Trends and Governing Factors. Ann Arbor Press, Chelsea, Michigan. 588 p.

Barringer, J. L., C. L. MacLeod, and R. A. Gallagher. 1997. Mercury in ground water, soils, and sediments of the Kirkwood-Cohansey aquifer system in the New Jersey Coastal Plain. USGS Water-Resources Investigation Report 95-475, U. S. Geological Survey, West Trenton, New Jersey. 260 p.

Breidt, F. J., D. C. Boes, J. I. Wagner, and M. D. Flora. 1991. Antidegradation water quality criteria for the Delaware River: A distribution-free statistical approach. Wat. Resourc. Bull., 27: 849-858.

Camp, Dresser & McKee. 1993. Evaluation of the Ocean County Health Department Domestic Well Test Database. Unpublished Consultant's Report, Edison, New Jersey.

Carter, G. P. 1997. Eight characterizing trends in the Barnegat Bay watershed, Ocean County, New Jersey. Pp. 1-16 *in* Flimlin, G. E. and M. J. Kennish, M.J. (eds.), *Proceedings of the Barnegat Bay Ecosystem Workshop*. Rutgers Cooperative Extension of Ocean County, Toms River, New Jersey.

Chow, V.T. 1964. Handbook of Applied Hydrology. McGraw Hill, New York. 1418 p.

Clawges, R. M., T. D. Oden, and E. J. Vowinkel. 1998. Water quality data for 90 community water supply wells in New Jersey, 1994-95. USGS Open-File Report 97-625, West Trenton, New Jersey. 31 p.

Clawges, R. M., P. E. Stackelberg, M. A. Ayers, and E. F. Vowinkel. 1999. Nitrate, volatile organic compounds, and pesticides in ground water - A summary of selected studies from New Jersey and Long Island, New York. U. S. Geological Survey Water Resources Investigations Report 99-4027, West Trenton, New Jersey. 32 p.

Dooley, J. H. 1992. Natural sources of mercury in the Kirkwood Cohansey aquifer system of the New Jersey Coastal Plain. New Jersey Geological Survey Report 27, West Trenton, New Jersey. 16 p.

Cosper, E. M., M. D. Gastrich, O. R. Anderson, and S. S. Benmayor. 1997. Viral infection and brown tide. Pp. 233-242 *in* Flimlin, G.E. and M. J. Kennish, (eds.), *Proceedings of the Barnegat Bay Ecosystem Workshop*. Rutgers Cooperative Extension of Ocean County, Toms River, New Jersey.

Fegeas, R. G., R. W. Claire, S. C. Guptill, K. E. Anderson, and C. A. Hallam. 1983. Land use and land cover digital data. U. S. Geological Survey Circular 895-E, Reston, Virginia. 21 p.

Goolsby, D. A., E. M. Thurman, M. L. Pomes, M. T. Meyer, and W. A. Battaglin. 1997. Herbicides and their metabolites in rainfall: origin, transport, and deposition patterns across the midwestern and northeastern United States, 1990-91. Environ. Sci. Technol., 31:1325-1333.

Harriman, D. A. and B. P. Sargent. 1985. Ground water quality in east-central New Jersey, and a plan for sampling networks. U. S. Geological Survey Water Resources Investigations Report 85-4243, Trenton, New Jersey. 114 p.

Harriman, D. A., and L. M. Voronin. 1984. Water quality data for aquifers in east-central New Jersey, 1981-82. U. S. Geological Survey Open-File Report 84-821, Trenton, New Jersey. 39 p.

Hay, L. E. and J. P. Campbell. 1990. Water quality trends in New Jersey streams. U. S. Geological Survey Water Resources Investigations Report 90-4046, West Trenton, New Jersey. 297 p.

Hickman, R. E. and T. H. Barringer. 1999. Trends in water quality of New Jersey streams, water years 1986 - 95. U.S. Geological Survey Water Resources Investigation Report 98-4204, West Trenton, New Jersey. 174 p.

Hunchak-Kariouk, K. 1999. Relation of water quality to land use in the drainage basins of four tributaries to the Toms River, New Jersey, 1994-5. U. S. Geological Survey Water Resources Investigation Report 99-4001, West Trenton, New Jersey. 120 p.

Hunchak-Kariouk, K., D. E. Buxton, and R. E. Hickman. 1999. Relations of surface water quality to stream flow in the Atlantic Coastal, Lower Delaware River, and Delaware Bay Basins. U. S. Geological Survey Water Resources Investigation Report 98-4244, West Trenton, New Jersey. 146 p.

Ivahnenko, T. and D. E. Buxton. 1994. Agricultural pesticides in six drainage basins used for public water supply in New Jersey: 1990. U. S. Geological Survey Water-Resources Investigation Report 93-4101, West Trenton, New Jersey. 56 p.

Jaworski, N. A., R. W. Howarth, and L. J. Hetling. 1997. Atmospheric deposition of nitrogen oxides onto the landscape contributes to coastal eutrophication in the Northeast United States. Environ. Sci. Technol., 31:1995-2004.

Johnsson, P. A. and J. L. Barringer. 1993. Water quality and hydrogeochemical processes in McDonalds Branch basin, New Jersey Pinelands, 1984-88. U. S. Geological Survey Water Resources Investigation Report 91-4081, West Trenton, New Jersey. 111 p.

Jones, W. D. and M. J. DeLuca. 1997. Water resources data New Jersey water year 1996. U.S. Geological Survey Water-Data Report NJ-96-2, West Trenton, New Jersey. 207 p.

Kozinski, J., Z. Szabo, O. S. Zapecza, and T. H. Barringer. 1995. Natural radioactivity in, and inorganic chemistry of, ground water in the Kirkwood-Cohansey aquifer system, southern New Jersey, 1983-89. U. S. Geological Survey Water Resources Investigations Report 92-4144, West Trenton, New Jersey. 130 p.

Leamond, C. E., R. J. Haefner, S. J. Cauller, and P. E. Stackelberg. 1992. Groundwater quality in five areas of differing land use in Nassau and Suffolk Counties, Long Island, New York. U. S. Geological Survey Open-File Report 91-180, Syosset, New York. 67 pp.

Lopes, T. J. and D. A. Bender. 1998. Nonpoint sources of volatile organic compounds in urban areas - relative importance of land surfaces and air. Environ. Pollut., pp. 221-230.

Lord, D. G., J. L. Barringer, P. A. Johnsson, P. F. Schuster, R. L. Walker, J. E. Fairchild, B. N. Sroka, and E. Jacobson. 1990. Hydrogeochemical data from an acidic deposition study at McDonalds Branch basin in the New Jersey Pinelands, 1983-86. U. S. Geological Survey Open-File Report 88-500, West Trenton, New Jersey. 132 p.

Lynch, J. A., V. C. Bowersox, J. W. Grimm. 1996. Trends in precipitation chemistry in the United States, 1983-94: an analysis of the effects in 1995 of Phase I of the Clean Air Act Amendments of 1990, Title IV. U. S. Geological Survey Open-File Report 96-0346, Reston, Virginia. 100 p.

Meade, R. H. (ed.). 1995. Contaminants in the Mississippi River: U. S. Geological Survey Circular 1133, Reston, Virginia. 140 p.

Moser, F. C. 1997 Sources and sinks of nitrogen and trace metals, and benthic macrofauna assemblages in Barnegat Bay, New Jersey. Ph.D. Thesis, Rutgers University, New Brunswick, New Jersey. 135 p.

Moser, F. C. and R. F. Bopp. 1996. A comparison of trace metals in bay and marina sediments in Barnegat Bay. Pp. 95-108 *in* Flimlin, G. E. and M. J. Kennish (eds.), *Proceedings of the Barnegat Bay Ecosystem Workshop*. Rutgers Cooperative Extension of Ocean County, Toms River, New Jersey.

National Atmospheric Deposition Program. 1997. National Atmospheric Deposition Program 1997 Wet Deposition. Illinois State Water Survey, Champaign, Illinois. 16 p.

National Atmospheric Deposition Program. 1995. NADP/NTN Wet Deposition in the United States 1995. Illinois State Water Survey, Champaign, Illinois. 12 p.

New Jersey Department of Environmental Protection. 1995. New Jersey 1994 State Water Quality Inventory Report. New Jersey Department of Environmental Protection, Office of Environmental Planning, Trenton, New Jersey. 176 p.

New Jersey Department of Environmental Protection. 1990. New Jersey 1990 State Water Quality Inventory Report. New Jersey Department of Environmental Protection, Division of Water Resources, Trenton, New Jersey. 471 p.

Novotny, V. and G. Chesters. 1981. Handbook of Nonpoint Pollution Sources and Management. Van Nostrand Reinhold Company, New York. 555 p.

O'Brien, A. K., R. G. Reiser, and H. Gylling. 1997. Spatial variability of volatile organic compounds in streams on Long Island, New York, and in New Jersey. U. S. Geological Survey Fact Sheet FS-194-97, West Trenton, New Jersey. 6 p.

O'Brien, A. K. 1997. Presence and distribution of trace elements in New Jersey streambed sediments. J. Am. Wat. Resour. Assoc., 33, No. 2.

Preston, S. D. 1996. Study of nonpoint source nutrient loading in the Patuxent River Basin, Maryland. U. S. Geological Survey Water Resources Investigation Report 96-4273, Baltimore, Maryland. 6 p.

Reed, T. J., G. L. Centinaro, M. J. DeLuca, and J. H. Oden. 1998. Water Resource Data, New Jersey, Water Year 1997. U. S. Geological Survey Water-Data Report NJ-97-1, West Trenton, New Jersey. 608 p.

Reiser, R. G. 1999 Relation of pesticide concentrations to season, stream flow, and land use in seven New Jersey streams. U. S. Geological Survey Water Resources Investigations Report 99-4154, West Trenton, New Jersey. 19 p.

Reiser, R. G. and A. K. O'Brien. 1998. Occurrence and seasonal variability of volatile organic compounds in seven New Jersey streams. U. S. Geological Survey Water Resources Investigations Report 98-4074, West Trenton, New Jersey. 11 p.

Robinson, K. W., T. R. Lazaro, C. Pak. 1996. Associations between water quality trends in New Jersey streams and drainage-basin characteristics, 1975-86. U. S. Geological Survey Water Resources Investigation Report 96-4119, West Trenton, New Jersey. 148 p.

Stackelberg, P. E. 1997. Presence and distribution of chlorinated organic compounds in stream bed sediments, New Jersey. J. Am. Wat. Resour. Assoc., 33:271-284.

Stackelberg, P. E., J. A. Hopple, and L. J. Kauffman. 1997. Occurrence of nitrate, pesticides, and volatile organic compounds in the Kirkwood-Cohansey aquifer system, southern New Jersey. U. S. Geological Survey Water Resources Investigation Report 97- 4241, West Trenton, New Jersey. 8 p.

Szabo, Z. and V. DePaul. 1998. Radium-226 and radium-228 in shallow ground water, southern New Jersey. U. S. Geological Survey Fact Sheet FS-062-98, West Trenton, New Jersey.

6 p.

Szabo, Z., D. E. Rice, C. L. McLeod, and T. H. Barringer. 1997. Relation of distribution of radium, nitrate, and pesticides to agricultural land use and depth, Kirkwood Cohansey aquifer system, New Jersey Coastal Plain, 1990-91. U. S. Geological Survey Water Resources Investigations Report 96-4165A, West Trenton, New Jersey. 107 p.

Terracciano, S. A. and A. K. O'Brien. 1997. Occurrence and distributions of VOCs in streams on Long Island, New York, and in New Jersey--A review of existing and reconnaissance data. U. S. Geological Survey Fact Sheet FS-063-97, West Trenton, New Jersey. 4 p.

Valigura, R. A., W. T. Luke, R. S. Artz, and B. B. Hicks. 1996. Atmospheric nutrient input to coastal areas--reducing the uncertainties. National Oceanic and Atmospheric Administration, NOAA Coastal Ocean Program, Decision Analysis Series No. 9, NOAA Coastal Ocean Office, Silver Springs, Maryland. 24 p,.

Vowinkel, E. F. and W. A. Battaglin. in press. Analysis of nonpoint source ground water contamination in relation to land use: Chapter D, Relation of ground water quality to hydrogeology and land use in the Coastal Plain of New Jersey. U. S. Geological Survey Water Supply Paper 2381-D, Reston, Virginia. 110 pp.

Vowinkel, E. F., R. M. Clawges, D. E. Buxton, and D. A. Stedfast. 1996. Vulnerability of public drinking water supplies in New Jersey to pesticides. U.S. Geological Survey Fact Sheet FS-165-96, West Trenton, New Jersey. 3 p.

Vowinkel E. F., R. M. Clawges, and C. G. Uchrin. 1994. Evaluation of the vulnerability of water from public supply wells in New Jersey to contamination by pesticides. Pp. 495-510 *in* Weigmann, D. L. (ed.), New Directions in Pesticide Research, Management, and Policy. Virginia Water Resources Research Center, Nov. 1-3, 1993, Blacksburg, Virginia.

Vowinkel, E. F. and S. F. Siwiec. 1991. Plan to evaluate the effects of hydrogeologic conditions and human activities on water quality in the Coastal Plain of New York and New Jersey. U. S. Geological Survey Water Resources Investigations Report 91-4091, West Trenton, New Jersey. 42 pp.

Wang, D. 1984. Fire and nutrient dynamics in a pine-oak forest ecosystem in

the New Jersey Pine Barrens. Ph.D. Thesis, Yale University, New Haven, Connecticut. 217 p.

Watt, M. K., M. L. Johnnson, and P. J. Lacombe. 1994. Hydrology of the unconfined aquifer system Toms River, Metedeconk River, and Kettle Creek basins, New Jersey, 1987-90. U. S. Geological Survey Water Resources Investigation Report 93-411, West Trenton, New Jersey. 5 plates.

Windisch, M. A, and R. A. Zampella. 1989. New Jersey Pinelands surface water quality data, 1983-88. Tech. Rept. Prepared by the New Jersey Pinelands Commission in cooperation with the Cape May County, Burlington County, and Ocean County Health Departments, 515 p.

Yuretich, R. F., D. A. Crerar, D. J. J. Kinsman, J. L. Means, M. P. Borscsik. 1981. Hydrogeochemistry of the New Jersey Coastal Plain. 1: Major element cycles in precipitation and river water. Chem. Geol., 33:1-21.

I. INTRODUCTION

This chapter describes how the aboriginal people lived and used the environment of Ocean County, and discusses the impact that contact with the Europeans had on their way of life. The arrival of European settlers in Ocean County affected the environment through changes in land use and creation of colonial industries. As the natural resources were depleted, the colonial industries (e.g., lumbering and sawmills, bog iron manufacture, and charcoal manufacture) disappeared. Some people left Ocean County with the demise of the main industries, but the people who remained in the colonial settlements endured and survived by farming, hunting, fishing, and berry harvesting. In the last half of the 19th Century, the recreational tourist industry began to expand, and this industry helped to produce the tremendous growth experienced in Ocean County during the last half of the 20th Century.

II. PREHISTORIC OVERVIEW

New Jersey has undergone vast geologic changes since Precambrian time. Most human-induced changes, however, have occurred during the past 10,000 years, since retreat of Wisconsin continental glaciation. Aboriginal people migrated to New Jersey during that time, but their numbers were so few that they had little environmental impact. The New Jersey of that prehistoric time was pristine and untouched, with unbroken stretches of forest as far as the eye could see (Cunningham, 1966). The outer coastal plain forests contained mixed pine, oak, chestnut, and hickory in the uplands. The lowland sites, which were wetter, contained holly, white cedar, red maple, blackgum and birch. Although there were minor climatic fluctuations over the past 10,000 years, the forest vegetation remained stable (Hartzog, 1981). As stated by Harshberger (1916), "...the pine barrens vegetation...is an old vegetation in a long occupancy of the territory in which it is found. The age of this forest is attested by its surviving through the changes of several geologic epochs antedating the glacial period, when the northern part of the state was covered with ice." The natural resources, such as iron, copper, quartz sand, and vast quantities of pure water were hidden in the mountains, swamps, plains and unconsolidated sand aquifers. No ships sailed the bays or rivers, and there were no coastal settlements, except for the few scattered summer camps of the aboriginal people (Cunningham, 1966).

III. PRE-EUROPEAN CULTURES

When the first European explorers and settlers came to the area now known as New Jersey, they found the native people who had existed there for thousands of years. The people who lived in the lower half of "Lenapehoking" (The Land of the Lenape) called themselves "Lenape," meaning "common" or "ordinary" people (Kraft, 1985).

The prehistoric ancestors of the Lenape kept no written records, so we do not know what they called themselves. In the absence of written records, archaeologists have created names such as Paleo-Indian, Archaic, and Late Woodland to identify the different prehistoric periods and cultures. Three major cultural traditions dominated the prehistory of New Jersey and the Middle Atlantic Coastal Plain: (1) the Paleo-Indian Tradition (15,000 to 10,000 years ago); (2) the Archaic Tradition (10,000 to 3,000 years ago); and (3) the Woodland Tradition (3,000 years ago to European contact) (Hartzog, 1981).

Paleo-Indian artifacts provide the earliest documented evidence of the existence of human populations in New Jersey. The Paleo-Indians were aboriginal hunter-gatherers that roamed over a wide geographic

area more than 13,000 years ago. Glaciers covered large parts of Europe, Asia, and North America. It is thought that these people came to the western hemisphere across a "land bridge" created by the lowering of sea level in the Bering Sea. This land bridge connected Siberia with Alaska. The indians arrived on the Atlantic Coast about 12,000 years ago, eventually settling in New Jersey and present-day Ocean County, where they harvested plants, animals, and sea life for sustenance. The changing climate affected their lifestyle. The climate was harsh and cold, and edible vegetation was scarce. They hunted cold-adapted animals such as woolly mammoth, mastodon, musk-ox, caribou, moose, elk and walrus (Hartzog, 1981). Remnants of their existence have been researched throughout the New Jersey Pinelands (Pinelands Comprehensive Management Plan, 1980).

As the glaciers melted and sea level increased, the flooding of coastal lands accelerated. The woolly mammoth and mastodon became extinct. Caribou, moose, and other cold-adapted animals migrated north as tundra vegetation was replaced by pine and spruce forests. Many hunters followed the migrating animals north. Some of the descendants of the Paleo-Indians remained in the Atlantic Coast area, adapting to the changing conditions. New people with different tools and weapons migrated to Lenapehoking from the south and west and created a new culture during the Archaic Period. Aboriginal populations, which had become more skilled in the use of available resources by this time, occupied estuarine areas with greater frequency. Traps, spears, deadfalls, snares, and bolas were means of obtaining game. Fish were speared, caught in nets, or trapped in fishweirs. Gardening was unknown, and people were completely dependent upon conditions of nature (Kraft, 1985). Increased reliance on lacustrine and marine resources was partially responsible for the increase in human populations observed during the Late Archaic Period (Stoltman and Baerreis, 1983). By 1900 B.C., remnants of indian habitation included cremated burials and grave artifacts (Pinelands Comprehensive Management Plan, 1980). The remains of the deceased were sometimes accompanied by "...spearpoints and knives, spear-thrower weights, axes, and other tools, as well as food for the journey to the afterlife" (Kraft, 1985).

The Late Woodland Period represents the interval from approximately 900 A.D. until the coming of European explorers and settlers (Pinelands Comprehensive Management Plan, 1980). Ceramic vessels were first used during this period, and there was increased use of broadspear projectile points for fishing (Custer, 1984). In the Atlantic Coastal Plain region, larger settlements were located on major waterways, such as the Toms River, while smaller sites were found on tributaries and near springs. Marine and riverine resource exploitation contributed to higher population densities and more complex social relationships (Custer, 1984). The people of this period were organized into many subtribes known collectively as the Lenni-Lenape. They had discovered horticulture, and their camps included gardens and agricultural fields. The Lenni-Lenape manipulated the forests by burning the understory to produce forage for white tailed deer and other game animals. They harvested clams and oysters, and fished for various marine species. During the Woodland Period, oyster exploitation may have occurred during times when other food sources were scarce (Thurman, 1976). The people were adept at using the resources of the woodlands, rivers, and estuaries for survival.

Early 20th Century archaeological surveys identified many physical remains in and around the Toms River. In 1950, indian burial-ground artifacts were found along the Gilford Park shore of the Toms River, and these artifacts were retained by the New Jersey State Museum (Miller, 1992). According to Boyd (1991), the larger native settlements were located on the inner coastal plain rather than in the Pine Barrens. There is evidence that they lived near the shore during the summer and traveled back and forth to the coast for fishing and shell collecting. Piles of shells called "middens" were left behind along the coast. One of the biggest mounds, located in the sedges near Tuckerton, was once 12 ft (3.7 m) high, 100 ft (30.5 m) long, and 50 ft (15.4 m) wide at its peak 2,000 years ago (Jahn, 1980; Oxenford, 1992). The Tuckerton site, within a coastal marsh protected by a shore road, was once adjacent to a tidal estuary and located on the shores of an inland bay. Its occupation from the Archaic Period through much

of the Woodland Period is testimony to the stability of the shellfish resources in the Tuckerton area (Williams and Thomas, 1982). The occurrence of other middens indicate that the larger village sites exploited mollusks. These villages were located along the estuarine segment of Toms River below the head of tide (Grubb, 1998). The shell piles that were found not only provided evidence of the use of shellfish as food but also for wampum production. Shell wampum was of two types: white and black. White wampum was made of periwinkle conches, or whelks, and black wampum, from the purple inside of the clamshell. Other types of wampum were made from mussel and oyster shells. Wampum was the indian currency, and it was made in the form of sashes and scarves, or necklaces, which contained thousands of shells (Wilson, 1953).

Compliance-related archaeological surveys conducted over the past 20 years have produced no additional pre-historic sites in the Ocean County area. This may indicate that the Toms River area was sparsely inhabited during prehistoric times (Grubb, 1998). Sea level rise, caused by glacial melting during the early to mid-Holocene, (post-glacial time), could have covered sites that may have been located on the continental shelf along the New Jersey coast. The exposed shelf along southern New Jersey is estimated to have been 50 mi (80 km) wide in Pleistocene time (Hartzog, 1981). The gloabally rising sea level has left little evidence of the aboriginal human occupation in present-day coastal areas. However, archaeologists have discovered over 1,000 indian sites scattered through and surrounding the Pine Barrens, which seems to support the theory that the more established villages were located inland from the coast.

The first Europeans encountered the Lenni-Lenape people of the Late Woodland Period. The Lenni-Lenape were divided into three groups: (1) the Unalachtigo, "the people who lived near the ocean," (2) Unami, "the people down the river," and (3) Unalimi or Minisink, "the people of the stony country" (Cunningham, 1966; Weslager, 1972; Goddard, 1978). The Unalachtigo inhabited the coastal areas of southern New Jersey and Delaware Bay, and had a more estuarine focus to their existence than the other Lenni-Lenape groups, as evidenced by shell middens found at the mouth of Cedar Creek (Glosque, 1975) and the Toms River. According to Kraft and Mounier (1982), the collective Late Woodland bands in southern New Jersey consisted of the ancestral Sankhikan, Navasink, Assiscunck, Rancocas, Schackamaxon, Yacomanshaghking, Eromiex, Narraticon, Mantese, Siconesse, Sewaposee and Kechemeche. The term "Proto-Unami" has been proposed to describe this collective group.

The Proto-Unami subtribes occupied the southern New Jersey peninsula. Each subtribe had a "sakima" (subchief). The Unami sakimi, located in the Trenton area, was considered to be chief of all subtribes. Each subtribe had its own hunting and fishing lands, and every summer the tribesmen traveled well-defined trails across the state to the coast to fish and gather shells for wampum. These trails eventually formed the basis of several colonial highways and the routes of some modern roads. "Their trails ran from 10 mi (16 km) south of Port Jervis to the Shrewsbury River (the Minisink Trail), from Trenton to Somers Point, from Camden to Tuckerton, and from Gloucester to Somers Point" (Cunningham, 1966). Route 537, which now forms the northwestern border between Monmouth and Ocean Counties, was known as the Burlington Path, a major shore route for the indians. Squankum Road in Lakewood Township was also a principal indian trail (Ocean County Planning Board, 1988).

The indians traded with the early Europeans for "...glass, beads, bottles, iron axes, hoes, brass kettles, cloth and clothing, guns and knives using the pelts of beaver, deer, bear, and otter" (Kraft, 1985). As a hunter, the indian needed 600 ac (243 ha) to provide sufficient game fare for food to support his family and tribe (Nelson, 1902). Demand for furs and pelts for trade soon exhausted the local animal populations and forced the indians to venture farther away from their own territories to obtain pelts, often causing conflict with other tribes to the north and west (Kraft, 1985).

The indians and Europeans had very different attitudes toward the use of the land and the animal

inhabitants. Indians considered themselves to be a part of nature, and nature could not be owned. The European settlers, however, believed that land could be owned and nature had to be "...tamed and improved" (Kraft, 1985). A century after European colonization, the last remaining indians left Lenapehoking. At the Treaty of Easton, in 1758, the Lenape and Minisink Indians in New Jersey relinquished title to the lands that their ancestors had inhabited for thousands of years. Only one small area of Lenapehoking, consisting of 3,044 ac (1233 ha) in Evesham Township, Burlington County, was set aside for the use of the Lenape. This area became known as the Brotherton Reservation, or Indian Mills. Finally in 1801, the last of the indians sold their land and moved west (Kraft, 1985).

IV. EARLY EUROPEAN HISTORY

There are many theories as to who was the first non-native person to see the shores of North America, dating back to the Vikings. In 1497, England sent the Cabots in search of a northwest passage. While it is known that they sailed the North Atlantic coastline from Newfoundland to Florida, no written records of this voyage exist in the historical sources consulted (Nelson, 1902). England's claim to the peninsula between the Hudson River and the Delaware River originated with this voyage. Although the Dutch and Swedes settled in New Jersey in the 1600's, King Charles II of England acted in 1664 to force the Dutch to relinquish claim to the only non-English territory between Massachusetts and Virginia (Cunningham, 1966).

According to historical sources, the first recorded European to sight land in Ocean County was Henry Hudson in 1609, although there is written evidence that Giovanni da Verrazano made contact with the Lenni-Lenape in 1524, 85 years before Henry Hudson sailed the New Jersey coast (Cunningham, 1966). Captain Cornelius Jacobsen Mey came ashore near Egg Harbor in 1614. Captain Cornelius Hendricks discovered Barnegat Bay in 1614 when he sailed through Barnegat Inlet in his boat the "Onrest," from which he charted what was to become the Toms River, the forks of Forked River, and Great Bay (Ocean County Board of Chosen Freeholders, 1999). The Toms River is thought to be named for Captain William Tom, a British officer who visited the Toms River area in 1673. The first recorded settler was Henry Jacob Falkinburg of Schleswig-Holstein, who purchased 800 ac (324 ha) of land near Tuckerton from the East Jersey Proprietors in 1698 (Ocean County Planning Board, 1988).

When the old world immigrants arrived in the mid-1600's and early 1700's in the lands that became New Jersey, they settled first along the coastal bays and inlets of the Hudson, Hackensack, Passaic and Raritan River valleys in northern New Jersey, as well as the Delaware River valley and inner coastal plain south of Trenton. The area between the Delaware and the Atlantic Ocean in the southern part of the outer coastal plain was still "unsettled" in 1765 (Wacker, 1979). This vast area, eventually called the "Pine Barrens," was used largely for lumbering and hunting, and later for the resources that produced the colonial industries. A large area of what was to become Ocean County is located in the Pine Barrens.

Ocean County was created from lands divided from Monmouth County on February 15, 1850. The county had been settled since colonial times, but the political subdivisions that existed in 1850 consisted of Jackson, Plumsted, Stafford, Union, Dover and Brick Townships. Part of Jackson Township was returned to Monmouth County in 1851 and part of Little Egg Harbor, originally a part of Burlington County, was added in 1891. Stafford Township dated from a much earlier period and was incorporated in 1749, making it the oldest incorporated municipality in Ocean County (Ocean County Planning Board, 1988).

The topography of the area determined the location of the early immigrant settlements, which were located along the Atlantic coast within easy access of the ocean and the coastal rivers and bays (Harshberger, 1916). Principal early settlements in Ocean County consisted of Barnegat (settled in 1668) and Egg Harbor (settled in 1690 and renamed Tuckerton in 1786).

V. LATER DEVELOPMENT

A. Inlets

The colonial industries were becoming established during the early 1700's. The 18th Century witnessed tremendous industrial growth in Ocean County. Water transport of raw materials and finished goods enabled a vast shipping trade to develop. A description of the inlets that connected Barnegat Bay with the Atlantic Ocean, and their changing configurations from the 1600's to the 1900's is necessary to understand the vital role they played in the development of the county. The Historical and Biographical Atlas of the Jersey Coast (1878) explained the dynamic nature of the beaches and inlets:

> "All the beaches are continually undergoing changes. Those south of Barnegat Inlet are wearing away on the northeast ends.
>
> The inlets move southward. New ridges and dunes form on the south and southwest ends of the old. In some cases they work seaward, extending outside of and overlapping older beaches. A recent instance is that of Long Beach, having made two or three miles of new beach within a few years, shutting up entirely the old Little Egg Harbor Inlet, sweeping outside of and around Tucker's Beach and crowding the surf back a quarter of a mile from its former bed.
>
> North of Barnegat the inlets work in an opposite direction. The old Cranberry Inlet, opposite Toms River, moved nearly a mile northward during its sixty years of continuance.
>
> New inlets suddenly break out through the beaches, usually in the neighborhood of the earlier channels of the old, and the process is again repeated."

Each inlet had a particular influence on its surrounding area.

• Beginning at the southernmost portion of Ocean County, near the terminus of the barrier island, an inlet existed between Holgate and Tucker's Island from the early 1700's. This inlet was 2 mi (3.2 km) wide and deep enough for any sloop or schooner going to Tuckerton. This inlet began to "sand up" in the

1790's. In 1840, this "Old Inlet," as it was now called, opened again and was renamed the 1840 Inlet. The inlet closed in 1874 as the result of a storm, reconnecting Long Beach Island with Short Beach, or Tucker's Beach. On February 4, 1920, a violent northeaster reopened Old Inlet, which was then renamed Beach Haven Inlet in 1922. Erosion along the south side of the Beach Haven Inlet caused Tucker's Island to be completely lost by 1940 (Lloyd, 1990; Oxenford, 1992).

• At the southern end of the barrier island, a "New Inlet" opened in the winter of 1800, along the creek that separated Tucker's Island from Little Beach to the south. This New Inlet later became known as Little Egg Harbor Inlet, and is now nearly 200 years old (Lloyd, 1990).

• Barnegat Inlet has existed since the time of the earliest explorers. Although the inlet has shifted position many times over the centuries, it has provided access to Barnegat Bay in the same general area across the bay from Barnegat, West Creek and Waretown. The inlet was directly responsible for the settlement and growth of these areas during colonial times (Lloyd, 1990).

• Cranberry Inlet opened north of Barnegat Inlet on the border of Dover Township and Seaside Heights during a violent storm in 1740. This inlet was responsible for the growth of Toms River as a seaport during the Revolutionary War. It allowed a vast shipping trade to exist, with sloops and schooners transporting the products of the interior colonial industries, such as lumber and iron, to New York and the West Indies. Cranberry Inlet began to shoal early in the 19th Century and was closed during a great northeast storm in the winter of 1812. After the closure of the inlet, Squan Beach and Island Beach were joined to become a 22-mi (35-km) long peninsula. Captains that previously had ready access to Toms River and the northern part of the bay now had to sail 12 mi (20 km) south to Barnegat Inlet to access the bay (Jahn, 1980; Miller,1992).

• Kettle Creek Inlet existed north of Cranberry Inlet in the 1700's, although the date of its opening and closing could not be found. This inlet was located opposite Kettle Creek (Miller, 1992).

• Herring Inlet, also known as the Metedeconk River Inlet, existed a few miles north of Kettle Creek Inlet, opposite Herring Island and the Metedeconk River. This inlet opened Brick to a shipping trade that carried the products of the forest and forges to the cities. It was closed during the same violent storm in 1740 that opened Cranberry Inlet (Oxenford, 1992).

• At various times during recorded history there were at least 10 inlets across the barrier island to Barnegat Bay (Oxenford, 1992). These inlets were responsible for the establishment and growth of a maritime industry in Ocean County.

The settlements were located near harbors because most goods were transported by water. The character of the wilderness west of the bay was intimidating. Consider the following quote about the woodlands by Vermeule in 1885, almost 200 years after the first settlers arrived:

> "From Manchester southward to the Mullica River is one of the wildest, most desolate portions of the state. If we accept the clearings on the shore road and along the marl border, not more than 2% of the area is under cultivation. Here and there are narrow roads, barely wide enough for a single vehicle to pass

> clear of the trees, which thread their lonely way from clearing to clearing. They are relics of a time when the manufacture of iron from bog ore found in the swamps was an important industry of the region. Here and there one comes upon abandoned forge sites, or still more suggestive, abandoned villages, the relics of unsuccessful glass manufacture in the wilderness. An indescribable silence prevails. The soughing of the wind through the pines oppresses, while the crowing of a cock or the barking of a dog indicates the approach to a clearing and human habitation."

Many "sand roads" from the 1700's still exist, the most well known being the Tuckerton stage route. Roads built to connect early settlements were constructed across "...a wilderness populated by red deer, bears, wolves, panthers, wild-cats, foxes, rabbits, opossums, pole-cats, hedgehogs, wild turkeys, pheasants, grouse and quails" (Harshberger, 1916). It is no wonder that early immigrant settlements grew around riverine and estuarine areas, which provided easy access by boat.

B. Maritime Uses

The maritime industry in Barnegat Bay originated with the first settlers in the early 1700's and was centered in Waretown, Toms River, Forked River, Barnegat and Tuckerton. The vast forests of southern New Jersey and bog iron provided the natural resources and conditions necessary to establish a colonial maritime industry. The unsettled interior represented a seemingly inexhaustible supply of raw materials for ship building. The woodlands yielded large quantities of cedar, oak, pine, maple, walnut, hickory and wild cherry. The pitch pines supplied tar to caulk hulls and resins that produced turpentine (Pinelands Comprehensive Management Plan, 1980). It is estimated that the forests in Ocean County near water transportation were clear cut every 25 years, and less accessible forests were lumbered every 40 years. It is also estimated that since the time of colonial settlement, cedar swamps have been harvested repeatedly. The Three Partners Sawmill (from 1786) was located on the South Branch of the Metedeconk River. Potters Sawmill (from 1765) was located on Cedar Creek in Lacey and Berkeley Townships between Toms River and Forked River. David Wright's sawmill (pre-1793) was located on the Horicon branch of the Toms River. Water powered sawmills operated at Double Trouble as far back as 1765 (Boyd, 1991).

Iron was abundant in the stream beds and bog, and it was used to produce ship hardware (Pinelands Comprehensive Management Plan, 1980). Bergen Iron Works and Butcher's Forge were located on the South Branch of the Metedeconk River from the early to mid-1800's. Dover Forge (1809-1868) was located on Dover Forge Pond on the Middle Branch of Cedar Creek, 4 mi (4.8 km) downstream from Bamber.

From the late 1600's to the early 1800's the pitch pine forests provided the resources for the distillation of turpentine, tar, and pitch used in ship building. Slits were made in the sides of pitch pine trunks to encourage the flow of oleoresin, which was gathered and distilled into turpentine and resin. Tar, or "pine-wood tar" was distilled using stumps, roots and other waste material. Pitch was a residue of tar distillation. It is highly adhesive and water repellent, and was used for caulking the seams of boats and ships (Boyd, 1991).

By the 1790's, the ship building industry was flourishing around Barnegat Bay. Sneakboxes, garveys and catboats were first built on the New Jersey coast and were the earliest means of short distance travel until the invention of the automobile prompted improved road construction. The first "sneakbox" was

designed by Hazelton Seaman (ca. 1836) at West Creek across from Barnegat Inlet. New Jersey cedar was used for the greater part in the construction. The center board, tiller, and trim were either mahogany, oak, or sassafras. The spars were of spruce or fir (Kraft, 1960). J. H. Perrine, a resident of Barnegat, was building 15 ft (4.6 m) sneakboxes by the late 1800's. By the end of the century, the sneakbox was the most popular sailing boat on the bay. Peculiar to the Barnegat Bay region, the sneakbox is designed for the changing water depths of the bay. With its center board up, it draws very little water and can go almost anywhere. It is also very seaworthy in heavy weather. It was designed to be used as a duck blind that could be moved easily and camouflaged with marsh grass. The design had a unique feature in the rail around the stern of the boat that allowed for storage of decoys during transport to the hunting sites (Ocean County Historical Society, 1997).

> "The sneakbox was usually about 12 feet long with a pointed bow, which had no conventional stem; the keel sloped back on a long curve from the level of the deck at the bow, while the afterdeck was square and surrounded by a high coaming, providing an area to carry lots of decoys. The small square cockpit had room for only one man. There was no rudder - it was steered with an oar and also had rowlocks. A slot through the foredeck accommodated a daggerboard, easily pulled out when the boat was to be dragged into the reeds. A small gaffed sail was carried on an unstayed mast, set through the deck to a step on the keel, also easily lifted out and set aside once the boat had been pulled up" (Methot, 1988).

The sneakbox was perfectly suited to the shallow tidal waters of the Barnegat Bay. One old timer declared that sneakboxes "... could sail with ease across the Jersey meadows after a heavy dew" (Schoettle, 1966). Bay Head became a center for sneakbox building in 1874 and produced some famous boat builders. The 18 foot gaff-rigged sneakbox was introduced before the turn of the 20th Century and was used to race and sail the bay (Jahn, 1980; Oxenford, 1992).

The garvey was an all-purpose boat used for fishing, clamming, and oystering. It was designed by Jarvis (Gervis or Garvey) Pharo of Tuckerton. The boat could be rowed, towed, powered by the wind or a motor. A small cabin was often added to provide shelter from the wind. The broad, open deck could be filled with the "catch." A clammer and his garvey were a common sight on the bay (Ocean County Historical Society, 1997).

The roomy, shallow-draft catboat was the universal vessel for sport and transportation. The most prominent feature was the single mainsail. The catboat required a perfect harmony between sail and hull because it had no jib, staysail or foresail. There was great pride in ownership of these boats, and Barnegat Bay captains loved to race their boats to determine who was the best sailor and who had the fastest boat (Lloyd, 1990).

Ocean County has had a long history of maritime traditions. The earliest commercial activities were connected to shipbuilding, and included whaling and fishing. Toms River and Tuckerton were important privateering ports during the Revolutionary War. The privateers brought the Revolutionary War to British shipping, sailing out of Barnegat Bay and Little Egg Harbor to pursue merchant vessels off the coast and seize their valuable cargo, which generally consisted of such items as pounds sterling, loaf sugar, London porter, Bristol beer, molasses, salt, lumber, coffee, cocoa, and rum. The vessels themselves were frequently taken as well. The captured cargo provided prosperity to Toms River and Tuckerton, and a small privateer boom town arose at the forks of the Mullica River. "By midsummer of 1778, no British merchant ship was safe off the Jersey coast without armed escort" (Cunningham, 1966). Captured British cargo was carried to Philadelphia on roads cut through the Pine Barrens. At the conclusion of the Revolutionary War, President Washington made Tuckerton the official port of entry

for the New Jersey coast extending from Barnegat Inlet south to Brigantine Inlet.

Boat building in the Barnegat Bay area continued to expand through the 19th Century. During the 50-year period from the War of 1812 until the Civil War, shipbuilding developed an active coastal shipping trade from Tuckerton to Toms River. About 50 to 60 small schooners per week transported cordwood and charcoal from the pinelands out of Toms River. By the late 1800's, new sloops and schooners were built by small shipyards from Kettle Creek to Tuckerton. The 28 to 33 ft (8.5 to 10 km) gaff-rigged catboats were the fisherman's workboat and the freight carrier from Seaside Park to Bay Head. Ninety sloops and schooners were launched on the bay between 1860 and 1870 (Miller, 1994). Bay Head had a thriving boat-building industry from the late 1800's into the middle of the 1900's. Bay Head boat building originated in the shop of Benjamin Hance in 1878. Hance built duck boats, row boats, and small sail boats. Morton Johnson started a boat-building yard in 1891. This establishment grew into one of the largest of its kind in New Jersey, and its boats were highly prized by sailors and collectors. In 1902, Samuel Loveland purchased the Hance yard, and restored and repaired boats. Morton's son, Hubert, started a boat-building business in 1912 on the east side of West Lake Avenue in Bay Head. In 1916, Hubert purchased Samuel Loveland's yard and added it to his West Lake Avenue boat yard. This boat yard, illustrative of the maritime tradition in the Barnegat Bay-Little Egg Harbor estuary, eventually became known nationally and internationally for its boat designs. During the 1940's, this facility was known as the largest yacht storage plant on the coast and one of the largest boat-building concerns in New Jersey; it employed approximately 100 men (Ocean County Principals' Council, 1940). This once thriving boat-building facility eventually declined, and in the 1990's it consisted of covered boat slips, marina slips, marine sales, yacht dry storage, and launching ramps.

C. Lumbering and Sawmills

Sawmills are among the earliest and most durable sites of historic settlement in southern New Jersey. Many of these sites were established in Ocean County by the first decade of the 18th Century in order to secure lumber for shipbuilding and domestic structures, as well as for export. Some of these mills were established rather far up the streams. The lumber was formed into small narrow rafts and floated down towards the bay, where ships were waiting to transport it to market. Old Cranberry Inlet was open then, making water travel to New York more convenient than today (Salter, 1890).

Sawmill sites seem to have been selected for two principal resources: waterpower and timber (Mounier, 1984). Certain environmental characteristics were required to establish sawmills, all of which were present in the Ocean County area: 1) a reliable water supply; 2) topographic features sufficient to allow for the elevation and storage of a body of water; 3) proximity to the raw materials; and 4) economic routes of access to deliver the extracted or processed material to its destination. Since groundwater significantly affects streamflow in Ocean County, the streams on which mills were established provided power even during dry seasons. Atlantic white cedar (*Chamaecyparis thyoides*) occurs along streams, which made its exploitation by water-driven sawmills inevitable (Mounier, 1984). Because of the heavy demand and a relatively effective extractive and processing technology, private and corporate concerns recognized the value of prime timber in the early years of the industry. As early as 1707, the General Assembly of New Jersey had adopted an act making it illegal to cut timber under 12 in (30.5 cm) in diameter. Subsequent legislation further regulated the cutting of timber and the export of all forest products from New Jersey (Boyd, 1991).

As a result of the lumbering activities associated with ship building and the other uses for wood products, the virgin pitch pines, oaks and stands of Atlantic white cedar were "...virtually wiped out by the mid-1800's" (Boyd, 1991). As early as 1749, Benjamin Franklin published an essay in Poor

Richard's Almanack in which he advocated forestry methods, especially the "...planting of red-cedar to supply the country when the white cedar should fail" (Harshberger, 1916; Pierce, 1957). Harvesting of Atlantic white cedar terminated before the end of the 19th Century due to the lack of marketable tree stands (McCormick, 1970). Atlantic white cedar requires 60 years to produce lumber in economic quantities (Harshberger, 1916). By 1899, the oldest Atlantic white cedar tree in Ocean County (at Whitings) studied by Pinchot (1899) was 80 years old.

Cedar mining became important after the cedar swamps were clearcut in the mid-1800's. Cedar mining consisted of locating former cedar swamps where trees had been blown down by storms, or had died in former years and were covered by mud and peat to various depths. The peaty earth containing the buried cedar was soft and spongy, and some trees had been covered for hundreds of years. The recovered timber was used mainly for shingles. This industry was not widespread in Ocean County, but was a major industry in Burlington, Atlantic, and Cape May Counties (Weiss, 1965). Cedar logs are still mined from time to time. During World War II, wood from sunken cedar logs was used in the hulls of patrol torpedo boats (McPhee, 1967).

The locations of the sawmills frequently became the focus of settlements. The communities, which developed as an extension of the sawmills, shared a number of common characteristics: 1) location upon a stream at the head of tide or at the head of navigation; 2) location convenient to surface transportation; 3) location convenient to raw materials needed for extractive or processing industries; and 4) sufficient population for labor needs and to maintain the physical and social integrity of the community. Table 3 provides a list of settlements associated with sawmills in Ocean County (Mounier, 1984).

By 1823, Tuckerton had become the prosperous principal village of Little Egg Harbor Township:

> "Little Egg Harbor was once a place...of great commerce and prosperity. The little river there used to be filled with masted vessels. It was a place rich in money. As farming was but little attended to, taverns and boarding-houses were filled with comers and goers. Hundreds of men were engaged in the swamps cutting cedar, and saw-mills were numerous, and always in business cutting cedar and pine boards" (Historical and Biographical Atlas of the Jersey Coast, 1985).

After the decline of the water-powered sawmills due to the lack of timber resources from clearcutting, early sawmill sites were converted to cranberry culture, thus capitalizing upon existing investments by converting cleared wetlands to cranberry production (Mounier, 1984). Eventually cranberry production became a major industry in southern New Jersey, and it continues today.

D. Charcoal Manufacture

The lumbering industry eventually turned to second- and third-growth trees. The smaller second- and third-cut trees were used to make charcoal, which was used to fire furnaces for the manufacture of bog iron and glass. "Charcoal is partially burned wood from which water, volatile gasses, tars, resins and impurities have been driven off, leaving a residue of practically pure carbon" (Boyd, 1991). Three-and-a-half or four cords of wood will make one hundred bushels of charcoal. Substantial acreage was required to manufacture charcoal, and the clear cutting methods used to harvest the wood destroyed vast forests.

To make charcoal, the colliers placed heaps of wood into a domelike pile, with a chimney in the middle extending from the ground to the top. The heaps were compactly covered with turf cut from the edges of swamps, and then overlain with sand sufficient to clog all the crevices. The so-called kiln was then fired by dropping burning chunks of wood down the chimney to the ground and heaping in brush and other combustible material to the top of the chimney which was then shut with a piece of turf cut to fit the top. Small holes were made through the turf at the bottom and sides, to regulate the draft just enough to char the wood but not to burn it. The kiln had to be watched night and day throughout the process. One collier usually watched 15 or 20 kilns at a time. Ten days to two weeks were needed to convert the wood into charcoal (Historical and Biographical Atlas of the Jersey Coast, 1878).

Large amounts of charcoal were used as fuel for the bog iron furnaces. It is estimated that 20,000 ac (8100 ha) of woodlands were required to produce the charcoal needed to fire one bog iron furnace for 20 years. Each season's harvest of 1,000 ac (405 ha) continued until the end of a 20-year cycle, when the first plot was expected to be regrown (Boyd, 1991). Regrowth did not always occur as planned, and this may have been a factor in the demise of both the charcoal and bog iron industries. As of 1865, there were only a few small charcoal operations remaining in the Pinelands.

E. Bog Iron Manufacture

Iron works were important to the colonial economy. They were first started in Ocean County near Lakehurst in 1789 by David Wright (Ocean County Planning Board, 1988). As stated by Boyd (1991), "Bog iron ore is formed by the chemical action of decayed vegetative matter in streams upon iron salts found in and around stream beds. A soluble form of iron is found in the strata of marls, greensands, streams, marshes and other slow-moving waters. Cedar waters are acid waters, and a chemical reaction is formed when the water percolates down and picks up the iron, in solution, and carries it to the surface. Upon contact with the air, and aided by bacterium such as *Leptothrix ochracea*, it oxidizes. The reddish floc or sludge can be found deposited in the beds of slow moving waters." Sometimes it is deposited in wetlands and bogs. The major ingredients of this industry existed in the Ocean County area: raw "ore" or bog iron; wood to make charcoal to fire the furnaces; water to provide power; and clam and oyster shells used as flux (Boyd, 1991). In order to operate a furnace, batches of ore, charcoal, and flux were weighed in certain proportions, taken by wheelbarrows over a trestle bridge to a platform around the top of the furnace stack, and dumped into the furnace stack in layers. This was known as the "charge," and setting the charge required men to work all day and night. More than two tons of ore and 180 bushels of charcoal were required to produce one ton of pig iron. The furnaces were in constant operation - 24 hours a day, seven to nine months of the year - until the streams froze in winter, which curtailed the water power. Water powered both the furnaces and forges. After the iron was formed, the often brittle, impure, and somewhat porous pig iron was refined and resmelted into wrought iron. Whereas pig iron was limited to stoves, kettles, sash weights and firebacks, wrought iron could be used for tools, horseshoes, wagon tires and many other products requiring metal of great strength (Pierce, 1957).

Forges existed in Ocean County, (e.g., Butchers Forge on the south branch of the Metedeconk River, Martha Forge on a branch of the Toms River, Dover Forge on the middle branch of Cedar Creek, and Stafford Forge on the north branch of West Creek). By 1865, the bog iron industry had declined due to a combination of events that included the discovery of anthracite coal in Pennsylvania, the invention of steel, the depletion of the bog iron ore beds, and clear-cutting of the forests of southern New Jersey. As noted by Pierce (1957), "rarely had an industry been so patiently built, and rarely had one been obliterated so swiftly." Nothing was left but memory.

According to Boyd (1991), "The southern New Jersey area could be characterized as having been

heavily industrialized from 1765 to about 1865." Today, most of the old industries and many of their surrounding communities are gone, and the Pine Barrens has more or less reclaimed its own wild, little developed, sparsely populated condition. Yet, over the past 225 years, there probably is not a single acre of Pine Barrens terrain that has not been burned, cut over, or otherwise disturbed repeatedly" (Boyd, 1991).

F. Cranberry and Blueberry Cultivation

Native American Indians used cranberries for food, dyes, as well as well as for medicinal purposes. They introduced cranberries to the early settlers who consumed them as a wild, edible fruit. The name "cranberry" was given to the vine by the early settlers because it resembled a crane in its full flowering stage. The name "crane-berry" later became cranberry (Boyd, 1991).

The cultivation of the native wild cranberry, *Vaccinium macrocarpon*, has existed in Ocean County since John Webb cultivated the first cranberries near Cassville in 1845. Nearly all of New Jersey's cranberry bogs have been and are still located in the Pine Barrens (Boyd, 1991). By 1869, more than 50% of the total cranberry production in the United States was from New Jersey (Ocean County Planning Board, 1988). Statistics of the 1876 Centennial (Historical and Biographical Atlas of the Jersey Coast, 1878) show that Ocean County had a total of 1,849 ac (749 ha) of cranberry production in 1876, with 1,625 ac (658 ha) planted on a muck bottom and 564 ac (228) planted on a savannah bottom. The total county investment for the entire acreage, three years after planting, was $887,769.43. The average price for a bushel of cranberries at the time was $3.26.

Pure, unpolluted, high quality acidic water is essential for cranberry culture, which is why a farmer requires substantial acreage of upland watersheds surrounding habitats. Cranberry plants need soil with an adequate and controlled moisture content, afforded by irrigation. Cultivation is restricted to Atsion, Berryland, St. Johns and Muck soils (Pinelands Comprehensive Management Plan, 1980). Cranberry bogs are flooded in the winter months to keep the roots of the plants from freezing. In spring, the water is drained off for an early bloom in June. The plants grow, blossom, and bear fruit during the summer and early fall by maintaining adequate moisture around the roots. The amount of water is controlled by the height of boards in the cranberry gates. Flooding in the summer is rare, and only used to control insect infestations (Boyd, 1991).

The soils for successful culture must have a peaty nature, with the water level within a few inches of the surface. Flooding is necessary from 18 inches to 2 feet (46 to 61 cm) from November to May, in order to protect the plants from frost and insect damage. Preparation of the bog requires removal of all bushes and trees along with the top layer of soil down to a depth of about 2 to 4 inches (5 to 10 cm). The surface must then be graded, dams and sluice gates constructed, and ditches dug to manipulate drainage. The surface must be sanded to a depth of 3 to 4 inches (7.5 to 10 cm), and the young plants must be set out as cuttings, in rows, around the first of June (Harshberger, 1916).

The wet-harvesting method was pioneered in New Jersey during the mid-1960's. Cranberries are very buoyant, and when the bogs are flooded at harvest time, the buoyancy of the ripe berries lifts the vines off the beds of the bogs, enabling mechanical cranberry machines, called "beaters," to strip the cranberries from the vines. The loose berries are then guided into booms and onto loading conveyors, dropped into crates on truck beds, and driven to the processing plants for cleaning and shipment to market (Boyd, 1991).

Plant diseases became widespread after 1925, and only a few bogs remain active in Ocean County. Most cranberry production is now located in the North Branch Rancocas Creek subbasin and the Wading River, Batsto River, and Atsion-Sleeper Branch subbasins of the Mullica River Basin. The Mill Pond Bog in Double Trouble State Park, at one time the largest cranberry bog in the state, has been restored by a private grower under the supervision of the New Jersey Department of Environmental Protection (Ocean County Planning Board, 1988). With 3,000 ac (1215 ha) in cultivation in 1980, New Jersey accounts for 13% of the nation's cranberry acreage, and it produces approximately 9% of the national harvest, third to Massachusetts and Wisconsin in nationwide production (Pinelands Comprehensive Management Plan, 1980; Boyd, 1991).

In contrast, blueberry cultivation is more widespread, but is not located in Ocean County. In 1980, blueberry cultivation covered 7,800 ac (3159 ha) in the North Branch Rancocas drainage basin, in the Hammonton Creek subbasin, near Chatsworth in the Wading River subbasin of the Mullica River drainage basin, and near Mays Landing in the Great Egg Harbor River basin (Pinelands Comprehensive Management Plan, 1980).

G. Salt Hay Harvesting

The tide marshes of Ocean County are dominated by three distinctive areas of vegetation. The first, and smallest, area is covered at every high tide. Smooth cordgrass (*Spartina alterniflora*) predominates here (Tiner, 1985). This type of marsh gradually merges into a second type of marsh that is sometimes covered by normal tides. This area is so close to mean high water that the slightest rise results in flooding by water. This part of the marsh is primarily inhabited by the short form of smooth cordgrass, sedges, and marsh grass. The third marsh type, or high marsh, occurs above mean high tide and is characterized by a greater diversity of vegetation. This area is inundated only by the spring and fall tides, and the winter or storm tides. It is divided by water channels which usually have well-defined beds and banks (Weiss, 1965; Teal, 1969; Tiner, 1985).

The salt marsh sedges are exposed at low tide. At high tide, only the tips of the sedges are visible. The roots of the sedges are deeply extended into the mud, and as the plants die each year, new shoots regenerate in the spring. The mud and plant detritus accumulates until the flats of the first marsh type merge into the second type. Other plants begin to appear here, such as spike grass (*Distichlis spicata*), sea lavender (*Limonium carolinianum* and *L. nashii*), glassworts (*Salicornia bigelovii*, S. europaea, and *S. virginica*), salt marsh asters (*Aster subulatus* and *A. tenuifolius*), marsh pinks (*Sabatia dodecandra* and *S. stellaris*), spikerushes (*Eleocharis* spp.), salt marsh bulrush (*Scirpus robustus*), and three square grass (*Scirpus americanus*) (Tiner, 1985). Three square grass has a vigorous root system, and as the plant develops from year to year, it forms a turf-like landscape. Other coarse grasses are found at higher elevations on the marsh. Salt grass (*Spartina patens*) occupies the high salt marsh, which is only periodically inundated by the tides. The marsh becomes useful for agriculture at this point, in areas that are so high above ordinary tides that flooding takes place only occasionally. At slightly higher elevations, the black grass (*Juncus gerardi*) is evident. This species has been used as livestock forage (Weiss, 1965).

Salt hay (*Spartina alterniflora*) has been harvested for several purposes. For example, the use of salt bedding for livestock was a common practice in the late 1600's, and "salt hay manure" was utilized by farmers to fertilize their land in the spring. The marshes, although owned by the proprietors, were considered to be common lands by the colonists, who used the marsh grasses as pasture for their livestock as well as for bedding. Mainland farmers often let their cattle loose to wander over the marshes until the fall roundup (Weiss, 1965; Teal, 1969). Salt hay was also harvested for use as packing material

in the glass industry, for insulating ice, and for producing paper. Shallow draft hay-scows were employed in the bay, rivers, and creeks to transport the harvested salt hay. In 1896, Sadoc Estlow of Barnegat was called the "Hay King," and hay harvesting was a thriving industry in the Barnegat and Tuckerton region, with up to 500 tons harvested annually. The blacksmith craft, from Forked River to Tuckerton, manufactured mud-boots for horses to keep them from miring in the marsh during harvesting periods. The industry started to decline in the 1900's, with 7,500 tons of salt hay being produced in Ocean County in 1910, and only 1,300 tons in 1930. In 1965, only three or four farmers continued to harvest salt hay in Barnegat (Weiss, 1965).

H. Eelgrass Harvesting

Early settlers were adept at taking advantage of nature's bounty, and by the turn of the 20th Century, eelgrass (*Zostera marina*) was so plentiful in Barnegat Bay that its harvesting was one of the principal occupations of the inhabitants of Long Beach Island. Eelgrass had many industrial uses. For instance, funeral directors utilized eelgrass to line coffins because it is bugproof and fire resistant. Steamship companies and prisons used it for mattresses. The auto industry employed it for upholstery in Model T Fords. The common method of harvesting was by wagons along the bayfront or by scow from the bay islands. The eelgrass was washed to remove the salt; it was then dried, pressed, and packed into bales for shipment to cities. The gathering of eelgrass continued until 1929, when a blight occurred, causing eelgrass to largely disappear from the bay (McMahon, 1973). The importance of eelgrass as a habitat for larval and juvenile finfish and invertebrates is well-known. It supports commercial shellfish and finfish resources, and provides wintering grounds for several thousand waterfowl and other wildlife. Although eelgrass returned to Barnegat Bay in 1950, extending from the Route 72 Bridge at Manahawkin north to Mantoloking, wasting disease was observed again in the bay in 1995 and 1996. It destroyed an estimated 1,000 ac (405 ha) of eelgrass beds (McLain, 1996).

I. Moss Harvesting

Sphagnum moss gathering was once a major industry in southern New Jersey, and is still practiced today. Sphagnum moss was used by the florist industry because of its water retention capabilities. It was also used as a bandage during the Revolutionary War because of its antiseptic qualities. The moss was gathered in the white cedar swamps with a long-toothed rake, or moss dray, and dried in a cleared area called a moss landing. After drying, the moss was pressed into 2-foot bales and tied up for shipping. When the moss was dried, its weight declined from 200 pounds (90 kg) wet to 15 pounds (6.8 kg) dry (Ocean County Historical Society, 1997).

J. Resource Extraction

Minerals have been extracted in Ocean County since the earliest settlements in the 1700's. The region's sedimentary deposits provide sand and gravel in large enough quanitites to be commercially important.

The Cohansey Formation and the Bridgeton and Cape May Formations, where they occur locally, provide many grades of sand and gravel. Sand and gravel mining in Ocean County is a viable economic activity, supplying the construction industry with sand and gravel, the glass industry with silica, and the paint industry with ilmenite. Ilmenite deposits are believed to underlie an extensive area of Ocean County in Lakehurst, Lakewood, and Jackson.

Sand and gravel are broadly grouped as construction grade (used primarily for concrete, asphalt, road base material, water filtration, and road sand) and industrial grade (used for glass and ceramics, foundry molds and cores, sand blasting, and other specialized industrial applications) (Bell et al., 1991). Construction sand and gravel is the second leading mineral commodity produced in New Jersey, after crushed stone. The materials range from fine-grained, high silica sands to coarse sand and gravel found in the different geologic formations (e.g., Tertiary alluvial deposits of the Bridgeton, Pensauken, and Beacon Hill Formations within the coastal plain). The Kirkwood, Cohansey, and Cape May Formations provide smaller quantities of sand and gravel. Industrial grade sand use originated with the commercial glass making industry in Salem County in 1739. All of New Jersey's industrial sand production derives from coastal plain formations, primarily from the Cohansey (Bell et al., 1991).

Ocean County contains many sand pits, some that are abandoned and others that are still operating today. Records compiled by the U.S. Bureau of Mines, the Department of Labor and Industry, Bureau of Mine Safety, Department of Transportation, Bureau of Materials, and the New Jersey Geologic Society Bulletin list the following sand pits for Ocean County (Bell et al., 1991):

• Barnegat Township - Ten sand pits are identified for Barnegat, with five of the locations presently active and the rest abandoned.

• Berkeley Township - Four sand pits are identified for Berkeley, with one listed as active.

• Brick Township - Three locations are listed for Brick, with no definitive dates of operation.

• Dover Township - One location is listed for Dover, indicating that it was active in 1952.

• Eagleswood Township - Three locations are listed for Eagleswood, with two of these in current operation.

• Jackson Township - Thirteen locations are listed for Jackson, with two listed as currently operating.

• Lacey Township - Seven locations are listed for Lacey, with six in current operation.

• Lakewood Township - Four operations are listed for Lakewood, with one in current operation.

• Little Egg Harbor Township - Five locations are listed for Little Egg Harbor, with two listed as currently operating.

• Manchester Township - Eight locations are listed for Manchester, with one location currently operating.

• Plumsted Township - Three locations are listed, with one listed as currently operating.

• South Toms River Boro - One location is listed, with no closure date indicated.

• Stafford Township - Four locations are listed, with none currently operating.

• A total of 56 sand pits have existed in Ocean County, dating from the late 1800's to the present day.

The cost of shipping large amounts of sand and gravel has limited the areas of mining to within 20 to 30 mi (32 to 48 km) of the end use. Because much of the sand mining in Ocean County has been used for construction of roads and development, shipment of sand to local sites has remained feasible. The Department of Labor and Industry has estimated that there were 7,800 ac (3,159 ha) of sand and gravel extraction operations in Ocean County in 1977, based on the number of sand pits registered (Bell et al., 1991). The acreage figures for Ocean County include two operations with greater than 1,000 active areas, and a total 5,100 ac (2,065 ha) of active or abandoned mining sites. Jackson Township, Lacey Township, and Manchester Township each have sand and gravel extraction sites with more than 1,000 ac (405 ha).

It is estimated that an acre of sand and gravel mined to a depth of ~ 3 ft (~ 1m) can produce approximately 6,000 tons of raw material before processing (Pinelands Comprehensive Management Plan, 1980). The extraction process requires total site clearing and topsoil removal over a large area. The environmental impacts from mining occur when pits are excavated below the water table, making the groundwater vulnerable to contamination from surface sources. In the past, excavated sites have been converted to landfills, which exposes the aquifer to contamination from landfill leachate (Pinelands Comprehensive Management Plan, 1980).

K. Hunting

Waterfowl hunting in the Barnegat Bay-Little Egg Harbor estuary has historically been the basis for cultural, social, recreational, and economic endeavors. By the 20th Century, the area had become one of the most famous waterfowl hunting areas in North America (Nichols and Castelli, 1996). When the first people came to the Barnegat Bay thousands of years ago, the great flocks of wild waterfowl darkened the skies in winter and nested in the marshes around the bay in summer. When the bay's headwaters were still brackish, before construction of the Point Pleasant Canal, wild celery grew along the marshes and nearly every species of waterfowl could be found - red heads, canvasback, scaup, black duck, brant, Canada goose, and other forms. From the earliest days, man took to the sedges and streams to hunt. Duck decoys were a native American folk craft dating back to the feathered mud-and-reed decoys of the Lenni-Lenape. The advent of the muzzle-loading, double-barreled shotgun around 1800 increased the popularity of hunting. Sneakboxes and duck blinds were camouflaged with reeds, salt hay, seaweed, tree branches, and other vegetation to hide the hunters, while their decoys lured the flocks within the range of their guns. Sometimes live, tame birds were used with the decoys to attract the flocks. Marsh ice was often baited with corn or other feed. Game was so plentiful that it not only provided food but also initiated the local tradition of guiding recreational gunners to the marshes for sport shooting (Jahn, 1980).

In the 1870's and 1880's, hunting progressed from an activity necessary for sustenance to a pursuit of the masculine ideals of courage and self-sufficiency. The sportsman conquered nature with a gun. A sportsman had to be versatile enough to sail a sneakbox before dawn, to endure miserable weather conditions upon reaching the hunting grounds, to sit in the wet sedge all day in a blind until the ducks descended, and then to shoot accurately enough to be acknowledged as a "crack shot," which was an indication of prowess in nearly everything else as well. The self-imposed hardship of marshland shooting allowed the practitioner to exhibit a sense of discipline to his peers, while braving mosquitoes

in the spring or shivering in freezing cold and dampness when lying in wait for ducks in winter. It was no sport for the weakling, and those that excelled at it could brag to the envy of less successful, less worthy, and less affluent acquaintances. One has only to review the old photographs to recognize that this was a breed of men apart from the ordinary - with the right guns (14 pound, 8-gauge, breech-loaded shotgun made in England, with English leather case), the right clothes (thick woolen socks and India rubber boots with layers and layers of underwear and outerwear, finished off by an oilskin suit the color of sedge), the right accessories (heavy buffalo robe or India rubber army blanket, good whiskey or applejack, plenty of tobacco, a deck of cards, and a good dog or two), and the right amount of money to hire a guide and pay for lodging at inns catering to sportsmen scattered throughout the bay (Lloyd, 1990). In addition to recreational hunting, game fare was in great demand in the cities during the late 1800's, and marketing wildfowl became another important business until the Migrating Bird Act of 1918 banned shipment of game birds. Recreational duck hunting continues today, but it is a highly regulated sport. The sport of hunting declined by the early part of the 20th Century due to laws enacted to regulate the numbers of game that could legally be taken.

L. Bay Fishing and Shellfishing

According to early records, Barnegat Bay was an ideal place for fishing with an abundance of oysters, clams, crabs, and fish (Salter, 1890). The Oyster Creek area had large quantities of oysters. Bay fishing (including fish and shellfish) was the principal occupation of early inhabitants. It has remained an important industry since the days of the earliest settlers, who operated their small boats from Toms River and Tuckerton. Forked River, Barnegat, and Waretown were known as the best of the fishing grounds. Promotional literature in 1889 included the low cost of rental boats and bait as contributors to the well-organized sporting industry along the bay (Allaback, 1995). Large numbers of weakfish, sheepshead, and kingfish were caught on a regular basis. The spring run of herring from the Metedeconk River and Kettle Creek was legendary. The herring were largely smoked and brined for eating, while the balance was used as fertilizer. Seining of perch and pickerel occurred during the winter. A large hole was cut through the ice and other smaller holes were used to pass the line that drew the seine around the fish. In 1878, New Jersey passed its first law to regulate seine fishing in bays (Cunningham, 1958). At the turn of the 20th Century, the perch fishing industry was estimated to have revenues of $200,000 annually. Eels provided another money crop from the bay. When the Point Pleasant Canal was opened in 1926, the introduction of saline waters led to the decline of yellow perch, sunfish, pickerel, and largemouth bass in the bay, while marine fish became more abundant (Colie, 1970)

Oysters were prolific, and natural seeding oyster beds were found at the mouth of the rivers and creeks emptying into saline bays and inlets, the most prolific of these being in Barnegat Bay and Little Egg Harbor. Hundreds of bushels of oysters were gathered annually in Barnegat Bay near the mouths of Cedar Creek, Forked River and Oyster Creek. The beds were located all the way from Goodluck Point to Oyster Creek (Historical and Biographical Atlas of the Jersey Coast, 1878). The results of consumptive harvesting became apparent by 1719, and protective measures were passed by the General Assembly. Non-residents were prohibited from harvesting oysters in New Jersey's inland waters. In February 1775, a new law was enacted for the preservation of the oyster. Burning oyster shells for lime was also an offense, since the discarded oyster shells served as seed beds for new oysters. There was actually a joke in the legislature that all legislation with reference to oysters, clams, and fish had to have originated in Ocean County. Over subsequent years, more legislation was passed to protect the oyster industry from extermination. In 1899, the legislature passed an act "...for the better regulation of the taking, planting, and cultivating of oysters on lands lying under tidal waters..." (Cunningham, 1958).

By 1830, the planting of oysters was occurring in Barnegat Bay; however, it was not successful everywhere and poaching was common. The competition between clammers and oystermen was also a factor in the localized decline of oyster seed beds. In 1880, Barnegat Bay oyster beds extended from the

southern end of the bay to the mouth of Forked River ~10 mi (16 km) to the north (Ford, 1997). In 1899, the Oyster Commissioners of New Jersey conducted a field test in Great Egg Harbor and other inlets, with the following results: oysters planted August 15, 1899 reached an average size of 0.75 in (1.9 cm) in length by 0.5 in (1.3 cm) in width by April 1, 1900. By June 8 of the same year, they were 1.5 in (3.8 cm) in length by 0.75 in (1.9 cm) in width, and by October 6, they reached 3 in (7.6 cm) in length by 1.75 in (4.4 cm) in width. On May 15, 1901, the oysters were 4 in (10.2 cm) in length by 2 in (5.1 cm) in width, and in a "fine marketable condition" (Nelson, 1902). Legislation was later passed which made it obligatory for oystermen to cull the catch and throw the old shells and refuse overboard at once. Clean shells, stones, sticks or other substances are needed for the attachment and growth of young oysters. The settlement surface must be clean and free of slime and mud.

New Jersey passed broad shellfish legislation in 1846 entitled "An Act for the Preservation of Clams and Oysters." The peak of the New Jersey oyster industry was from ca 1870 to 1930. In 1896, there were ~5,000 ac (2025 ha) of productive oyster grounds in New Jersey waters. Tuckerton had 528 ac (214 ha) of oyster grounds, and Barnegat 296 ac (120 ha). Reports of the New Jersey Bureau of Shellfisheries between 1902 and 1905 made frequent reference to conflicts between quahogers and oystermen, and between oystermen who wanted all areas open to public harvest and planters who wanted to lease acreage for private cultivation. Conflicts still exist because many clammers do not want public areas to be leased for private culture (Ford, 1997).

In 1919, a major storm drastically altered Beach Haven Inlet, increasing salinity in Little Egg Harbor and providing the conditions favorable for the proliferation of oyster predators. Eventually the oysters died out, but the quahogs flourished in the more saline conditions. The Point Pleasant Canal was considered to be another factor in the demise of the oyster fishery, through the introduction of salt water to the head of the bay, altered circulation patterns, and the spread of predators. The Barnegat Bay-Little Egg Harbor oyster fishery eventually crashed due to changes in the salinity regime, overharvesting, and disease. By the 1950's, Barnegat Bay produced only a few thousand bushels of oysters a year, and landings in later years have been insignificant (Ford, 1997).

The northern quahog (*Mercenaria mercenaria*), also known as the hard clam, is the most important commercial molluscan species found in the estuary. It requires higher salinity waters than oysters. Salt water enters Barnegat Bay at the head of the bay through the Point Pleasant Canal, at Barnegat Inlet to the east, and at Little Egg Inlet to the south. Freshwater flows to the bay from the Metedeconk River, Toms River, and surface waters of the Pinelands, which also provide groundwater seepage. Salinity ranges from 12-32o /oo, with a mean of about 25o/oo in the center of the bay (Ford, 1997). Eelgrass, *Zostera marina*, is also found in Barnegat Bay and once provided important nursery areas for the bay scallop, *Argopecten irradians*.

Quahogs are found in the coastal bays of New Jersey where salinity ranges are high enough to support them (Kennish et al., 1984). Clamming has existed since pre-historic times, and was an occupation of the early settlers and later local people. It became an important commercial crop ca 1930, with total landings approaching those of oysters. The area just inside of Barnegat Inlet produced great numbers of quahogs, which were sold to boats from New York. Quahogs are harvested by three principal methods: (1) bull raking; (2) treading; and (3) tonging. As of 1997, about 1,575 fishermen were licensed to harvest quahogs commercially in New Jersey.

As northern waters were condemned for clam harvesting, clammers turned to the southern bay waters. Eventually the state instituted a relay program in 1970 where quahogs were relocated to southern waters from condemned northern waters. State regulations governing sewage discharge to the bay and the decision to shift sewage treatment plant outfalls from the back bays to the ocean have significantly improved the quality of coastal waters.

M. Salt Works

Salt was a necessity to the colonial settlers. Before the Revolutionary War, salt was imported, but the war eliminated this trade. Salt works were numerous in the Barnegat Bay area during the Revolutionary War. They were located at Barnegat, Waretown, Forked River, and Toms River (Salter, 1890). Salt works were created by searching out places in the salt-meadows devoid of grass, or where blue-green algae forms dense mats. These shallow depressions, called pannes, exist just above the low marsh. They are subject to extreme temperature and salinity levels. Salinity may exceed 40 parts per thousand (Tiner, 1985). Wells dug in a panne produced the saltiest water, which was placed in large boilers with arched ovens underneath. After the water was boiled, the residue of salt was poured into baskets and drained. Another method of salt production involved digging ditches and allowing the salt water to be reduced to brine. Salt was important for food preservation and flavoring, and for production of gunpowder. Nearly all of these salt works were destroyed by the British during the Revolutionary War (Beck, 1962).

N. Forest Fires

Forest fires are mentioned in the early historical narratives as too numerous to fully document. Large areas of forest were continually swept over, and timber losses repeatedly amounted to tens of thousands of dollars. Around 1840, a fire broke out between Oyster Creek and Forked River and spread so fast that the lives of firefighters were threatened. One man was overtaken by the flames and burned to death. "With a high wind, the roar of the fire in the woods, the flames leaping from tree-top to tree-top and running along the dried leaves and bushes on the ground make an appalling scene never to be forgotten...the appearance of the sky is appalling" (Salter, 1890). Fire was as responsible for shaping the landscape as any of the extractive colonial industries, but unlike the industries that have come and gone, fire remains a threat into modern times.

In the 1960's, there were about four hundred forest fires in the Pinelands every year, and fifteen or twenty of them covered more than 100 ac (40 ha). "Fire in the pines is never spontaneous, and lightning sets only about one percent. A remarkably common cause of fire in the pines is arson" (McPhee, 1967). Vegetation returns to an area quite rapidly after a fire. There has been so much fire in the pines for so many centuries that the vegetation has developed considerable resiliency. Many woody species in the pines sprout shoots from their roots after a fire. It is a generally accepted theory that if fire was eliminated from the pines, the forests would eventually be dominated by black oaks, white oaks, chestnut oaks, scarlet oaks, hickories, and red maple. Fire has played an important role in the development of the pines since post-Wisconsin time (McPhee, 1967). Several fires that occurred in the 1990's, impacted more than 1,000 ac (400 ha) of forest.

VI. CHANGES THROUGH THE CENTURIES

In the 17th Century, there was still little impact to the environment from human habitation. By the end of the 17th Century, lumbering activities began to change the landscape. At the beginning of the 18th Century, people were sparsely settled in hamlets along the western side of the bay, but these settlements were beginning to grow as a result of lumbering and ship building. The people in the southern portion of the bay had been leading self-sufficient lives for more than a century, while settlements to the north,

such as Lovelandtown, were just becoming established. The tourist industry that started to flourish at the end of the 19th Century was responsible for the continued growth of Ocean County, and it continues up to the present day. A few highlights are provided from local historical records on early lifestyles, along with discussions of some of the 20th Century environmental impacts.

A. 17th Century

Robert Juet, aboard Henry Hudson's ship the Half Moon, provided an early description of Barnegat Bay. According to Juet's journal entry of September 2, 1609, the Half Moon was sailing northerward along the coast from Delaware Bay. Juet noted the following:

> "The course along the land we found to be N.E. by N. from the land which we first had sight of until we came to a great lake of water as we could judge it to be (Barnegat Bay), being drowned land which made it rise like islands, was in length ten leagues. The mouth of the lake has many shoals and the sea breaks upon them as it is cast out of the mouth of it (Barnegat Inlet). And from that lake or bay the land lays N. by E. and we had a great stream out of the bay, and from thence our soundings were ten fathoms two leagues from land. At five o'clock we anchored in eight fathoms water, wind light. Far to the northward we saw high hills" (Salter, 1890).

Eighty-nine years after that voyage, the first settler purchased property in 1698 in what was to become Tuckerton. "Tuckerton was a 17th Century bastion of civilization in a near wilderness north of the Mullica River. It had fertile uplands and gigantic salt meadows as nurseries for fish and innumerable wild fowl" (Ocean County Historical Society, 1997). Thus, the lower or southern portion of the Barnegat Bay area was settled before the head of the bay, which was settled in 1837.

For most of the 17th Century, the land of Ocean County remained as it had been for thousands of years. Prehistoric people continued to live as they had for countless generations, and the Europeans settled in areas adjacent to Philadelphia and New York. In 1614, Captain Cornelius Mey named the inlet "Barnedegat" Inlet, so-called because of the foaming breakers of its shoals, or "breakers inlet" (Salter, 1890). A few temporary whaling outposts sprang up on the beaches above and below Barnegat Inlet, as it was later called through common usage. One was Harvey's Whaling Quarters located at what is now Harvey Cedars. The whalers were the first recorded people on Long Beach Island. Whaling continued to be practiced by island inhabitants as late as 1820 (McMahon, 1973). The mainland continued to be sparsely inhabited. Settlers began to branch out from the main population centers by the end of the 17th Century. The vast expanse of pine forests in southern New Jersey presented a tremendous natural barrier for colonists migrating between the Delaware River and the Atlantic Ocean. The forests were underlain with dirty white sand (sugar sand) that bogged down wagons. Only an occasional settler lived in the coastal lands before 1700 (Cunningham, 1966).

It did not take long after the first exploratory voyages in the 1600's for men to realize that the vast stretches of woodlands beyond Barnegat Bay, accessible by rivers and streams, contained natural resources that could build a nation. The first sawmill in Ocean County was established in 1699 at

Tuckerton Mill Creek. A second mill in Ocean County was located on the North Branch of the Forked River in 1700. Other mills were established throughout the Pinelands during this early period. The cutting of lumber was so pervasive that, the first regulations restricting timber cutting were passed by the New Jersey General Assembly by the early 1700's (Mounier, 1984). This is an astonishing statistic considering the vastness of the forests, and one realizes that all the trees were cut by hand. This clear-cutting eventually depleted the mineral nutrients in the excessively-drained sandy soils, further limiting vegetative diversity in the regrown forests (Hartzog, 1981).

B. 18th Century

"In the early 1700's, when whalers, smugglers and pirates sailed the waters off these shores, Barnegat was the common name for the sparsely settled beach and mainland north of Barnegat Inlet up to the Metedeconk River" (Jahn, 1980). Squan Beach is described as "... a peninsula, which extends from the Manasquan River to the former site of Cranberry Inlet. It lies nearly its whole length between the upper part of Barnegat Bay and the Atlantic Ocean. It nowhere extends a half mile in width, and the distance named for its length is about 12 miles." Island Beach is described as "...that portion of the peninsula reaching from the site of Cranberry Inlet to Barnegat Inlet, about 12 miles" (Historical and Biographical Atlas of the Jersey Coast, 1878). Cranberry Inlet, opposite Toms River at present-day Chadwick Beach, was 1,550 ft (472 m) wide and 15 ft (4.6 m) deep, allowing passage for the sloops and schooners that sailed the coast during the Revolutionary War. Herring Inlet, also called Metedeconk River Inlet, had existed earlier in the century at the head of the bay near the Metedeconk River, at a place called High Hill Point. Some locals said that this area contained the tallest sand dunes on the coast (Jahn, 1980). For a time during the early 1700's, Herring Inlet enabled Brick to serve as a port for ocean-going ships. In the mid-1700's, the same storm that closed Herring Inlet also opened Cranberry Inlet, which played an important role in the early part of Ocean County's history (Oxenford, 1992). Kettle Creek Inlet also existed for a short period of time. It was located at the dividing line between Dover and Brick Townships, north of Normandy Beach and opposite Kettle Creek. It supposedly derived its name from the kettles used to extract whale oil on the beach near the small inlet (Miller, 1992).

During the Revolutionary War, only one inlet provided access to Little Egg Harbor, between Holgate and Tucker's Island. This inlet was almost 2 mi (3.2 km) wide and deep enough for sloops and schooners to access Tuckerton. This inlet was used to avoid the British fleet at Philadelphia and New York, allowing the colonists to avoid paying import duties on rum and molasses from the West Indies. It began to sand up in the 1790's and became nearly impassable. On a winter night in 1800, a northeaster cut a new inlet along the creek that separated Tucker's Island from Little Beach, to the south. Within a year, the new inlet was as wide and deep as the previous one, and it would keep the name of New Inlet for about a hundred years until it officially became Little Egg Harbor Inlet. The old inlet, 3 mi (4.8 km) to the north and completely filled in, was called "Old Inlet" (Lloyd, 1990). Thus, the changing nature of the coastline is amply illustrated by the opening and closing of inlets along the shore over the centuries.

C. 19th Century

1. Lower (Southern) Bay Lifestyles - Toms River to Tuckerton

In the last half of the 19th Century, after the failure of the iron and lumber industries, the people in the southern portion of Ocean County were leading self-sufficient lives. The village of Barnegat was an

early example of this self-sufficient lifestyle. The people farmed, made their own clothes from homespun fabrics and woven wool from their sheep, harvested salt hay for their livestock, made molasses from the sugar cane, and built boats to harvest fish and shellfish (Beck, 1962). Early in the spring they went into the lowland forests and gathered sphagnum moss. In June and July, wild blueberries were harvested and sold. Cranberries followed blueberries in the harvesting cycle. At first, the wild cranberries were harvested, but in the 1860's to the 1870's, they were transplanted to the cleared and excavated bogs where bog iron had previously been mined, or where Atlantic white cedar had been harvested. When winter came, the cycle moved to cordwood and charcoal. In those days, charcoal was made in Barnegat, close by the shore, as well as in the interior woodlands (Beck, 1962). In the 1850's, 50 schooners made regular runs with charcoal from the Pine Barrens to New York. Four-mule teams hauled charcoal over the sand roads to Philadelphia. The woods were full of colliers specializing in charcoal for sale to the city markets. The sphagnum, wild blueberry, wild cranberry, wood, and charcoal cycle were supplemented by hunting, fishing, and shellfishing. Holly, laurel, mistletoe, ground pine, pine cones, greenbriar, inkberry, plume grass, and boughs of pitch pine were gathered in December and sent to New York for Christmas decorations. Plants were collected for medicinal purposes, and flowers were sent to landscape gardeners (McPhee, 1967). The collapse of the most important colonial industries during the mid-to-late 1800's did not prevent people from continuing to live in Ocean County, although some people did leave the area when the industries disappeared. Other occupations continued, such as basket-making, because baskets were needed to harvest seasonal resources, as well as to carry and store things. Flour-making was pursued at the grist mills that were associated with the sawmill settlements, including the one built by Mordecia Andrews at the mouth of Tuckerton Creek in 1704. Brick-making and terra-cotta manufacturing were located in Pasadena. Glass-making was introduced to Barnegat in 1894 at the Atlantic Glass Company, and it remained a business until 1914.

Boating grew into a popular recreational pursuit. The Beach Haven Yacht Club was formed in 1882, 11 years after the Toms River Yacht Club. Little Egg Harbor was swarming with sailboats in the 1870's and 1880's. The most popular boat was the shallow-draft catboat. At the first sign of a breeze, the keenly competitive charter boat captains would organize a race. By the 1890's the really expensive catboats - Herreshoffs built at the boatworks in Bristol, Rhode Island - so out-classed the locally-built catboats that by 1903 all catboat races ended at the Beach Haven Yacht Club (Lloyd, 1990).

2. Upper Bay (Northern) Lifestyles - Bay Head to Toms River

The people in the north settled along the shores of the bay later than their southern counterparts. Settlers migrated to the land adjoining the bay, or "head of the bay" as it was known, from Point Pleasant around 1837. The hamlet near the shores of the Barnegat Bay was called Lovelandtown, after the original settlers. There were several creeks located along this part of the bay, the most notable being Herberts Creek, which later became the Point Pleasant Canal connecting the Manasquan River with Barnegat Bay. Ditches crossed an area of high knolls surrounded by low meadows that led down to the head of Barnegat Bay. Ponds were full of lillies, toads, and turtles. In the spring and summer, the meadows near the settlement "...were dotted with hollyhocks, larkspur, daisies and many other flowers that flourished in fresh water. White cedars formerly clustered in the meadows. Blueberries, blackberries, cranberries, beach plums, cherry and persimmon trees grew in abundance" (Miller, 1993). A person could stand on a high hill on Loveland Dock Road (now Bay Avenue on the Bay Head/Point Pleasant border) and have a clear view of the ocean about a mile away. It is possible that this was one of the hills that Juet recorded when the Half Moon anchored offshore in 1609. Indian artifacts were found here as the settlers cleared the land for their houses. A 10,000-year-old ceremonial blade was found on Meadow Avenue, Lovelandtown, in 1891 (Miller, 1993).

This area produced many baymen because of its location near the water. They were boatbuilders, tradesmen, captains, guides for fishing and gunning clubs, decoy carvers, and artists. Paintings depicting the early landscapes in this area are today the prized possessions of some local collectors. These baymen built and sailed catboats and established a long tradition of building boats that were eventually recognized worldwide for their beauty, craftsmanship, and seaworthiness. The Barnegat Bay catboat, introduced to Barnegat Bay in 1855, was preferred by most of the captains and early sailors, and was built in the local boat yards. The sneakbox was widely used in the area for duck hunting (Miller, 1993). Sailing was part of the business of being a guide, but sailing was also recreation. When they were not working as guides, the captains sailed their catboats to Atlantic City for outings with the entire family on-board. The lifestyle of the early settlers was entirely dependent on the bay and its ecosystem, and the tourists that came to the area to enjoy its natural resources. "Barnegat Bay was the playground and workplace of baymen and sportsmen alike" (Miller, 1993).

During the Civil War, the federal blockade of southern ports slowed commercial shipping activity along the Atlantic coast and prevented local captains from sailing south for trade. Racing catboats became a way "to fill in the time," and the exciting weekend races eased the doldrums caused by the distant war. Enthusiastic observers waited on the shore for the sound of gunfire signaling the start of the race. The first sailboat regatta was held in 1864 on the Toms River. The Challenge Cup, the oldest racing trophy in the country, was introduced in 1870 at the first race of the Toms River Yacht Club. The first sneakbox race was held in the 1880's and spurred the formation of yacht clubs at Mantoloking, Bay Head, Lavallette, and Seaside Park. Soon sneakbox sailing and racing were common around the bay.

The families expanded and homesteads were built. "Every property had an outhouse, chicken pens, a coal bin, and, in some cases, hog pens. Pigs were slaughtered in the fall and salted down for winter use. Every house had a pump inside, as well as coal and a wood range. All of the homes had wells where buckets were lowered to bring up a pail of fresh water. People lived on fish and clams, migrating waterfowl, the fruits of the cranberry bogs, and the animals and poultry kept at every home" (Miller, 1993). The men made their living by serving as guides on fishing and hunting trips. Barnegat Bay is a part of the Atlantic flyway, and ducks, geese, red heads, black ducks, broadbills, and mergansers were abundant. Other birds "...once fed on the wild celery which grew in the formerly brackish waters of the bay"... until saline water from the Point Pleasant Canal destroyed these feeding grounds during the first half of the 20th Century. Hunting was a means of survival for the baymen, but it also became a great sport. In September, hunters hired the boat captains to take them "down bay" to the gunning clubs and the duck blinds located on the sedge islands in the bay (Miller 1993). The only lodging available to hunters were the sportsmen's inns built in the early 1800's: Jacob Herbert's Tavern in Mantoloking; Bill Chadwick's House in Chadwick Beach; Michael Ortley's House in Ortley Beach; John Reed's Hotel in Island Beach (which was blown down by a hurricane in the late 1870's) (Jahn, 1980), Britton Cook Tavern on Island Beach, the Herring House at the inlet on Long Beach Island (later called the Ashley House), the Samuel Perrine Hotel at Harvey Cedars, the Thomas Bond Hotel at Beach Haven, and the Tuckers Hotel built in 1765 on Tuckers Island (Miller, 1994).

Decoy carving originated from the necessity to entice flocks of birds to gunning grounds. It later became an art form and a Barnegat Bay tradition. Barnegat Bay baymen began carving decoys more than 150 years ago. Most of the local duck, goose, and brant decoys "... were designed to float on the surface of the water. A lead or iron weight was built into the bottom of the decoy to stabilize its flotation. Decoys for black ducks, pintails, and mallards were made to stick up in the marsh meadows" (Miller, 1993).

3. Growth of Recreational Tourism

Tucker's Beach on Tucker's Island, located off of the southern tip of Long Beach Island, is considered by historians to be the earliest resort in Ocean County. Reuben Tucker's house was the first and oldest house on the coast that was opened for lodging and entertainment for recreational visitors. This property was acquired sometime between 1725 and 1765. Fishermen and waterfowl hunters from Philadelphia took stagecoaches to Tuckerton and sailed to Tucker's Island. Tucker's Island was a 5 mi (8 km) long island separated from the mainland by continual wave action in an area known as "the slough" (Lloyd, 1990). The island contained trees, ponds, a lighthouse, a Coast Guard station, a school, and two hotels. It was a popular resort up until 1920 when a violent winter storm created a new inlet north of the lighthouse and threatened homes, forcing evacuation of the island for the next seven years. The lighthouse fell into the sea on October 12, 1927. The island gradually submerged and disappeared completely under the ocean in 1938 (Allaback, 1995). Tucker's Island remained submerged until a small portion of the island reappeared in 1995. A grassy sandbar is now established there (Miller, 1998).

The early growth of the southern end of Long Beach Island can be traced to its proximity to Tuckerton directly across the bay. Hunters preferred Little Egg Harbor to Barnegat Bay because of its numerous small islands ideal for waterfowl habitation. The northern end of the barrier island was too far from Tuckerton to develop, but a small boarding hotel for gunners was established at Barnegat Inlet in the early 1820's (Lloyd, 1986).

Railroads reached the beaches in 1870, and the summer resort industry was born. Point Pleasant Beach was laid out in 1870, and in that same year, Beach Haven was founded by the Society of Friends. While Seaside Park grew from a Baptist meeting ground in 1876, Island Heights developed from a Methodist campground in 1878. Lakewood became a resort by 1879 (McMahon, 1973). Hotels began to appear on the mainland from Point Pleasant Beach and Bay Head to the barrier island that stretched to Tuckers Beach. These hotels became lodging for the wildfowl hunters and fishermen.

Recreational fishing was responsible for the growth of Beach Haven. As in the case of the northern portion of the bay where visitors arrived by train from New York and northern New Jersey, the railroad brought vacationing tourists from southern New Jersey and Philadelphia (Sheppard, 1997). Guiding the visitors to fishing grounds became a means of local employment, and local catboats ferried fishing parties from the barrier island in search of the best fishing grounds. With growing numbers of visitors, the tourism industry began to flourish. Most travelers from Philadelphia and South Jersey sought places to vacation for longer periods. Soon spacious hotels at Beach Haven, capable of housing hundreds of visitors, replaced the formerly limited accommodations. "By the 1890's, more than 1,000 hotel rooms and scores of private cottages existed for visitors" (Sheppard, 1996).

D. 20th Century

By the 20th Century, some human activities began to affect the bay's ecosystem. As in the case of the inlets which allowed easy access to the mainland west of Barnegat Bay in colonial times, the railroads of the 19th Century and the modern highways of the 20th Century had the same kind of effect on development and growth in Ocean County. These transportation facilities allowed easy access to the shore resorts from metropolitan centers, and enabled people to establish year-round residences.

While more and more people traveled to the shore and remained throughout the summer months, mosquitoes became a threat to the quality of human life and health. In 1908, the State of New Jersey ordered a survey of the meadows from Toms River to Bay Head. Ditching and draining, the elimination of sheltering stands of bayberry, better drainage, and the use of insecticides dramatically mitigated

mosquito problems at the shore resorts. According to one local historian (Colie, 1970), the decline of mosquitoes had unexpected ecological impacts on the dragonfly, or mosquito hawk, and the damselfly, or darning needle. Both of these insects fed voraciously on mosquitos, flies, and other insects. They, in turn, were preyed upon by martins, frogs, and toads. Subsequent to ditching of the salt meadows in 1908, local residents began to notice a decline in the numbers of dragon and damselflies, and toads. Since the toads were the hog-nosed snake's preferred prey, the lower toad population led to the decline and eventual elimination of the hog-nosed snake, or puff-adder, which was common in the dunes between Bay Head and Chadwick Beach. Fish hawks, or ospreys, were constantly seen flying over the ocean in the early part of the 20th Century, and their nests were common in dead trees on the mainland. About this time, local observers noticed that suitable nesting and feeding grounds were declining for ducks, brant, and shorebirds (Colie, 1970).

1. Early 20th Century Hunting

When the first settlers arrived, there were an estimated 500 million ducks making annual flights over Barnegat Bay. By 1934, that number had dropped to 30 million (Oxenford, 1992). It became apparent by the beginning of the 20th Century that the uncontrolled shooting of game from September through May would eventually eliminate all of the waterfowl and ruin the sport. In April 1901, a law was passed that restricted shooting to one hour before sunrise and one hour after sunset. All boats, blinds, and sinkboxes had to be firmly secured to land and could not drift. Game birds continued to be supplied to the city markets, but the 20th Century market hunters advanced the sport of hunting to the business of wholesale slaughter. The waterfowl flocks of Barnegat Bay were decimated by the early part of the 20th Century, until game limits and restrictions on hunting were finally imposed.

By the 1930's, most of the old gun clubs began to decline due to shorter seasons, bag limits, and prohibitive game laws. Between the indiscriminate number of birds killed, the great droughts of the northern prairies, and the eelgrass blight of 1929-1931, the disappearance of the birds was very noticeable to local residents all over Barnegat Bay. The brandt, which fed on large quantities of eelgrass, all but vanished. In addition, the draining of the marshes to eliminate the mosquitoes affected the diet of the birds (Lloyd, 1992).

Hunting has had an important historical impact on the Barnegat Bay watershed. It drew the aboriginal people, providing a dependable food source, and it later sustained other inhabitants and settlers. It then became a recreational activity that helped to shape the seasonal or tourist industry. Hunting was, and to a limited degree remains, important to the lifestyles of the baymen and recreational visitors alike - for both business and social reasons. Hunting activity leaves historic evidence in the form of hunting or gunning clubs, which have existed since the 1700's. The most famous hunting site of the 20th Century is the Albert Brothers Cabin in Waretown. This site dates from the 1920's (Sinton, 1981).

2. 20th Century Fishing and Shellfishing

Bay fishing was popular throughout the 20th Century. In the last half of the 19th Century, the west side of the upper reaches of the bay supported sunfish and yellow perch, which were found in the deep holes. Kettle and Beaver Dam Creeks were excellent for pickerel, and the Metedeconk River was prime water for pickerel and largemouth bass. The freshwater species in this area had disappeared by the early part of the 20th Century due to saline water input through the Point Pleasant (Colie, 1970).

The lower bay remained excellent for weakfish and striped bass. On Long Beach Island in the 1920's, the Barnegat docks contained the first cooperative fishery in America. Commercial fishing centered around five fisheries in 1936: Barnegat City Fishery, Surf City Fishery, Ship Bottom Pound Fisheries, Crest Fishery, and Beach Haven Fish Company (Allaback, 1995). These particular fisheries were no longer operating by the late 20th Century, and the buildings that housed them have since been converted to commercial shops. However, commercial fishing continued as an active industry on Long Beach Island.

Four fisheries were located in South Seaside Park in the early 20th Century: Seaside Park, Hiering, Spring Lake, and United. Often 20 truckloads of fish per day were sent to the mainland (Allaback, 1995). The Point Pleasant Fishery was founded in 1936 by Axel Carlson, who had earlier worked for the Seaside Fisheries (Woolley, 1995). Point Pleasant continues to have an active commercial fishing fleet to this day.

Nearly all 19th Century fishing was in the bays and rivers. Marine motors changed the focus of fishing in the 20th Century, as party boats, embracing a wide range of craft, transported fishermen out to sea. Striped bass migrate northward along the coast in April, and then in October or November, they return to their winter homes and migrate down the coast. The head boats fish for porgy, sea bass, fluke, ling, cod, blackfish, mackerel and weakfish. The charter boats fish for bluefish, striped bass, mackerel, fluke, tuna, and albacore. Fishermen on the bay fish for weakfish, stripers, bluefish or fluke. Many fishermen also fish from banks, docks, jetties, and the surf. Sport fishing continues to be a major industry, with a tremendous investment being made in docks, boats, and facilities to house and feed transient fishermen. All of these elements provide a vast economic benefit to the Barnegat Bay area.

Sports fishermen and commercial fishermen have been clashing for nearly a century over the amount of their fish and shellfish harvest. Dwindling fish stocks have largely fueled this conflict and have led to the enactment of federal and state regulations that limit the catch of marine fish for both recreational and commercial fisherman alike.

The once thriving oyster industry in Barnegat Bay and Little Egg Harbor collapsed during the 20th Century. The hard clam (*Mercenaria mercenaria*) industry supported a large clam fishery throughout the 1950's and 1960's, but now appears to be declining. Serious management actions are needed if this industry is to survive and thrive, but basic information is lacking. In addition to possible diminishing stocks, some areas producing clams yield non-marketable product due to the discoloration of the clam meats. The last survey of Barnegat Bay hard clam stocks was in the mid-1980's (Kraeuter et al., 1996).

3. Point Pleasant Canal

Herberts Creek was located at the head of the bay and stretched almost to Point Pleasant. It was a freshwater creek, probably fed by groundwater much the same as the headwaters of Twilight Lake, a few miles to the east. During the 19th Century, it was a favorite place to take a canoe or rowboat for a tour. As early as 1833, residents began to dream of connecting the Manasquan River with Barnegat Bay at this location. By an act of the legislature on February 1, 1833, authority was given to connect the headwaters of the Barnegat Bay with the Manasquan River and Inlet via a canal (Historical and Biographical Atlas of the Jersey Coast, 1878). The task was easily envisioned, but the reality was more complex. The work was delayed until the early part of the 20th Century.

"In 1903, the Geological Survey employed Mr. C. C. Vermeule to make a survey for a tide waterway

between the river and the bay. The primary purpose was to admit sufficient salt water into upper Barnegat Bay to convert it into oyster grounds; the secondary purpose was to provide a waterway for boats" (Colie, 1970). When the inland waterway was being dredged in 1908, the subject of a canal was again considered, and several routes were studied: one was from the Manasquan River to Beaver Dam Creek, and then down the Metedeconk River to the bay. Because of the length of this route and the associated high cost, it was rejected in favor of the existing canal route. Another route considered was the joining of Twilight Lake in Bay Head with three lakes in Point Pleasant Beach. The land for the present canal entrance along the Manasquan River was donated by the owner of Pine Bluff Inn to the Army Corps of Engineers (Oxenford, 1992). Construction of the Point Pleasant Canal was finally initiated on January 4, 1916. Work had to be stopped during World War I, but it resumed in 1918. Work continued unabated over the next seven years, and on December 15, 1925, dredging broke through at the Manasquan River (Woolley, 1995). The canal was opened to boat traffic in 1926, forever changing the ecosystem at the head of the bay from a freshwater environment to a saline system.

The opening of the canal in 1926 contributed to sand filling in the Manasquan River Inlet. The banks of the canal were not bulkheaded when they were originally excavated, and the movement of the tides through the canal caused the sand banks to erode, eventually closing the inlet. In 1930, a project was initiated to dig an opening through the sand dunes to the ocean at the river's mouth. The inlet was opened on February 10, 1931, aided by a full-moon tide. As work at the inlet progressed, rocks were placed along the sides of the opening to keep the inlet open. Constant maintenance has kept the inlet open, creating the entrance to the Intercoastal Waterway, which starts at the head of Barnegat Bay (Oxenford, 1992). The waterway took eight years to complete.

New Jersey provides 116 mi (186 km) of ocean bypass that eventually goes all the way south to Florida, where the Intercoastal Waterway ends. The section between the Manasquan Inlet and Cape May protects boats from the unpredictable conditions of the ocean. Channel markers function as signs to guide boaters to the channel locations. Every channel is designated with triangles (to starboard) and squares (to port) to guide boaters. The federal government assumed responsibility for dredging and marking the main stem of the waterway in 1953, with the Coast Guard marking the channels and the Army Corps of Engineers dredging them. Both of these functions were state responsibilities from 1915 to 1953. The state is still responsible for the dredging, maintenance, and marking of tributary channels.

4. Boating and Sailing

The racing of sailboats, sneakboxes, and catboats gained in popularity during the 20th Century. The towns at the head of the bay were established by the beginning of the 20th Century, and almost every family had a sailboat that was frequently used. Sailors from the Point Pleasant, Bay Head, and Mantoloking area could be seen on the bay on any summer weekend.

> "One of the favorite routes for shallow draft boats was from Northwest Point to Seaside Park by way of Inner Thorofare, Gap's Cove, Four Foot Ditch, Swan Pond, ...then inside Wild's, Ortley's, Stooling and Meeks' Islands and through Middle Thorofare to where the present bridge ends at Seaside Heights. It was a delightful sail through quiet waters with the banks profusely lined with colorful pink and white marshmallows and with the chattering of the marsh wrens and the song of the meadowlarks to accompany the ripple of the bow wave" (Colie,

1970).

Motorized boating was introduced on Barnegat Bay during the early part of the 20th Century. This activity has affected the water quality of the bay by introducing petroleum by-products into bay waters. Boat building was still a leading industry in Ocean County during World War II, but declined during the last half of the century. Racing continues to be popular, with all types of boats skimming across the bay in formal or informal races.

Population growth experienced during the 20th Century has led to an increase in boat use on Barnegat Bay and the growth of the marina industry. In addition to offering dock space for boats, the marina facilities often provide other services and material such as launching ramps, fuel pumps, repair shops, open or enclosed dry-land boat storage, boat haul-out facilities, rest rooms, retail stores, bait and tackle shops, and parking lots (Chmura and Ross, 1978).

The later half of the 20th Century witnessed the invention of the "jet-ski," or personal watercraft, which allows the user access to shallow waters where larger boats cannot maneuver. Operation of jet skis can impact various habitats such as submerged aquatic vegetation, fish nursery areas, and colonial nesting bird sites (Chin, 1998). The effects of personal watercraft on shallow water habitats of Barneget Bay remain unresolved. Due to the lack of research on this subject, no conclusions have been reached.

5. Chicken Farming

By the start of the 20th Century, the Lakewood and Toms River area had become one of the major poultry-raising areas of the country. In 1909, a Lakewood farm was described as the world's largest, with 35,000 single comb white leghorns (Axel-Lute, 1986). One farm in Lakewood in the 1940's was known to contain 10,000 laying birds and 19,000 baby chicks (Ocean County Principals' Council, 1940). After World War II, the egg industry began to grow, with the establishment of several hundred new poultry farms, many of which were still in operation during the early 1970's. Eggs accounted for more than 90% of farm income. Poultry farming began to decline in Ocean County by the mid-1970's. However, this industry still exists, on a smaller scale, in the Lakewood and Toms River area.

Nuisance algal blooms, such as those experienced in Barnegat Bay during the 1990's, have been attributed to increasing nitrogen levels, which may also be responsible for the decline of eelgrass beds in localized areas. The New Jersey Department of Environmental Protection calculated nonpoint source nitrogen loads of 454 mt/yr to bay waters in the late 1980's (Carter, 1996). Much of the nitrogen loading to the bay is attributed to nonpoint source pollution, such as residential lawn fertilizers and atmospheric deposition. No studies have been conducted on the impact of poultry farms within the Barnegat Bay watershed on groundwater moving toward the bay. Groundwater flow along progressively deeper pathways varies from a few feet per year (in low permeability deposits such as silt/clay) to a few feet per day (in permeable sand and gravel) (Horsley and Witten, Inc., 1996). Since the sources of non-point source pollution are not well known, nitrogen loads produced by chicken farms from the 1940's to the 1970's may have contributed to nitrification in the bay during the 1990's.

6. Modern Tourism

During World War II, gas restrictions reduced automobile travel and the number of tourists visiting Ocean County. Construction of the Garden State Parkway in the mid-1940's crossed 11 counties in New Jersey from Montvale to Cape May City. In early 1952, the New Jersey Highway Authority commenced operation, and opened the Garden State Parkway in 1954. This highway has had a profound effect on Ocean County by opening a direct route to all of New Jersey's shore towns and facilitating commuting to northern New Jersey's urban centers. Before the opening of the Garden State Parkway, there were few boats on the bay. However, by the end of the 1950's there were literally thousands of new boats there - rowboats, sailboats, small craft with inboard or outboard motors, and even larger cruisers (Cunningham, 1958).

During the 19th Century, the railroads enabled resorts to grow from speculative real estate ventures to thriving communities with individual residences and grand hotels and cottages. The railroads made the resort industry possible by providing mass transit with a direct and scenic link from New York and Philadelphia to the mainland and barrier island resorts. "In the opening years of the 20th Century, Long Beach Island was so sparsely settled and had so little identity that out-of-staters confused it with Long Island in New York" (Lloyd, 1990). In those early years, the advent of the automobile and improved transportation routes combined to spur interest in summer homes for city visitors. The causeway over Manahawkin Bay opened on June 20, 1914, and caused a greater celebration than the advent of the railroad in the late 1800's. This improved transportation access lasted 45 years, and enabled the tourist industry to boom. In the mid-20th Century, the bridge to Long Beach Island was built, and the Garden State Parkway was opened (Lloyd, 1986). In 1950, the Thomas A. Mathis Bridge was opened from Dover Township to Seaside Heights. An incredible demand developed for small shore homes. From Mantoloking south to Seaside Park, new cottages were built on the dunes. There was a sudden increase in construction of small lagoon homes on the land side of Barnegat Bay. On the bay side of the Barnegat peninsula, man-made lagoons were observed nearly everywhere (Cunningham, 1958).

First the railroad, then the causeway, and finally the bridge have spurred growth of the resort industry and development of Long Beach Island. The Garden State Parkway has made the resorts of Ocean County readily accessible for people living in northern metropolitan areas. More and more visitors have pursued permanent housing at the shore. In the later half of the 20th Century, there was a surge in the construction of summer residences and year-round homes, as visitors became full-time residents. There are now more permanent residences in Ocean County than seasonal residences, and the year-round population continues to grow.

Through all the growth of the shore area, there has remained one common theme - the desirability for recreational activity associated with the ocean, the bay, and the natural surroundings - including boating, sailing, fishing, hunting, ocean and bay swimming. In the later decades of the 20th Century, other recreational pursuits such as hiking, bird watching, and botanical explorations have led to an interest in "eco-tourism," or tourism directly related to the natural resources of the Barnegat Bay watershed. An increased appreciation of the natural resources associated with the watershed has led to a heightened awareness of the fragility of the ecosystem of the Barnegat Bay-Little Egg Harbor, and has made protection of bay water quality a high priority for the Barnegat Bay Estuary Program.

Literature Cited

Allaback, S. and C. C. Milliken (Ed.). 1995. Resorts and recreation. an historic

theme study of the New Jersey Coastal Heritage Trail Route: the Atlantic shore - Middlesex, Monmouth, Ocean, Burlington, Atlantic, and Cape May Counties. Layout, design, and contributing editor, The Sandy Hook Foundation, Inc. and National Park Service, U.S.D.I., Sandy Hook, New Jersey.

Historical and Biographical Atlas of the Jersey Coast. 1878. Philadelphia, Pennsylvania. Reprinted by the Ocean County Historical Society, 1985. Taylor Publishing Company, Dallas, Texas.

Axel-Lute, P. 1986. Lakewood-in-the-Pines: A History of Lakewood, New Jersey. Paul Axel-Lute, South Orange, New Jersey. 74 pp.

Barnegat Bay Watershed Association. 1998. Watershed Waves. Newsletter of the Barnegat Bay Watershed Association, Inc., Toms River, New Jersey.

Beck, H. C. 1962. The Jersey Midlands. Rutgers University Press, New Brunswick, New Jersey, pp. 179-194.

Bell, C., R. Simmons, and C. Behroozi. 1991. New Jersey Geological Survey. Inventory of active and abandoned sand and gravel mining operations in New Jersey. Pp. 67-71 *in Geological Survey Report GSR 25*. Geological Survey, New Jersey Department of Environmental Protection, Trenton, New Jersey.

Boyd, H. P. 1991. Field Guide to the Pine Barrens of New Jersey. Plexus Publishers, Medford, New Jersey.

Carter, G. P. 1996. Eight characterizing trends in the Barnegat Bay watershed. Pp. 1-16 *in* Flimlin, G. and M. J. Kennish (eds.), *Proceedings of the Barnegat Bay Ecosystem Workshop*. Cooperative Extension of Ocean County, Toms River, New Jersey.

Chin, M. 1998. Issues and Problems Associated with Personal Watercraft in Barnegat Bay. Rutgers Cooperative Extension of Ocean County, Cook College Education Program Paper. Toms River, N.J.

Chmura, G. L and N. W. Ross. 1978. The environmental impacts of marinas and their boats: a literature review with management considerations. Marine Advisory Service, University of Rhode Island, Narragansett, Rhode Island.

Colie, F. R. 1970. An Exercise in Nostalgia: Mantoloking 1880 - 1920. Compton Press Inc., Morristown, New Jersey.

Cunningham, J.T. 1958. The New Jersey Shore. Rutgers University Press, New Brunswick, New Jersey.

Cunningham, J. T. 1966. New Jersey, America's Main Road. Doubleday & Company, Garden City, New York.

Custer, J. 1984. The Paleoecology of the Late Archaic: exchange and adaption. Pennsylvania Archaeologist, 54: 32-47.

Ford, S. E. 1997. History and present status of shellfisheries from Barnegat Bay to Delaware Bay. New Jersey Agricultural Experiment Station, Publication No. D-32405-x-9x, Rutgers University, New Brunswick, New Jersey.

Glosque, L. D. 1975. Berkeley Township: The First 100 Years. Berkeley Township Centennial Commission, Berkeley, New Jersey.

Goddard, I. 1978. Delaware, in Handbook of North American Indians. Vol. 15. B.G. Trigger ed., pp.213-39. Smithsonian Institution, Washington, D.C.

Grubb, R. and Associates, Inc. 1988. Phase I Cultural Resources Survey, Jakes Branch Golf Course, Beachwood Borough, Ocean County, N.J.

Harshberger, J. W. 1916. The Vegetation of the New Jersey Pine Barrens. Christopher Sower Company, Philadelphia (Reprinted by Dover Publications, Inc., New York).

Hartzog, S. 1981. Palynology and late Pleistocene-Holocene environment on the New Jersey Coastal Plain. Pp. 6-14 *in* Sinton, J. W., (ed.), *History, Culture and Archaeology of the New Jersey Pine Barrens: Essays from the Third Annual Pine Barrens Research Conference*. Stockton State College, Pomona, New Jersey.

Horsely and Witten, Inc. 1996. Coastal Protection Program. Management Techniques for Estuaries, Wetlands, and Near Coastal Waters. Office of Wetlands, Oceans and Watersheds, U.S. Environmental Protection Agency, Washington, D.C.

Jahn, R. 1980. Down Barnegat Bay: A Nor'easter Midnight Reader. Beachcomber Press, Mantoloking, New Jersey.

Kennish, M.J., S.J. Vouglitois, D.J. Danila and R. A. Lutz. 1984. Shellfish. Pp. 171-200 *in* Kennish, M. J. and R. A. Lutz (eds.), *Ecology of Barnegat Bay, New Jersey*. Springer-Verlag, New York.

Kraeuter, J. N., J. Dobarro, S. R. Fegley, G. E. Flimlin, Jr., J. Joseph and C. L. MacKensie, Jr. 1996. Rehabilitations of hard clam habitats in Barnegat Bay. Pp. 173-184 *in* Flimlin, G. and M. J. Kennish (eds.), *Proceedings of the Barnegat Bay Ecosystem Workshop*. Cooperative Extension of Ocean County, Toms River, New Jersey.

Kraft, H. C. and R. A. Mounier. 1982. The Archaic Period in New Jersey: ca. 8000 B.C. - 1000 B.C. Pp. 52-102 in Chesler, O., (ed.), *New Jersey's Archaeologic Resources From The Paleo-Indian Period to the Present: A Review of Research Problems and Survey Prorities*. Office of New Jersey Heritage, Trenton, New Jersey.

Lloyd, J. B. 1986. Eighteen Miles of History on Long Beach Island. Down The Shore Publishing and The SandPaper, Inc., Harvey Cedars, New Jersey.

Lloyd, J. B. 1990. Six Miles at Sea: A Pictorial History of Long Beach Island, N.J. Down the Shore Publishing and The SandPaper, Inc., Harvey Cedars, N.J.

McGorty, K. 1981. New Jersey Historic Sites Inventory: Ocean County. Vol. 1. Technical Report, Ocean County Cultural and Heritage Commission, Toms River, New Jersey.

McLain, P. P., and M. McHale. 1996. Barnegat Bay Eelgrass Investigations 1995-1996. Pp. 165-171 *in* Flimlin, G. and M. J. Kennish (eds.), *Proceedings of the Barnegat Bay Ecosystem Workshop*. Cooperative Extension of Ocean County, Toms River, New Jersey.

McMahon, W. 1973. South Jersey Towns. Rutgers University Press, New Brunswick, New Jersey.

McPhee, J. 1967. The Pine Barrens. Farrar, Straus & Giroux, New York.

Methot, J. 1988. Up and Down the Beach. Whip Publishers, Navesink, New Jersey.

Miller, P. 1992. The Township of Dover, 1767-1992. Corrigan, E. J. (ed.). Ocean County Cultural and Heritage Commission, Toms River, New Jersey.

Miller, P. 1993. Lovelandtown, A small Hamlet in Ocean County, New Jersey. Ocean County Cultural and Heritage Commission, Toms River, New Jersey.

Miller, P. 1994. The Great Sedges. Ocean County Cultural and Heritage Commission, Toms River, New Jersey.

Miller, P. 1998. The Disappearing Island: Tucker's Beach. Ocean County Cultural and Heritage Commission, Toms River, New Jersey.

Mounier, R. A. 1984. A Study of Waterpowered Sawmills in the Pine Barrens of New Jersey. Pp. 93-141 *in* Chesler, O. (ed.), *Selected Papers on the Identification, Evaluation, and Protection of Cultural Resources*. Office of New Jersey Heritage, Trenton, New Jersey.

Nelson, W. (Ed.) 1902. The New Jersey Coast in Three Centuries. History of the New Jersey Coast, with Genealogical and Historic-Biograpical Appendix, Volume I. The Lewis Publishing Company, New York.

Nichols, T. C. and P. M. Castelli. 1996. Waterfowl Hunting in Barnegat Bay and Little Egg Harbor Bay, New Jersey. Pp. 309-328 *in* Flimlin, G. and M. J. Kennish (eds.), *Proceedings of the Barnegat Bay Ecosystem Workshop*. Cooperative Extension of Ocean County, Toms River, New Jersey.

Ocean County Board of Chosen Freeholders. 1999. Government Directory, Ocean County. Ocean County Printing and Graphic Arts Department, Toms River, New Jersey.

Ocean County Historical Society. 1997. Downshore From Manahawkin to New Gretna. Arcadia Publishing, Dover, New Hampshire.

Ocean County Planning Board. 1988. Comprehensive Master Plan. Ocean County Planning Board, Toms River, New Jersey.

Ocean County Principals' Council. 1940. Tides of Time. History of Ocean County, Toms River, New Jersey.

Oxenford, D. D. 1992. The People of Ocean County. George Valente, Brick, New Jersey.

Pierce, A. D. 1957. Iron in the Pines. Rutgers University Press, New Brunswick, New Jersey.

Pinelands Commission. 1980. Comprehensive Management Plan for the Pinelands National Reserve (National Parks and Recreation Act, 1978) and Pinelands Area (New Jersey Pinelands Protection Act, 1979). Technical Report, Pinelands Commission, New Lisbon, New Jersey.

Salter, E. 1890. A History of Monmouth and Ocean Counties. E. Gardner & Sons, Publishers, Bayonne, New Jersey.

Schoettle, W. C. 1966. Bay Head 1879 - 1911. Pickering Press, Philadelphia, Pennsylvania.

Sheppard, C. A. 1996. Little Egg Harbor and the birth of the American recreational fishery. Pp. 273-282 *in* Flimlin, G. and M. J. Kennish (eds.), *Proceedings of the Barnegat Bay Ecosystem Workshop*. Cooperative Extension of Ocean County, Toms River, New Jersey.

Sinton, J. W., R. Regensburg, and B. Wilson. 1981. Study Units: Historic Land-Use Patterns and Economic Activities in the Pinelands. Pp. 6-14, 144-145 *in* Sinton, J. W. (ed.), *History, Culture and Archaeology of the New Jersey Pine Barrens: Essays from the Third Annual Pine Barrens Research Conference*. Stockton State College, Pomona, New Jersey.

Stoltman, J. B. And D. N. Baerreis. 1983. The Evolution of Human Ecosystems in the Eastern United States. Pp. 252-268 *in* Wright, H. E., Jr., (ed.), *Late Quaternary Environments of the United States*, Vol. 2. University of Minnesota Press, Minneapolis, Minnesota.

Teal, J. and M. Teal. 1969. Life and Death of the Salt March. Ballantine Books, New York.

Tiner, R. W. 1985. Wetlands of New Jersey. U.S. Fish and Wildlife Service, National Wetlands Inventory, Newton Corner, Massachusetts.

Thurman, M. 1976. Report on Archaeological and Historical Survey of the Proposed Sanitary Sewers in Dover Township. Technical Report, State Historic

Preservation Office, Trenton, New Jersey.

Wacker, P. O. 1979. Human Population of the New Jersey Pine Barrens before 1900. Pp. *in* Forman, R.T.T., Ed., Pine Barrens Ecosystem and Landscape. Academic Press, New York.

Weiss, H. B. and G. M. Weiss. 1965. Some Early Industries of New Jersey (Cedar Mining, Tar, Pitch, Turpentine, Salt Hay). New Jersey Agricultural Society, Trenton, New Jersey.

Williams, L. E. and R. A. Thomas. 1982. The Early/Middle Woodland Period in New Jersey: ca 1000 B.C.-A.D. 1000. Pp. 103-138 Chesler, O. (ed.), New Jersey's Archaeologic Resources from the Paleo-Indian Period to the Present: A Review of Research Problems and Survey Priorities. Office of New Jersey Heritage, Trenton, New Jersey.

Wilson, H. F. 1953. The Jersey Shore: A Social and Economic History of the Counties of Atlantic, Cape May, Monmouth and Ocean, Volume I. Lewis Historical Publishing Company, Inc., New York.

Woolley, J. A. 1995. Images of America - Point Pleasant. Arcadia Publishing, Dover, New Hampshire.

TABLE 1

SELECTED PLACE-NAMES OF LENAPEHOKING (KRAFT, 1985)	
PLACE NAME	**MEANING**
Allamuchy	place of cocoons
Assunpink	rocky place that is watery
Cheesequake	land which has been cleared
Cinnamonson	rocky place of fish
Conshohocken	elegant land
Hackensack	place of sharp ground
Hoboken	tobacco pipe

Kittatinny	big mountain
Lackawanna	sandy creek; sandy river
Manahawkin	where the land slopes
Manasquan	place to gather grass
Manhattan	place that is an island
Monongahela	where the land erodes
Neshanic	two creeks
Pakim Pond	cranberry
Passaic	valley
Tacony	cold river
Watchung	hilly place
Wickatunk	the finishing place

TABLE 2

INVENTORY OF OCEAN COUNTY SAWMILLS (Mounier,1984)			
SAWMILL	**LOCATION**	**STREAM**	**EARLIEST DATE**
1. Collier's Mill	Colliers Mill	Ridgeway Branch	ca. 1816
		Toms River	
2. Ridgeway Sawmill	Ridgeway	Ridgeway Branch	ca. 1751
		Toms River	

3. Giberson's Sawmill	Keswick	Van Horns Brook Toms River	ca. 1829
4. Union Sawmill	Lakehurst	Union Branch Toms River	ca. 1750
5. Dover Furnace Mill	Lakehurst	Union Branch Toms River	ca. 1789
6. Irish/Murray Mill	Van Hiseville Cassville	Toms River	ca. 1839
7. A. Van Hise Sawmill	Cassville	Toms River	ca. 1799
8. Gaskin's Mill	Holmansville	Maple Root Branch Toms River	ca. 1794
9. Hulet's Sawmill	Unknown	Toms River	ca. 1802?
10. Jacobs Sawmill	Beachwood	Jakes Branch Toms River	ca. 1760
11. Randall's Mill	Toms River	Davenport Branch Toms River	ca. 1765
12. Schenck's Mill	Pine Lake Park	North Branch Toms River	ca/ 1765/
13. Dove Mill	Whitesville	Dove Mill Branch Toms River	ca. 1765
14. Francis Mills	Francis Mills	Toms River	ca. 1818
15. R&D Debow Mill	Homeson	Toms River	ca. 1777
16. Success Mills	Colliers Mill	Bordens Mill Branch	ca. 1779
17. Webb's Mill	Bamber	Webb Mill Branch Cedar Creek	Before ca. 1774
18. Bamber Forge Mill	Bamber	Cedar Creek	ca. 1810
19. Double Trouble	Double Trouble	Cedar Creek	ca. 1839

Mill			
20. Falkinburg Sawmill	Forked River	North Branch Forked River	ca. 1700
21. Holmes Mill	Forked River	Forked River	ca. 1795
22. Wells Mills	Brookville	Field Branch Oyster Creek	Before ca. 1849
23. Millville Sawmill	Brookville	Oyster Creek	ca. 1814
24. Waier's Mill	Waretown	Waretown Creek	ca. 1762
25. Shinn Oliphant's Mill	Manahawkin	Mill Creek	ca. 1813
26. James Haywood Sawmill	Unknown	Mill Creek	ca. 1763
27. Littleworth Mill	Manahawkin	Four Mile Branch Mill Creek	ca. 1872
28. Macajah Williams Mill	Cedar Run	Cedar Run	ca. 1763
29. Macajah Willets Mill	Cedar Run	Cedar Run	18th c.
30. Pharo Mill	West Creek	Westecunk Creek	ca. 1758
31. Tuckerton Sawmills (2)	Tuckerton	Mill Branch	Before 1849
32. Gifford's Mill	Nugentown	Giffords Mill Branch	Before 1849
33. Candlewood Sawmill	Fawn Lakes	East Branch Wading River	Before 1834
34. Corlie's Sawmill	Warren Grove	East Branch Wading River	ca. 1765
35. Brindletown Sawmill	Brindletown	South Run Wading River	ca. 1840
36. Gedree Coward's Sawmill	Prospertown	Lahaway Creek Crosswicks Creek	ca. 1762

37. Kimmin's Mill	New Egypt	Crosswicks Creek	ca. 1784

TABLE 3

SETTLEMENTS ASSOCIATED WITH SAWMILLS IN OCEAN COUNTY (Mounier, 1984)		
TOWN	**STREAM**	**EARLIEST DATE**
1. Bamber	Cedar Creek	ca. 1809
2. Cassville	Toms River	ca. 1799
3. Colliers Mills	Toms River	ca. 1816
4. Forked River	Forked River	ca. 1761
5. Keswick Grove	Toms River	ca. 1829
6. Lakehurst	Toms River	ca. 1789
7. Manahawkin	Mill Creek	ca. 1723
8. New Egypt	Crosswicks Creek	ca. 1784
9. Nugentown	Giffords Mill Creek	Before 1849
10. Tuckerton	Tuckerton Mill Creek	ca. 1699
11. Van Hiseville	Toms River	ca. 1812
12. Waretown	Waretown Creek	ca. 1737
13. Warren Grove	Wading River	ca. 1765
14. Webb Mills	Cedar Creek	Before 1774
15. Wells Mills (Brookville)	Oyster Creek	ca. 1823
16. West Creek	Westecunk Creek	ca. 1758
17. Pine Lake Park	Toms River	ca. 1765
18. Brindletown	Croswicks Creek	?

19. Cedar Run	Cedar Run	ca. 1763
20. Prospertown	Crosswicks Creek	ca. 1762
21. Ridgeway	Toms River	ca. 1751

I. INTRODUCTION

Ocean County is located in the outer Atlantic Coastal Plain, the largest of the five physiographic provinces of New Jersey. The topography of the county is gently undulating terrain with low relief. Elevations range from 0 to 225 feet (0 to 675 m). The highest elevations occur in Plumsted Township. A major ridgeline in the western portion of the County separates drainage to the Atlantic Ocean and to Delaware Bay. Although located in Ocean County, Crosswicks/Rancocas Creek and the Mount Misery Brook flow to the Delaware River. The Oswego River flows to the Mullica River. The remaining rivers, creeks, and streams in Ocean County flow to Barnegat Bay. Few areas of steep slope are found in the county, with most slopes being 5% or less. Approximately 5% of the land has slopes of 10% or more (Ocean County Planning Board, 1988).

II. LAND USE WITHIN THE WATERSHED

An accurate characterization of the watershed and estuary requires a description of the existing land uses throughout the geographic areas that drain to the Barnegat Bay-Little Egg Harbor estuary. The term "land use" describes any activity or use which occurs either directly on the land or within structures erected on the land. A study of land-use data and population projections is necessary to estimate future land-use growth needs. Future projections must be made using environmental resource data in order to determine where development can be accommodated without harming environmentally sensitive areas, such as wetlands, stream corridors, groundwater aquifers, and seasonal high water table areas.

Ecological changes in the estuary appear to be closely coupled to temporal changes in land use within the watershed. Barnegat Bay currently exists in a relatively eutrophic state, as evidenced by high phytoplankton and chlorphyll *a* concentrations, and elevated water column turbidity during the summer (Seitzinger and Piling, 1993). High nutrient inputs from residential runoff and farmfields lead to increased algal blooms, elevated water column turbidity, changes in species composition, loss of submerged aquatic vegetation, and oxygen depletion which can decimate aquatic species. Little is known about the source and concentrations of halogenated hydrocarbons, polycyclic aromatic hydrocarbons and trace metals in the estuary. These compounds are toxic to marine and estuarine organisms above threshold concentrations and they can destroy habitats and species. Pathogens, like bacteria and viruses, can threaten human health through ingestion from eating contaminated seafood or from swimming in affected waters (Kennish, 1998). Clean water is essential for continued human health, quality of life and maintenance of species biodiversity.

III. POPULATION AND DEMOGRAPHICS

The Barnegat Bay watershed lies almost entirely within Ocean County. An exception is the portion of southern Monmouth County within the Metedeconk River drainage basin which discharges to the Barnegat Bay. Ocean County is the second largest county in the state, and one of four New Jersey counties which is located along the Atlantic Coast.

Ocean County was officially formed in 1850, and since that time, the county population has steadily increased. Population growth in the county was greatest during the period from 1950 to 1990, with the decade from 1960 to 1970 experiencing a 92.6% increase in numbers (Ocean County Planning Board, 1988). The 1990 population statistics show that the population is concentrated in the northeastern and

central municipalities and along the barrier island. Dover Township leads the county in population with 85,436 residents estimated in 1998, followed by Brick, Lakewood, Manchester, Jackson, Berkeley, Lacey, Point Pleasant, and Little Egg Harbor. Stafford, Barnegat, and Beachwood are the next three most populated areas. The remainder of the county has experienced little or no growth in recent years (Ocean County, Department of Planning, 1998).

Age-restricted adult communities have continued to flourish and are responsible for the growth of the older age groups in the county. The median age in 1990 was 38.5 compared to 35.5 years in 1980. Of a total population of 433,203 people in 1990 (Ocean County Department of Planning, 1998), there were 204,181 males and 229,022 females. Dover and Berkeley led the county in residents over 60 years of age. Dover, Brick, Lakewood, and Jackson had the most residents between ages 40 and 60. Overall population density was 740.93 persons per square mile of land area in 1998. The highest year-round population densities are in Seaside Heights and Point Pleasant, both with over 5,000 residents per square mile of land area. The lowest population densities are in Lacey, Ocean, Plumsted, Eagleswood, Mantoloking, Harvey Cedars, and Barnegat Light, all around or below 1,000 persons per square mile of land area (Ocean County Department of Planning, 1998).

IV. HOUSING

Rapid population growth has resulted in a great increase in Ocean County housing stock. The total units of housing in 1990 were 219,863, up from 173,532 in 1980. Of these units, 168,147 were occupied year-round, and 51,716 were occupied for only part of the year. In 1990, 35,017 units were used seasonally. As in the past, single family detached housing is the largest category, with 113,267 units in 1990. Duplex and multi-family housing totaled 20,496 units, and mobile homes or trailers totaled 4,834 units.

The County Planning Board approved 565 subdivision and site plan applications in 1998 for a total of 4,053 new lots, primarily residential. Most of the new lots were located in Jackson, Lakewood, Dover, and Brick Townships.

Ocean County currently has a total of 79 adult communities with a total of 56,200 units/lots. The largest of these is Crestwood Village (I-VI), with 6,500 units/lots in Manchester Township. The next largest is Holiday City at Berkeley - I and II, with 3,250 units/lots in Berkeley Township. Towns having adult communities are: Barnegat, Berkeley, Brick, Dover, Eagleswood, Jackson, Lacey, Lakewood, Little Egg Harbor, Manchester, Plumsted, Stafford, and Tuckerton.

According to the 1990 Census, Ocean County had 186,404 homes connected to a public water system or private water company. There are a total of 30,495 drilled wells, with the largest number of these in Lacey Township (7,607), Jackson Township (4,959), Berkeley Township (3,375), Dover Township (3,113), Manchester Township (2,450), Stafford Township (2,362), Plumsted Township (1,449), Ocean Township (1,291), Lakewood Township (1,263), and Little Egg Harbor Township (1,026). Berkeley, Dover, Jackson, Lacey, Lakewood, Manchester, Ocean, Plumsted and Stafford Townships all had hundreds of wells each.

In 1990, Ocean County had 193,899 homes connected to public sewer and 25,405 homes with septic tanks or cesspools. An additional 559 homes had other means of sewerage disposal. The following municipalities have the largest number of septic systems in the county: Jackson (6,122), Manchester (5,987), Lakewood (2,885), Berkeley (2,190), Plumsted (2,054), and Stafford (1,766) (Ocean County Department of Planning, 1998).

V. EMPLOYMENT AND INDUSTRY

As of 1997, Ocean County had a potential labor force of 211,299 residents. Of these residents, 199,958 were employed. The 1997 unemployment rate for the county was 5.4%.

The health care industry is the fastest growing employment sector and the top employer in Ocean County. The greatest number of jobs in the county are professional, paraprofessional, and technical occupations (e.g., engineers, accountants, architects, physical scientists, computer analysts, social scientists, lawyers, teachers, librarians, health practitioners, writers, and editors). The next category with the most employees consists of service occupations, followed by administrative support and clerical occupations, including secretarial and general office workers. Marketing and sales comprise the fourth largest category, with the construction industry being the fifth greatest employer (Ocean County Department of Planning, 1998). Residents hold the bulk of the jobs available in the county, with 9,968 employees commuting from Monmouth County and 2,099 commuting from Burlington County. Ocean County residents also commute to Monmouth County (33,142), Middlesex County (9,629), Atlantic County (4,703), and New York (4,454).

Ocean County industrial parks are centrally located near major highways. Rail service is available in Lakewood. The industrial parks are designed to house light manufacturing and warehousing, with some offices and research and development companies. A total of 2,321,600 ft^2 (208,944 m^2) of industrial space was approved in 1997, representing a 39% increase from 1996. The largest amount of industrial space was approved in Dover, Lakewood, and Jackson Townships.

Ocean County has 197 marinas with a total of 15,368 slips. The municipalities having the most marinas are: Brick (25 marinas), Dover (19 marinas), Lacey (18 marinas), and Tuckerton (17 marinas) (Ocean County Department of Planning, 1998).

VI. ECONOMIC AND TOURISM DATA

The Ocean County Planning Board and State Department of Commerce have tabulated the following economic statistics, which provide an idea of how tourism and recreation are related to good water quality:

• In 1997, there were 21,347,305 pounds (960,629 kg) of finfish and 19,724,768 pounds (887,615 kg) of shellfish harvested by vessels with a port landing in Ocean County .

• In 1995, 920,700 travelers rented shore units.

• Barrier island rental unit expenditures were $238 million in 1995.

• Tourist industry jobs totaled 45,000 in 1995.

• Contribution of tourism jobs to the payroll in Ocean County was $631 million in 1995.

• Tourist dollars expended in Ocean County amounted $1.71 billion in 1995.

New Jersey residents are the largest market for Ocean County rentals, along with visitors from New York and Pennsylvania. It is obvious that clean water is a high priority for the continuation of the healthy tourist economy enjoyed by Ocean County, since most of the recreational uses are connected to bay and ocean water quality.

The economic value of New Jersey's natural resources exceeds that of Maryland, a much larger Mid-Atlantic State (Savits, undated). This is evident from the data provided below:

Economic Value of Resources	Maryland	New Jersey
Wildlife Associated Recreation	$1.1 billion	$3.1 billion
Dockside Value of Commercial Fish Landed	$64.3 million	$97.9 million
Economic Contribution of Sportfishing	$475.3 million	$1.0 billion
Ecosystem Value of Wetlands Remaining	$2.6 billion	$5.5 billion

VII. PLANNING ACTIVITIES

Ocean County contains 638.36 mi2 (1,659.7 km2) of total land area, or 408,550 ac (165,462 ha). Of that land, 185,674 ac (75,198 ha), or 45.4%, is located within the jurisdiction of the Pinelands Comprehensive Management Plan. An additional 178,024 ac (72,100), or 43.6%, is regulated by the Coastal Area Facilities Review Act (CAFRA) regulations. The county contains 44.13 mi (70.6 km) of ocean frontage and 197.79 mi (316.5 km) of bay frontage.

A. Federal Planning

1. 208 Water Quality Management Planning

The Federal Water Pollution Control Act Amendments of 1972 produced the Water Quality Management Program (WQMP), more commonly known as the "208" plan. This program promoted regional or "areawide" planning aimed at cleaning up or maintaining water quality to meet the national goal of fishable and swimmable waters by 1983. Section 208 federal grants were available from the U.

S. Environmental Protection Agency to establish water quality management planning in each state.

Under the WQMP, the Ocean County Utilities Authority is the designated management agency for wastewater treatment. Federal and state acts require that all sewerage facility plans are in conformance with the WQMP, and all permits issued under the New Jersey Pollutant Discharge Elimination System must also conform to this plan.

In 1973, three new regional publicly-owned wastewater treatment plants were proposed for Ocean County. These plants eventually supplanted 39 public or privately owned and operated wastewater treatment plants that discharged to surface water bodies, including Barnegat Bay and the Atlantic Ocean. As a result of these actions, bay water quality significantly improved during the past two decades.

2. Clean Water Act:

In 1977, the Clean Water Act was passed by the U. S. Congress to protect, restore and maintain the chemical, physical and biological integrity of the nation's waters. The objective of the act was to attain a level of water quality that provides for the protection and propagation of fish, shellfish and wildlife, and provides for recreation in and on the water by 1983, and to eliminate the discharge of pollutants into navigable waters by 1985. Among the many areas regulated by the Clean Water Act are the effluent limitations for the Section 307 Pollutant Discharge Elimination System Permit (in New Jersey, NJPDES Permits issued by the New Jersey Department of Environmental Protection for surface water and ground water discharges), and Discharge of Dredged or Fill Materials (Section 404 Permits administered by the U. S. Army Corps of Engineers).

3. National Estuary Program

In 1987, Congress established the National Estuary Program, which recognizes the vital importance of the natural ecology of wetlands, tidal marshes and estuaries to fish and wildlife resources. The National Estuary Program seeks to maintain the health and ecological integrity of estuaries. The Barnegat Bay Estuary Program was added to the National Estuary Program in 1995. This program will evaluate the environmental, recreational and commercial needs of the bay and develop recommendations for water quality improvements.

B. State Planning

The State of New Jersey has taken a regulatory approach to the protection of coastal lands and other environmentally sensitive areas. Ocean County is directly affected by these regulations because of its location in the coastal zone, the Pinelands, and the large amount of tidal and freshwater wetlands.

1. Tidelands

Tidal, or coastal wetlands, are defined as low lands subject to tidal action, whose surface is at or below

an elevation of 1 ft (.3 m) above local extreme high water, and which are capable of supporting certain listed types of vegetation (Goldshore, 1979). A significant amount of tidal marshes in Ocean County has been lost to development during the past century. For example, marshes have been converted to lagoon developments, which feature dredged channels for boat traffic and fill for adjacent residential development. Tidal wetlands are considered to be unsuitable for development because the marsh soils are wet, exhibit low bearing capacity, and are subject to seasonal high water table fluctuations, coastal flooding, and storms.

The Wetlands Act of 1970 (N.J.S.A. 13:9A-1 et seq.) was adopted to regulate the construction of structures and the draining, dredging, excavation, or deposition of material in any coastal wetlands. A Tidal Wetlands Permit is required for the cultivation and harvesting of naturally occurring agricultural or horitcultural products. It is also required for minor projects, including excavation of small boat mooring slips, maintenance or repair of bridges, roads, highways or the facilities of any utility or municipality, and construction of catwalks, piers, docks, landings, and observation decks. Permits also regulate the installation of utilities, excavation of boat channels and mooring basins, construction of impoundments, construction of sea walls, diversion of water, use of pesticides, driving a mechanical conveyance on wetlands, and excavation and filling, or the construction of any structure.

Tideland grants, leases and/or licenses are required for the use of state-owned riparian lands. The state ownership of land flowed by the tide originates with the Public Trust Doctrine. New Jersey's title to these lands is as trustee for the public, and their utilization and alienation are subject to limitations imposed by the Public Trust Doctrine.

2. Coastal Area Facility Review Act (CAFRA)

The energy crisis of the early 1970's led to a search for domestic oil and gas reserves. The U. S. Department of the Interior leased extensive offshore tracts on the outer continental shelf for purposes of oil and gas extraction. Potential landside terminal points for transmission and storage of oil and gas were perceived to be detrimental uses in New Jersey's environmentally sensitive coastal area. The Coastal Area Facility Review Act (CAFRA) of 1973 (N.J.S.A. 13:19-1 et seq.), and subsequently the Coastal Zone Management Rules of 1980 (N.J.A.C. 7:7E-1 et seq.), were adopted to regulate development in the coastal area, from the first use within 150 ft (45.7 m) of the mean high water line to all development beyond 500 ft (152 m) from tidal waters within the CAFRA zone. The CAFRA region extends from the confluence of the Cheesequake Creek and Raritan Bay in Middlesex County, along the Atlantic Ocean coastline and Delaware Bay, and northwest along the Delaware River to Pennsville in Salem County. It includes all riparian, tideland, and coastal wetland acreage, encompassing 1,276 mi2 (3,317 km2) of land area; the jurisdiction ranges to 24 mi (38.4 km) inland from the waterline.

In December 1998, the New Jersey Department of Environmental Protection published a Coastal Zone Management Rule proposal to revise Sub-chapter 5 of the rules and replace the existing criteria for determining acceptable development intensities in the Coastal Zone with new criteria based on the State Development and Redevelopment Plan. The new criteria assigns limits on impervious surface coverage and forest preservation based on planning areas and designated centers. The proposed rules are being rewritten because of public comments, and are scheduled for implementation in 1999 or early 2000.

3. Waterfront Development Act

The Waterfront Development Act (N.J.S.A. 12:5-3) was initially enacted in 1914 and amended in 1975. The focus of this statute is the preservation and enhancement of navigable waterways for purposes of marine commerce through regulation of waterfront development. It applies to all the waterfronts of all coastal waterways in the state, with the exception of upland areas regulated by the CAFRA Rules. A Waterfront Development Permit is required for all development activities in the area 100 ft (160 km) above to 500 ft (800 km) below the mean high water line. Developments up to 500 ft (800 km) from the mean high water line in the Coastal Zone, but outside of the CAFRA area, are also regulated by this statute.

4. Freshwater Wetlands Protection Act

Since July of 1988, all development activities in freshwater wetlands need a permit from the New Jersey Department of Environmental Protection (NJDEP) pursuant to the Freshwater Wetlands Protection Act (N.J.S.A. 13:9B-1 et seq.) and the Freshwater Wetlands Protection Act Rules (N.J.A.C. 7:7A-1 et seq.). Prior to 1988, freshwater wetlands were under the jurisdiction of the U.S. Army Corps of Engineers, which still regulates the majority of wetlands throughout the United States. An NJDEP permit is needed prior to: (1) engaging in the removal, excavation, disturbance or dredging of soil, sand, gravel or aggregate material of any kind; (2) the drainage or disturbance of the water level or water table; (3) the dumping, discharging or filling with any materials; (4) the driving of pilings; (5) the placing of obstructions; and (6) and the destruction of plant life which would alter the character of a freshwater wetland or transition area, including the cutting of trees. New Jersey issues statewide general permits for such activities as filling isolated wetlands (SGP-6), minor road crossings (SGP-10), and stormwater outfalls (SGP-11, which requires water quality pre-treatment of runoff prior to discharge to surface waters). Impacts that affect more than 1 ac (.4 ha) must be mitigated by the creation of new wetlands on the project site at a ratio of 2:1. The use of watershed mitigation banks to offset wetlands losses has gained acceptance in New Jersey and other parts of the country.

5. New Jersey Flood Hazard Control Act Rules

The New Jersey Flood Hazard Area Control Act Rules (N.J.A.C. 7:13-1 et seq.) regulate construction within, and proximate to non-tidal flood hazard areas in order to minimize potential on and offsite damage to public or private property, to protect and enhance the public's health and welfare by minimizing the degradation of water quality from point and non-point pollution sources discharging into the flood hazard area, and to protect wildlife and fisheries by preserving and enhancing water quality and the environment associated with the flood hazard area. A stream encroachment permit is required for the construction, installation or alteration of any structure or permanent fill along, in or across, the channel or flood plain of any non-tidal watercourse, or the discharge or alteration of any non-tidal watercourse.

6. Pinelands Comprehensive Management Plan

In 1964, a report from the Pinelands Regional Planning Board proposed a 950 mi2 (2,470 km2) area,

called the Pinelands Region, to be the site of a supersonic jetport and new metropolitan area. The design limits of the new city projected an estimated population of 120,000 to 160,000 residents by 1985, with a maximum population of 250,000, making it the third most populated area in the state. After this proposal failed to gain popular support, the importance of the region was eventually recognized, and the Pinelands were designated as the Pinelands National Reserve under the National Park and Recreation Act of 1978. In the early 1980's, New Jersey implemented the Pinelands Comprehensive Management Plan (CMP) (N.J.A.C. 7:50-1 et seq.) to protect the Pinelands. Today, 45% of Ocean County is in the jurisdiction of the Pinelands CMP, which is administered by the Pinelands Commission, the planning entity of the federal act. Most of the municipalities under the jurisdiction of the Pinelands CMP have revised their land use ordinances to be consistent with the CMP, thereby allowing the review of development to remain at the local level. The Pinelands Commission also reserves the right to review all applications for development, including those that fall into the CAFRA zone overlap area along the coast.

7. Soil Erosion and Sediment Control

In 1975, standards for soil erosion and sediment control were promulgated pursuant to the Soil Erosion and Sediment Control Act (N.J.S.A. 4:24-3 and 4:24-42) and the Standards for Soil Erosion and Sediment Control in New Jersey (N.J.A.C. 2:90-1.1 et seq.). Municipalities and all other public agencies are required to condition development approvals on the Soil Erosion and Sediment Control Certification approval from the local Soil Conservation District for projects disturbing more than 5,000 S.F. of land. Certification is also required for demolition of structures, construction of parking lots and public facilities, operation of mining or quarrying activities, and clearing or grading of land for purposes other than agriculture or horticulture. Single family dwellings are excluded unless they are part of a project involving two or more single family units. The Ocean County Soil Conservation District has been an active participant in environmental issues affecting Ocean County.

C. County Planning

The primary function of the Ocean County Planning Board is development review. By statute, the Planning Board reviews development applications for their impacts on county roads and drainage facilities. The review process helps to ensure that developments are constructed according to adopted regulations and design standards. The Department of Planning works with the Planning Board on a number of regional issues and administers a number of programs for the county. The Ocean County Department of Planning also collects statistical data for use by county residents. Demographics, such as employment figures, population estimates, residential building permits, and subdivision and site plan approvals are analyzed to generate economic indicators. Planning Board activities also include involvement in the following matters.

1. State Development and Redevelopment Plan

The Ocean County Planning Board serves as the Negotiating Entity for the Cross-Acceptance process of the State Development and Redevelopment Plan. This process is conducted every three years to achieve consistency between the State Plan and local land use plans. The Ocean County Cross-Acceptance

Report was forwarded to the Office of State Planning in September 1998. Several Center Designation Petitions were contained in this report. A joint Center Designation Petition was submitted by the Borough of Tuckerton and the Townships of Little Egg Harbor and Eagleswood, in an effort to plan jointly for the future development of the southern portion of Ocean County. Other center petitions were submitted by Jackson Township, Ocean Township and Seaside Heights Borough. Two certified Centers exist in Ocean County: Manahawkin in Stafford Township and New Egypt in Plumsted Township.

2. Water Quality Management Planning

The Ocean County Board of Chosen Freeholders is the designated Water Quality Management Planning Agency for Ocean County and the portion of Monmouth County located within the Metedeconk River drainage basin. In August 1998, Ocean County received final approval from the NJDEP for the Northern Planning Area Water Quality Management Plan. The plan covers portions of all of the 9 municipalities in northern Ocean County and southern Monmouth County and permits the expansion of the Northern Water Pollution Control Facility of the Ocean County Utilities Authority from 28 million gallons per day (106.4 million liters per day) to 32 million gallons per day (121 million liters per day). Mapping associated with the Wastewater Management Plan for the Southern Planning Area has been incorporated into the county's Geographic Information System (GIS) and is ready for review by local agencies prior to submission to the NJDEP for approval.

3. Drinking Water Supply

The Ocean County Planning Board has been involved in potable water supply projects related to maintenance of potable water supply in the county. In 1987, the County Planning Board commissioned the study of water supply issues, prepared by CDM Associates. Based on this study, over 70% of the public wells and most domestic wells obtained potable water from the shallow Cohansey and Kirkwood aquifers. These aquifers are susceptible to contamination from surface activities due to their shallow depth and the existence of well-drained soils. Saltwater intrusion was another threat to public potable water supply along the barrier islands of Ocean County. An investigation of groundwater quality in the county found that many private wells contained low levels of organics, below drinking water quality limits. "Organic contamination forced the closing of nearly 100 drinking wells in Jackson Township in 1972" (Hess, 1993). The county assisted residents experiencing well water contamination in obtaining compensation through the State Spill Fund Compensation Program. This program has reimbursed eligible residents of Ocean County for expenses incurred in resolving domestic well contamination. The county also studied recharge areas of public water supply wells and wellfields in Brick, Dover, Manchester, Lacey, and Stafford Townships to determine possible pollution sources to the wells. In conjunction with this Wellhead Protection Demonstration Project, a computer listing of over 300 known potential contamination sites was assimilated into the county's GIS.

4. Solid Waste Management

In 1979, the New Jersey Solid Waste Management Act required Ocean County to develop a plan for management and disposal of solid waste generated within the county. The original Ocean County District Solid Waste Management Plan was adopted in 1979 by the Board of Chosen Freeholders and

amended through 1987. A Recycling Plan was also adopted in 1987. Ocean County became the first county in the state to receive full certification under the New Jersey Recycling Act. In 1990, a Department of Solid Waste was established in the county by the Board of Chosen Freeholders in 1990.

Ocean County's solid waste management program consists of two primary elements. A private state-of-the-art landfill, the Ocean County Landfill Corporation in Manchester Township, receives the county's nonrecyclable waste. Secondly, the county has a very successful and aggressive recycling program that includes the operation of the Ocean County Recyclable Materials Processing Facility. The county owns and operates two Recycling Centers. The Northern Recycling Center is located on New Hampshire Avenue in Lakewood Township. The Southern Recycling Center is located near the State Motor Vehicle Inspection Station at the intersection of Recovery and Hay Roads (off Route 72) in Manahawkin, Stafford Township. These facilities handle household battery recycling, waste oil recycling, antifreeze recycling, tire recycling, phone book recycling, empty paint can recycling, as well as leaves, brush, and other vegetative waste. Compost and mulch are available to county residents at these locations. County residents recycled 48.8% of generated waste in 1997 (McKeon, 1999).

5. New Jersey Clean Vessel Act

The Ocean County planning staff participates on the New Jersey Clean Vessel Act (CVA) Steering Committee. As part of the Clean Vessel Act Program, the first mobile pumpout boat in New Jersey began operation in central Barnegat Bay in 1998. The boat is moored off Island Beach State Park and is operated by the Borough of Seaside Park. Its efforts are concentrated in the Tice's Shoal area. As of March 1999, 47 pumpout units had been installed at Ocean County marinas, with another 14 pending applications in the Clean Vessel Act Grant Program (McKeon, 1999).

6. Ocean County Natural Lands Trust

The Planning Department provides staff support to the Ocean County Natural Lands Trust Fund Program. This fund, approved by the voters of Ocean County in November 1997, will be used to acquire undeveloped land from willing sellers and maintain it in a natural state. The goal of this fund is the protection of water supplies, critical habitats, and environmentally sensitive land. A total of 530 ac (215 ha) have been preserved under the program as of April 1999 (McKeon, 1999).

7. Farmland Preservation

The Planning Department staff works with the Ocean County Agriculture Development Board to administer the Farmland Preservation Program in Ocean County. This program is part of a larger statewide effort to preserve large tracts of agricutural land in New Jersey. Agriculture is preserved through the acquisition of development easements on farms and not through the direct purchase of property. The property owner retains ownership of the land and pays taxes on the agricultural value. To date, 12 farms totaling 1,705 ac (690 ha), have been preserved in Plumsted Township (Ocean County Department of Planning, 1998).

D. Local Planning

Ocean County contains 33 municipalities within the Barnegat Bay-Little Egg Harbor watershed. Local development in New Jersey is governed by the Municipal Land Use Law (N.J.S.A. 40:55D-1 et. seq.) The purpose of the act is to guide the appropriate use or development of all municipal lands in the state. The act gives municipalities the power to zone in an attempt to provide appropriate locations for a variety of agricultural, residential, recreational, commercial, and industrial uses as well as open space, both public and private, according to the respective environmental requirements. Among the goals of the act are:

"...to promote conservation of historic sites and districts, open space, energy resources, and valuable natural resources in the state and to prevent urban sprawl and degradation of the environment through improper use of land."

The Municipal Land Use Law, under 40:55D-28b, states that a Master Plan shall include at least a land-use plan, and defines the contents of the land-use plan as:

> "a) taking into account and stating its relationship to a statement of objectives, principles, assumptions, policies and standards upon which the constituent proposals for the physical, economic and social development of the municipality are based; taking into account the other Master Plan elements; and taking into account natural conditions, including but not necessarily limited to, topography, soil conditions, water supply, drainage, flood plain areas, marshes and woodlands; and
>
> b) showing the existing and proposed location, extent and intensity of development of land to be used in the future for varying types of residential, commercial, industrial, agricultural, recreational, educational and other public and private purposes or combination of purposes; and stating the relationship thereof to the existing and any proposed zone plan and zoning ordinance; and
>
> c) including a statement of the standards of population density and development intensity recommended for the municipality."

A Conservation Plan element is also required:

> "...providing for the preservation, conservation, and utilization of natural resources, including, to the extent appropriate, energy, open space, water supply, forests, soil, marshes, wetlands, harbors, rivers and other waters, fisheries, endangered or threatened species (of) wildlife and other resources, and which systematically analyzes the impact of each other component and element of the Master Plan on the present and future preservation, conservation and utilization of those resources."

Public involvement is an essential element of the Master Plan development process. Master Plans determine the general arrangement and development intensity of future land uses in New Jersey's municipalities, with input from the residents. It is necessary to update Master Plans every six years.

1. Ocean County Development Patterns

Development in Ocean County has traditionally occurred along the coastal beaches and in the corridor formed by the Garden State Parkway and U. S. Route 9. Major interchanges along the Garden State Parkway have allowed easy access along east-west corridors, such as County Route 526, County Route 528, State Highway 37, and State Highway 72. The northern portion of the county is experiencing more development since construction of Interstate 195, which provides transportation access to the employment areas in and around Trenton to the west, and Monmouth County to the northeast. The communities along the coastal beaches in Ocean County are primarily developed, and the beaches continue to be the focal point of seasonal visitors to the area (Ocean County Department of Planning, 1998).

Three development regions have been identified within Ocean County: (1) the coastal beaches; (2) the bay corridor; and (3) the western inland area (Ocean County 208 Project, 1978). Development in Ocean County has traditionally been focused along the coastal beaches and in urban and suburban areas along the bay corridor. The inland areas west of the Garden State Parkway that are within the Pinelands area are sparsely developed, due to the influence of the Pinelands Comprehensive Management Plan. Areas west of the Garden State Parkway in the northern portion of the county in Lakewood Township have been more densely developed in the past 15 years due to the Lakewood Industrial Park and various retirement communities. Jackson Township will be undergoing more development due to the completion of Interstate I-195, which travels in a northeast-west direction across the northern portion of Ocean County.

Development has occurred in a north-south direction along the coastal beaches and the U. S. Route 9/Garden State Parkway corridor. Major interchanges along the Parkway have enabled secondary east-west corridors to be developed. These areas are along County Routes 526 and 528 from Brick Township to Lakewood, along State Highway Route 37 from Dover Township to Manchester Township and Lakehurst Borough, and along State Highway Route 72 from Beach Haven West to Manahawkin and Ocean Acres in Stafford Township.

a. Coastal Beach Development

The coastal beach extends from Point Pleasant Beach south to Long Beach Township in a generally continuous strip of development, which is interrupted by Island Beach State Park, Barnegat Inlet, and Barnegat Lighthouse State Park. The coastal strip includes Island Beach and Long Beach Island, barrier islands which extend the full length of Ocean County. Existing development is primarily composed of commercial, commercial recreation, seasonal, and year-round residential housing.

b. Bay Corridor Development

The bay corridor extends north-south between Barnegat Bay on the east and the Garden State Parkway on the west. This area includes many of the county's older population centers, such as Point Pleasant, Toms River, Forked River, Barnegat, Waretown, and Tuckerton. This area is now heavily populated, and most of the county's development since 1960 has occurred in the bay corridor, with the bulk of the development north of Toms River. Development in the bay corridor has included major new subdivisions, senior citizen developments, thousand of lagoon homes and commercial development in shopping center strips along major highways.

c. Inland Development West of the Parkway

This inland region is still sparsely developed and includes vast areas of vacant and wooded land under the protection of the Pinelands Comprehensive Management Plan, and county, state and federal publicly owned land. The northwest section, in Plumsted Township, is the principal agricultural area in Ocean County. The publicly owned lands include Lakehurst Naval Air Station, Fort Dix Military Reservation, Greenwood Forest Fish and Wildlife Management Area, Colliers Mills Fish and Wildlife Management Area, Robert J. Miller Airpark and Recreation Area, and other smaller tracts. Traditional development centers in the inland region include Lakewood, Lakehurst, Cassville in Jackson Township, and New Egypt in Plumsted Township. More recently, development has occurred in northwestern Dover, Manchester, and Jackson Township (Ocean County 208 Project, 1978; Ocean County Planning Board, 1988; Ocean County Department of Planning, 1998).

Development patterns in Ocean County have affected the lower reaches of most of the subwatersheds in the county. The upper reaches of the subwatershed streams have experienced less development than the lower reaches, and they have not had as direct an impact on bay water quality as the more developed areas of the watershed. The regulatory effects of the Pinelands Comprehensive Management Plan have had a direct effect on the development patterns west of the Garden State Parkway in Ocean County.

E. Watershed

A watershed can be defined as the land area that contributes runoff to a particular point along a waterway (Caraco et al., 1998). In this particular instance, the watershed contributes runoff to the Barnegat Bay-Little Egg Harbor estuary. Therefore, the land area contributing runoff to the Barnegat Bay is known as the Barnegat Bay watershed. Watersheds can be subdivided into subwatersheds, which are smaller geographic segments of a larger watershed unit with a drainage area of between 2 to 15 mi2 (5.2 to 39 km2), and whose boundaries include all the land area draining to a point where two second-order streams combine to form a third-order stream.

A subwatershed is a watershed management unit used to describe watersheds and their smaller segments. The terms "watershed" and "subwatershed" are not inter-changeable. The term "watershed" is used to describe the broader management area, while the term "subwatershed" is used to refer to smaller areas where specific actions for watershed protection can be defined. Each subwatershed contains a network of small stream channels known as headwater streams.

Stream classification provides a spatial connection between the stream and its watershed. A network of

streams drain each watershed. Streams are classified according to their order in the overall network. A stream without tributaries or branches is defined as a first-order stream. When two first-order streams combine, a second-order stream is created, and so on. Headwater streams are defined as first- and second-order streams, and are good indicators of watershed quality (Caraco et al., 1998).

The largest watershed management unit is the basin. A basin drains to a major receiving water, such as a large river or estuary. Basin drainage areas usually exceed several thousand square miles and often include major portions of a single state. For instance, the Atlantic Coast drainage basin includes every region in New Jersey which drains to the Atlantic Ocean, including the Passaic region and the Raritan region, along with the Atlantic Coast region. A subbasin extends over several hundred square miles and is composed of a group of watersheds, (e.g., the Barnegat Bay watershed, the Monmouth County watershed, the Mullica and Wading River watersheds, and the Cape May watersheds). The smallest management unit is the catchment, which is the area that drains an individual development site to its first intersection with a stream.

1. Watershed Hierarchy

a. Catchment (0.05 to 0.5 mi2; 0.13 to 1.3 km2 - smallest management unit);

b. Subwatershed (2 to 15 mi2; 5.2 to 39 km2 - best unit for management));

c. Watershed (10 to 100 mi2; 26 to 260 km2 - includes subwatersheds);

d. Subbasin (100 to 1,000 mi2; 260 to 2,600 km2 - includes watersheds); and

e. Basin (1,000 to 10,000 mi2; 2600 to 26,000 km2 - largest management unit).

Principal streams within Ocean County include the Metedeconk River, Toms River, Kettle Creek, Forked River, Cedar Creek, Oyster Creek, Mill Creek, and Westecunk Creek. River patterns in Ocean County are dendritic, with stream flow derived in large part from base flow discharge. Stream beds are narrow and flood plains are wide. Stream velocity is slow due to the flat topography (Ocean County 208 Project, 1978).

2. Subwatersheds

The Barnegat Bay-Little Egg Harbor watershed is comprised of several subwatersheds which have experienced varying degrees of development.

a. Metedeconk River Subwatershed

The North Branch of the Metedeconk River borders Howell Township and flows through southern Freehold Township in the southern portion of Monmouth County, which is within the Barnegat Bay watershed. Haystack Brook, in southern Howell is a principal tributary of the North Branch of the Metedeconk River. Tributaries of Hay Stack Brook include Ground Hog Brook, Muddy Ford Brook, and

Dick's Brook. The South Branch of the Metedeconk River also originates in and flows through southern Freehold Township.

The Metedeconk River subwatershed includes the following Ocean County municipalities:

- A portion of Jackson Township
- A portion of Lakewood Township
- A portion of Brick Township
- A portion of Point Pleasant Boro
- A portion of Point Pleasant Beach Boro
- Bay Head

Jackson Township is the largest municipality, with over 100 mi2 (260 km2), and is not as developed as the other municipalities. The majority of development in Jackson is located in the northeastern portion of the township, in the Bennett Mills area, near the boundary of Lakewood Township. This area of Jackson is served by public sewer and potable water. Jackson Township has the potential for growth in the near future due to the availability of new sanitary sewer trunk lines; the Jackson Township Master Plan maps indicate the location of proposed/approved development. Jackson Township contains large areas of open space due to government-owned land and land relegated for recreational use. Lakewood Township and Brick Township are more densely developed with residential uses of land extending throughout the townships, and commercial uses along Route 9 and Route 70. Point Pleasant Boro, Point Pleasant Beach Boro, and Bay Head are completely developed. Brick Township, while heavily developed, has recently purchased several potential development sites for open space preservation.

b. Kettle Creek Subwatershed (includes Reedy Creek)

The Kettle Creek subwatershed contains the following municipalities:

- A portion of Lakewood Township
- A portion of Brick Township
- A portion of Dover Township

It is a densely developed subwatershed, primarily characterized by residential uses.

c. Silver Bay Subwatershed (includes Goose Creek)

The Silver Bay subwatershed is located east of the Garden State Parkway and contains a portion of Dover Township, and a portion of Seaside Heights Borough. This area includes development adjacent to and surrounding Fischer Boulevard, which is densely developed with lagoons, residential housing, and

commercial land uses, but which also contains Cattus Island County Park, a significant open space bordering the bay.

d. Toms River Subwatershed

i. Union Branch

ii. Wrangle Brook/Jake's Branch

The Toms River subwatershed includes the Union Branch and Wrangle Brook/Jake's Branch tributaries and the following municipalities:

- A portion of Jackson Township
- A portion of Manchester Township
- A portion of Dover Township
- A portion of Berkeley Township
- A portion of Lacey Township
- South Toms River Boro
- Beachwood Boro
- Pine Beach Boro
- A portion of Ocean Gate Boro
- Island Heights Boro

With the exception of Jackson Township, all of these municipalities are densely developed. Union Branch is bordered by Leisure Village West and Pine Lake Park, and flows into Pine Lake. Wrangle Brook flows through Holiday City at Berkeley, a large retirement community. The headwaters of Jakes Branch are located in an undeveloped area, but the lower portion of the tributary flows through South Toms River and Beachwood Boro. Working cranberry bogs are located above South Toms River on Jake's Branch. Manchester (outside of the Pinelands), Dover, Berkeley, and Lacey Townships are continuing to grow. The Toms River watershed contains the Six Flags Great Adventure Theme Park and Safari. It also contains the Colliers Mills Wildlife Management Area, the Francis Mills Park Preserve, the Butterfly Bogs Wildlife Management Area, the Jackson Forest Preserve, the State Forestry Station, Lakehurst Naval Air Engineering Center, the Manchester Wildlife Management Area, the Whiting Wildlife Management Area, and a portion of Lebanon State Forest. These areas provide significant acreage of forested land for watershed protection. A portion of the Toms River subwatershed is located in the New Jersey Pinelands. The lower portion of the Toms River subwatershed has experienced water quality problems associated with inadequate septic systems and stormwater runoff.

e. Potters Creek Subwatershed

The Potters Creek subwatershed is located east of the Garden State Parkway and contains a portion of Berkeley Township and a portion of Ocean Gate Boro, both of which have dense residential development. Berkeley Township contains many lagoon developments.

f. Cedar Creek Subwatershed

The Cedar Creek subwatershed contains:

- A portion of Lacey Township
- A portion of Berkeley Township
- A portion of Manchester Township

This subwatershed contains a large percentage of undisturbed land west of the Garden State Parkway. Although these areas are continuing to develop east of the Garden State Parkway, Cedar Creek is protected to the west of the Garden State Parkway by Double Trouble State Park, which encompasses some of the headwaters of Cedar Creek. The Berkeley Township recreational area is located along Cedar Creek, and the Cedar Creek Golf Course provides open space adjacent to Cedar Creek. Lacey Township also contains the Greenwood Forest Wildlife Management Area. Land west of the Garden State Parkway is in the New Jersey Pinelands.

g. Stouts Creek Subwatershed (includes Wrangle Creek)

This subwatershed is located within Lacey Township, east of the Garden State Parkway and east of U. S. Route 9. The immediate area is undeveloped; however, this subwatershed is surrounded by lagoon developments in Laurel Harbor, Murray Grove and Sunrise Beach.

h. Forked River Subwatershed

The Forked River subwatershed contains a portion of Lacey Township and a portion of Ocean Township.. The Forked River has three branches: (1) the Middle Branch, which is almost 100% forested and undisturbed; (2) the South Branch; and (3) the North Branch. The North Branch has three lakes east of the Garden State Parkway. Lacey Township continues to develop east of the Garden State Parkway. Ocean Township still has large areas of undeveloped land east of the Garden State Parkway. The land west of the Garden State Parkway in this subwatershed is undeveloped. It lies in the New Jersey Pinelands.

i. Oyster Creek Subwatershed (includes Double Creek)

This subwatershed contains:

- A portion of Ocean Township
- A portion of Barnegat Township
- A portion of Stafford Township

These areas are less developed than the northern portion of the watershed. Most development here is located east of the Garden State Parkway. Wells Mills Park is located west of the Garden State Parkway off of County Route 532. Land located west of the Parkway is in the New Jersey Pinelands.

j. Mill Creek/Westecunk Creek Subwatershed (includes Gunning River, Cedar- Manahawkin Creek, Cedar Run, Dinner Point, Mud Cove)

This subwatershed contains:

- A portion of Barnegat Township
- A portion of Stafford Township
- A portion of Little Egg Harbor Township
- Eagleswood Township

This subwatershed contains a portion of the Stafford Forge Wildlife Management Area, and a portion of the Edwin B. Forsythe National Wildlife Refuge. The wildlife refuge is located north of Manahawkin Creek up to Double Creek Wide Place opposite Bay Shore Drive in Barnegat Township, and from Mill Creek south to Dinner Point. These areas are less developed from the bay west to Route 9, than other areas along the bay corridor. However, there is development in this watershed south of Manahawkin Creek and Route 72 in Beach Haven West, and west of the Garden State Parkway northeast of Route 72, between Route 72 and Straight Road. This area is located in the Pinelands Regional Growth Area.

k. Tuckerton Creek Subwatershed (includes Parker Run)

This subwatershed contains:

- a portion of Bass River Township (Burlington County)
- Little Egg Harbor Township
- Tuckerton Boro (a "Pinelands" town)

These areas are less developed than the northern portion of the watershed, and most development is located east of the Garden State Parkway. Residential development amounts to 8.8% of the watershed (902 ac; 365 ha), commercial development is at 1% (102 ac; 41 ha) and other urban is 0.5% (49 ac; 19.8

ha). Approximately 77.2% of the watershed is forested (7,904 ac; 3201 ha) and contains a portion of the Stafford Forge Wildlife Management Area, a portion of Bass River State Forest, and a portion of the Edwin B. Forsythe National Wildlife Refuge. Land to the west of the Garden State Parkway is in the New Jersey Pinelands (Ocean County Department of Planning, 1998).

l. Barrier Islands

The barrier island communities from Bay Head Boro down to Holgate Boro are almost entirely developed and contribute stormwater runoff to the bay and freshwater inputs to wetlands. However, they are not located within the subwatershed of any landward stream.

m. Watershed Baseline

To establish a watershed baseline, land-use planning should contain a description of the subwatersheds, as described above, as well as an estimate of existing development and future build-out, based on municipal master plan projections. Subwatersheds are small enough to perform watershed assessment tasks in a relatively short time frame. However, future projections for land zoned for development are also subject to fluctuation because of market and economic conditions, and may not occur exactly as projected.

Subwatershed	% Developed land, 1972	% Developed Land, 1984	% Developed Land, 1995
Metedeconk River	27	36	46
Kettle Creek	40	44	58
Silver Bay	58	56	67
Toms River Union Branch Wrangle Brook/Jakes Branch	7 9 16	13 11 27	25 16 34
Potters Creek	32	29	39
Cedar Creek	4	4	7

Forked River	14	14	17
Stouts Creek	27	20	24
Oyster Creek	13	13	18
Mill Creek/ Westecunk Creek	13	14	18
Tuckerton Creek	12	13	17

(Lathrop et al., 1999)

F. Open Space

Although Ocean County is the third fastest growing county in the state (behind Somerset and Hunterdon counties), it contains vast areas of open space as a result of implementation of the Pinelands Comprehensive Management Plan (45.4% of Ocean County) and other state regulations and open space initiatives described in this chapter. Despite the rapid population growth and development in Ocean County, there has been a large amount of protected open space. The area west of the Garden State Parkway contains large tracts of state land, forests, and wildlife management areas. Approximately 20,000 ac (8,100) of land east of the parkway are protected under the Edwin B. Forsythe National Wildlife Refuge. New Jersey Fish, Game and Wildlife has a total of 69,607 ac (28,191 ha) in Ocean County. The Natural Lands Trust has preserved a total of 1,828 ac (740 ha) in Ocean County. New Jersey Parks and Forestry owns a total of 27,157 ac (10,999 ha) in Ocean County (Ocean County Department of Planning, 1998).

The County Farmland Preservation Program is preserving active farmland in the northwest portion of the county. To date, over 1,705 ac (691 ha) of productive farmland have been preserved outside of New Egypt in Plumsted Township. It must be noted, however, that this preserved farmland is not in the Barnegat Bay watershed, but lies in the Delaware River watershed. To date, no farmland has been preserved within the Barnegat Bay watershed. The Ocean County Department of Parks and Recreation maintains an active capital program for park land acquisition and development (over 4,100 ac; 1661 ha in 1999) to ensure that a variety of recreational opportunities is in close proximity to residents throughout the county. In 1997, the voters of Ocean County approved the Ocean County Natural Lands Trust Fund Program, which has acquired several undeveloped tracts for county open space.

Literature Cited

Caraco, D., R. Claytor, P. Hinkle, H. Yeong Kwon, T. Schueler, C. Swann, S. Vysotsky and J. Zielinski. 1998. Rapid watershed planning handbook: a resource guide for urban subwatershed management. Technical Report, Center for Watershed Protection, Ellicott City, Maryland.

Goldshore, L. P. 1979. The New Jersey Riparian Rights Handbook, 2nd ed.

State of New Jersey, County and Municipal Government Study Commission, New Jersey Department of Environmental Protection, Trenton, New Jersey.

Hess, K. 1993. Environmental Site Assessment, Phase I: A Basic Guide. Lewis Publishers, Boca Raton, Florida.

Kennish, M. J. 1998. Data synthesis/characterization report support document. Technical Report, Rutgers University, New Brunswick, New Jersey.

Lathrop, R. G., J. A. Bognar, and A. C. Hendrickson. 1999. Data synthesis effort for the Barnegat Bay Estuary Program: habitat loss and alteration in the Barnegat Bay Region. Technical Report, Center for Remote Sensing and Spatial Analysis, Cook College - Rutgers University, New Brunswick, New Jersey.

New Jersey Department of Environmental Protection. 1988. Comprehensive Master Plan. Department of Planning, Toms River, New Jersey.

Ocean County. 1998. Ocean County Data Book, 8th ed. Ocean County Planning Department, Toms River, New Jersey.

Ocean County 208 Project Planning Staff. 1978. Population, Land Use, and Environmental Resources. Technical Report, Ocean County and Southern Monmouth County, Toms River, New Jersey.

Pinelands Commission. 1980. Comprehensive Management Plan for the Pinelands National Reserve (National Parks and Recreation Act, 1978) and Pinelands Area (New Jersey Pinelands Protection Act, 1979), State of New Jersey. Technical Report, Pinelands Commission, New Lisbon, New Jersey.

Savitz, J. Undated. Pointless pollution: preventing polluted runoff and protecting America's coasts. Technical Report, Coast Alliance, Washington, D.C.

Seitzinger, S.P. and I. E. Pilling. 1993. Eutrophication and nutrient loading in Barnegat Bay: sediment-water phosophorus dynamics. Report No. 92-33F, The Academy of Natural Science, Philadelphia, Pennsylvania.

I. WATERSHED PLANT COMMUNITIES

The Barnegat Bay watershed is comprised of a wide diversity of vegetation from coastal dune communities and low-lying estuarine and freshwater wetlands to uplands of pine/oak forests. All of these communities have been affected in some way by human development and related activities.

A. Barrier Islands

Undeveloped stretches of the barrier island complex consist of extensive primary and secondary dune habitat along the ocean side and saltmarsh and tidal flats on the backside of the barrier. Island Beach State Park provides the most extensive example of the natural vegetation typical of New Jersey's barrier islands and spits. Eight plant community zones exist on Island Beach State Park including primary dune, secondary dune, road edge, thicket, freshwater wetlands, bayshore, tidal marsh/estuary, and maritime forest (Table 1). American beach grass (*Ammophila breviligata*) dominates the primary dune plant community, with the Beach pea (*Lathyrus maritimus*), Japanese sedge (*Carex kobomugi*), seaside goldenrod (*Solidago sempervirens*) and sea rocket (*Cakile edentula*) also observed in this zone. Seabeach knotweed (*Polygonum glaucum*), a state listed endangered species, is found at Island Beach and also at Holgate.

The secondary dune community is much more diverse; nearly 30 species of plants have been identified here. Representative species occurring in this community include beach plum (*Prunus maritima*), bayberry (*Myrica pensylvanica*), beach heather (*Hudsonia tomentosa*), pineweed (*Hypericum gentianoides*), and salt spray rose (*Rosa rugosa*). The thicket, edge, and freshwater wetland communities have 73, 140, and 55 species, respectively. The bayshore community (22 species) and tidal marsh community (20 species) are much less diverse. American holly (*Ilex opaca forma sabintegra*), Atlantic white cedar (*Chamaecyparis thyoides*), White oak (*Quercus alba*), pitch pine (*Pinus rigida*), and several other species exist in the coastal woodland or maritime forest community.

While a flourishing plant community exists at Island Beach State Park and to a lesser extent at Holgate, the dune and maritime forest communities of the barrier islands fronting Barnegat Bay have largely been destroyed or substantially altered. The natural dune system has been obliterated along great stretches of New Jersey's Atlantic shoreline. Dune grass vegetation serves a useful role in stabilizing dunes and protecting beaches against wind and wave erosion. Where feasible, dunes are being reconstructed and revegetated to help impede beach erosion. Barrier island vegetation communities such as maritime shrublands and woodlands provide important stop-over habitat for numerous species of songbirds and raptors migrating along the Atlantic coastal flyway.

B. Tidal Wetlands

The barrier island and mainland shores of Barnegat Bay are fringed with coastal wetlands whose vegetation form and character are largely controlled by the tidal regime and salinity of neighboring bay waters. The saltwater wetlands are subject to high salt concentrations (up to 28-30 ppt), are regularly inundated by the tide, and are typically flat meadowlands dominated by *Spartina* species. In these tidal wetlands, *Spartina alterniflora*, *S. patens*, *Juncus gerardi*, and *Salicornia virginica* are the characteristic

forms of a New England type salt marsh community (Nixon, 1982; Tiner, 1985). The smooth cordgrass (*Spartina alterniflora*) dominates low marsh habitat, proliferating in intertidal areas. Smooth cordgrass occurs in two growth-forms, short and tall-form, with a taller form growing along tidal waterways, largely due to better soil aeration and greater supply of available nutrients. Low elevation depressions within the salt marsh are often highly saline due to a combination of impeded drainage, irregular tidal flushing, and intense evaporation (Redfield, 1972). Except for saltworts (*Salicornia* spp.) and blue-green algae, these "salt pannes" are often largely devoid of vegetation. Salt-meadow cordgrass (*Spartina patens*), spike grass (*Distichlis spicata*) and black grass (*Juncus gerardi*) dominate higher elevation marshes which are only irregularly flooded by saline waters. Shrub species such as salt marsh elder (*Iva frutescens*) and groundsel tree (*Baccharis halimifolia*) commonly occur on areas of slightly higher elevation within the salt marsh (e.g., spoil mounds adjacent to ditches) (Sneddon et al., 1995). Common reed (*Phragmites australis*), narrow-leaved cattail (*Typha angustifolia*), and bulrushes (Scirpus spp.) commonly occur as a narrow fringe along the upland edge due to decreased tidal flooding, greater freshwater runoff, and thereby lower salinity levels.

Proceeding upstream along some of the larger streams and rivers tributary to Barnegat Bay, salinity levels drop and plant communities diversify. Big cordgrass (*Spartina cynosuroides*), various sedges (*Scirpus* spp.), salt marsh fleabane (*Pluchae purpurascens*), and swamp rose mallow (*Hibiscus moscheutos*) add greater variety to this brackish marsh community. Tidal freshwater marshes occur where the water becomes fresher (below 0.5 ppt salinity) but still remains tidally influenced (Sneddon et al., 1995). The lower reaches are dominated by forbs such as arrowhead (*Sagittaria latifolia*), pickerelweed (*Pontederia cordata*), and arrow arum (*Peltandra virginica*). Tall stands (> 2 m high) of wild rice (*Zizania aquatica*) occur along the upper reaches of some tidal freshwater marsh areas. The common reed, an aggressive invader, will colonize and dominate brackish and freshwater tidal marsh areas especially in areas that have been disturbed due to ditching and dredge-spoil dumping (Sneddon et al., 1995; Windham and Lathrop, 1999).

Saltmarshes are characterized by high biomass and organic productivity values. Although standing crops are high, herbivory remains low, resulting in the generation of large amounts of detritus that support detritus-based food chains. The export of a portion of the detritus accumulating in saltmarshes may stimulate productivity in contiguous waters. Leaves and stems effectively increase the substrate surface area for epiphytic flora and fauna, thereby enhancing the primary and secondary productivity of the habitats. The epibiota also provide a rich food supply for fish and invertebrates. A canopy of dense leaves typically found in the coastal wetlands causes lower insolation than in surrounding unvegetated areas. Protected from excessive illumination and insolation, this shaded habitat appears to be beneficial to the benthos. The lateral zonation observed in these wetlands presents a diversity of habitats for the protection and proliferation of epiflora, epifauna, benthic infauna, fishes, birds, and various wildlife species. In the Barnegat Bay-Little Egg Harbor estuarine system, saltmarshes support numerous endangered, threatened or rare species.

Apart from their high production, wetlands are effective in the removal of excess nutrients, metals, and other pollutants from surface waters. The sequestration of nutrients and chemical contaminants is potentially important in water quality protection of estuarine waterbodies. Adsorption of contaminants onto suspended particulates and their subsequent deposition is the primary means of removal. Leaves, stems, and roots reduce wave and current action and facilitate sediment deposition. In addition, the roots and rhizomes bind sediments, stabilize the substrate, and mitigate erosion. Saltmarshes provide natural flood control in the watershed because they tend to slow and hold water. The broad expanses of saltmarshes also stabilize banks and protect the shoreline from other destructive natural and human forces.

C. Uplands and Freshwater Wetlands

The western shores of Barnegat Bay directly border the region of New Jersey known as the Pine Barrens or Pinelands. Situated on the sandy, acid soils of New Jersey's outer coastal plain, the Pine Barrens comprise a landscape of upland pine-oak forests interlaced with a network of "tea-water" streams, dense swamps and ericaceous bogs. The Pine Barrens supports more than 500 species of animals and 800 species and varieties of plants (McCormick and Forman, 1979; Buchholz and Good, 1982; Good and Good, 1984). By no means an undisturbed wilderness area, the Pine Barrens were heavily impacted by bog iron mining, glass blowing, timber harvesting and charcoal-making industries during the 1700's and 1800's. Subsequent to this early industrial period, human disturbance has been comparatively light allowing the regrowth of the extensive forests that give the Pine Barrens its name. Occupying a contiguous area of approximately 450,000 ha, this lightly settled region represents one of the largest tracts of comparatively "natural" landscape remaining on the US eastern seaboard. To protect the Pine Barrens from inappropriate development, legislation was passed in 1978 to create the New Jersey Pinelands National Reserve (NJPNR) (Collins, 1988).

The Pine Barrens landscape is characterized by a complex mosaic of ecological land types: discrete patches or, more often, corridors of cedar and hardwood swamps amidst a background matrix of upland pine and oak forests (Forman, 1979). The upland forests are better characterized by a continuous gradient with pure pitch pine (*Pinus rigida*) stands on one end grading into pure oak (*Quercus spp.*) at the opposite (McCormick, 1979). Due to the relatively open canopy of the upland forests, the generally well-developed understories are dominated by either scrub oak (*Quercus ilicifolia*) or various heath plants such as mountain laurel (*Kalmia latifolia*), huckleberry (*Gaylussacia spp.*), and blueberries (*Vaccinium spp.*). These upland forests in turn grade into pitch pine lowland forests depending on the hydrological regime.

Over the past two hundred years, humans have had a tremendous influence on determining the characteristics of the region's vegetation communities (McCormick, 1979; Zampella and Lathrop, 1997). The pitch pine (*Pinus rigida*) dominated forests of southern New Jersey are a fire-dependent vegetation community. The intensity and frequency of fire are among the most important factors determining the structure and composition of Pinelands forest communities (Little, 1979; Forman and Boerner, 1981). Subsequent to fire, pitch pine has the ability to resprout from the basal root crown and along the trunk and limbs (Harshberger, 1916). Oaks also exhibit basal sprouts. Pitch pine also displays the ability to produce serotinous cones which protect the pine seed from the high temperatures of the fire. Subsequent to the fire, the cones then release the seed, permitting pitch pine to rapidly colonize newly available sites suitable for seedlings. Areas of high-fire frequency have been shown to have greater local incidence of serotiny (Givnish, 1981). Under the highest fire frequencies, the upland forest vegetation assumes more of a dwarfed scrubby woodland locally known as pygmy pine plains (McCormick and Buell, 1968; Buchholz and Zampella, 1987). The East Pine Plain, home to a number of unusual prostrate shrubs such as bearberry (*Arctospaphylos uva-ursi*), pyxie moss (*Pyxidanthera barbulata*) and the endangered broom crowberry (*Corema conradii*) (Harshberger, 1916), is on the extreme western border of the Barnegat Bay watershed. It is suggested that changes in fire regime related to more effective fire control may result in changes in landscape patterns, including a gradual transition from pine to oak-dominated forests (Little, 1979; Forman and Boerner, 1981).

The composition of Pinelands wetland plant communities has been extensively studied and described (Roman and Good, 1983; Tiner, 1985; Zampella 1991). Following McCormick's (1979) widely used classification of community types, Pinelands wetlands include Atlantic white cedar (*Chamaecyparis thyoides*) swamp forests (Little, 1950, 1951; Olsson, 1979; Roman et al., 1990; Ehrenfeld and

Schneider, 1991; Zampella and Lathrop, 1997), broadleaf or hardwood swamp forests dominated by red maple (*Acer rubrum*) and black gum (*Nyssa sylvatica*) (Olsson, 1979; Bernard, 1963; Ehrenfeld and Gulick, 1981), pitch pine lowland and pine transition forests (Olsson, 1979; Roman et al., 1985; Zampella et al., 1992), shrubby wetland communities (Olsson, 1979), and herbaceous wetland communities, including both submerged and aquatic vegetation (Olsson, 1979; Morgan and Philipp, 1986). Atlantic white cedar swamps are presently receiving consideration for additional conservation and restoration efforts due to years of indiscriminate logging and past modifications associated with residential development and cranberry bog agriculture.

The unique character of Pinelands flora is widely recognized (Christensen, 1988). Pinelands wetlands support a large portion of the region's floral biodiversity, including many rare plant species (Fairbrothers, 1979; Snyder and Vivian, 1981; Roman and Good, 1983). Although forested wetlands are dominated by a few tree species, including red maple, Atlantic white cedar, black gum, pitch pine and sweetbay (*Magnolia virginica*), more than 20 shrub species are found in the understory. Blueberries (*Vaccinium* spp.), swamp azalea (*Rhododendron viscosum*), sweet pepperbush (*Clethra alnifolia*), and greenbrier (*Smilax spp.*) are generally dominant. Where these forested wetlands merge into the Barnegat Bay coastal region, American Holly (*Ilex opaca*) often becomes an important component of the sub-canopy. Biologically significant species occurring in wetlands include endemics such as New Jersey rush (*Juncus caesariensis*) and sand myrtle (*Leiophyllum buxifolium*), peripheral and disjunct southern species such as turkeybeard (*Xerophyllum asphodeloides*) and false asphodel (*Tofieldia racemosa*), and curly grass fern (*Schizaea pusilla*), a northern peripheral species (Fairbrothers, 1979). The federally endangered swamp-pink (*Helonias bullata*) and Knieskern's beakrush (*Rhynchospora knieskernii*) are also found in Pinelands wetlands.

II. SUBMERGED AQUATIC VEGETATION

Benthic macroalgae and vascular plants (seagrasses) comprise the submerged aquatic vegetation (SAV) community of Barnegat Bay, Manahawkin Bay, and Little Egg Harbor. Loveland et al. (1984) recorded 116 species of benthic algae in Barnegat Bay, with the dominant forms being *Ulva lactuca*, *Gracilaria tikvahiae*, *Codium fragile*, *Zostera marina*, *Ceramium fastigiatum*, and *Agardhiella subulata* (Table 2). The benthic macroflora exhibit considerable temporal and spatial variation. Only a few species are common year-round due to the sensitivity of most of the plants to changes in solar radiation and water temperature. Species diversity peaks in late spring, and is lowest in late summer. Although the community composition varies greatly during the year, the dominant species persist.

Many of the benthic macroalgae are unattached to any substrate, and drift along the bottom. Sea lettuce (*Ulva lactuca*) is consistently one of the most abundant macroalgal species in the estuary. Sea lettuce provides food and shelter for some fauna, but may grow excessively in nutrient enriched areas, causing problems such as hypoxia, smothering of fauna, and lowered aesthethic value. Areas with reduced circulation (e.g., dead-end canals) are particularly prone to the buildup of sea lettuce. In some estuaries (e.g. Delaware inland bays), excess sea lettuce is harvested to reduce impacts on water quality.

Vascular plants occur along the shallow margins of the estuary in waters less than 1 m in depth. Eelgrass (*Zostera marina*) is the dominant seagrass species in Barnegat Bay, forming dense beds particularly on sandflats along the backside of the barrier island system. Widgeon grass (*Ruppia maritima*) is of secondary importance, also attaining highest concentrations on the eastern sand flats. Locally dense beds

of sago pondweed (*Potamogeton pectinatus*) appear north of Toms River, with lesser quantities of horned pondweed (*Zannichellia palustris*), widgeon grass, and eelgrass.

The occurrence of SAV species in the estuary strongly depends on environmental conditions. Each species has its own requirements for and tolerances of physical characteristics, such as temperature, salinity, sediment composition, water velocity, and turbidity. Vascular plants compete with each other and with algae for light, space, and nutrients. The abundance of vascular plants is a function in part of the amount of seeds set the previous year and the successful germination of the seeds. Annuals that grow from rhizomes and tubers (e.g., horned pondweed) may reappear in the same location year after year. The temporal and spatial shifts of SAVs in the Barnegat Bay ecosystem likely result from naturally-occurring cycles (Loveland et al., 1984), although anthropogenic activities such as dredging, nutrient loading, boating, and the use of personal watercraft may be detrimental.

Disease is responsible for significant declines of seagrasses during certain years. For example, McClain and McHale (1997) showed that wasting disease, presumably caused by the protist *Labyrinthula zosterae*, destroyed about 400 ha of eelgrass beds in Barnegat Bay in 1995. Less disease and SAV destruction occurred in 1996, although as much as 50% of eelgrass leaves exhibited wasting disease at this time.

SAVs have several functional roles in the Barnegat Bay estuarine ecosystem. They provide a substantial amount of primary production for the Barnegat Bay estuary, and serve as critically important habitat for benthic epifauna and infauna. Some organisms graze on SAV (e.g., gastropods, fish, ducks, muskrats). Some benthic macrovegetation (e.g., *Zostera marina*) also represent valuable spawning, nursery, and feeding grounds for finfish populations in the estuary. They likewise stabilize the benthic habitat by baffling waves and currents and mitigating substrate erosion.

III. PLANKTON

A. Phytoplankton

Phytoplankton are free-floating, microscopic plants - unicellular, filamentous, or chain-forming species - inhabiting bay waters. Unicellular forms comprise the bulk of phytoplankton populations in the bay. Based on their size, phytoplankton are classified as: (1) picoplankton (< 5 μm), (2) nanoplankton (5-70 μm), (3) microphytoplankton (70-100 μm), and (4) macrophytoplankton (> 100 μm). Most of the phytoplankton species in the Barnegat Bay-Little Egg Harbor estuary belong to the picoplankton and nanoplankton.

Here, the species composition and dynamics of phytoplankton in the Barnegat Bay-Little Egg Harbor estuary are considered, together with standing crop and primary production. Review of the primary production of phytoplankton logically leads to some discussion of the factors which limit it, namely light, temperature, nutrients, salinity, and zooplankton grazing. As in other temperate estuaries, phytoplankton in the Barnegat Bay-Little Egg Harbor estuary experience seasonal cycles in species composition (succession), biomass, and primary production related to changes in physical, chemical, and biological conditions. Annual successional patterns are well documented for phytoplankton communities in the estuary (Mountford, 1971, 1984).

Barnegat Bay, Manahawkin Bay, and Little Egg Harbor are dynamic waterbodies characterized by a continuum of diurnal, tidal, and seasonal changes in temperature, salinity, and other physical and chemical factors. Light and nutrient availability likewise vary temporally. In addition, water circulation and turbidity, which often exhibit acute perturbations, influence other parameters that may be critical to the success of phytoplankton populations. Hence, the composition of the phytoplankton communities changes through time in response to both abrupt fluctuations and seasonal oscillations in physical-chemical conditions of the environment.

Several factors greatly influence primary production of phytoplankton in the Barnegat Bay-Little Egg Harbor estuary. For example, phytoplankton production is closely coupled to photoperiod, light intensity, and light attenuation in the water column. Light availability is important in initiating seasonal phytoplankton blooms. Barnegat Bay has higher light attenuation coefficients and water column turbidities than other east coast estuaries (e.g., Chesapeake Bay, Delaware Bay, and Narragansett Bay) (Seitzinger and Pilling, 1990) (Figure 1). Particularly in summer, high water column turbidity results in very low light levels at the bay bottom. The phytoplankton populations themselves, as well as suspended sediments and dissolved and particulate organic matter, contribute to water column turbidity.

Phytoplankton alter their reproductive rate, assimilation number, and chemical composition in response to different light intensities. Adaptations of phytoplankton to variable light intensities include a change in the amount of pigments or photosynthetic enzymes in the cells. Phytoplankton have different tolerances to light intensity. Diatoms, for example, are light saturated at a less intense light level than dinoflagellates. Therefore, dinoflagellates may be expected to be more numerous near the estuarine surface.

Temperature affects enzymatic activities (respiration and photosynthesis) and growth rate processes of phytoplankton. In laboratory cultures, the division rates of marine phytoplankton generally increase by two to four times with a 10°C rise in temperature, as long as the temperatures lie within a range favorable to growth (Vernberg, 1975). Temperature also exerts indirect effects on phytoplankton aside from the direct influence it has on their growth, enzymatic activities, and other metabolic processes. For example, in the deeper waters of the estuary (e.g., the Intracoastal Waterway), there may be a tendency for water column stratification to develop during some periods due in part to temperature differences. This can influence phytoplankton growth and productivity in these areas.

Nutrients are necessary for adequate growth and production of phytoplankton. The major nutrient elements include nitrogen, phosphorus, and silicon. Trace elements, such as iron, manganese, zinc, copper, cobalt, and molybdenum, may limit phytoplankton growth if present in insufficient concentrations. However, some trace metals (e.g., copper and zinc) can be toxic to phytoplankton even at low concentrations and, consequently, may hinder their productivity. Certain phytoplankton require the vitamins cobalamine, thiamin, and biotin, as well as other organic compounds.

Nitrogen is the nutrient limiting to phytoplankton growth in the Barnegat Bay estuarine system. Ammonia (lumped here with ammonium), nitrite, and nitrate comprise the principal dissolved inorganic forms of nitrogen. Urea, amino acids, and peptides are important dissolved organic forms. Phytoplankton incorporate both dissolved inorganic and organic nitrogen for growth.

Zooplankton grazing regulates the standing crop of phytoplankton in the estuary. Phytoplankton blooms are superseded by peaks in zooplankton abundance, although the time lag between a phytoplankton bloom and subsequent zooplankton expansion can be quite variable. Variations in the time lag can foster substantial differences in phytoplankton standing crop.

The earliest investigations of phytoplankton in the Barnegat Bay-Little Egg Harbor estuarine system were conducted by Martin (1929) who identified 41 dinoflagellates, five of which he described as new species. Nearly 40 years later, Mountford (1965) reported a serious "red tide" in upper Barnegat Bay during the summer, which stressed fish and shellfish in the area. Silva (1967) described the causative species of that "red tide" as the dinoflagellate *Cochlodinium heterolobatum*. Mountford (1969, 1971, 1984) subsequently initiated a comprehensive study of phytoplankton communities in the bay.

Mountford (1984) documented more than 180 species of phytoplankton in Barnegat Bay (Table 3). He also followed the seasonal appearances and disppearances of phytoplankton populations, interpreting the conspicuous seasonal periodicity of 44 species and groups of species as a response of the organisms to complex interactive effects of temperature, photoperiod, and nutrient supply. Alternating warm-water and cold-water flora appeared annually in a successional sequence. Seasonal periodicities in abundance and primary production also typified the phytoplankton community. Phytoplankton abundance was maximum in summer and minimum from late fall to mid-winter. Phytoplankton densities ranged from 80,000 to 800,000 cells/ml in the summer; although microflagellates (5-15 µm) were numerically important, picoplankton (spherical green cells 2-4 µm) dominated the community. Microflagellates and larger dinoflagellates were more numerous than diatoms in the summer and fall, attaining densities greater than 106 cells/l in the summer. Common dinoflagellate species at this time included the naked forms *Gymnodinium incoloratum* and *G. punctatum* and the thecate forms *Gonyaulax digitalis*, *G. spinifera*, *Prorocentrum micans*, *P. redfieldi*, *P. scutellum*, and *P. minimum*. Intense luminescent, dinoflagellate blooms have been observed during the summer and fall. Only three diatom species were reasonably abundant in the warmer months: *Skeletonema costatum*, *Cyclotella* sp., and *Cylindrotheca closterium*. Some summer populations persisted into the fall, as diatoms (e.g., *Amphiprora* sp., *Licomophora* sp., and *Thalassionema nitzchioides*) begin to reestablish. Phytoplankton concentrations decreased in the fall with declining insolation and temperature. Diatoms became numerically dominant in early to mid-winter; the standing crop and productivity of phytoplankton dropped to minimum levels during periods of ice cover. A diatom bloom developed in mid to late winter each year subsequent to the breakup of ice cover with rising water temperature and insolation. A succession of diatom populations generated this bloom, with *Thalassiosira nordenskioldii* and *Detonula confervacea* being the principal phytoplankton populations in the spring as water temperature approached 20°C and light intensified. Over an annual cycle, *S. costatum* was the most common diatom in Barnegat Bay. It is probable that *T. nordenskioldii*, *D. confervacea*, and *S. costatum* were inoculated from nearshore oceanic waters into the estuary in the late winter and spring, where nutrient-rich waters enhanced their rapid growth.

In terms of standing crop, chlorophyll *a* determinations ranged from 1 to greater than 35 µg/l. Chlorophyll *a* values, as an estimate of biomass, were greatest during the winter-spring diatom bloom or during the period of maximum cell counts in the summer. As noted previously, phytoplankton productivity also peaked in the summer when maximum gross productivity surpassed 750 mg O2/m3/hr. Productivity measurements were minimum in the winter, approaching 0 mg O2/m3/hr.

Intense blooms of picoplanktonic algae have occurred each summer in the Barnegat Bay-Little Egg Harbor estuarine system since at least 1985 (Olsen, 1997). These blooms persist summer-long in the estuary from about mid-June through September, with maximum cell counts often exceeding 106 cells/ml (Table 4). They are dominated by a minute nonmotile chlorophycean (green) alga (*Nannochloris atomus*) having spherical cells generally ranging from 1.5-3.5 µm in diameter. In large numbers (> 105 cells/ml), this phytoplankter causes a yellowish to greenish-brown water discoloration. Olsen (1997) observed a maximum concentration of picoplankton in lower Barnegat Bay and Little Egg Harbor (~ 3 x 106 cells/ml) in August 1996. In the southern perimeter of the system, the blooms usually commenced earlier (mid-late June), continued considerably longer with sustained high cell densities (> 5 x 105 to > 1.2 x 106 cells/ml), and lasted later (to early October) than elsewhere in the estuary.

Olsen (1997) also identified other picoplankton associated with these summer blooms, including a few minute flagellates (*Chlamydomonas*, *Micromonas* ? sp.), short cylindrical forms (a chlorophyte *Stichococcus* or a diatom *Minutocellus* sp.), and a coccoid (often aggregate or chain-forming) cyanobacterium. Somewhat larger forms were the pennate diatoms *Phaeodactylum* ?, *Nitzschia* sp., and flagellates *Pyramimonas micron*, as well as the chrysophyte *Calycomonas ovalis*. Several nannoplankton species were also associated with the picoplankton blooms, notably the phytoflagellates *Chroomonas* spp., *C. minuta*, *Pyramimonas grossii*, and *Chrysochromulina* sp., the diatoms *Nitzschia* and*Cyclotella* sp. and another chlorophyte *Chlorella* sp. (coccoid forms > 5 μm). A larger diatom, *Cylindrotheca closterium*, was sometimes abundant.

Using standard light microscopy, *Nannochloris atomus* could not be readily distinguished from the chrysophyte picoplankter *Aureococcus anophagefferens* which occurred in bloom proportions (> 106 cells/ml) in Little Egg Harbor from May through mid-July in 1995; this was determined using definitive immunofluorescence microscopy (Mahoney et al., 1997). Brown tides of *A. anophagefferens* have been an annual occurrence in eastern Long Island coastal bays since 1985, apparently causing devastation of the bay scallop fishery there. Their presence in the Barnegat Bay-Little Egg Harbor estuarine system may signal a regional problem associated with this organism. The brown tide of *A. anophagefferens* in Little Egg Harbor in 1995 adversely affected shellfish (hard clam) growth in an aquaculture facility on Tuckerton Bay and caused a distinctive golden-brown discoloration of the water. It is possible that increasing numbers of *N. atomus* in the summer may mask the escalating numbers of *A. anophagefferens*. Although *A. anophagefferens* normally blooms earlier in the season than *Nannochloris atomus*, temporally there is some overlap. While *N. atomus* blooms have been ongoing, blooms of *A. anophagefferens* have reoccurred in 1997 and 1999. The densest blooms to date were recorded in 1999.

The occurrence of *Nannochloris* and *Aueococcus* blooms in the Barnegat Bay-Little Egg Harbor estuarine system is of great concern because development of these blooms may be linked to increasing eutrophication of the estuary. As shown by Seitzinger and Pilling (1990, 1992, 1993), Barnegat Bay is currently in a moderately eutrophic state. However, greater incidence or intensity of *Nannochloris* and *Aueococcus* blooms in future years would be indicative of potential eutrophication problems in the estuary. Therefore, it is necessary to continue to closely monitor phytoplankton communities in general and blooms of undesirable species in particular. This will be an important step is understanding the factors responsible for initiating such blooms in the estuary. The likelihood of adverse effects on our indigenous shellfish populations and extensive seagrass beds, both valuable resources, certainly requires further investigation.

B. Zooplankton

1. Introduction

There have been no recent investigations of zooplankton in the Barnegat Bay-Little Egg Harbor estuary. With the exception of the research of Moser (1997) and McClain and McHale (1997), there also have been no recent studies of the benthic fauna and flora of the system. The most comprehensive work on zooplankton in the estuary was conducted in the 1970's (Loveland et al., 1969; Mountford, 1971; Tatham et al. 1977, 1978; and Sandine, 1984). Detailed benthic surveys, in turn, were performed in Barnegat Bay during the late 1960's and early 1970's (Phillips, 1972; Loveland et al., 1972, 1974; Loveland and Vouglitois, 1984). Zooplankton and benthic assemblages of Little Egg Harbor are largely

uncharacterized. The following discussion provides an overview of the structure and dynamics of the zooplankton and benthic communities of Barnegat Bay based on the aforementioned studies.

2. Zooplankton Characteristics

Zooplankton are volumetrically abundant animals typically several microns to 2 cm in size that drift passively in the water column due to limited capabilities of locomotion. They are classified according to their size or length of planktonic life. Three major size categories of zooplankton are recognized, namely microzooplankton, mesozooplankton, and macrozooplankton. Microzooplankton comprise those forms which pass through plankton nets with a mesh size of 202 µm. Larger zooplankton retained by nets with a mesh size of 505 µm are defined as macrozooplankton, with mesozooplankton comprising those forms intermediate in size.

In regard to the duration of planktonic life, zooplankton may be grouped into three classes: (1) holoplankton, (2) meroplankton, and (3) tychoplankton. Holoplankton are those organisms which spend their entire life in the plankton, in contrast to meroplankton which remain planktonic for only a portion of their life cycle. Tychoplankton refer to small animals, primarily benthic organisms, temporarily translocated into the water column by currents, behavioral activity (e.g., diurnal vertical migration), or other mechanisms.

Zooplankton constitute the principal herbivorous component of estuarine ecosystems. Whereas most zooplankton consume phytoplankton or detritus and serve as an essential link in aquatic food chains by converting plant to animal matter, others are primary carnivores. Some species obtain nutrition by the direct uptake of dissolved organic nutrients. Zooplankton basically gather food via filter feeding or raptorial feeding. Raptorial feeders seize and consume individual cells, removing a few selected prey. Grazing pressure by herbivorous zooplankton commonly regulates the standing crop of phytoplankton populations.

Both biological and physical-chemical conditions in estuaries control the species composition, abundance, and distribution of zooplankton. These microfauna must adapt to varying stresses associated with biological (e.g., scarcity of food, competition, and predation) and physical-chemical (e.g., temperature, salinity, mass movements of water, and dissolved oxygen levels) factors. Estuarine zooplankton are characterized by large variations in abundance and distribution.

a. Microzooplankton

In their comprehensive investigations of the zooplankton communities of Barnegat Bay, Loveland et al. (1969), Tatham et al. (1977, 1978), and Sandine (1984) showed that calanoid copepods, particularly *Acartia hudsonica*, *A. tonsa*, and *Oithona colcarva*, dominated the microzooplankton of Barnegat Bay. During the winter months, *A. hudsonica* was most abundant, and during the summer months, *A. tonsa* or *O. colcarva* predominated. Sandine (1984) identified ten other copepod species in Barnegat Bay samples: *Paracalanus crassirostris*, *P. parvus*, *Oithona similis*, *Centropages hamatus*, *C. typicus*,

Temora longicornis, *Pseudocalanus minutus*, *Pseudodiaptomus coronatus*, *Tortanus discaudatus*, and *Labidocera aestiva*. Of these forms, *P. crassirostris*, *O. similis*, and *P. coronatus* usually were most abundant.

Based on the aforementioned studies, microzooplankton abundance was greatest in the spring and summer months. The maximum mean monthly densities exceeded 1 x 105/m3 at these times. Copepods were responsible for a substantial portion of the total microzooplankton numbers, with *Acartia hudsonica*, *A. tonsa*, and *Oithona colcarva* being the dominant species (Tatham et al., 1977, 1978). Sandine (1984) noted that *Acartia hudsonica* was the most abundant form during the spring, whereas *A. tonsa* or *O. colcarva* dominated during the summer.

Rotifers comprised 11% of the mean annual density of microzooplankton collected during plankton sampling from September 1975 to August 1977, yielding a peak density of 3.8 x 105/m3 in February 1976 (Tatham et al., 1977, 1978). The maximum density of tintinnids was 1.6 x 105/m3 during this two-year period. Those microzooplankton species with high abundances and rapid generation times (e.g., protozoans) act to stabilize the planktonic community by capturing energy - as from a phytoplankton pulse - that would otherwise be lost from the community to some environmental or biotic compartment (e.g., bottom sediments, benthic communities, etc.).

Microzooplankton maxima in the spring and summer often involve pulses of meroplankton. Meroplankton larvae accounted for 1 to 49% of the total mean monthly microzooplankton density in 1975 and 1976, with bivalve, gastropod, polychaete, barnacle, and cyphonaute larvae all being important. The quantity of meroplankton approached peak numbers in the spring, especially during April (1977) when a maximum mean monthly density of 6.7 x 104/m3 was recorded. From September 1975 to August 1976, larvae of barnacles (49% of the mean annual meroplankton density), polychaetes (25%), bivalves (11%), and gastropods (6%) dominated the meroplankton. From September 1976 to August 1977, polychaetes accounted for 33% of the mean meroplankton density, followed by gastropods (23%), barnacles (15%), and bivalves (15%). In spite of the continued reproduction of various benthic invertebrate species, an overall decline in meroplankton density occurred through the summer months.

Tatham et al. (1977, 1978) collected bivalve larvae year-round, although peak numbers were found during spring. While the maximum density of bivalve larvae during winter was generally much less than 100/m3, the peak density during the spring of 1976 approached 2 x 104/m3. *Mulinia lateralis* was the dominant larval bivalve, appearing in collections from May to November. Other bivalve larvae identified in the estuary were *Mercenaria mercenaria*, *Mytilus edulis*, *Argopecten irradians*, *Crassostrea virginica* (one specimen), *Geukensia demissa*, *Laevicardium mortoni*, *Tellina* spp., and Teredinidae.

Gastropod larvae exhibited abundance patterns similar to those of bivalve larvae. Although occurring in Barnegat Bay year-round, gastropod larvae attained maximum abundance from May through September, when the mean density ranged from about 1,000 to 10,000/m3. Minimum mean density values (< 100/m3) for this group were recorded from November through March (Sandine, 1984).

Barnacle larvae attained highest numbers in the bay during spring. Tatham et al. (1977, 1978) found maximum mean monthly densities of this larval group each April over a two-year sampling period. The highest mean monthly densities, which exceeded 10,000/m3, were observed in spring 1976.

Peak abundance of polychaete larvae was also recorded during spring. For example, the greatest abundance of polychaete larvae in 1976 and 1977 occurred during April, when the maximum mean monthly density exceeded 10,000/m3 each year. Larvae of *Polydora* spp. were most abundant .

b. Macrozooplankton

Macrozooplankton in the estuary were dominated by *Rathkea octopunctata*, *Neomysis americana*, *Crangon septemspinosa*, *Neopanope texana*, *Panopeus herbstii*, *Jassa falcata*, *Sagitta* spp., and *Sarsia* spp. Less abundant, albeit common, macrozooplankton species included zoeae of the mud crab *Rhithropanopeus harrisii*, the sand shrimp *Crangon septemspinosa*, and grass shrimp *Palaemonetes* spp. The abundance of macrozooplankton varied markedly from year to year. For example, hydromedusae (*R. octopunctata*) had a maximum mean monthly density of less than 1/m3 during 1975/1976 but greater than 200/m3 during 1976/1977. The density of *R. octopunctata* on April 21, 1977 exceeded 100/m3, but it decreased to less than 5/m3 only four days later. The mean density of *N. texana* zoeae ranged from 16/m3 to 60/m3 during night sampling in May, June, and July.

Macrozooplankton abundance, similar to that of microzooplankton abundance, peaked during the spring and summer. Predation by macrozooplankton played a significant role in controlling population sizes of microzooplankton during these seasons. The mean annual density of macrozooplankton ranged from 51 to 115/m3 during the period from September 1975 to September 1977.

Ctenophores (*Mnemiopsis leidyi*) and arrow worms (*Sagitta* spp.) preyed heavily on microzooplankton, especially copepods. Mountford (1980) noted that the biomass of microzooplankton (principally copepods) decreased substantially as the number of *M. leidyi* increased in the estuary. He observed a peak density of *M. leidyi* in June amounting to 107/m3. Tatham et al. (1978), however, registered the maximum density of this species in late August (29/m3), although it was present from spring to fall.

Beroe sp., another ctenophore, is a predator of *Mnemiopsis leidyi*. It first appeared in surveys when *M. leidyi* was abundant (Tatham et al., 1977, 1978). As such, the occurrence of *Beroe* sp. appeared to be governed by the abundance of *M. leidyi*. Sandine (1984) reported a maximum density of *Beroe* in early September (1/m3); however, the abundance of this ctenophore declined rapidly as the number of *M. leidyi* decreased in late September and October.

3. Conclusions

Zooplankton abundance in Barnegat Bay closely follows that of phytoplankton. Maximum phytoplankton biomass occurs in mid to late winter and in the summer. Phytoplankton numbers peak in the summer. Abundances of microzooplankton, macrozooplankton, and ichthyoplankton reach maxima in the spring or summer. Pulses of zooplankton appear shortly after phytoplankton blooms. For example, Loveland et al. (1969) reported a lag of 27 days between the winter-spring phytoplankton bloom (February) and a subsequent peak of zooplankton (March). The success of zooplankton populations in the estuary is closely coupled to abundances of phytoplankton.

IV. BENTHIC FAUNA

The benthic invertebrate community includes animal populations that live on the estuarine floor or on a firm substrate (epifauna), as well as animal populations that live in the bottom sediment (infauna). There are four size classes of benthic invertebrates: microfauna, meiofauna, macrofauna, and megafauna. The microfauna consist of those bottom dwelling animals which pass through sieves of 0.04-0.1 mm mesh. The meiofauna comprise larger forms captured on sieves of 0.04-0.1 mm mesh, but passing through 0.5 mm mesh sieves. The macrofauna are larger metazoans retained by sieves of 0.5-2 mm mesh. Megafauna are large animals, such as adult crabs and shrimp, typically caught using nets and dredges rather than bottom grab samplers.

The term meiofauna has also been used to define benthic metazoans that weigh less than 10-4 g (wet weight) (Fenchel, 1969; Fenchel, 1978). These organisms can be further subdivided into permanent and temporary members. While the permanent meiofauna incorporate adults of sufficiently small size to be classified in this group, the temporary meiofauna constitute juvenile stages of the macrofauna. Among the permanent meiofauna are nearly all gastrotrichs, kinorhynchs, nematodes, rotifers, archiannelids, halacarines, harpacticoid copepods, ostracods, mystacocarids, and tardigrades as well as representatives of the bryozoans, gastropods, holothurians, hydrozoans, oligochaetes, polychaetes, turbellarians, nemertines, and tunicates. The microfauna are composed essentially of protozoans, although some workers also include bacteria.

Other classifications of the benthic fauna are based on their life habits and adaptations. Nonparasitic species, for example, have been separated into epibenthic, infaunal, interstitial, boring, swimming, and commensal-mutualistic types. Epibenthic animals may attach to a substrate by basally cemented structures (e.g., serpulid polychaetes), holdfasts (e.g., stalked barnacles), or roots (e.g., stalked crinoids). Whereas some epifauna have a sessile habit living permanently attached to a substrate, others are vagile with considerable mobility over a surface. The infauna live in burrows and tubes, or they move freely through unconsolidated sediment. The amphipod, *Corophium volutator*, builds U-shaped burrows. The fiddler crabs, *Uca pugilator* and *U. pugnax*, excavate burrows, which in the case of *U. pugilator* have single openings that are almost always plugged at high tide on tidal flats. The polychaete, *Pectinaria gouldii*, constructs a tube of fine sand grains. *Nephtys incisa*, another polychaete, is motile and traverses through sediment in search of food.

Interstitial animals typically range from 0.2 to 3 mm in size. Many interstitial fauna have an oblong shape which greatly facilitates their movement through the grain interstices below the sediment-water interface. Meiobenthic organisms (e.g., nematodes, gastrotrichs, and harpacticoid copepods) are important interstitial forms.

Animals that bore into hard substrates do so via chemical or mechanical processes. Hence, the boring sponge, *Cliona celata*, and the boring turbellarian, *Stylochus ellipticus*, produce bore holes by means of chemical attack, and the woodborers, *Bankia gouldi* and *Teredo navalis*, generate burrows mechanically by rasping with their valves to excavate wooden substrates. *Urosalpinx cinerea*, the common oyster drill, utilizes both chemical attack and mechanical abrasion to bore through the valves of its prey. Examples of swimming benthic invertebrates are species of polychaetes (e.g., *Nereis* and *Nephtys*) and bay scallops (*Argopecten irradians*).

Benthic fauna can also be broadly classified according to their mode of obtaining food. Five categories are recognized: deposit feeders, suspension feeders, herbivores, carnivores-scavengers, and parasites. Loveland and Vouglitois (1984) examined the feeding types of the ten numerically dominant macrobenthic species at the mouth of Stouts Creek in Barnegat Bay. The most abundant deposit feeder at this location was the polychaete, *Pectinaria gouldi*. The suspension-feeding coot clam, *Mulinia*

lateralis, consistently ranked high in abundance. Of the carnivorous species, *Acteocina canaliculata* and *Mitrella lunata* had the highest ranking. *Cyathura polita* represented the only abundant scavenger. *Turbonilla interrupta* was the predominant benthic parasitic form. Herbivores were not tabulated, but the grazing periwinkle (*Littorina saxatilis*), in addition to several other grazing species, occurs in the estuary.

Physical and chemical factors in the estuarine environment clearly influence the functional morphology and behavior of the benthos. A salinity gradient along the longitudinal axis of an estuary affects the abundance and diversity of the benthos, although salinity profiles tend to be more stable in interstitial than overlying waters, and consequently the benthic infauna may be less impacted than the epifauna by salinity variations in the water column. The species composition of benthic communities depends greatly on the sediment type, which often varies appreciably within short distances. Fluctuations in other physical and chemical factors (e.g., dissolved oxygen, temperature, turbidity, wave action, and turbulence) can also alter the structure of the benthic community. The availability of organic matter and oxygen below the sediment-water interface has profound effects on the vertical distribution of the benthos in the sediment column.

Biotic factors, such as predation and species competition, cannot be discounted in studies of the occurrence and distribution of benthic fauna. They also act as limiting factors. Therefore, the mere tolerance of a species to physical and chemical conditions may not provide sufficient explanation for an observed distribution pattern. The occurrence of a species depends on biological adaptation as well. Differences in reproductive seasons, modes of feeding, size, and other biotic factors, for instance, may enable cohabitation of several species in the same general environment.

A. Faunal Categories

1. Infauna

With the exception of the research of Moser (1997), there have been no recent studies of the benthic fauna of the Barnegat Bay-Little Egg Harbor system. Phillips (1972) and Loveland et al. (1972, 1974) conducted detailed studies of the benthic invertebrate community in western Barnegat Bay between 1965 and 1973 as part of a larger study to assess the effects of the Oyster Creek Nuclear Generating Station on the ecology of the estuary. Loveland and Vouglitois (1984) reviewed results of these investigations. More recently, Moser (1997) examined the distribution and density of benthic infauna at two sites in the Barnegat Bay-Little Egg Harbor estuarine system. A significant, albeit more than 25-year-old, benthic database has only been developed for the western portion of Barnegat Bay between Stouts Creek and Oyster Creek, with comprehensive baseline data lacking for the remainder of the estuary. The benthic community of Little Egg Harbor is largely uncharacterized.

Between August 1969 and December 1973, 216 benthic invertebrate species were collected in Barnegat Bay (Loveland and Vouglitois, 1984) (Table 5). The mean density of benthic macroinvertebrates in the bay during this 53-month period amounted to 2,775 individuals/m2 and ranged from 56 to 43,220 individuals/m2. The numerically dominant species included the bivalve, *Mulinia lateralis*, the polychaete, *Pectinaria gouldi*, and the gastropod, *Acteocina canaliculata*, which preys on *M. lateralis*. These species are opportunistic forms that experience large fluctuations in density.

In the mid-1960's, Phillips (1972) recovered *Mulinia lateralis* in densities ranging from 1 to 318 individuals/m2, and *Pectinaria gouldii* in densities from 2 to 700 individuals/m2. *Acteocina canaliculata* was rare. By 1969, the densities of the three species increased dramatically; *M. lateralis* occurred in numbers as high as 36,840 individuals/m2, with a mean value of 10,890 individuals/m2. The maximum and mean densities of *P. gouldii* in 1969 equalled 4,980 individuals/m2 and 1,649 individuals/m2, respectively. Somewhat less abundant, *A. canaliculata* appeared in densities up to 2,540 individuals/m2. The mean density of this species was 224 individuals/m2.

Benthic invertebrates were extremely abundant in Barnegat Bay during 1969, but from 1969 to 1973, a marked decline in the number of invertebrates ensued. The densities of the dominant forms (i.e., *Mulinia lateralis*, *Pectinaria gouldii*, and *Acteocina canaliculata*) dropped substantially during this 4-year period, and other common species (e.g., the gastropods, *Turbonilla interrupta* and *Mitrella lunata*, and the polychaete, *Scoloplos fragilis*) followed similar trends. Some species, such as *Ampelisca* spp. and *Molgula manhattensis*, increased in abundance during this interval of generally diminishing densities. The mean abundance of benthic invertebrates dropped from 9,000-17,000 individuals/m2 in 1969 to less than 500 individuals/m2 in 1973.

While the absolute abundance of benthic species varied considerably during the 1969-1973 period, the species composition of the community remained quite stable in space and time. Most of the benthic species collected during this period were deposit feeders. From 1970 to 1973, for example, 53-85% of the individuals identified in benthic samples were deposit feeders, 6-47% suspension feeders, and 3-23% carnivores. The numerical dominance of these deposit feeders seems to typify a less stable, medium-successional stage, estuarine soft-bottom benthic community.

Moser (1997) collected benthic infauna at one site on the western side of Little Egg Harbor adjacent to undeveloped saltmarsh near Westecunk Creek and at a second site in a restricted basin in Barnegat Bay near Barnegat Inlet. The second site was located between the open bay and marinas connected to the suburbanized barrier island. Both sampling sites were euhaline, subtidal, and predominantly fine grained. Replicate sediment cores for infauna analysis were collected by divers in August 1993 and March 1994.

At the western Little Egg Harbor sampling site, *Cossura* sp. was the only abundant species present both in August 1993 (4,091 individuals/m2) and March 1994 (3,203 individuals/m2) samples. Although *Sphaerosyllis* spp. (*S. taylori*, *S. longicauda*, and *S.* sp.) were also abundant in March 1994 (4,091 individuals/m2), they were much less numerous in August 1993 (130 individuals/m2). Table 6 provides the mean density of the most abundant benthic invertebrates at this location.

The opportunistic *Capitella* spp. dominated the infauna (24,935 individuals/m2) at the Barnegat Bay site in March 1994. No samples were collected at this site in August 1993 when bottom waters were anoxic. *Capitella* spp. are pollution tolerant forms, and their overwhelming dominance at the Barnegat Bay site may be an indicator of elevated organic concentrations or other contamination in bottom sediments (Grassle and Grassle 1974, 1976).

Moser (1997) attributed the differences in benthic infaunal communities at the two sampling sites to several factors. At the Barnegat Bay site, a combination of factors probably accounted for the dominance of *Capitella* spp., including: (1) high total organic carbon concentrations, possibly due to the proximity of marinas and the suburbanized portion of the barrier island; (2) seasonal anoxia leading to an absence of competition; and (3) the proximity of Barnegat Inlet which may act as a conduit for transporting larvae to the site. At the Little Egg Harbor sampling site, the exclusive presence of the opportunistic polychaete species, *Cossura* sp., was ascribed to occasional low oxygen conditions coupled to high organic carbon concentrations in the sediment.

2. Mobile Epifauna

The estuary supports a rich assemblage of mobile epifauna, including such important groups as crabs, shrimp, and echinoderms. These organisms are more difficult to sample quantitatively than the infauna, and thus have been less well characterized. Nevertheless, they remain ecologically significant in this shallow water system. For example, sand shrimp (*Crangon septemspinosa*) and grass shrimp (*Palaemontes vulgaris* and *P. pugio*) provide forage for resource species and predators on smaller fauna. Mysid shrimp (*Neomysis americana*) commonly occur on or near the bottom, but are less closely associated with it than the aforementioned taxa. These diminutive shrimp also constitute a valuable food source for recreationally and commercially important finfish in the estuary.

Mud crabs (i.e., *Neopanope texana*, *Panopeus herbstii*, and *Rhithropanopeus harrisii*) are common on the bay bottom, and may be a factor in limiting recruitment of harvestable clams. These crabs may consume large numbers of juvenile hard clams (*Mercenaria mercenaria*) in the estuary. They may have contributed to the decline in landings of hard clams in the system during the 1990's.

Other notable members of the mobile epifauna are horseshoe crabs (*Limulus polyphemus*), gastropods (e.g., *Busycon canaliculatum*, *B. carica*, and *Polinices duplicatus*), and starfish (*Asterias forbesi*). These species also consume hard clams. Hence, the gradual reduction in the abundance of hard clams during the 1990's may be impacting these populations as well, although no recent quantitative sampling has been conducted in the estuary to verify such a relationship.

3. Fouling Organisms

Shafto (1974) and Loveland and Shafto (1984) investigated the fouling community of the estuary, concentrating on the settlement and growth of epiflora and epifauna on man-made materials. Shafto (1974) recorded 38 species (21 mobile and 17 sessile forms) of fouling organisms from more than 100 exposure panels deployed in Barnegat Bay. Bacteria, algae, amphipods, barnacles, bryozoans, molluscs, polychaetes, sponges, and tunicates are the principal components of the fouling community. Although both sessile and mobile biofouling populations existed in the bay, the dominant forms were sessile, with *Balanus eburneus* and *Hydroides dianthus* being most abundant. These two species plus *Bowerbankia gracilis* and *Membranipora* sp. consistently dominated the fouling community in most regions. Maximum settlement occurred from May to October when food supply and water temperature are optimum, and minimum settlement, from November to April. In areas with salinities below 15 ‰, *B. eburneus*, *B. gracilis*, *Membranipora* sp., *Polydora ligni*, and *Melita nitida* predominated. Where salinity exceeded 15 ‰, *Botryllus schlosseri*, *Corophium* sp., *H. dianthus*, and *Molgula manhattensis* were most abundant.

The species composition of the fouling community varied monthly but repeated seasonally in response to predator-prey interactions, cycles of reproduction and settlement, and seasonal changes in environmental conditions. Therefore, some fouling species, such as *Botryllus schlosseri* and *Hydroides dianthus*, dominated during the summer, whereas others, such as *Balanus improvisus* and *B. balanoides*

attained peak abundance in winter. Biofouling algal populations, which are seasonally abundant, can affect abundance of the biofouling fauna. *Codium fragile*, *Enteromorpha intestinalis*, *Polysiphonia harveyi*, and *Ulva lactuca* are the most important biofouling flora in the system.

Larval dynamics strongly influenced the complexity of the fouling community. The settlement of biofouling larvae was responsive to mud and detritus accumulation on substratum surfaces and to illumination. Some biofouling larvae (e.g., *Corophium* sp., *Melita nitida*, *Polydora ligni*, *Sabellaria vulgaris*) appeared to be photopositive, setting most densely on the upper surfaces of wooden substrata. Others (e.g., *Balanus eburneus*, *B. schlosseri, B. gracilis*, *Hydroides dianthus*, *Membranipora* sp., and *Molgula manhattensis*) settled most heavily on the lower surfaces of substrata and seemed to be photonegative. The observed distribution and density patterns of adult biofouling populations in the estuary were thought to be the result of attraction of larvae to microflora, bacteria, substratum chemicals, and the same species, as well as avoidance of interspecific competition.

4. Boring Organisms (Teredinids)

Investigations of the boring community of the estuary during the 1970's and 1980's revealed the occurrence of four teredinid species: *Bankia gouldi*, *Teredo navalis*, *T. bartschi*, and *T. furcifera* (Richards et al., 1984). *Bankia gouldi* was the dominant teredinid along the western perimeter of Barnegat Bay, and *T. navalis* was the dominant form along the eastern perimeter. *Teredo bartschi* and *T furcifera*, tropical-subtropical woodboring species which are no longer found in the estuary, became adapted to areas affected by thermal discharges from the Oyster Creek Nuclear Generating Station during the 1970's and 1980's. Of the four teredinid species identified in the estuary, *B. gouldi* had the greatest spatial distribution.

Spawning of teredinids in Barnegat Bay occurred primarily during the warmer months of the year (April through October). Successful settlement of larvae on wooden surfaces took place between July and December. Maximum teredinid abundance and destruction developed during the summer season, but most teredinids did not survive the winter.

Survival, growth, abundance, and intensity of attack of teredinids appeared to be dependent primarily on water temperature, salinity, presence of humic material, and the availability of untreated (noncreosoted) wood. Of these factors, water temperature and the presence of a wooden substratum probably exerted the greatest influence on the behavior of teredinids. Low temperatures during the winter precluded spawning, arrested growth, and caused substantial mortality of the adult populations. The few adults that survived the winter months perpetuated the populations during the summer when more optimum water temperatures induced spawning and rapid growth, resulting in increased damage to wooden structures.

Aside from the teredinids, the crustacean borer *Limnoria* sp. caused damage to wooden structures in the southern portion of Barnegat Bay. *Limnoria* sp. destroys the outer portion of wooden structures, and its impact can be considerable. Consequently, untreated wooden pilings are typically reduced to an hourglass structure under attack by *Limnoria* sp.

B. Conclusions

Benthic fauna are a major component of the Barnegat Bay-Little Egg Harbor estuarine food web. In shallow estuaries, benthic fauna may rival zooplankton in their ability to regulate the abundance of phytoplankton. However, since Barnegat Bay and Little Egg Harbor presently have low stocks of large filter feeders (e.g., clams, oysters, and scallops), the capability of the benthos to control phytoplankton abundance is lessened. Benthic fauna are also important in nutrient regeneration. In addition, key taxa are potentially valuable for assessing water quality and habitat conditions. Some benthic populations are economically important. For example, hard clams are of recreational and commercial importance. Boring species have a more dubious distinction in that they can cause damage to man-made structures, and fouling assemblages increase maintenance requirements.

The overall health of the system is closely coupled to the abundance, distribution, and diversity of benthic fauna in intertidal and subtidal habitats. Clearly, benthic fauna are extremely important to the structure and function of biotic communities in the estuary. Future management strategies, therefore, must consider the development and implementation of restoration and maintenance programs to improve the health and long-term viability of benthic habitats and communities in the estuary.

V. FINFISH

A. Estuarine Fish

Finfish studies of the ichthyofauna of Barnegat Bay were conducted by Marcellus (1972) during the late 1960's and early 1970's and by several investigators from September 1975 through August 1981 (Tatham et al., 1977, 1978; Vouglitois, 1983; Tatham et al., 1984; Vouglitois et al., 1987) using trawls, seines, gill nets, or bongo nets. Most samples were taken along the western perimeter of the bay, with fewer collections made near Barnegat Inlet and extensive shoals in the eastern segment. Tatham et al. (1984) and Vouglitois et al. (1987) explain the sampling programs and life-history studies performed during these studies. More recently, Able and Fahay (1997) and Wilson and Able (1997) examined additional aspects of finfishes in the estuary.

According to Tatham et al. (1984), the fish community of Barnegat Bay is characteristic of mid-Atlantic estuaries and embayments, in general, and representative of the fish communities of New Jersey coastal bays. Only a few species numerically dominate the fish community of the estuary. For example, the bay anchovy (*Anchoa mitchilli*), Atlantic silverside (*Menidia menidia*), fourspine stickleback (*Apeltes quadracus*), spot (*Leiostomus xanthurus*), and winter flounder (*Pseudopleuronectes americanus*) constituted more than 90% of the total number of fish sampled in bay collections from September 1975 through August 1978, being responsible for 57.9, 22.1, 4.2, 3.8, and 1.9% of all individuals, respectively (Figure 2). During this period, 107 species belonging to 57 families were identified in the bay (Table 6).

Based on their spatial and temporal occurrence and their relative abundance within or outside the bay, the finfish were classified into five general assemblages: (1) residents (20 species) occupying the estuary year-round; (2) warm-water migrants (34 species) abundant primarily from April through November; (3) cool-water migrants (12 species) present from November through April; (4) marine strays (42 species); and (5) freshwater strays (7 species). Resident species comprised 31 % of all fish collected, warm-water migrants 65%, cool-water migrants 3%, and marine and freshwater strays 1% (Figure 3). Most

individuals were either small forage fishes, principally resident in the estuary, or young and juveniles of marine species present only seasonally. The diversity of fishes peaked from late summer through mid-fall (41 to 47 species per month). Warm-water migrants accounted for an increase in diversity from spring through fall. The number of species dropped sharply in the winter when only a few residents and cool-water migrants (13 species) inhabited the bay.

Migration and finfish distribution in the estuary are strongly affected by salinity, seasonal water temperature changes, spawning habitat, and food availability. Both resident and migratory fishes use the bay as a spawning area, with most reproduction triggered in the spring, summer, and winter. *Anchoa mitchilli*, *Gobiosoma* spp. (gobies), *Menidia menidia*, and *Syngnathus fuscus* (northern pipefish) were the main spawners during the spring and summer months, and *Ammodytes* sp. (sand lance) and *Pseudopleuronectes americanus* were the principal spawners during the winter months. From May through October, the young of most resident species (19 of 20 species) and the young of many warm-water migrants (21 of 34 species) utilized the estuary as a nursery area.

Examples of juvenile marine species which heavily utilize the estuary as a nursery during the summer months of the year are *Pomatomus saltatrix* (bluefish), *Brevoortia tyrannus* (Atlantic menhaden), *Cynoscion regalis* (weakfish), and *Leiostomus xanthurus* (spot.). Larval and young stages of *Ammodytes americanus*, *Micropogonias undulatus*, and *Pseudopleuronectes americanus* use the estuary as a nursery in the winter and early spring, as do young *Apeltes quadracus*. Immature *P. americanus* live in the bay year-round. Wilson and Able (1997) expressed concern that juvenile *P. americanus* readily use marina habitats in the estuary and may be exposed to hydrocarbons and heavy metals in these areas. Table 7 specifies the usage of Barnegat Bay by residents, warm-water migrants, and cool-water migrants. Seagrass beds, saltmarshes, and tidal creeks clearly provide important habitat for finfishes in the estuary. Each of these major habitats, which can contain important "micro-habitats", are often used by a unique assemblage of fish species (Rountree and Able, 1993; Able et al., 1996), thereby contributing to the diversity of species in Barnegat Bay. In a recent analysis of the temporal and spatial variation in fish species composition in Little Egg Harbor, the majority (98.7%) of three spine stickleback and most naked gobies (76.1%) and weakfish (68.6%) were captured in a freshwater creek; all silver perch, the majority (99.0%) of four spine stickleback, and most (75.0%) lizardfish were captured in seagrass; and all hakes (*Urophycis* spp.), skates, windowpane, and the majority (94.5%) of smallmouth flounder were collected in deeper-water channels (Jivoff and Able, in review).

The absolute abundance of fishes in Barnegat Bay is highest from May through November due to the arrival of warm-water migrants and the recruitment from spawning populations in the estuary. Far fewer individuals are present during the winter, although an increase in abundance becomes evident as early as March or April. Larvae and juveniles attain maximum numbers in the spring and summer months. Annual variations in absolute abundance of 50 to 100% are not unusual. Fluctuations in environmental conditions that influence reproductive success may be responsible for such large variations in abundance.

The bay anchovy and Atlantic silverside are the two most abundant species in the bay. During their three-year survey, Tatham et al. (1984) showed that the bay anchovy and Atlantic silverside were the first and second most abundant species in the bay, respectively. According to Vouglitois et al. (1987), the bay anchovy accounted for 27% of the total finfish catch from 1975 to 1981. This species is the mainstay of Barnegat Bay forage fish and a ubiquitous inhabitant of the creeks, lagoons, and local embayments of the system. The maximum abundance of bay anchovy occurs between May and October each year, but an offshore and southerly migration from the estuary to continental shelf wintering grounds takes place in the fall. Similarly, the Atlantic silverside migrates to deeper waters of the estuary or coastal ocean in the winter.

A bimodal peak in the abundance of trawl catches of bay anchovy has been documented; an initial peak corresponds to May or June and a second, often larger peak takes place in September or October. Bay anchovy eggs and larvae numerically dominate ichthyoplankton samples in the estuary, comprising up to 98 and 56% of the annual egg and larval catches, respectively. Little Egg Harbor plays a key role in determining the abundance and diversity of fish in Barnegat Bay because it offers a natural connection (Little Egg Inlet) to oceanic environments and contains a variety of habitats for various life history stages of fish. As a result, larval fishes from a variety of environments, are transported into the estuary and immediately find suitable settling habitats (see Witting et al., 1999). In a 1976 survey of Manahawkin Bay and Little Egg Harbor, the New Jersey Department of Environmental Protection and Energy registered 66 species of finfish. The ten most abundant species in this survey were the bay anchovy, Atlantic silverside, fourspine stickleback, mummichog, and inland silverside (*Menidia beryllina*), Atlantic menhaden (*Brevoortia tyrannus*), banded killifish (*Fundulus diaphanus*), silver perch (*Bairdiella chrysoura*), winter flounder, and white perch (*Morone americana*). The five most abundant species comprised up to 80% of all specimens for all gear types (U.S. Fish and Wildlife Service, 1996).

A more recent survey in Little Egg Harbor produced very similar results in terms of both the number (67 species in 28 families) and composition of species captured (Szedlmayer and Able, 1996). There was considerable temporal (among months) and spatial (among five sites; 2 seagrass beds, 1 freshwater creek, and 2 deep-water channels) variation in fish abundance and species diversity, indicating that these areas offer critical habitat to a variety of species and life history stages of fish (Jivoff and Able, in review). Finfish collections of Wilson and Able (1997) were dominated by shallow water estuarine residents or juveniles of species that utilized the area as nurseries. Included among the most abundant species were the Atlantic silverside, fourspine stickleback, sheepshead minnow (*Cyprinodon variegatus*), naked goby (*Gobiosoma bosc*), and winter flounder. However, strays from more southern waters were also recovered (e.g., *Chaetodon ocellatus*, *Chasmodes bosquianus*, *Hypsoblennius hentz*, *Lactophrys* sp., *Lutjanus griseus*, and *Monacanthus* sp.). In regard to the relative abundance of fishes in Barnegat Bay, the ten most common species recorded in numerical order are the bay anchovy, Atlantic silverside, fourspine stickleback, spot, winter flounder, inland silverside, northern pipefish, mummichog (*Fundulus heteroclitus*), bluefish, and oyster toadfish (*Opsanus tau*) (U.S. Fish and Wildlife Service, 1996). The bay is an important nursery area for some of these species (e.g., spot, bluefish, etc.). It also provides an important habitat for summer spawners (e.g., bay anchovy, Atlantic silversides, gobies, and northern pipefish) as well as winter spawners (e.g., sand lance).

In summary, the community structure, seasonal patterns, and populations trends of the finfish community of the Barnegat Bay-Little Egg Harbor estuarine system are similar to those of the larger New Jersey estuaries of Delaware Bay and Raritan Bay, and other coastal bays from Sandy Hook to Cape May. Forage fishes and juveniles numerically dominate the communities, utilizing the system primarily as a nursery area. Adult marine forms spawn or feed in the bay, but typically inhabit oceanic waters. Warm-water and cool-water migrants appear seasonally, occasionally being present in greater numbers than resident species. Warm-water migrants are more abundant than cool-water migrants, and account for large numbers of fish in the bay from July through November. At this time, young of resident and warm-water migrants coexisting in the estuary reach maximum population sizes. The finfish community, therefore, is characterized by: (1) numerical dominance of a few species; (2) forage fishes and juveniles; (3) seasonal occurrence of warm-water and cool-water migrants; and (4) large fluctuations in the size of populations (Tatham et al., 1984; Vouglitois et al., 1987).

B. Freshwater Fish

The acid waters of undisturbed Pinelands stream systems support a distinctive fish fauna characterized by thirteen native species and the absence of non-native forms (Hastings 1979, 1984; Graham and Hastings, 1984; Graham, 1993; Zampella and Bunnell, 1998). Native Pinelands fishes include mud sunfish (*Acantharchus pomotis*), yellow bullhead (*Ameiurus natalis*), American eel (*Anguilla rostrata*), pirate perch (*Aphredoderus sayanus*), blackbanded sunfish (*Enneacanthus chaetodon*), bluespotted sunfish (*Enneacanthus gloriosus*), banded sunfish (*Enneacanthus obesus*), creek chubsucker (*Erimyzon oblongus*), redfin pickerel (*Esox americanus*), chain pickerel (*Esox niger*), swamp darter (*Etheostoma fusiforme*), tadpole madtom (*Noturus gyrinus*), and eastern mudminnow (*Umbra pygmaea*).

Fish species that naturally occur in peripheral areas or that were introduced to New Jersey occur in degraded waters displaying elevated pH and dissolved solids. Peripheral species include pumkinseed (*Lepomis gibbosus*), brown bullhead (*Ameiurus nebulosus*), tessellated darter (*Etheostoma olmstedi*) and golden shiner (*Notemigonus crysoleucas*). Largemouth bass (*Micropterus salmoides*) and bluegill (*Lepomis macrochirus*) are among the most common introduced species. These nonindigenous species usually do not occur in Pinelands waters with pH less than 5.5 (Zampella and Bunnell 1998).

As part of a Pinelands-wide inventory of aquatic communities, Lloyd et al. (1980) described the status of fish communities in freshwater streams within the Barnegat Bay drainage area. This inventory, based on data collected through various surveys, is summarized in Table 8. Although these data reflect past conditions and are too general to assess conditions in individual tributaries, they provide a broad measure of the status of fish communities in the major stream systems discharging to Barnegat Bay.

Lloyd et al. (1980) reported that native, peripheral, and introduced species occurred in the Metedeconk River and the Toms River. The presence of peripheral and introduced species in the Toms River basin indicates that this system is modified in comparison to undisturbed basins. Except for the occurrence of white catfish (*Ameirus catus*) at one site, fish species reported in Cedar Creek reflect undisturbed conditions. Ten characteristic Pinelands species and two peripheral species were reported for the Oyster Creek and Forked River systems. The two peripheral species were pumpkinseed and golden shiner. Based on two collections, Lloyd et al. (1980) described the Mill Creek system as a modified Pinelands stream. Non-native Pinelands species found in this system included brown bullhead, golden shiner, and pumpkinseed. Collections from Westecunk Creek at Stafford Forge included only characteristic Pinelands species.

The establishment of non-native fish is frequently associated with human-related disturbances (Moyle, 1986). Since elevated pH appears to be a prerequisite for the occurrence of non-native fish species in Pinelands waters (Hastings, 1979, 1984; Graham and Hastings, 1984; Graham, 1993; Zampella and Bunnell, 1998), maintenance of acid-waters is critical for the preservation of the region's native fauna. Whether a non-native species is able to invade degraded water also depends on accessibility. However, the importance of this factor is somewhat diminished since species such as largemouth bass and bluegill are widely distributed throughout the Pinelands. Because many non-native species are more typical of lakes and ponds (Hastings, 1984), these habitats may be more susceptible than streams to changes in fish communities due to aquatic degradation.

VI. CRUSTACEANS

A number of studies have examined the abundance and species composition of decapod crustaceans in Barnegat Bay, particularly in Little Egg Harbor. Previous studies have examined the decapod assemblage in a variety of habitats, such as large and small intertidal creeks, seagrass beds, and macroalgae beds, using a variety of gears, including seines, weirs, trawls, and throw-traps (Wilson et al., 1990a; Sogard and Able, 1991; Rountree and Able, 1993; Szedlmayer and Able, 1996). Viscido et al. (1997) performed a beam trawl survey of the decapod species assemblage on the continental shelf adjacent to Little Egg Inlet. Species found in greatest abundance include, the blue crab (*Callinectes sapidus*), marsh grass shrimp (*Palaemonetes vulgaris*), seven-spined bay shrimp (*Crangon septemspinosa*), the false *Zostera* shrimp (*Hippolyte pleuracanthus*), the hermit crab, (*Pagurus longicarpus*), and green crab (*Carcinus maenas*). Other species that are less abundant include the rock crab (*Cancer irroratus*), lady crab (*Ovalipes ocellatus*), lesser blue crab (*Callinectes similis*), and spider crabs (*Libinia emarginata* and *L. dubia*). Species that are apparently common but either rarely considered or not consistently captured in commonly used collecting gears include mud crabs (e.g., *Panopeus herbstii*) and fiddler crabs (*Uca pugnax*, *U. minax*).

The decapod assemblage in Little Egg Harbor is characterized by both temporal and spatial variation in abundance of decapods. In general, decapod abundances are low in winter, increase through the spring and peak in the summer or fall. This pattern is also found in other mid-Atlantic estuaries (Orth and Heck, 1980; Heck and Thoman, 1984; Heck et al., 1989), as well as in previous studies in Barnegat Bay and adjacent Great Bay (Vouglitois, 1983; Wilson et al., 1990a; Sogard and Able, 1991; Rountree and Able, 1993). However, temporal patterns in decapod abundance can vary among habitats, indicating differential use of habitats. For example, habitat use by decapods is influenced by the presence of refuge against predators (Wilson et al., 1987; Wilson et al., 1990b; Dittel et al., 1995; Hines and Ruiz, 1995), life history pattern (Haefner, 1976; Wilson et al., 1990a; Hines et al., 1995), and physiological state, especially proximity to molting (Hines et al., 1987; Shirley et al., 1990; Metcalf and Lipcius, 1992) or spawning (Schaffner and Diaz, 1988). Temporal patterns in decapod abundance are also affected by physical parameters, such as temperature (Orth and Heck, 1980; Jamieson and Phillips, 1993; Szedlmayer and Able, 1996), and salinity (Heck et al., 1995), and seasonal changes in habitat quality (Orth and Heck, 1980; Butler et al., 1995; Beck, 1997).

There is likewise a considerable amount of temporal and spatial variation in the species composition of decapods. Previous studies have documented several species in each habitat surveyed, including the blue crab (*Callinectes sapidus*), marsh grass shrimp (*Palaemonetes vulgaris*), seven-spined bay shrimp (*Crangon septemspinosa*), the false Zostera shrimp (*Hippolyte pleuracanthus*), and the rock crab (*Cancer irroratus*) (Wilson et al., 1990a; Sogard and Able, 1991; Rountree and Able, 1993; Szedlmayer and Able, 1996). Alternatively, there are only a few species localized in one habitat, such as the hermit crab (*Pagurus longicarpus*) in marsh creeks (Rountree and Able, 1993), and the majority (99.4%) of lady crabs (*Ovalipes ocellatus*) in deep-water channels (Jivoff and Able, in review). In addition, there are several species present (regardless of habitat) at least one month per season, including the blue crab (*Callinectes sapidus*), rock crab (*Cancer irroratus*), lady crab (*Ovalipes ocellatus*), and spider crabs (*Libinia emarginata* and *L. dubia*). This is expected based on their life history mode, and their pattern of using estuarine habitats during all life stages (Bigford, 1979; Millikin and Williams, 1980; Able et al., 1996).

VII. SHELLFISH

The blue crab (Callinectes sapidus) and hard clam (*Mercenaria mercenaria*) are currently the only two

shellfish species which are of commercial and recreational importance in the Barnegat Bay-Little Egg Harbor estuary. Two other species which were once of commercial or recreational importance include the bay scallop, (*Argopecten irradians*) and the American oyster, (*Crassostrea virginica*). They are no longer harvested in the estuary. The blue mussel (*Mytilus edulis*) and soft-shelled clam (*Mya arenaria*) also occur in the estuary, but they are neither of recreational nor commercial importance. In the mid-Atlantic region, 7 of the 25 bivalve species found in Barnegat Bay are, or once were, commercially or recreationally important, including the hard clam, soft-shelled clam, bay scallop, American oyster, blue mussel, common razor clam, (*Ensis directus*), and surf clam (*Spisula solidissima*) (see Chapter 9).

VIII. BIRDS

The Barnegat Bay-Little Egg Harbor estuarine system also provides valuable habitat for shorebirds, seabirds, and waterfowl. The Atlantic coastal corridor of New Jersey is a major migrating pathway for many of these birds. Because of the location of the Barnegat Bay-Little Egg Harbor estuary on the Atlantic Flyway, thousands of shorebirds, seabirds, and waterfowl utilize the estuarine habitat as staging and overwintering areas. State and federal surveys have been conducted on avifauna of the estuary for many years (Castelli et al., 1997; Jenkins, 1997). These surveys are valuable in assessing the occurrence, distribution, migration chronology, and long-term trends of the populations. In addition, other avian investigations (e.g., Burger, 1996, 1997) have detailed the population dynamics and behavior of significant avifauna species utilizing the estuary.

A. Colonial Nesting Birds

Barnegat Bay supports large and diverse breeding colonies of birds (Burger 1996, 1997). It also provides habitat for one of the most diverse assemblages of colonial-nesting birds in the state. Twenty species of colonial waterbirds nest within Barnegat Bay-Little Egg Harbor estuarine habitats, including ten species of long-legged wading birds, six species of terns, three species of gulls, and black skimmers (Table 9). Colonial waterbirds are avifauna which nest in groups, either comprised exclusively of a single species or, more commonly, several species (Rogers et al., 1990). They include beach nesting birds (e.g., black skimmers and least terns), long-legged wading birds (e.g., herons, egrets, and ibises) which generally require trees and shrubs for nesting, and some gull and tern species which nest on salt marsh islands and dredged spoil islands (U.S. Fish and Wildlife Service, 1996). These avifauna are valuable bioindicators of environmental quality, notably the concentrations of chemical contaminants, levels of human disturbance, resource abundance, and habitat health in the system (Jenkins, 1997). They feed near the top of the food chain on numerous species of fish and invertebrates.

Regular census surveys of shorebirds and seabirds has revealed important long-term changes in population abundance, as well as recent changes associated with the degradation of critical habitat areas. For example, the New Jersey Department of Environmental Protection (Division of Fish, Game and Wildlife) has monitored colonial nesting waterbirds for more than 20 years. In addition, Burger (1997)

has conducted comprehensive investigations of colonial waterbird abundance over the same period of time. Declines in population abundance of some species during the past two decades have been attributed to the loss of habitat, increased human disturbance, and predation effects (e.g., from herring gulls and red foxes).

Results of state surveys conducted on colonial waterbird populations in the system between 1977 and 1995 indicate the following (see Tables 10 and 11):

• Among long-legged wading birds, the snowy egret was the only species which showed a significant decline in counts over the survey period;

• No long-legged wading bird species exhibited a long-term increasing trend of abundance;

• Among gulls, terns, and skimmers, the great black-backed gull was the only species which experienced a significant trend of increasing counts;

• Three species of long-legged wading birds (i.e., great egrets, snowy egrets, and glossy ibises) had an increase in the number of active nesting colonies;

• The number of herring gull and great black-backed gull colonies increased, whereas the number of active nesting colonies of black skimmers and least terns significantly decreased over the survey period.

Count trends in abundance of colonial waterbird populations in the Barnegat Bay-Little Egg Harbor estuary generally reflect statewide count trends (Jenkins, 1997).

The most recent comprehensive aerial colonial waterbird surveys were conducted by the New Jersey Department of Environmental Protection in 1989 and 1995. In 1989, 500 long-legged waders were recorded at seven heronies, compared to 435 long-legged waders registered at 14 heronies in 1995. The most abundant species observed for both years combined were, in decreasing order, the snow egret (*Egretta thula*), little blue heron (*E. caerulea*), tri-colored heron (*E. tricolor*), great egret (*Casmerodius albus*), glossy ibis (*Plegadis falcinellus*), black-crowned night heron (*Nycticorax nycticorax*), and yellow-crowned night heron (*N. violaceus*). Islands used as heronies include Middle Island (highest nesting abundance in 1989), Harvey Sedges (highest nesting abundance in 1995), Flat Island, Chadwick Island, Goosebar Sedge, Story Island, Island Beach, and Barnegat Inlet. More gulls were reported in 1989 (11,000 gulls dominated by laughing gulls, *Larus atricilla*) than in 1995 (5,000 gulls dominate by herring gulls, *L. argentatus*). The surveys revealed nearly 5,000 terns in 1989 and 2,600 terns in 1995. Colonies of terns have been documented on several islands in the northern and southern portion of the estuary. Barnegat Bay is an important area for nesting black skimmers (*Rynchops niger*), which occur on the beaches and bay islands. Barnegat Light is one of the most important sites for nesting black skimmers and least terns (*Sterna antillarum*).

B. Nesting Shorebirds

1. American Oystercatchers, Willets, and Piping Plovers

Although many shorebird species pass through the Barnegat Bay-Little Egg Harbor estuarine marshes

and beaches during both spring and fall migrations, the willet (*Cataoptrophorus semipalmatus*), American oystercatcher (*Haematopus palliatus*), and piping plover (*Charadrius melodus*) are the only three nesting species. During the summer months, these three shorebirds inhabit the beaches and dunes of the estuary, with the piping plover exhibiting the narrowest habitat preferences and the willet the broadest. Oystercatchers and willets also frequent broad sandy flats, marsh islands, and dredged material islands (Terres, 1980; Nol and Humphrey, 1994; Kibbe, 1995). Willets can be found in virtually any higher portions of the open marsh. Piping plovers and most willets leave the area of the Barnegat Bay estuary in early autumn to winter along the southeast Atlantic, Gulf of Mexico and Caribbean coasts (Haig, 1992; Nol and Humphrey, 1994; Kibbe, 1995; USFWS, 1996). While a majority of oystercatchers probably also leave the estuary in the fall, a sizable number remain along the southern New Jersey coast through the winter months, frequently overwintering in the southern portion of the estuary.

During late March and early April, all three species arrive in the area to begin nesting -- oystercatchers being the first to arrive, and willets the last (Haig, 1992; Nol and Humphrey, 1994). Willets prefer to nest along dunes covered by thick grasses and along the marsh-upland edge and other higher areas on the marsh and marsh islands (Terres, 1980; Kibbe, 1995). Along the marsh-upland edges, they select areas under dense brush, avoiding the open situations preferred by piping plovers and American oystercatchers. Burger and Shisler (1978) noted that willets often nest on low spoil piles associated with mosquito ditching and other open marsh water management practices. Nests range from shallow depressions in the sand to dense cups formed of marsh or dune vegetation (Kibbe, 1995). American oystercatchers, while inhabiting some of the same general areas as willets, tend to nest in much more open situations, such as broad sand flats, open beaches, sparsely vegetated dredge spoil, and sandy portions of marsh islands (Nol and Humphrey, 1994). The oystercatcher's nesting substrate is typically sand or shell fragments, but can include wrack on marsh islands. In contrast to the broader nesting habitat of both willets and oystercatchers, piping plovers in the estuary currently nest only on barrier island beaches, although they have occasionally nested on sandy dredge disposal sites (Haig, 1992; USFWS, 1996). Plovers usually nest in small shallow, shell-lined depressions on open sandy beaches, either along broad sand flats or on the upper beach berm (Haig, 1992). Less commonly, nests are located within the dune system, usually in overwash or blowout areas. Piping plovers locate their nests in totally exposed locations or sheltered areas at the base of a clump of beach grass (*Ammophila breviligulata*) or other beach vegetation.

Willets feed on a variety of marine invertebrates including marine worms, crustaceans, and mollusks as well as on insects found along the muddy banks of tidal creeks, mud flats, sand flats, and salt marsh ponds and panes (Kibbe, 1995). Oystercatchers consume marine mollusks, especially bivalves, but also ingest other marine invertebrates captured on mudflats, tidal washes, and on exposed marsh surfaces (Nol and Humphrey, 1994). Piping plovers feed on smaller marine invertebrates, including marine worms and crustaceans, as well as terrestrial insects, larvae and eggs captured in high wet sandy areas, at the wrack line and on the upper dry beach (Haig, 1992).

The recently completed New Jersey Breeding Bird Atlas project (New Jersey Audubon Society, in preparation) found that American oystercatchers and willets were "possible," "probable," or "confirmed" breeding in 12 and 25 survey blocks, respectively, within the Barnegat Bay-Little Egg Harbor estuary (a survey block = ~9.5 square miles). No trend data specific to the estuary or state are available for either the oystercatcher or willet. North American Breeding Bird Survey (BBS) routes do not adequately sample large roadless areas such as salt marsh habitat and sample sizes and are not sufficient to evaluate local trends. On a broader scale, the BBS data suggest that willet populations were roughly stable in the U.S. Fish and Wildlife Service (FWS) Region 5 (roughly the northeastern U.S., including New Jersey) between 1966-1996. BBS data were not available for American oystercatchers; however, the population is generally believed to be expanding (Nol and Humphrey 1994). Only the American oystercatcher is

regularly observed on Christmas bird counts and then only in the extreme southern portion of the estuary. Numbers counted on the Oceanville count have been generally increasing over the past 15 years.

Because they are listed as "threatened" under the federal Endangered Species Act and as "endangered" by the New Jersey Department of Environmental Protection, piping plovers populations are closely monitored. In the Barnegat Bay-Little Egg Harbor estuary area, piping plovers have nested at the following sites over the past 10 years: Mantoloking, South Mantoloking beach (Brick Twp.), Island Beach State Park, Barnegat Light, Loveladies, and the Holgate section of Forsythe National Wildlife Refuge (Table 12). Populations generally increased during the period from 1985 to 1992, peaking at 37 nesting pairs (Jenkins et al., 1998a). Since that time populations have declined markedly to the lowest levels (17 pairs in 1997) observed since intensive monitoring began in 1985.

The habitat for all three species has been significantly diminished or altered by beach stabilization, particularly at inlets, through the construction of jetties. Residential and commercial development has also been detrimental. Currently, however, the primary threats in the Barnegat Bay-Little Egg Harbor estuary region involve excessive predation and disturbance of nesting by humans, dogs, and vehicles (Jenkins et al., 1998b). This is especially true for the piping plover, with its habitat restricted to the more heavily developed and more highly disturbed barrier island beaches. Disturbance disrupts normal incubation and brood care, leading to increased nest and chick mortality from exposure and predation (Haig, 1992; USFWS, 1996). Humans also cause direct mortality by accidentally crushing cryptic nests and chicks. Vehicles operating on the beach pose a particular threat in this regard.

The most significant predators on these shorebirds in the Barnegat Bay-Little Egg Harbor estuary include red foxes (*Vulpes vulpes*), raccoons (*Procyon lotor*), gulls (*Larus* spp.) and crows (*Corvus* spp.) (Jenkins et al., 1998b). The populations of all of these predators have increased during the past few decades as these animals have adapted to anthropogenic changes in the estuary.

The piping plover is the only breeding shorebird for which there is an active management program in the estuary region. Because of their overlapping nesting habitats, American oystercatchers receive some benefit from these management efforts. Management is primarily directed at two areas: (1) reducing the direct and indirect impacts of human recreation; and (2) reducing losses of nests and chicks to predators.

Reducing the affects of human disturbance typically involves the construction of fencing and posting signs around nesting areas (Jenkins et al., 1998b). In historically used nesting areas, such as the northern end of Barnegat Light, fencing is erected prior to the nesting season. In other areas, "symbolic" string and post fencing are erected after individual nests have been established. At Holgate, which is part of the Forsythe National Wildlife Refuge, human disturbance is virtually eliminated by closing the beach to human access during the nesting season. Educational outreach designed to inform the beach-going public of the presence of beach-nesting shorebirds is a very important aspect of managing human disturbance.

The most common method employed to reduce predation of nests is the use of predator exclosures. Predator exclosures consist of a small circular fence (~3 m) topped with netting or twine placed over the nest. They are designed to allow normal ingress and egress by incubating birds while excluding most predators (USFWS, 1996). The limited success of predator exclosures and their inability to protect precocial chicks has led wildlife managers to consider the employment of other methods, including the removal of predators and control of predator populations by trapping, shooting, and poisoning.

2. Clapper Rails

In addition to shorebirds and colonial nesting birds, Barnegat Bay's marshes and islands are also home to the secretive clapper rail (*Rallus longirostris crepitans*). The clapper rail is a large gray-feathered salt marsh bird (4-5 cm high) commonly found nesting on any tributary of an estuary where marsh cordgrass (*Spartina alterniflora*) and fiddler crabs (*Uca* spp.) occur in association (Sanderson, 1977). It's calls can be heard on the tidal marshes from April through December in response to a sudden loud noise. While their primary food tends to be fiddler crabs, these birds are opportunistic feeders and will also consume marsh snails (*Melampus bidentatus*), grasshoppers, and other easily captured prey. The clapper rail is considered a common marsh nester from Little Egg Harbor north to the Barnegat Inlet. Farther north of the inlet, however, its numbers decrease as the tall marsh cordgrass it nests in also declines in abundance. The areal coverage of the salt marsh has been greatly reduced by residential fill. While always common, the population has declined over the centuries as marshes have been filled, diked or in other ways removed from tidal flow.

Some clapper rails can be found in the Barnegat Bay-Little Egg Harbor estuary throughout the winter; however, the local nesters arrive in the estuary as early as mid-March, with most appearing by mid-April. Nesting begins during the last week of May, and the peak of the first hatch occurs around the third week of June. The nest is usually located along tidal creeks or ditches where the tall cordgrass is found in linear bands at least 2 m wide, and the falling tide exposes adjacent mud flats for feeding. Only a few nests are found among high tide bush (*Iva frutescens*) and salt hay (*Spartina patens*) when these higher habitats occur adjacent to suitable feeding areas. In all cases a grass bowl 2-4 cm in diameter is constructed high enough to prevent daily flooding by tides. Some of the nests have a ramp built from the marsh floor to the bowl, and often a canopy of surrounding vegetation is pulled over the nest to provide overhead cover and protection from predators (Bent,1963). Nesting is usually completed by the end of July, and birds may start migrating south as early as the last week of August. Bandings indicate that the birds overwinter from South Carolina to Florida.

As with most animal populations, the major limiting factor for the clapper rail is adequate habitat. During the last fifty years of this century, almost 30% of the estuary marshes have been lost to dredging and filling (Ferrigno et al, 1973). However, clapper rail population numbers continually fluctuate in response to storms, high tides, and habitat changes associated with rainfall (Ferrigno and Kosinski, 1969). Other factors such as harsh winters, high predation, and human disturbance simply accentuate the trends. During the nesting season, storm tides and lunar tides often lead to the destruction of nests. Predators such as hawks and owls will take the young and adults, while fox, raccoons, gulls, and crows prey upon the eggs and fledglings. In years of low rainfall during the spring, growth of the marsh grasses is stunted. This renders the nests more vulnerable to predators and results in lower nest success and possibly lower survival of young (Ferrigno and Kosinski, 1969). Hurricanes have caused extensive losses of young and adults as well as nests due to high winds and storm surge (Shoemaker and Widjeskog, 1977). While this is an unusual occurrence in the Barnegat Bay area, the resulting reduction in population abundance can persist for years.

In past years, there was concern for clapper rail population loss due to the use of pesticides (i.e., DDT and malathion) on the marshes to control mosquito production. Pesticide spraying appears to have reduced the fiddler crab population which is heavily used by the clapper rail (Ferrigno and Kosinski, 1969). Changes in mosquito control practices have greatly reduced the use of pesticides, thereby mitigating their impact on clappers in the bay today.

Hunting of this bird continues on a very limited scale in New Jersey. There is no indication that hunting

has had a limiting effect upon the rail population in the Barnegat Bay-Little Egg Harbor area. The average bag taken annually by hunters is not known, but it is unlikely to be more than 3,000 clapper rails statewide. Within the estuary, harvest and hunter pressure is highest in the Little Egg Harbor area near the Seven Bridges Road that separates Great Bay from the Barnegat Bay-Little Egg Harbor system. There appears to be less and less hunting pressure upon this bird, and this trend is expected to continue.

Human disturbance during the breeding and nesting cycle may be important. Continual boat traffic and jet skiing in small creeks, as well as extensive fishing and crabbing from the shore, have the potential to reduce nesting success and brood survival. Wakes from speeding watercraft, which break onto the marsh, disturb the birds and destroy their nests. Destruction of grass under foot reduces the area suitable for nesting birds. Long-term management of this species in the Barnegat Bay-Little Egg Harbor estuary can best be accomplished by protecting the marsh from destruction and degradation by humans. Disturbance during the breeding and nesting period may be an important factor in reducing nesting success and brood survival.

2. Migratory Shorebirds

Shorebirds travel great distances between wintering grounds in South America and breeding grounds in the Arctic. They fuel these long flights by feeding heavily in a few areas (known as stopovers), where food is extremely abundant. This results in concentrations of shorebirds along the route, such as at Delaware Bay, the largest springtime stopover in the continental U.S. Their springtime migration is extremely time-limited: shorebirds make the journey and arrive in the Arctic just after snow-melt, and immediately begin nest initiation and egg-laying. They must arrive in good condition, since food is very limited and females lay four eggs that amount to 60% of body mass. Concentrating at stopovers is necessary, especially in spring before invertebrate prey is very abundant, but this activity makes the birds vulnerable to catastrophic events like oil spills. In Delaware Bay, the principal food for shorebirds is horseshoe crab eggs, made available by the high density of horseshoe crabs that spawn in May. In Barnegat Bay, shorebirds feed on invertebrates in marsh mudflats and beaches. In spring (April through mid-June), the most abundant species in the region are sanderling (*Calidris alba*), semipalmated plover (*Charadrius semipalmatus*), dunlin (*Calidris alpina*), short-billed dowitcher (*Limnodromus griseus*), red knot (*Calidris canutus*), ruddy turnstone (*Arenaria interpres*), and semipalmated sandpiper (*Calidris pusilla*). In the fall migration (mid-July through September), the same species occur, but may vary in abundance. Semipalmated sandpipers, for example, tend to concentrate in the Bay of Fundy, and spend less time in New Jersey on their southbound flight.

Shorebirds have affinities for particular types of habitat. Sanderling, red knot and ruddy turnstone prefer sandy beaches for feeding; they may also be found on shallow impoundments, but are usually in the marsh only for roosting or resting. Semipalmated sandpiper, dunlin, and dowitcher prefer mudflats and shallow impoundments for foraging, but may occasionally be seen on beaches. Semipalmated plovers prefer beaches but are found in fair numbers in marsh habitats.

Biologists from the Endangered and Nongame Species Program have conducted annual surveys of shorebirds on Delaware Bay beaches since 1986. The trend in total shorebirds has remained fairly stable, but significant declines have been documented in semipalmated sandpipers and sanderlings. There is also some concern over numbers of red knots, for which the lowest count recorded was in 1996. The red knot was listed as a state threatened species in 1999. Declining trends also have been observed in the

region and the Western Hemisphere.

Disturbance is one of the major problems facing migratory shorebirds. The cost of migration can be great, even when food is abundant and weather conditions are good. Spring migrants must feed nearly constantly to gain the weight necessary for their journey and to prepare them for nesting. Human presence, especially beach-walkers, unleashed dogs, and vehicles will disrupt the birds and cause them to leave optimal feeding beaches. When shorebirds constantly fly away from feeding areas due to disturbance, they cannot obtain sufficient energy for long migrations.

Since disturbance is one of the major threats to shorebirds, human activities should be managed to reduce intrusion into foraging and roosting areas. This can be done by establishing viewing areas marked with educational signs. Such an effort is most important during the spring migration in areas where shorebirds concentrate. In addition, marsh habitats where water control is available can be managed to provide shallow-water mudflat or impoundment habitat. In this case, water levels should be manipulated to provide shallow-water or moist-soil habitat during the spring and fall migration periods.

The Barnegat Bay-Little Egg Harbor estuarine system is also an important staging area and overwintering area for seabird populations. Cormorants (*Phalacrocorax* spp.), scoters (*Melanitta* spp.), loons (*Gavia* spp.), northern gannet (*Sula bassanus*), sooty shearwater (*Puffinus griseus*), and Wilson's storm petrel (*Oceanites oceanicus*) are examples of seabird populations migrating through the area. Surveys conducted from July through December 1995 in Cape May County registered more than 900,000 seabirds migrating along the coast (U.S. Fish and Wildlife Service, 1996).

3. Waterfowl

Barnegat Bay is an important migration and wintering habitat for waterfowl. Since 1956, the New Jersey Division of Fish, Game and Wildlife has conducted standardized aerial waterfowl surveys along the coastal wetlands of New Jersey, including the Barnegat Bay-Little Egg Harbor study area. The U.S. Fish and Wildlife Service also conducted waterfowl surveys on portions of the study area from 1985-1993. These surveys have been useful in documenting the occurrence, distribution, migration chronology, and long-term trends of waterfowl populations. New Jersey Division of Fish, Game and Wildlife aerial surveys were flown each January over the 40-year period. Between 1965 and 1972, state aerial surveys were also flown monthly from September through December (Castelli et al., 1997). These long-term aerial surveys clearly indicate that the Barnegat Bay-Little Egg Harbor system provides important migration and wintering habitat for waterfowl.

State surveys have revealed the occurrence of 22 waterfowl species and 3 groups of species (species of merganser, scaup, and scoter), and federal surveys documented 20 species and 3 goups of species (same as above) in the Barnegat Bay-Little Egg Harbor estuary study area (Table 14). Frequently observed waterfowl species were American black ducks (*Anas rubripes*) and mallards (*Anas platyrhynchos*) which were recorded during every survey. Atlantic brant (*Branta bernicla*), Canada goose (*Branta canadensis*), bufflehead (*Bucephala albeola*), common goldeneye (*Bucephala clangula*), canvasback (*Aythya valisineria*), scaup (*Aythya marila* and *Aytha affinis*), American widgeon (*Anas americana*), green-winged teal (*Anas crecca*), merganser spp. (*Mergus serrator, M. merganser*, and *Lophodytes cucullatus*), mute swans (*Cygnus olor*), and oldsquaw (*Clangula hyemalis*) were other commonly observed species.

Species present during September are largely resident breeders and a few early migrants. Species diversity peaks during fall migration and remains generally high throughout the winter. Waterfowl abundance appears to be maximum during the winter months (Castelli et al., 1997). Aerial surveys conducted in November show an average of more than 25,000 waterfowl migrating through the study area. The declining order of abundance of waterfowl species at this time was as follows: brant, American black duck, scaup, mallard, bufflehead, Canada goose, and mergansers. Aerial waterfowl counts during mid-winter surveys average nearly 50,000 birds, including significant concentrations, in descending order, of greater and lesser scaup (*Aythya marila* and *Aythya affinis*), brant (*Branta bernicla*), American black duck (*Anas rubripes*), bufflehead (*Bucephala albeola*), canvasback (*Aythya valisineri*a), mallard (*Anas platyrhynchos*), Canada goose (*Branta canadensis*), common goldeneye (*Bucephala clangula*), mergansers (*Mergus* spp.), and oldsquaw (*Clangula hyemalis*). In mid-winter surveys, migratory populations of sea ducks (e.g., canvasback, common goldeneye, and scaup) occur in significant concentrations (U.S. Fish and Wildlife and Service, 1996).

Analysis of the long-term waterfowl survey data for Barnegat Bay by Castelli et al., (1997) show that some species, notably mallard, northern pintail, Canada goose and oldsquaws displayed significant positive trends in population numbers. Scaup and redheads were identified as having significant negative trends.

Waterfowl concentration areas, as determined by aerial survey methods, vary widely by species, season, and weather conditions, making it difficult to identify "critical habitat areas". Individual species and multi-species flocks are widely scattered within individual flight survey segments; the location of waterfowl on specific habitats is not routinely recorded. During periods of severe weather with snow and extensive ice cover, waterfowl may also alter their behavior, concentrating in inlets and other open water areas. Standard aerial surveys provide only a diurnal snapshot of the distribution of waterfowl, often during the periods when some species are comparatively inactive (i.e., loafing in rafted concentrations). In addition, many waterfowl are crepuscular or nocturnal feeders and little is known about the location of important feeding areas. Some correlation can be drawn between aerial surveys, habitat, and food preferences (U.S. Fish and Wildlife Service, 1996). Castelli et al. (1997) found that dabbling ducks tend to dominate in areas where salt marsh habitat prevails. As might be expected, diving ducks dominate in open water areas. Swans were found primarily in areas of extensive beds of brackish water submerged aquatic vegetation, their preferred food source. However due to the incomplete knowledge of the habitat requirements of winter waterfowl, the identification of critical habitat areas is problematic. Future research must delineate more effectively the critical feeding habitats and concentration areas by employing telemetry and time activity budget studies (Castelli et al., 1997).

The Barnegat Bay-Little Egg Harbor estuary is an important waterfowl hunting area (Nichols and Castelli, 1997). Between 1961 and 1995, the total waterfowl harvest peaked during the 1971-80 period and declined thereafter (Figure 4). Black ducks, mallards, and buffleheads comprised the bulk of the harvest during this period, accounting for 20%, 14%, and 12% of the total harvest (Figure 5). Waterfowl have considerable economic and recreational value to the area.

F. Raptors

Osprey, peregrine falcon, and northern harrier are the primary raptors in this estuarine system. Ospreys are highly migratory; most winter in South America, with some birds remaining in the southeastern U.S.

Peregrine falcons that nest in New Jersey are mostly non-migratory, and remain in their nesting areas year around. Peregrines from northern nesting grounds migrate through and may winter in the state. Harriers are found in New Jersey marshes year around; New Jersey nesters probably also winter here, joined by many migrants from northern areas. All three species are on the New Jersey State endangered species list: the osprey is state threatened, the peregrine is state and federally endangered, and the harrier is state endangered.

These three species, all high trophic-level feeders, consume very different prey. Ospreys are primarily fish-eaters, taking ocean and bay fish such as white perch, menhaden and flounder. Peregrine falcons are bird-eaters that take their prey in flight. They feed on both local and migratory birds such as shorebirds, blue jays, flickers, and occasionally small ducks and gulls. Harriers hunt the marsh for rodents and small birds, in their characteristic low, "quartering" manner with a slight v-shaped profile.

Ospreys return to New Jersey in late March and begin building large stick nests on man-made nest platforms, duck blinds, channel markers, as well as on the ground. Three or four eggs are laid in mid- to late April, and incubation takes 35 days. Young are altricial, and fledge the nest at about 8 weeks of age, in mid- to late July. They begin migrating south in late August. Peregrine falcons begin nesting in mid-March. They nest on man-made coastal towers installed in the early 1980's to support the reintroduced population, as well as on large bridges and some buildings. They lay 3 or 4 eggs in a "scrape," a shallow depression in gravel; eggs hatch in about 32 days. Young fledge in 6 to 7 weeks, but remain in the area of the nest until they are able to fly and catch food. Harriers nest on the ground in the marsh, usually in *Spartina* and higher vegetation that keeps the nest above tidal water. They lay 4 or 5 eggs in early April, but may be delayed by spring flood tides. Young fledge in July. Timing and nest success is highly dependent on rodent populations and tides. During seasons when food is limited, the number of young that fledge is usually reduced.

Ospreys have increased statewide from 50 nests in 1975 to over 250 nests in 1998. Barnegat Bay has always been an important nesting area due to the density of nests and the excellent habitat. In 1997 and 1998, nest success was reduced in most colonies along the Atlantic coast, apparently resulting in starvation in some nestlings. The peregrine falcon population has been stable since 1992, with nest success in the estuary usually above average. Northern harriers have also been relatively stable, but it is normal for this species to have variable nest success year to year, depending on tidal conditions and prey populations. Available data suggest that the estuary nesting population is relatively low. Most nests occur in the Delaware Bay marshes.

These three aforementioned species are limited to varying degrees by human disturbance: all will abandon nesting when humans intrude nesting areas. Harriers and peregrines are particularly sensitive to disturbance. Ospreys in New Jersey are limited by the availability of trees and other structures for nesting, as a result of the reduction of natural habitats associated with development on barrier islands Predation can limit osprey and harrier nest success where predator populations are high. Toxins affect ospreys and peregrines. These birds are relatively long lived and bioconcentrate contaminants from their prey. Monitoring to date has not revealed significant toxic residues in Atlantic ospreys, but peregrines may have relatively high levels of PCBs and other organochlorines.

The greatest threat to these species is human disturbance. As a consequence, it is necessary to protect nest sites from disturbance throughout the nesting season. This can be accomplished by sign posting and enforcement of protection areas. Ospreys and peregrines require maintenance of nest structures. In the case of ospreys, placing nest platforms in suitable habitat has helped the population grow.

G. Songbirds

1. Estuarine (Marsh) Associated Birds

In contrast to the large long-legged wading birds, flocking shorebirds and waterfowl, and the raucous ubiquitous gulls, songbirds are relatively inconspicuous inhabitants of the Barnegat Bay-Little Egg Harbor estuarine marshes. Three species, more often heard than seen, characterize the emergent *Spartina* marshes and the adjacent brackish and freshwater marshes. These are seaside sparrow (*Ammodramus maritimus*), the sharp-tailed sparrow (*Ammodramus caudacutus*), and the marsh wren (*Cistothorus palustris*). Both sparrows breed in the saltmeadow (*S. patens*) and cordgrass (*S. alterniflora*) marshes, nesting from ground level to about a meter above the ground, often just above the reach of high tide (Greenlaw and Rising, 1994; Post and Greenlaw, 1994). Optimal seaside sparrow habitat occurs in extensive stands of *S. alterniflora*. The birds nest in clumps of overwintering or dead *S. alterniflora* (Post and Greenlaw, 1994; Greenlaw, 1992). Sharp-tailed sparrows are more typically associated with higher and drier areas of the marsh, usually dominated by *S. patens* (Greenlaw and Rising, 1994; Leukering, 1995). Marsh wrens inhabit a broader range of marshes, including tall cordgrass along tidal creeks, common reed (*Phragmites australis*) marshes, and cattail (*Typha spp.*) marshes. They build elevated nests attached to the stems of emergent vegetation (Kroodsma and Verner, 1997).

All three species can be found in the estuary's marshes during the winter months (National Audubon Christmas Bird Count data for Barnegat, Lakehurst, and Oceanville count circles), although the majority of the estuary's breeding populations probably migrate to more southern wintering grounds (Greenlaw and Rising, 1994; Post and Greenlaw, 1994; Kroodsma and Verner, 1997). Migrants arrive during April (seaside sparrow and marsh wren) and May (sharp-tailed sparrow), and the nesting season begins for all three species during early to mid-spring, lasting through the summer (Greenlaw and Rising, 1994; Post and Greenlaw, 1994; Kroodsma and Verner, 1997). All three species are capable of raising two broods. Migrants begin departing as early as mid-August and continue through October.

The seaside sparrow, sharp-tailed sparrow, and marsh wren primarily consume animal matter, such as adult and larval insects, spiders, and amphipods obtained from open stands of emergent marsh vegetation; shores of creeks, ditches, mudflats, and pools; and wrack (Greenlaw and Rising, 1994; Post and Greenlaw, 1994; Kroodsma and Verner, 1997). The marsh wren commonly feeds near the water, often among the emergent stems of marsh vegetation (Kroodsma and Verner, 1997). Seeds of marsh grasses also comprise a portion of the diet of the sparrows, but not the wren, especially during the fall and winter (Greenlaw and Rising, 1994; Post and Greenlaw, 1994; Kroodsma and Verner, 1997).

According to the synthesis of published studies found in Greenlaw and Rising (1994) and Post and Greenlaw (1994), the Barnegat Bay-Little Egg Harbor estuary lies within the region with the highest densities of both seaside and sharp-tailed sparrows. Breeding densities range from 0.3 - 20 singing males per hectare and 0.3 to 4.1 females per hectare for the seaside and sharp-tailed sparrows, respectively. Because the marsh wren is found in a much broader range of marsh habitat throughout North America, extrapolating published information on breeding is much more speculative. The situation in the Barnegat Bay-Little Egg Harbor estuary may be similar to that in Georgia where marsh wrens occupy narrow strips of cordgrass in tidal marshes along creeks and ditches (Kroodsma and Verner, 1997). In the narrowly defined habitat in Georgia, the densities of marsh wrens reached up to 110 territories per hectare. Integrating these densities over the entire marsh, however, would undoubtedly yield much lower density estimates.

The New Jersey Breeding Bird Atlas project found seaside sparrows, sharp-tailed sparrows, and marsh wrens "possible," "probable," or "confirmed" breeding in 17, 21 and 22 survey blocks, respectively, within the Barnegat Bay-Little Egg Harbor estuary area (a survey block = ~9.5 mi2). No trend data specific to the estuary or the entire state are available for any of the three species. North American Breeding Bird Survey (BBS) routes do not adequately sample large roadless areas such as saltmarsh habitat, and the sample sizes are not sufficient to evaluate local trends. On a broader scale, the BBS data suggest a decline in seaside sparrow numbers in the U.S. Fish and Wildlife Service (FWS) Region 5 (roughly the northeastern U.S., including New Jersey) between 1966-1996. BBS data show no trend in seaside sparrow numbers between 1966-1996 in FWS Region 5. No trend analysis was available on sharp-tailed sparrows for regions that include the Barnegat Bay-Little Egg Harbor estuary or the entire State of New Jersey.

Loss and alteration of suitable marsh habitats are the primary conservation concerns for marsh-nesting passerine birds. Ditching of marshes for mosquito control reduces the seaside sparrow's preferred foraging patches of smooth cordgrass (Post and Greenlaw, 1994). Decreasing water levels may also lead to invasion of bushes along ditch banks, thereby increasing access to predators (Post and Greenlaw, 1994). The effect of more "modern" open marsh water management mosquito control techniques is not clearly understood. When these techniques increase open water pools and channels on marshes without flooding higher nesting habitat, they may benefit seaside sparrows while reducing habitat for sharp-tailed sparrows (Greenlaw and Rising, 1994; Leukering, 1995). The use by marsh wrens of dense stands of *Phragmites*, an invasive wetland plant commonly believed to be of low wildlife habitat value, provides a note of caution for wetlands improvement and restoration programs that remove *Phragmites* stands.

2. Neotropical Migrant Landbirds: Forest, Scrub-shrub, Grassland Species

Neotropical migrant birds are defined as Western Hemisphere species whose populations, entirely or in part, breed in the Nearctic (North America and the Arctic) and overwinter in the Neotropics (tropical Mexico, Central and South America and the Caribbean) (Rappole et al., 1983). This definition includes 361 species of raptors, shorebirds, and wading birds, but the passerines, cuckoos, caprimulgids, swifts and hummingbirds are the groups most commonly referred to as "neotropical migrants." These landbird groups include tanagers, buntings, grosbeaks, New World sparrows, New World warblers, vireos, thrushes, flycatchers, swallows, cuckoos, nightjars, swifts, and hummingbirds - species which may spend six to seven months on wintering grounds, two to three months in migration, and three or less months on breeding grounds (DeGraaf and Rappole, 1995).

Twenty-five neotropical migrant species rely on the forested and scrub-shrub habitats of the Barnegat Bay-Little Egg Harbor estuary for breeding (Table 12). An additional 17 neotropical migrant species, of varying habitat affinity, breed in the estuary (Table 13). Because the Barnegat Bay-Little Egg Harbor estuary is strategically located along the Atlantic Flyway, spring and fall migrants require high-quality migratory stopovers for resting, foraging, and cover from predators. Abundant insects are critical for spring migration, and fruiting trees and shrubs augment the diet of many fall migrants that follow the coastline.

Neotropical migrants are good indicators of regional habitat quality. Many species are known to be area-sensitive, requiring large or contiguous tracts of habitat within which to breed. Some species are habitat

specialists, and many share both characteristics. As a group, these species are good indicators of the health of habitats and reflect the cumulative loss of smaller habitat patches on a regional level (Keller et al., 1993). Over the last two decades, population declines have been observed for many neotropical migrant species (Robbins et al., 1989). Early, long-term studies showed that neotropical migrant species are generally area-sensitive, are habitat specialists, or both (Lynch and Whitcomb, 1978; Briggs and Criswell, 1979; Robbins, 1979). Since the late 1970's, many studies have indicated that habitat loss and fragmentation over large regions are responsible for population declines of forest-interior, scrub-shrub, and grassland species.

Fragmentation creates openings in previously-contiguous habitat. Resultant "edge" habitat encourages increased abundance of mammalian and avian predators that forage near ecotones as well as brood parasitism by brown-headed cowbirds. Fragmentation alters the edge vegetation of forest patches through increased exposure to sun, wind, and wind-throw. Small patch size, along with altered vegetative structure and microclimate conditions, may render a habitat unsuitable for breeding. Small patches may act as a population sink where species are attracted to nest but experience poor reproductive success (Pulliam, 1988). Changes in vegetative and microclimate conditions may also decrease the availability of invertebrate prey for some forest-interior species so that the habitat patch is of marginal value for breeding (Burke and Nol, 1998). The degree of development adjacent to forest patches has been shown to negatively impact avian diversity and abundance regardless of patch size (Friesen et al., 1995).

The presence of species with diverse requirements is a good indicator of within-site habitat quality. Life history requirements (courtship, nest/height, foraging strategy, refugia, roost sites) vary widely among species. Forest, scrub-shrub and grassland birds rely on a variety of vegetative species and structural characteristics within habitats to provide for their needs. In the estuary, the majority of forest species generally breed in areas with both wetland and upland components. The diversity of vegetative structure enables birds to fulfill life history requirements within the constraints of territorial breeding systems. Grassland and scrub-shrub species rely on disturbance to provide an array of habitats in varying successional stages. In the watershed, non-row crop agriculture, fire, forestry practices, reclaimed sand mines, powerline corridors, and tall grass management (airports and military installations) can provide suitable early- and mid-successional habitat. The natural occurrence of maritime scrub-shrub and shrubby edges between forest and salt marsh can also provide habitat for some scrub-shrub species. However, creation of habitat for these species is usually incidental. The area of the disturbance may be too small, may succeed back to forest too quickly, or may be impacted by land-use practices and human disturbances that can cause decreased productivity for species colonizing these habitats (see Management Considerations).

In terms of land-use decisions, upland forest is not usually considered to be important wildlife habitat. Wooded wetlands are given regulatory protection; however, surrounding upland forest is usually cleared for development activities. The small (50 - 150 foot) upland buffer usually left surrounding wetland forests is not adequate to minimize disturbance, prevent runoff of pollutants, invasion by exotic vegetation, and dessication. In addition, it encourages increased abundance of mammalian and avian predators, domestic predators, and brown-headed cowbirds. Essentially, small buffers around wetland forests are not adequate to preserve the character of the wetland let alone the diversity of avian species that rely on the wooded wetland and the wetland/upland complex for breeding.

Grassland species in the watershed generally depend on reclaimed sand mines, military installations, airports, and to some extent, agriculture/abandoned farm fields to create early successional grasslands. As stated earlier, however, creation of this habitat is usually incidental, and species that colonize these areas can suffer from several problems. Reclaimed sand mines are often converted to high-density development or experience severe human disturbance from off-road vehicle use. Cropland may be

planted with row crops that are generally not conducive to breeding for grassland birds. If non-row, grass-like crops are planted, spring and early-summer harvest usually destroys broods and adults. These created habitats may be too small in size to attract many species or may act as sinks where birds experience high predation rates and low reproductive success. In New Jersey, the largest populations of endangered grassland birds exist on military bases and small airports. Several grassland species have been found to be area-sensitive (Vickery et al., 1997; Herkert, 1998).

Scrub-shrub species in the watershed depend predominantly on clear cuts, fire, powerline corridors, abandoned farm fields, and possibly military installations for mid-successional shrubby habitat. Scrub-shrub species have not been the focus of surveys on military installations; therefore, their occurrence is speculative. Here again, habitat creation is often incidental, and scrub-shrub species suffer from the same difficulties as grassland birds (i.e., habitat patches may be too small and may attract predators). Clearcuts or brush-hogged fields tend to reforest quickly because of the presence of woody species, whereas abandoned farmland often takes decades to become reforested. The decreased rate of farm-field abandonment and the suppression of fire has lead to a situation where successional habitats are being created by other means, and they quickly become unsuitable through succession or are lost to development. The temporal occurrence, in addition to size and quality of habitats, provides a double-gauntlet for successional species: they must be able to locate suitable sites for breeding and then attempt to successfully reproduce in habitats that may have abundant predators and cowbirds.

Although few neotropical migrant landbirds are listed as endangered or threatened, as many as 69 species have been reported in the literature to be declining (DeGraaf and Rappole, 1995). Altogether, declining population trends have been published for 21 of the 42 species that breed in the estuary (Sauer et al., 1997), and 24 species have significant proportions of their total breeding populations in the Mid-Atlantic Coastal Plain Physiographic Region (Bradley et al., 1998) (Tables 17 and 18). Loss and degradation of breeding habitat coupled with a short breeding season, low fecundity, the perils of migration (especially for juvenile birds), loss of habitat along migratory routes and on wintering grounds, pose serious problems for many species.

3. Management Recommendations

To ensure the maintenance of healthy populations of neotropical migrant songbirds in the Barnegat Bay watershed, high quality habitat must be preserved. Large, contiguous tracts of habitat are especially valuable. Robbins et al. (1989b) recommend 3,000+ ha as the minimum area expected to retain all species of forest-breeding birds. In particular, every effort must be made to maintain the greatest amount of "core habitat" within all habitat tracts (forest, grassland, and scrub-shrub). Core area is defined as the area of a habitat patch that lies at least 100 m inward from the habitat edge. A circular shape has the maximum core area; a linear shape is mostly edge habitat. Linear tracts should be avoided if area-sensitive species are the primary focus of the habitat management. Proximity of similar habitat types, proximity to contiguous habitats (conserved lands), and maintenance of connectivity of habitats are important considerations when making land-use decisions. In general, smaller patches in proximity of large/contiguous tracts are suitable and will support species that are area-sensitive. Clusters of many small patches are valuable habitat for moderately area-sensitive species.

Forest buffers, providing ~15-50 m of landcover along wetlands and stream/riparian corridors, are high-quality habitat and do not usually prevent degradation of the wetland habitat. Species generally rely on a

complex of upland and wetland forest. When land must be cleared for development, the larger the upland component left standing, the better. Within new development, the aggregation of forest patches and maintenance of forest canopy are preferable to scattered trees. The creation of grassy shoulders along roads in or near forested areas should be avoided. Grassy shoulders provide foraging areas for cowbirds where they can easily gain access to forest interiors (Rich et al., 1994).

Land planners should consider the impacts of human disturbance on breeding species when planning for development and recreation facilities. Offroad vehicles and an overabundance of personal watercraft negatively impact breeding species. Hiking trails on public lands should be located away from the most sensitive breeding areas. Wherever possible, it is important to monitor species' use of altered habitats to evaluate the success of management/land-use practices. Point counts during spring/fall migration and/or during the breeding season are relatively inexpensive and are easy to perform. If habitat management for bird species is a project goal, then it is essential to formulate a monitoring program.

IX. AMPHIBIANS AND REPTILES

A. Introduction

The Barnegat Bay-Little Egg Harbor estuary and watershed provide some of the best habitat for reptiles and amphibians in New Jersey. While many people are aware of the major breeding and migrating bird populations that inhabit the coastal salt marshes and islands of the estuary, few naturalists are familiar with the array of reptiles and amphibians that occur within floodplains and associated uplands of the streams and rivers that drain into the system. The Barnegat Bay-Little Egg Harbor estuary is notable for having highly diverse topography, vegetation, and water types (fresh water streams and rivers, brackish water, and salt water bays and ocean) which in turn support a rich herpetofauna. Amphibians and reptiles serve as both predator and prey in the local food chain.

B. Frogs and Toads

The Barnegat Bay region is home to some interesting amphibian fauna. Frogs and toads (anurans) appear similar in body shape with short front legs, long back legs, and the absence of a tail in the adult form. Both frogs and toads lay their eggs in standing (i.e., non-running) freshwater of permanent ponds and ditches, as well as seasonally ephemeral pools or puddles. Toads have a short larval period (tadpole stage) on the order of weeks. Treefrogs are intermediate, although some pond species such as bullfrogs take over a year to mature. In general, frogs are more aquatic than toads, but some species (e.g., leopard frogs) can be found significant distances from standing water, especially during periods of rain. Frogs have thinner, smoother skin than toads and must remain near freshwater to maintain proper body moisture, whereas toads generally have thicker, warty, rough skin allowing them to occupy drier uplands. Due to their habitat requirements for freshwater, frogs and toads are not found in the estuarine portion of the study area, but are restricted to the upland watershed (the Pinelands) and the barrier islands.

There are 12 species of frogs and 2 species of toads presently inhabit or have historically inhabited the Barnegat Bay region (Zappalorti and Sykes, 1998). The northern spring peeper (*Psuedacris crucifer*), northern gray treefrog (*Hyla versicolor*), New Jersey chorus frog (*Psuedacris triseriata kalmi*), bullfrog (*Rana catesbiana*), green frog (*Rana clamitans melanota*) wood frog (*Rana sylvatica*), southern leopard frog (*Rana utricularia*), pickerel frog (*Rana palustris*) and Fowler's toad (*Bufo woodhousii fowleri*) are generally widespread in the Barnegat Bay and have presently stable populations. The population status of the carpenter frog (*Rana virgatripes*) is undetermined. The northern cricket frog (*Acris c. crepitans*) was historically found within the region, but is presently of undetermined status. The eastern spadefoot toad (*Scaphiopus h. holbrookii*) is declining. The two species that are of special concern within the Barnegat Bay region are the Pine Barrens treefrog (*Hyla andersonii*) and southern gray treefrog (*Hyla chrososcelis*), both listed on the State of New Jersey Endangered Species List.

The acid waters of Pinelands streams and ponds significantly influence the distribution and abundance of anurans. Only the most tolerant species are capable of reproducing in acid waters due to severely negative impacts on embryonic and larval development and survival (Freda and Dunson, 1986). Only Pine Barrens treefrogs and carpenter frogs are tolerant of these harsh conditions and are considered native Pinelands anurans. The other more widespread anuran species successfully reproduce only where the water quality of Pinelands ponds has been altered (e.g., pH raised to more neutral conditions). Therefore, they are more commonly associated with areas of human disturbance (Bunnell and Zampella, 1998).

Due to restrictive habitat requirements and limited distribution, the Pine Barrens treefrog, the symbol of the Pinelands National Reserve, deserves special consideration. The range of the Pine Barrens treefrog is fragmented, with three distinct populations occurring from New Jersey to Florida. The northern-most population in the Pine Barrens of southern New Jersey. A second population ranges from southern North Carolina to South Carolina, and a third population is found from the Florida panhandle to extreme southern Alabama (Conant and Collins, 1991). The Pine Barrens treefrog is nocturnal and occupies trees or shrubs in or near wetland areas. During the day, the frogs hide on or beneath rough tree bark, in moist holes in hollow trees, or rest between tree leaves. Pine Barrens treefrogs select wetland areas such as sphagnum bogs, hardwood swamps, cranberry irrigation ditches, pitch pine lowland ponds, and wet borrow pits for depositing their eggs. These treefrogs disperse more than 100 m into adjacent upland areas (Freda and Gonzalez, 1986) and thus utilize upland wooded buffers and breeding ponds as habitat.

C. Salamanders and Lizards

Although salamanders are often confused with lizards because they have the same general appearance (four limbs and a tail), salamanders are amphibians whereas lizards are reptiles. Salamanders have smooth scaleless skin, lack claws on their digits, breed in the water, and are usually found in moist areas such as under rotting logs. Lizards lay their eggs concealed on dry land and not in water, and can tolerate drier situations because they are able to retain body moisture better due to their thick, scaly skin. Only three species of lizards are found in the Barnegat Bay region: the fence lizard (*Sceloporus undulatus hyacinthinus*), ground skink (*Scincella lateralis*), and five-lined skink (*Eumeces fasciatus*) (Zappalorti and Sykes, 1998). Fence lizards are relatively common, typically inhabiting open pine and pine-oak uplands on pine trees, wood piles, or fallen logs. Ground skinks prefer open sandy wooded areas, whereas five-lined skinks occur in wetter woodland areas such as hardwood swamps. Both tend to hide among rotting stumps, logs, and other decaying debris, and under flat boards on the ground (Conant, 1958). Five-lined skinks live in a few isolated colonies in the Barnegat Bay region (Zappalorti

and Sykes, 1998). The four most common salamanders in the Barnegat Bay region are: (1) the red-backed salamander (*Plethodon cinereus*), being by far the most common; (2) the northern two-lined salamander *(Eurycea bislineata*), found under logs along stream edges; (3) the four-toed salamander (*Hemidactylium scutatum*), easily distinguished by a constriction at the base of the tail and speckled belly pattern; and (4) the northern red salamanders (*Psuedotriton r. ruber*), a very bright red salamander inhabiting cedar swamps and moist woodlands under logs and leaf litter (Zappalorti and Sykes, 1998).

D. Turtles

With the exception of the terrestrial box turtle (*Terrapene c. carolina*), most turtles in the Barnegat Bay drainage basin occupy brackish or freshwater (aquatic) environments. Some of these turtles, such as the eastern painted turtle (*Chrysemys p. picta*) and red-belly turtle (*Psuedemys rubriventris*) can be readily observed when they bask on stumps, logs, or other debris sticking out of the water. Other turtles, such as the spotted turtles (*Clemmys guttata*) and mud turtles (*Linosternon odoratus*) are more secretive, and not as easily observed. The bog turtle (*Clemmys muhlenbergii*) and wood turtle (*Clemmys insculpta*) are considered of endangered and threatened status, respectively, in New Jersey. Bog turtle and wood turtle habitats are not widespread in the Barnegat Bay watershed, and most areas that have been examined are considered marginal habitat. Past wetland alteration may have had a negative impact on bog turtle populations in Ocean County. Included here are wetland alteration, stream-flow alteration, and cranberry bog construction. In addition, increased water demand due to escalating development may have raised the water level in some areas and lowered it in others, which can affect turtle populations. Natural factors, such as plant succession (especially of invading hardwood trees) may also have impacted bog turtle populations by shading-out nesting and basking areas. Wetland alteration by beavers may have flooded *Carex stricta* marshes in other areas.

The northern diamondback terrapin (*Malaclemys terrapin terrapin*) is the only permanent year-round resident turtle species in the estuarine portion of Barnegat Bay. This attractive turtle can be found in many coastal settings, from oceanic to riverine, but the most preferred habitats are estuaries and *Spartina* grass salt marshes (Wood, 1996). Although they were once very abundant in Barnegat Bay, the population has been declining in recent years. Northern diamondback terrapins are mainly carnivorous, but will also consume plant material. The large head of the females is especially useful for crushing of mollusc shells such as periwinkles and other gastropods, as well as bivalves (e.g., mussels and clams). Terrapins will also ingest crabs, insects, marine annelids, fish, and carrion. Terrapins hibernate from November-December through April-May. They lie on the bottom of the bay or bury themselves in bottom sediments. Some may seek shelter along embankments in tidal creeks or burrow into the sand individually or in groups (Yearicks et al., 1981; Lawler and Musick, 1972). Terrapins nest in sandy upland areas adjacent to the bay during the months of June and July, with eggs hatching in late summer-early autumn.

Many predators attack the nests of diamondback terrapins, including ghost crabs (*Ocypode quadrata*), crows (*Corvus*), shrikes (*Lanius*), gulls (*Larus*), hogs (*Sus*), rats (*Rattus*), muskrats (*Ondatra*), foxes (*Vulpes*), raccoons (*Procyon*), skunks (*Mephitis*), and mink (*Mustela*). Along small islands in Barnegat Bay where the turtles nest, Burger (1977) showed that 73% of nests were destroyed within a single year. Raccoons and bald eagles are important predators of adult terrapins.

The largest predator on diamondback terrapins are humans who treasure the terrapins as a source of

food. Diamondback terrapins were harvested extensively for food from about 1880 to 1930, and many populations were nearly depleted (Ernst et al., 1994). In the early 1900's, considerable effort was expended to propagate these turtles in captivity for the restaurant market (Coker, 1906; Hildebrand, 1929, 1932). The market declined after 1930 which enabled the terrapins to make a comeback in many areas. More recently, Asian immigrants in the United States have again created a demand for this species as a restaurant food item and in fish markets. In the northeastern part of its range, including New Jersey, the species is currently being harvested at unknown rates. Since 1998, the diamondback terrapin has been classified as a game animal with a harvest season from November through March. Terrapins are captured as they hibernate, and many individuals can be harvested at one time because they hibernate in large groups.

Each year an unknown, but substantial number of terrapins are drowned in crab pots left unattended by both commercial and recreational crabbers. The installation of terrapin excluders (BRAS) on crab pots can significantly reduce the number of terrapins killed in this way. Because females may travel a significant distance from the water to a suitable upland nesting site, many hundreds of gravid female terrapins are killed annually on highways that pass through salt marshes and bayshore access roads (Dr. Roger Wood, personal communication). Terrapins are also threatened by water pollution and coastal development which destroy their feeding grounds, food sources, and nesting beaches (Ernst et al., 1994). In the Delaware Estuary, construction of bulkheads and sea walls have excluded turtles from upland nesting sites (Sutton et al., 1996).

The status of the diamondback terrapin population is unknown in Barnegat Bay. Trapping for the restaurant market (Dunson, 1970) and incidental capture and drowning of these turtles in crab pots have had a detrimental effect on New Jersey's populations. Barnegat Bay populations have noticeably declined over the past 20 years (Zappalorti, personal observations). The status of this species was not been seriously questioned until it became apparent that these turtles were being sold to restaurants in the northeast. Quantitative data on annual harvest rates and incidental capture by crab pots, coupled with population ecology data, are urgently needed to formulate management decisions on harvest season duration, legal sizes, and seasonal limits. This species has been recently included in the special concern category by the New Jersey Department of Environmental Protection, and can only be legally collected with a license during the winter months.

Sea turtles are also known to inhabit the Barnegat Bay-Little Egg Harbor estuary. Sea turtles, as their name implies, are largely pelagic species, preferring deep ocean waters, but will enter shallow coastal waters during the warm summer months. No nesting occurs along Barnegat Bay beaches, though there has been an unsuccessful attempt in recent years by the loggerhead turtle (*Caretta caretta*) to nest in Island Beach State Park. The protected waters and submerged aquatic beds of Barnegat Bay may serve as a nursery area for an unknown number of juvenile sea turtles. The bay may also be utilized as a feeding ground by the turtles, offering an abundance of invertebrate prey, particularly crabs.

Sea turtles are threatened worldwide due to the loss of nesting habitat, commercial harvest, incidental take by commercial fishing operations, boat strikes, anthropogenic marine debris, dredging operations, and impingement on water intake structures (Schoelkopf and Stetzar, 1995a). The degree to which these factors are a problem in Barnegat Bay-Little Egg Harbor waters is unknown. New Jersey lists all marine turtles as endangered, and they are protected by a number of state and federal laws.

E. Snakes

A few snake species, such as the eastern king snake (*Lampropeltis g. getula*), northern water snake (*Nerodia s. sipedon*), and eastern ribbon snake (*Thamnophis s. sauritus*) can be found in wetland areas, but most other snake species usually inhabit the drier upland forested areas. The upland snake species include the black racer (*Coluber c. constrictor*), pine snake *(Pituophis m. melanoleucus*), corn snake (*Elaphe g. guttata*), worm snake (*Carphophis p. punctatus*), and eastern hognose snake (*Heterodon platirhinos*) to name a few. Some snakes, such as the timber rattlesnake (*Crotalus h. horridus*), require both upland and wetland forested areas as habitat during different times of the year. There are several species of snakes that are characteristic of the Barnegat Bay-Pinelands region and are considered either threatened (the pine snake) or endangered (the corn snake and timber rattlesnake) and therefore will be highlighted here.

The pine snake is a large, powerful constrictor. A true lover of the uplands, the northern pine snake inhabits the dry pitch pine/oak areas of the Pine Barrens, away from the creeks and cedar swamps that are also found in this unique ecosystem (Burger and Zappalorti, 1989a; Zappalorti, et al., 1983). Pine snakes exhibit high fidelity to their hibernating locations; as individuals can be observed using the same den for many years. This species often hibernates in groups and with other snake species, including black racers (*Coluber constrictor*) and corn snakes (*Elaphe guttata*). In the early fall, pine snakes return to the dens by following scent trails of other snakes. Cold weather in mid-October or early November promotes the descent of the snakes into hibernation chambers, where they will remain until the spring thaw. In the spring, the snakes occupy areas near the den for a short period of time, until temperatures begin to remain consistently above the soil temperature. Mating may occur during this time, but can also occur into late spring and early summer after the snakes have dispersed from the dens. During June and early July, female pine snakes find sunny, open areas of sand where they dig 1-2-km long horizontal tunnels ending in a chamber. Through mark-recapture studies it has been determined that a large percentage of female pine snakes (75%) return to the same general area to dig their nests.

Corn snakes, or red rat snakes, are non-venomous constrictors, feeding primarily on warm-blooded prey including mice, voles, shrews, moles, rats, birds and their eggs. These snakes are most often found in sandy pine barrens, open deciduous woodlands, rocky ledges, trash dumps, or old buildings. They are nocturnal and very secretive, spending a lot of time hidden in stump holes, underground mammal burrows (i.e., mole tunnels), and tree root canals (Mitchell, 1994; Tennant 1997). Corn snakes are good climbers and can sometimes be found in trees and bushes in search of bird eggs or chicks. In New Jersey, corn snakes may hibernate in communal dens with pine snakes and black racers, or they may hibernate alone. The dens selected are usually abandoned mammal burrows, usually from foxes, such as skunks or woodchucks.

The timber rattlesnake is 1 of 2 venomous snakes found in New Jersey. The other, the northern copperhead, is found only in northern New Jersey. There are two disjunct population centers of timber rattlesnakes in New Jersey, one located in the Pine Barrens, and the other in the mountainous region of northern New Jersey. During September, when the day length shortens and the evenings begin to cool, timber rattlesnakes begin to move toward their hibernation sites; they enter their hibernacula in mid- to late October. Timber rattlesnakes in the Pine Barrens of southern New Jersey are known to hibernate along cedar streams rather than in rocky outcroppings such as those in northern New Jersey. In the coastal plain, the absence of rocky outcroppings necessitates a different hibernation strategy (Zappalorti and Reinert, 1989). The Pine Barrens rattlesnakes position themselves in underground flowing water at the base of cedar trees where the root system of the trees provides protection. The constantly flowing water of the stream prevents the snakes from freezing, enabling these ectothermic animals to remain relatively close to the surface of the ground. Warmer water temperatures stimulate the snakes to emerge from hibernation, initially in mid- to late April. After emerging from hibernation, timber rattlesnakes do

not remain in their den areas for long, but quickly migrate to upland foraging sites.

Due to a number of factors, timber rattlesnakes have a very low reproduction potential, leading to a slow recovery of depleted populations. Timber rattlesnakes do not reach sexual maturity until four to eleven years of age, although an age of nine to eleven years is more typical in the northern portion of its range (Galligan and Dunson, 1979; Martin, 1988, Brown, 1993). In addition to this late age of reproduction, the frequency of reproduction is only once every two years for rattlesnakes in the Pine Barrens of southern New Jersey (Zappalorti, personal observation). Although fully equipped with venom and ready to fend for themselves, the survival rate of neonate snakes is typically low, and the overall contribution of new snakes to the population is important.

The overall consensus of timber rattlesnake researchers is that there is a definite population decline in populations over most of the rattlesnake's range. Stechert (1992) found that, in a sample of 139 dens in New York, 76% were in various stages of depletion, while only 5% contained large populations of rattlesnakes. Martin (1982) stated that most timber rattlesnake dens are at 15 to 20% of the level observed 40 years ago. Numerous factors have contributed to population declines over the years, although the major cause is most likely habitat disturbance and destruction.

F. Conservation and Management

1. Reasons for the Decline of Amphibian and Reptile Populations

The decline of many reptile and amphibian species in Ocean County over the past several decades should be a cause for alarm. There are a number of reasons for the observed decline in herptiles, including:

1. Habitat degradation and destruction from land development.

2. Road mortality.

3. Pollution of critical wetland and upland habitats.

4. Illegal collecting and wanton killing.

5. Predation from domestic and feral animals.

Habitat degradation and destruction from development is by far the greatest threat to the populations of reptiles and amphibians in the Barnegat Bay watershed. Development around ponds and lakes destroys crucial feeding areas for timber rattlesnakes, pine snakes, and king snakes. It also eliminates turtle nesting sites and negatively impacts emergent aquatic vegetation on which these turtles feed and bask. Increased human activity in an area can have detrimental impacts on populations of reptiles and amphibians. The primary threat to large snake species (king snakes, corn snakes, pine snakes, and timber rattlesnakes) is the loss of pine-oak and hardwood forest habitat due to the construction of housing projects and associated development. These snake species have relatively large home ranges (25 to 300 acres) (Zappalorti and Reinert, 1989; Zappalorti, personal observations), and consequently require a large amount of unbroken habitat.

Much infrastructure development impinges on critical herptile habitat. Increased traffic on existing roads adds to road mortality of turtles. The herptiles appear to be particularly susceptible to road kill during annual breeding periods.

The loss and alteration of wetlands habitat from development and associated human activities often impact reptiles that live in or near the water, such as aquatic turtles and northern water snakes. They can also affect amphibians which utilize the water for breeding. Many adult amphibians live directly in or near the water and have extremely thin skin. The vast majority of amphibians lay their eggs in water and have a aquatic larval stage; thus, water pollution can have an extremely detrimental effect on their populations. For example, chemical contaminants can be toxic to these animals or their critical food sources.

Although not as great a threat to wildlife populations as destruction of habitat, illegal collection has also taken a toll on the herptile populations in the Barnegat Bay watershed. Basking aquatic turtles, such as eastern painted, red-bellied, spotted, red-eared, mud, and musk turtles, are not considered species of special concern in New Jersey at this time. However, illegal collection for commercial purposes (the pet industry) has added to the decline of these forms. Data on collection rates and their effects on populations need to be determined so management plans for these species can be developed.

Reptiles and amphibians, especially snakes, are sometimes killed because they are a perceived threat to humans. Many people fear snakes and will kill any snake they encounter. Nonpoisonous snakes are often killed because they are assumed to be poisonous. Unfortunately, many people do not understand that the snakes, including venomous ones, do not pose a threat to humans unless cornered or handled. It is illegal to kill any species of snake, particularly an endangered species such as the timber rattlesnake.

Predation by domestic and feral animals such as cats and dogs also impacts populations of reptiles and amphibians, as well as small mammals and birds. Unwanted stray pets and domestic animals are often allowed to roam free in the woods around homes. They often capture and kill many species of reptiles and amphibians. Cats like to eat the head of snakes or play with frogs until they die. Dogs like to pick turtles up in their mouth, toss them around, and chew on them, frequently resulting in severe injury or even death.

2. Management Considerations and Recommendations for Amphibians and Reptiles

Although three species of snakes are now legally protected by the NJDEP, there may be other species that should be designated as endangered or threatened species. However, not enough information is known about the status of these populations. Examples of such populations in the Barnegat Bay watershed include the eastern mud turtle, spotted turtle, ground skink, eastern kingsnake, black rat snake, eastern worm snake, northern black racer, and northern cricket frog. More field surveys are clearly needed to identify population centers and critical breeding habitats for the species of snakes inhabiting the watershed. The Herp Atlas Project of the New Jersey Department of Environmental Protection's Endangered and Nongame Species Program is an effective way of measuring population declines. Accurate distribution records of various herptile species must be supported and expanded.

Management for the protection of reptile and amphibian populations should consider seasonal limitations or complete bans on logging practices in known critical habitats, exclusion of logging from

some areas, and maintenance of open, canopy-free sunlit areas for gravid females to bask and nest because of the higher temperatures (e.g., snake management fields ~50 m wide by 100 m long). Several experimental snake management fields were made in the Greenwood Forest Wildlife Management Area by the New Jersey Division of Fish, Game, and Wildlife in 1995. Preliminary monitoring results suggest that both gravid northern pine snakes and timber rattlesnakes are using these openings in the forest for egg laying and birthing rookeries (Zappalorti and Reinert, personal observations). This type of active management will help to ensure the future presence of these species in the Barnegat Bay watershed. Other management strategies for protecting these species include the creation of natural landscaped areas with adjacent woodlots, protection of forest fragments in and around urban and suburban areas, reduction of pesticide use, and wildlife tunnels and culverts under roads that pass through and around these wildlife management areas.

The continued existence of many species of reptiles and amphibians requires the preservation and maintenance of their existing habitats. Habitat protection and water quality improvement should be high priorities to the U.S. Environmental Protection Agency, New Jersey Department of Environmental Protection, Endangered and Nongame Species Program, the Division of Coastal Resources and the Land-Use Regulation Program, nonprofit conservation organizations, and the Barnegat Bay Estuary Program. Protection of large undisturbed tracts of land is essential if all existing herptile species are to survive in Ocean County and southern New Jersey into the 21st century. Many species of reptiles and amphibians will be extirpated if we do not take steps to protect the remaining populations and their critical habitat within the Barnegat Bay watershed and throughout New Jersey. Reptiles and amphibians are important components of the estuarine food chain.

X. MAMMALS

A. Fur-bearing Mammals

B. Marine Mammals and Sea Turtles of the Jersey Shore

B. 1. Introduction

Stranding data indicate that marine mammal and sea turtle activity is increasing along the inshore waters of the New Jersey coast. Specifically, waterways such as New Jersey coastal bays are experiencing more marine mammal activity with each passing year. Migrating marine mammals and sea turtles are being sighted more often and in larger numbers each year in these waters (Schoelkopf and Stetzar 1995). The appearance of these animals in the bays and surrounding waters provide indicators of the water quality and overall health of the marine ecosystems. Several species of cetaceans, pinnipeds and sea turtles have been documented through stranding and sighting data collected by the Marine Mammal Stranding Center in Brigantine, New Jersey, over the past twenty years. These data suggest that careful management strategies should be developed to insure the maintenance of these areas as habitat for marine mammals and sea turtles and other endangered species.

2. Seasonal Bay Inhabitants

Seasonal trends dictate what species will be found along the New Jersey coastline at any given time. However, it is important to note that animals can and do appear out of season. Past strandings and sightings show that cetaceans, specifically harbor porpoises (*Phocoena phocoena*) and bottlenose dolphins (*Tursiops truncatus*) are among the most frequently sighted species, from May through September. Bottlenose dolphins inhabit the inshore waters of the Atlantic from Nova Scotia to Venezuela, as well as the Gulf of Mexico (Boschung et al., 1983). Harbor porpoises can be found along the east coast of North America from the Davis Straits to North Carolina (Leatherwood et al., 1983). While the harbor porpoises and bottlenose dolphins appear during the late spring and summer months, these and other delphids (e.g., the common and striped dolphin) can be found sporadically during the colder winter months. (Schoelkopf, 1975-1999a).

In the late summer months, rising water temperatures attract four species of sea turtles: Loggerhead (*Caretta caretta*), Kemp's Ridley (*Lepidochelys kempii*), Leatherback (*Dermochelys coraciea*) and Green (*Chelonia mydas*) turtles. They inhabit the area for a relatively short time, and, as the weather turns cold, begin their southerly migration. It is during these periods of intense climatic change that "cold stunning" often causes the turtles to strand in back bays, being slowed by the sudden drop in temperature (Schoelkopf, 1975-1999b).

Four species of seals visit the inshore waters of the New Jersey coast during the onset of winter. Harbor Seals (*Phoca vitulina*) are among the most commonly seen animals in January and February. From mid-March into April, hooded (*Cystophora cristata*) and harp (*Phoca groenlandica*) pups arrive after travelling several hundred kilometers from their Arctic breeding grounds (Lavigne and Kovacs, 1988). Hooded and harp seals are followed by the arrival of a samll number of gray seal pups. These animals are usually very young and exhausted by the long southern migration. These animals often seek refuge in the bays from rough seas during winter storms. The colder water temperatures cause most inshore cetaceans to migrate south at this time of year, but several species of offshore cetaceans can still be found. It is not uncommon for long finned pilot whales (*Globicephala maleana*) or Pygmy sperm whales (*Kogia breviceps*) to strand in the bays.

3. Threats to the Species Inhabiting the New Jersey Coast

Due to the delicate population status of marine mammals and sea turtles that frequent the New Jersey coast and its bays, careful management is necessary. There are many different threats to the marine mammal populations that frequent the New Jersey coast: natural predation, fisheries interactions, recreational and commercial boat traffic, and poaching.

Various types of fishing lines and nets pose a serious hazard to marine mammals if they are left unchecked for long periods of time. Marine mammals and sea turtles can become entangled or hooked on the fishing gear and are unable to rise to the surface for air. As the animals struggle with the gear, they become further entangled and evenually drown. Proper maintenance and regularly scheduled checks of nets and lines can help to reduce the number of animals taken in fisheries interactions.

The ingestion of foreign materials also poses a large threat to local marine mammal and sea turtle species. Much of the trash that we throw away finds its way into the ocean and becomes a threat to the

marine mammal populations. Plastic bags and other non-biodegradable trash can often resemble jellyfish, squid, and other prey species. Several marine mammal and sea turtle deaths each year along the New Jersey coast are attributed to plastic ingestion or entanglement in fishing gear. Marine mammals and sea turtles mistakenly ingest these items and the digestive tract becomes blocked, eventually killing the animal. Discarded fishing gear or plastic strings can become tangled around fins, flippers, or tail stocks, acting as a tourniquet which damages limbs. (Schoelkopf, 1998).

Recreational and commercial boat traffic must be carefully monitored to protect marine mammals and sea turtles. Current whale-watch regulations allow for the safe viewing of marine mammals; however, the public is largely unaware of these regulations. Public education and outreach programs should ensure that the regulations are clearly understood by the general public. Seals are a protected species in New Jersey and are regulated by state non-game laws as well as the federal Marine Mammal Protection Act of 1972 (Sutton et al., 1996). Emphasis should be placed on protecting selected haul-out spots. Special care should be taken by boaters not to approach seal resting spots (haul-outs) too closely for fear of disturbing resting animals or striking swimming animals.

Dredging and electric generating station operation can also affect these animals. Dredging operations involve a process of moving large amounts of sand and water through high pressure hoses. Curious animals can be impinged on the intake pipes and injured or killed. Electric generating stations often release large amounts of heated effluent into surrounding natural waters. These areas are havens for local migrating fish species and offer marine mammals and sea turtles unique feeding opportunities. However, the plants also use estuarine waters to cool condensers. Marine mammals and sea turtles may become trapped on intake screens or trash racks designed to keep foreign objects out of the plant.

It is important to note that all of the marine mammal and sea turtle species found in the New Jersey waters are federally protected. Handling any of these animals is strictly prohibited and should be done only under the proper supervision of trained professionals. Interfering with, or removing, any marine mammal or sea turtle can deprive scientists of information that may prove useful in managing the populations.

4. Data collection

The data presented here has been gathered by the Marine Mammal Stranding Center in Brigantine, New Jersey over the past 20 years. These data provide information on animals that have stranded, or have been directly sighted by the Marine Mammal Stranding Center and its staff. Due to the non-uniform nature of the data collections (i.e. reporting of dead animals and release of rehabilitated animals), the data cannot be interpreted as a definite indication of population size. Currently, there are no reliable estimates for the population size and seasonal occurrence of these animals in the bay. The data are intended to provide a basic introduction to the species found in the coastal areas of New Jersey, specifically Barnegat Bay. It is clear that further research is needed to make an accurate estimation of the populations that inhabit New Jersey coastal waters.

C. Land Mammals

Over 30 species of mammals occur in the Barnegat Bay watershed in assemblages characteristic of natural communities of the Mid-Atlantic coastal regions (Wolgast, 1979; U.S. Fish and Wildlife Service, 1999). Forest species include red fox (*Vulpes vulpes*), grey fox (*Urocyon cinereoargenteus*), raccoon (*Procyon lotor*), long-tailed weasel (*Mustela frenata*), short-tailed weasel (*Mustela erminea*), striped skunk (*Mephitis mephitis*), opossum (*Didelphelis virginiana*). The red fox and raccoon are especially widespread, occurring both on the mainland and barrier islands. White-tailed deer (*Odocoileus virginianus*), the region's largest mammal, is restricted to the mainland portions of the Barnegat Bay watershed. Upland forest dwelling rodents include the grey squirrel (*Sciuris carolinensis*), red squirrel (*Tamiasciurus hudsonicus*), chipmunk (*Tamias striatus*), southern flying squirrel (*Glaucomys volans*), white-footed mouse (*Peromyscus leucopus*), and the pine vole (*Microtus pinetorum*). The red-backed vole (*Clethrionomys gapperi*) is generally restricted to wetland forests and bogs. Insectivorous species include the masked shrew (*Sorex cinerus*), short-tailed shrew (*Blarina brevicauda*), eastern mole (*Scalopus aquaticus*), and a variety of bat species. Among the shrubland and grassland species of mammals are the meadow vole (*Microtis pennsylvanicus*), meadow jumping mouse (*Zapus hudsonius*), woodchuck (*Marmota monax*), eastern cottontail (*Sylvilagus floridanus*), and several of the forest and wetland species. Mammals associated with wetlands and waterways include the mink (*Mustela vison*), river otter (*Lutra canadensis*), beaver (*Castor canadensis*), muskrat (*Ondatra zibethicus*), southern bog lemming (*Synaptomys cooperi*), and least shrew (*Cryptotis parva*). While the beaver is restricted to the freshwater portions of the bay's tributaries, the muskrat extends into the brackish portions of the bay's marshes. The river otter inhabits both Pine Barrens streams as well as the bay's salt marshes and islands.

Several mammals have substantial impacts on the habitat and other animal populations. For example, high densities of white-tailed deer have negatively affected the structure and composition of plant communities (Wolgast, 1979). Red fox inhabiting the barrier islands prey on the eggs and chicks of threatened and endangered beach-nesting birds such as the piping plover. In some cases, nuisance foxes have been trapped and removed to limit the losses to these protected birds. Beavers have become a nuisance on some streams by plugging up culverts and flooding roads and property.

The hunting and trapping of various mammal species are important recreational activities in the Barnegat Bay region. Deer hunting clubs that formed early in the 20th Century still dot the Pine Barrens section of the Barnegat Bay watershed. White-tailed deer, cottontail rabbits, and gray squirrels are the most commonly hunted species (Applegate, 1979). Less commonly hunted forms are raccoons and red and gray foxes. Muskrats are commonly trapped on the bay's tributaries and coastal marshes. The red and grey fox, raccoon, skunk, opossum, weasel, mink, and beaver are among those species that are trapped (Applegate, 1979). Due to low population densities, otters are protected from trapping. Hunting and trapping activities are regulated by the New Jersey Department of Fish, Game and Wildlife. The State Wildlife Management Areas, state forests, and portions of the Forsythe National Wildlife Refuge as well as certain private lands are open to hunting and trapping.

XI. INSECTS

Barnegat Bay's marshes, swamps and forests are home to hundreds of species of insects and arachnids (e.g., spiders). Insects are an important food source for many estuarine species, serving as an important link within the food web. Though not particularly conspicuous, various species of leafhoppers, aphids,

beetles, spiders, and mites live on the stems and leaves of salt marsh plants, moving up and down vertically with the tide (Tiner, 1974). True spiders are terrestrial, but some species do inhabit shorelines and salt marshes. Wolf spiders (*Lycosidae*) are among the most common and conspicuous spiders in the bay's coastal zone as well as in the Pinelands interior (Boyd, 1991). Though the class Insecta has more species than any other animal group, only 3 of the more than 2 dozen orders contain saltwater, aquatic adults: the beetles (*Coleoptera*), bugs (*Hemiptera)* and springtails (*Collembola*) (Gosner, 1978). Several additional orders of insects have saltwater aquatic larvae, with the most infamous being the various families of the biting flies (Order Diptera). While dragonflies and damselflies (*Odonata*) are a common sight hovering over Barnegat Bay wetlands, only a few species have aquatic larvae that are actually tolerant of saline or brackish conditions. One of these, the seaside dragonlet (a dragonfly) is an extremely abundant insect in New Jersey's tidal marshes (Barber, 1994). Monarch butterflies (*Danaus plexippus*) are another more conspicuous species, especially during its annual fall migration, when Barnegat Bay serves as a major migration corridor.

As with other coastal estuaries, Barnegat Bay is infamous for its mosquitoes (Culicidae) and various kinds of biting flies. One of the most voracious is the salt marsh greenhead fly (*Tabanus nigrovittatus*), a large insect (up to 25 mm in size) characterized by bright green eyes and aggressive behavior. Greenhead flies have aquatic larvae that are found chiefly in intertidal salt marsh habitats (Gosner, 1978). Sand flies or no-see-ums (*Culicoides* spp.) are another ubiquitous pest that have larvae that inhabit salt marshes and intertidal sands (Gosner, 1978). Another coastal pest, the stable fly (*Stomoxys calxitrans*), appears similar to the common house fly, but it bites. The larvae develop in windrows of eelgrass (*Zostera maritima*) and seaweeds cast up along bay shores (Gosner, 1978). While the various flies can be considered nuisance species, only mosquitoes have been implicated as vectors in the transmission of serious illness. Of the 37 mosquito species found within the Barnegat Bay drainage basin, 5 breed in coastal salt marshes. Two are permanent water breeders: *Culex salinarius,* and *Anopheles bradleyi.* The other three, *Aedes sollicitans, Aedes cantator* and *Aedes taeniorhynchus*, are flood water breeders.

The white-banded saltmarsh mosquito, *Aedes sollicitans*, often called the "New Jersey mosquito," is by far the most abundant and pestiferous form in the Barnegat Bay-Little Egg Harbor estuary region. Although confined primarily to coastal regions, the species also has also reported from numerous inland areas of the United States where brackish water is present, as well as in several freshwater habitats (Richards, 1938; Fellton, 1944; Carpenter and Middlekauf, 1944; Ostergaard et al., 1961; Lake 1965). Within the Barnegat Bay-Little Egg Harbor estuary, *A. sollicitans* can generally be found breeding in salt marshes, hydraulic dredge spoil sites, and/or areas of brackish water.

Each year periodic broods of this species are produced in the vast expanses of the tidal wetlands. The adults are strong fliers capable of migrating many kilometers inland from the salt marshes where they breed. Their migratory habits are well documented; they have been collected up to 176 km from any known breeding site (Matheson, 1944). In the Barnegat Bay-Little Egg Harbor estuary, area migrations of 40 to 64 km are common. *Aedes sollicitans* migrates inland from coastal breeding marshes as far west as New Egypt. Weather, wind patterns, and topography are reported to be important factors in determining the duration and distances of the flights. In addition to its significance as a major pest species, *A. sollicitans* is a known vector of eastern equine encephalitis, a viral disease of horses and man (Kandle, 1961, 1967; Goldfield et al., 1968; Crans et al., 1986), as well as dog heartworm (Beam, 1965; Ludlam et al., 1970).

As with all mosquitoes, fully functional, piercing mouthparts and the habit of biting are restricted to the females. Lacking piercing mouthparts, males are unable to bite. Female *Aedes sollicitans* are persistent and vicious feeders, seeking blood meals anytime of the day or night (Headlee, 1945; Carpenter and LaCasse, 1955). Lake (1965), examining the species in Delaware, reported that the greatest blood-

seeking activity occurred within the first two hours of darkness. The reaction of humans to their bites varies significantly with the individual, ranging from only a temporary annoyance to bites that produce lesions that may last for days or months.

The life cycle of *Aedes sollicitans* involves four separate stages: the egg, larva, pupa, and adult. Like all mosquitoes, the species requires water in which to complete its larval and pupal stages. The intake of blood is vital to the female for the development of eggs to proceed, and as an energy source. Following a blood meal, and at the time of oviposition, the female instinctively selects the habitat for the immature aquatic stages and may lay 100 or more eggs. Eggs are deposited singly on moist mud or on the bases of emergent vegetation along the edges of tidal depressions, in areas of the salt marsh that periodically dry between spring tides or storm events. In the Barnegat Bay-Little Egg Harbor estuary, almost any moist depression within the higher, drier portions of *Spartina patens* and *Distichlis spicata* marsh may contain eggs of *A. sollicitans*. *A. sollicitans* is also found breeding in those portions of short *Spartina alterniflora* marsh that is isolated by higher portion of marsh. Of the approximately 11,350 acres of saltmarsh in Ocean County, more than 5,000 acres provide breeding habitat for *A. sollicitans* on a regular basis.

Following oviposition, the eggs require a dry period of at least 24 hours to insure the maturation of the embryo and hatching (Smith, 1905). The eggs may remain in diapause for months following oviposition. This ability to remain dormant enables the mosquito to bridge the gap from one tidal flooding to the next, and allows it to utilize temporary salt marsh depressions and tidal pools for breeding sites. The egg also represents the stage for overwintering of the species. Hatching of the eggs occurs following re-inundation of oviposition sites by spring or storm tides, or by rainfall. Millions of larvae may appear in the tidal pools within minutes following inundation. Larvae may appear on the tidal wetlands as early as mid-March, with adults appearing on the wing from late April through mid-November (Headlee, 1945; Lake, 1965). The number of generations produced annually within the Barnegat Bay-Little Egg Harbor estuary area is directly influenced by the frequency of tidal flooding due to spring and storm tides, and precipitation during the active mosquito season. Although the species may produce up to 10 separate broods per year, 5 to 8 broods are normally produced in a typical season.

The periods for development of the immature stages vary, however, depending upon water temperatures and the availability of food. In the Barnegat Bay-Little Egg Harbor estuary, the time from egg hatching to emergence of the adult mosquito may range from 5 to 12 days. During July and August the period of development is closer to 5 days. Lake (1965) reports an average of 9 days to complete the life cycle, at water temperatures ranging from 20° to 23 °C (68 to 73.4 F). The newly emerged adults remain on the salt marsh for 1 or 2 days during which time mating females seek blood meals, often moving 32 to 64 km from the marshes to feed. Upon obtaining a blood meal, the females return to the tidal marshes to lay their eggs, thereby completing the cycle.

A. Special Problems

Due to its abundance, migratory capabilities, and vector potential, *Aedes sollicitans* is the most economically important mosquito species in New Jersey. Its impact upon land values, agricultural production, recreation, and tourism justify a multi-million dollar abatement effort conducted at the local and state levels. *A. sollicitans* is the principal mosquito species targeted for control within the Barnegat Bay-Little Egg Harbor area. See Chapter 7 for more information on mosquito control activities.

Salt-hay farming, in addition to dredging activities by the U.S. Army Corps of Engineers and the State of New Jersey, present special problems for mosquito control. The harvesting of salt-hay from the tidal areas from Waretown down to Little Egg Harbor Township was carried on for more than a century. The removal of salt-hay biomass over the years has retarded the rise of the marsh surface in this area to the point that it has not kept pace with sea level rise. These areas are now intermittently flooded flats surrounded by higher marsh, and thus have become significant mosquito producers. In addition, the use of harvesting equipment for years on this marsh has left tire ruts which also produce significant mosquito breeding. In addition to salt-hay farming, numerous U.S. Army Corps of Engineers, State of New Jersey, and local dredge spoil disposal sites are also located in the Barnegat Bay-Little Egg Harbor area. These spoil disposal sites represent major areas of *Aedes sollicitans* breeding. Various authors have addressed disposition sites in New Jersey (Shisler, 1977; Kent et al., 1987; Mulligan et al.,1990).

XII. THREATENED AND ENDANGERED SPECIES

Table 14 provides a list of 156 species of special emphasis in the Barnegat Bay barrier beach/backbarrier lagoon complex. This list contains 52 species of fish and 79 species of birds, and includes the following state and federal-listed species:

• State-listed endangered

eastern tiger salamander (*Ambystoma t. tigrinum*)

northern harrier (*Circus cyaneus*)

black skimmer (*Rhynchops niger*)

least tern (*Sterna antillarum*)

seabeach knotweed (*Polygonum glaucum*)

• State-listed threatened

great blue heron (*Ardea herodias*)

little blue heron (*Egretta caerulea*)

osprey (*Pandion haliaetus*)

barred owl (*Strix varia*)

• Federally listed endangered

peregrine falcon (*Falco peregrinus*)

roseate tern (*Sterna dougalii*)

• Federally listed threatened

piping plover (*Charadrius melodus*)

swamp pink (*Helonias bullata*)

• Federal species of concern

northern pine snake (*Pittuophis m. melanoleucus*)

northern diamondback terrapin (*Malaclemys t. terrapin*)

black rail (*Laterallus jamaicensis*)

pine barren boneset (*Eupatorium resinosum*)

Literature Cited

Able, K. W. and M. P. Fahay. 1997. Natural history patterns for estuarine fishes during the first year: a progress report. Pp. 185-191 *in* Flimlin, G. E. and M. J. Kennish, M. J. (eds.), *Proceedings of the Barnegat Bay Ecosystem Workshop*. Rutgers Cooperative Extension of Ocean County, Toms River, New Jersey.

Able, K.W., D. A.Witting, R. S. McBride, R. A. Rountree, and K. J. Smith. 1996. Fishes of polyhaline estuarine shores in Great Bay-Little Egg Harbor, New Jersey: a case study of seasonal and habitat influences. Pp. 335-353 *in* Nordstrom, K. F. and C. T. Roman (eds.), *Estuarine shores: evolution, environments and human alterations*. John Wiley and Sons, New York.

Barber, R. D. 1994. Dragonflies and damselflies of Cumberland County, New Jersey. Special Publication, Cape May Bird Observatory, New Jersey Audubon Society.

Beam, F. D. 1965. Laboratory studies of *Aedes sollicitans* infected with Dirofilaria immitis, the dog heartworm. Proc. N. J. Mosq. Exterm. Assoc., 52:200-205.

Beck, M. W. 1997. A test of the generality of the effects of shelter bottlenecks in four stone crab populations. Ecology, 78:2487-2503.

Bent, A. C. 1963. Life histories of North American marsh birds. Dover Publications, New York.

Bigford, T. E. 1979. Synopsis of biological data on the rock crab, *Cancer Irroratus* Say. Circular 426, NOAA Technical Report, National Marine Fisheries Service, Washington, D. C., 25 pp.

Boschung, H. T., Jr., D. K. Caldwell, and M. C. Caldwell. 1983. The Audubon

Society Field Guide to North American Fishes, Whales, and Dolphins. Alfred A. Knopf, New York.

Boyd, H.P. 1991. A field guide to the Pine Barrens of New Jersey. Plexus Publishing, Medford, New Jersey.

Bradley, J. S., M. F. Carter, and K. Barker. 1998. Setting neotropical migratory bird conservation priorities for states and physiographic regions within the U.S. The Partners in Flight Prioritization Database, Colorado Bird Observatory, Brighton, Colorado.

Briggs, S. A. and J. H. Criswell. 1979. Gradual silencing of spring in Washington. Atlantic Nat., 32:19-26.

Brown, W. S. 1993. Biology, Status, and Management of the Timber Rattlesnake (*Crotalus horridus*): A Guide for Conservation. SSAR Herpetological Circular No. 22:1-78.

Buchholz, K. and R. A. Zampella. 1987. A 30-year fire history of the New Jersey Pinelands. Bull. N. J. Acad. Sci., 32:61-69.

Buchholz, K. and R. E. Good. 1982. Compendium of New Jersey Pine Barrens literature. Technical Report, Division of Pinelands Research, Center for Coastal and Environmental Studies, Rutgers University, New Brunswick, New Jersey.

Bunnell, J. and R. A. Zampella. 1998. Acid water anuran pond communities along a regional forest to agr-urban ecotone. Copeia (in review).

Burger, J. 1977. Determinants of Hatching success in diamondback terrapin, *Malaclemys terrapin*.. Am. Midland Nat., 97:444-464.

Burger, J. and J. Shisler. 1978. Nest site selection of willets in a New Jersey salt marsh. Wilson Bull., 90:559-607.

Burger, J. and R. T. Zappalorti. 1989a. Habitat use by pine snakes (*Pituophis melanoleucus*) in the New Jersey Pine Barrens: individual and sexual variation. J. Herpetol., 23(1):68-73.

Burger, J. 1996. A Naturalist Along the Jersey Shore. Rutgers University Press, New Brunswick, New Jersey.

Burger, J. 1997. Avian studies on Barnegat Bay. Pp. 345-350 *in* Flimlin, G. E. and M. J. Kennish (eds.), *Proceedings of the Barnegat Bay Ecosystem Workshop*. Rutgers Cooperative Extension of Ocean County, Toms River, New Jersey.

Burke, D. M. and E. Nol. 1998. Influence of food abundance, nest-site habitat, and forest fragmentation on breeding ovenbirds. Auk, 115:96-104.

Butler, M. J. I., J. H. Hunt, W. F. Herrnkind, M. J. Childress, R. Bertelsen, W. Sharp, T. Matthews, J. M. Field, and H. G. Marshall. 1995. Cascading disturbances in Florida Bay, USA: cyanobacteria blooms, sponge mortality, and implications for juvenile spiny lobsters *Panulirus argus*. Mar. Ecol. Prog. Ser.,

129:119-125.

Carpenter, S. J. and W. J. LaCasse. 1955. Mosquitoes of North America (North of Mexico). University of California Press, Los Angeles, California.

Carpenter, S. J. and W. W. Middlekauf. 1944. Inland records of salt marsh mosquitoes. J. Econ. Ent., 37:108.

Castelli, P. M., D. Olson, and V. Turner. 1997. Aerial surveys of Barnegat Bay and Little Egg Harbor, New Jersey 1956-1996. Pp. 329-344 *in* Flimlin, G. E. and M. J. Kennish (eds.), *Proceedings of the Barnegat Bay Ecosystem Workshop*. Rutgers Cooperative Extension of Ocean County, Toms River, New Jersey.

Christensen, N. L. 1988. Vegetation of the Southeastern Coastal Plain. Pp. 317-363 *in* Barber, G. (ed), *North American Terrestrial Vegetation*, Cambridge University Press, Cambridge.

Clark, R. B. 1992. *Marine Pollution*, 3rd ed. Clarendon Press, Oxford.

Coker. 1906. (top of page 68)

Collins, B. R. 1988. The backdrop for the Pinelands legislation. Pp. 275-295 in Collins, B. R. and E. B. Russell (eds.), *Protecting the New Jersey Pinelands: A New Direction in Land-use Management*. Rutgers University Press, New Brunswick, New Jersey.

Conant, R. 1958. A Field Guide to reptiles and amphibians of Eastern North America. Houghton Mifflin Company, Boston, Massachusetts.

Conant, R. and J. T. Collins. 1991. A Field Guide to Reptiles and Amphibians of Eastern and Central North America, 3rd ed. Houghton Mifflin Company, Boston, Massachusetts.

Crans, W. J., J. McNelly, T. L. Schulze, and A. Main. 1986. Isolation of eastern equine encephalitis virus from Aedes sollicitans during an epizootic in southern New Jersey. J. Am. Mosq. Control Assoc., 2:68-72.

DeGraaf, R. M. and J. H. Rappole. 1995. Neotropical Migratory Birds: Natural History, Distribution, and Population Change. Cornell University Press, Ithaca, New York.

Dittel, A.I., A. H. Hines, G. M. Ruiz, and K. K. Ruffin. 1995. Effects of shallow-water refuge on behavior and density-dependent mortality of juvenile blue crabs in Chesapeake Bay. Bull. Mar. Sci., 57:673-702.

Dunson, W. A. 1970. Some aspects of electrolyte and water balance in three estuarine reptiles, the diamondback terrapin, American and "salt water" crocodiles. Comp. Biochem. Physiol., 32:161-174.

Ehrenfeld, J. G. and Schneider. 1991. Chamaecyparis thyoides wetlands and suburbanization: effects of nonpoint source water pollution on hydrology and plant community structure. J. Appl. Ecol., 28:467-

490.

Ernst, C. H., J. E. Lovich, and R.W. Barbour. 1994. Turtles of the United States and Canada. Smithsonian Institution Press, Washington D. C.

Fairbrothers, D. E. 1979. Endangered, threatended, and rare vascular plants of the Pine Barrens and their biogeography. Pp. 395-405 *in* Forman, R. T .T., (ed.), *Pine Barrens: Ecosystem and Landscape*. Academic Press, New York.

Fellton, H. L. 1944. The breeding of the salt marsh mosquito in midwestern states. J. Econ. Ent., 37:245-247.

Fenchel, T. M. 1969. The ecology of marine microbenthos. IV. Structure and function of the benthic ecosystem, its chemical and physical factors and the microfauna communities with special reference to the ciliated protozoa. Ophelia, 6:1-17.

Fenchel, T. M. 1978. The ecology of micro- and meiobenthos. Annu. Rev. Ecol. Syst., 9:99- 125.

Ferigno, F. and R. Kosinski. 1969. Clapper rail study. Technical Report, Project W-34-R-15.

Ferrigno, F., L. Widjeskog, and S. Toth. 1973. Marsh destruction. Technical Report, Project, P. R. Project W-533-R-1.

Forman, R. T. T. 1979. The Pine Barrens of New Jersey: an ecological mosaic. Pp. 569-585 *in* Forman, R. T .T., (ed.), *Pine Barrens: Ecosystem and Landscape*. Academic Press, New York.

Forman, R. T. T. and R. E. Boerner. 1981 Fire frequency and the Pine Barrens of New Jersey. Bull. Torrey Botan. Club, 108:34-50.

Freda, J. and W. A. Dunson. 1986. Effects of low pH and other chemical variables on the local distribution of amphibians. Copeia, 1:454-466.

Freda, J. and R. J. Gonzalez. 1986. Daily movements of the treefrog *Hyla andersonii*. J. Herpetol., 26:429-433.

Friesen, L. E., P. F. Eagles, and R. J. Mackay. 1995. Effects of residential development on forest-dwelling Neotropical migrant songbirds. Conserv. Biol., 9:1408-1414.

Galligen, J. H. and W. A. Dunson. 1979. Biology and status of timber rattlesnake (*Crotalus horidus*) populations in Pennsylvania. Biol. Conserv., 15:13-58.

Givnish, T. J. 1981. Serotiny, geography and fire in the Pine Barrens of New Jersey. Evolution, 35:101-123.

Goldfield, M. D., O. Sussman, W. Gusciora, R. Kerlin, W. Carter, and R. P. Kandle. 1968. Arbovirus activity in New Jersey during 1967. Proc. N. J. Mosq.

Exterm. Assoc., 55:14-19.

Good, R. E. and N. F. Good. 1984. The Pinelands National Reserve: an ecosystem approach to management. BioScience, 34:169-173.

Gosner, K. L. 1978. A Field Guide to the Atlantic Seashore. Houghton Mifflin, Boston, Massachusetts, 329 pp.

Graham, J. H. 1993. Species diversity of fishes in naturally acidic lakes in New Jersey. Trans. Am. Fish. Soc., 122:1043-1057.

Graham, J. H. and R. W. Hastings. 1984. Distributional patterns of sunfishes on the New Jersey coastal plain. Environ. Biol. Fish. 10:137-148.

Grassle, J. F. and J. P. Grassle. 1974. Opportunistic life histories and genetic systems in marine benthic polychaetes. J. Mar. Res., 32:253-284.

Grassle, J. F. and J. P. Grassle. 1976. Sibling species in the marine pollution indicator *Capitella* (Polychaeta). Science, 192:567-569.

Greenlaw, J. S. 1992. Seaside sparrow, *Ammodramus maritimus*. Pp. 211-231 *in* Schnieder, K. J. and D.M. Pence (eds). Migratory Nongame Birds of Management Concern in The Northeast. U.S. Department of the Interior, Fish and Wildlife Service, Newton Corner, Massachusetts.

Greenlaw, J. S. and J. D. Rising. 1994. Sharp-tailed sparrow (*Ammodramus caudacutus*). *In* Poole, A. and F. Gill, (eds.), The Birds of North America, No. 127, The Academy of Natural Sciences, Philadelphia and the American Ornithologists' Union, Washington,

D. C.

Haefner, P. A. 1976. Distribution, reproduction and moulting of the rock crab, *Cancer irroratus* Say, 1917, in the Mid-Atlantic Bight. Journal of Natural History 10:377-397.

Haig, S. M. 1992. Piping Plover (*Charadrius melodus*). *In* Poole, A., P. Stettenheim, and F. Gill, (eds.), The Birds of North America, No. 2. The Academy of Natural Sciences, Philadelphia and the American Ornithologists' Union, Washington, D. C.

Harshberger, J. W. 1916. The Vegetation of the New Jersey Pine Barrens. Dover Publications, New York, 329 pp.

Hastings, R. W. 1979. Fish of the Pine Barrens. Pp. 489-504 *in* Forman, R. T. T. (ed.), Pine Barrens: Ecosystem and Landscape. Academic Press, New York.

Hastings, R. W. 1984. The fishes of the Mullica River, a naturally acid water system of the New Jersey Pine Barrens. Bull. N. J. Acad. Sci., 29:9-23.

Headlee, T. J. 1945. The mosquitoes of New Jersey and their control. Rutgers University Press, New Brunswick, New Jersey.

Heck, K. L. J., K. W. Able, M. P. Fahay, and C. T. Roman. 1989. Fishes and

decapod crustaceans of Cape Cod eelgrass meadows: species composition, seasonal abundance patterns, and comparison with unvegetaged substrates. Estuaries, 12:59-65.

Heck, K. L. J., K. W. Able, C. T. Roman, and M. P. Fahay. 1995. Composition,

abundance, biomass, and production of macrofauna in a New England estuary:

comparisons among eelgrass meadows and other nursery habitats. Estuaries, 18:379-389.

Heck, K. L. J. and T. A. Thoman. 1984. The nursery role of seagrass meadows in

the upper and lower reaches of the Chesapeake Bay. Estuaries, 7:70-92.

Herkert et al. (page 61)

Herkert, J. R., R. E. Szafoni, V. M. Kleen, J. E. Schwegman. 1998. Habitat establishment, enhancement, and management for forest and grassland birds in Illinois. Natural Heritage Technical Publication 1, Division of Natural Heritage, Illinois Department of Conservation, Springfield, Illinois.

Hildebrand, S. F. 1929. Review of experiments on artificial culture of diamond-back terrapin. Bull. U.S. Bureau Fish., 45:25-70.

Hildebrand, S. F. 1932. Growth of diamond-back terrapins: size attained, sex ratio and longevity. Zoologica, 9:551-563.

Hines, A. H., R. N. Lipcius, and A. M. Haddon. 1987. Population dynamics and habitat partitioning by size, sex, and molt stage of blue crabs, *Callinectes sapidus,* in a subestuary of central Chesapeake Bay. Mar. Ecol. Prog. Ser., 36:55-64.

Hines, A. H. and G. M. Ruiz. 1995. Temporal variation in juvenile blue crab mortality: nearshore shallows and cannibalism in Chesapeake Bay. Bull. Mar. Sci., 57:635-672.

Hines, A. H., T. G. Wolcott, E. Gonzalez-Gurriaran, J. L. Gonzalez-Escalante, and J. Freire. 1995. Movement patterns and migrations in crabs: telemetry of juvenile and adult behaviour in Callinectes sapidus and Maja squinado. J. Mar. Biol. Assoc. of the U.K., 75:27-42.

Jamieson, G. S. and A. Phillips. 1993. Megalopal spatial distribution and stock separation in Dungeness crab (*Cancer magister*). Can. J. Fish. Aquat. Sci., 50:416-429.

Jenkins, C. D., Jr., 1997. Recent trends in colonial waterbird populations of the Barnegat Bay-Little Egg Harbor estuary. Pp. 361-377 *in* Forman, R. T .T. (ed.), *Pine Barrens: Ecosystem and Landscape*. Academic Press, New York.

Jenkins, C. D., S. Canale, T. Shutz. 1998a. Federal aid Performance Report

XIV-A. Piping plover nesting survey. Federal Aid Project Number E-1-21.

Jenkins, C. D., S. Canale, T. Shutz. 1998b. Federal aid Performance Report XIV-A. Piping threat assessment and management. Federal Aid Project Number E-1-21.

Jivoff, P. and K. Able. In review. Characteristization of the fish and selected decapods in Little Egg Harbor. J. Coastal Res.

Kandle, R. P. 1961. Summary of our present knowledge of EEE in New Jersey. Proc. N. J. Mosq. Exterm. Assoc., 54:15-19.

Keller, C. M. E., C. S. Robbins, and J. S. Hatfield. 1993. Avian communities in riparian forests of different widths in Maryland and Delaware. Wetlands, 13:137-144.

Kent, R.E., W. Fisher, and P. Mulligan. 1987. Surveillance and control of N. J. mosquito populations on U.S. Corps of Engineers' dredge spoil areas: a pilot program utilizing aerial insecticides. Proc. N. J. Mosq. Control Assoc., 74:78-84.

Kibbe, D. P. 1995. Willet. Pp. 465-468 *in* Dove, L. E. and R. M. Nyman (eds.), Living Resources of the Delaware Estuary, The Delaware Estuary Program, U.S. Environmental Protection Agency, New York.

Kroodsma, D. E. and J. Verner, J. 1997. Marsh wren (*Cistothorus palustris*). *In* Poole, A. and F. Gill (ed.), The Birds of North America, No. 127, The Academy of Natural Sciences, Philadelphia and the American Ornithologists' Union, Washington, D. C.

Lake, R. W. 1965. Bionomics of *Aedes sollicitans* (Walker). M.S. Thesis, University of Delaware, Newark.

Lavigne, D. M. and K. M. Kovacs. 1988. Harps and Hoods: Ice Breeding Seals of the Northwest. University of Waterloo Press, Waterloo, Ontario, Canada.

Lawler, A. R. and J. A. Musick. 1972. Sand beach hibernation by a northern diamondback terrapin, *Malaclemys terrapin terrapin* (Schoepff). Copeia, 1972:389-390.

Leatherwood, S., R. Reeves, and L. Foster. 1983. The Sierra Club Handbook of Whales and Dolphins. Sierra Club Books, San Francisco.

Leukering, T., 1995. Seaside and sharp-tailed (salt marsh) sparrows. Pp. 449-453*in* Kove, L. E. and Nyman, R. M. (eds.), Living Resources of the Delaware Estuary. The Delaware Estuary Program, U.S. Environmental Protection Agency, New York.

Little, S. 1950. Ecology and silviculture of white cedar and associated hardwoods in southern New Jersey. Yale University School of Forestry Bulletin, 56:1-103.

Little, S. 1951. Observations on the minor vegetation of the Pine Barrens swamps in southern New Jersey. Bull. Torrey Botan. Club, 78:153-160.

Little, S. 1979. Fire and plant succession in the New Jersey Pine Barrens. Pp. 297-314 *in* Flimlin, G. E. and M. J. Kennish (eds.), *Proceedings of the Barnegat Bay Ecosystem Workshop*. Rutgers Cooperative Extension of Ocean County, Toms River, New Jersey.

Lloyd, T., R. W. Hastings, J. White-Reimer, J. R. Aresenault, C. Arsenault, and M. Merritt. 1980. Aquatic ecology of the New Jersey Pinelands. Technical report prepared for the New Jersey Pinelands Commission, New Lisbon, New Jersey.

Loveland, R. E.; E. T. Moul, F. X. Phillips, J. E. Taylor, and K. Mountford. 1969. The qualitative and quantitative analysis of the benthic flora and fauna of Barnegat Bay before and after the onset of thermal addition. Technical Report, Rutgers University, New Brunswick, New Jersey.

Loveland, R. E., E. T. Moul, D. A. Busch, P. H. Sandine, S. S. Shafto, and J. McCarty. 1972. The qualitative and quantitative analysis of benthic flora and fauna of Barnegat Bay before and after the onset of thermal addition. Technical Report, Rutgers University, New Brunswick, New Jersey.

Loveland, R. E., P. Edwards, J. J. Vouglitois, and D. Palumbo. 1974. The qualitative and quantitative analysis of benthic flora and fauna of Barnegat Bay before and after the onset of thermal addition. Technical Report, Rutgers University, New Brunswick, New Jersey.

Loveland, R. E., J. F. Brauner, J. E. Taylor, M. J. Kennish. 1984. Macroflora. Pp. 78-94 *in* Kennish, M. J. and R. A. Lutz (eds.), *Ecology of Barnegat Bay, New Jersey*. Springer-Verlag, New York.

Loveland, R. E. and S. S. Shafto, S. S., 1984. Fouling organisms. Pp. 226-240 *in* Kennish, M. J. and R. A. Lutz (eds.), *Ecology of Barnegat Bay, New Jersey*. Springer-Verlag, New York.

Loveland, R. E. and J. J. Vouglitois. 1984. Benthic fauna Pp. 135-170 *in* Kennish, M. J. and R. A. Lutz (eds.), *Ecology of Barnegat Bay, New Jersey*. Springer-Verlag, New York.

Ludlam, M. K., L. A. Jachowski, and G. F. Otto. 1970. Potential vectors of *Dirofilaria immitis*. J. Am. Vet. Med. Assoc., 157:1354-1359.

Lynch, J. F. and R. F. Whitcomb. 1978. Effects of the insularization of the eastern deciduous forest on avifaunal diversity and turn over. Pages 461-489 *in* Marmelstein, A. (ed.), Classification, Inventory, and Analysis of Fish and Wildlife Habitat. Obs-78/76, U.S. Department of the Interior, Fish and Wildlife Service, Washington, D. C.

Mahoney, J. B., A. Codella, and K. I. Keating. 1997. Occurrence of brown tide, *Aureococcus anophagefferens*, in the Barnegat Bay system. Pp. 153-163 *in*

Flimlin, G. E. and M. J. Kennish (eds.), *Proceedings of the Barnegat Bay Workshop*. Cooperative Extension of Ocean County, Toms River, New Jersey.

Marcellus, K. L. 1972. Fishes of Barnegat Bay, New Jersey, with particular reference to seasonal influences and possible effects of thermal discharges. Ph.D. Thesis, Rutgers University, New Brunswick, New Jersey.

Martin, G. W. 1929. Dinoflagellates from marine and brackish waters in New Jersery. University of Iowa Studies in Natural History XII(9), Iowa City.

Martin, W. H. 1982. The timber rattlesnake in the northeast: its range, past, and present. Bull. N. Y. Herpetol. Soc., 17:15-20.

Martin, W. H. 1988. Life History of the timber rattlesnake. Catesbeiana, 8:9-12.

Matheson, R. 1944. A Handbook of the Mosquitoes of North America. Comstock Publishing Company, Ithaca, New York.

McClain, P. and M. McHale 1997. Barnegat Bay eelgrass investigation 1995-96. Pp. 165-171 *in* Flimlin, G. E. and M. J. Kennish (eds.), *Proceedings of the Barnegat Bay Workshop*. Cooperative Extension of Ocean County, Toms River, New Jersey.

McCormick, J. and M. F. Buell. 1968. The Plains forests of the New Jersey Pine Barrens: a review and annotated bibliography. Bull. N. J. Acad. of Sci., 13:20-34.

McCormick, J. 1979. The vegetation of the New Jersey Pine Barrens. Pp. 229-243, *in* Forman, R. T. T. (ed.), *Pine Barrens: Ecosystem and Landscape*. Academic Press, New York.

Metcalf, K. S. and R. N. Lipcius. 1992. Relationship of habitat and spatial scale with physiological state and settlement of blue crab postlarvae in Chesapeake Bay. Mar. Ecol. Prog. Ser., 82:143-150.

Millikin, M. R. and A. B. Williams. 1980. Synopsis of biological data on the blue crab, *Callinectes sapidus* Rathbun. FAO Fisheries Synopsis No. 138, NOAA Technical Report 1, National Oceanic and Atmospheric Administration, Washington, D. C.

Mitchell, J. C. 1994. The Reptiles of Virginia. Smithsonian Institution Press, Washington,

D. C.

Morgan, M. D. and K. R. Philipp. 1986. The effect of agricultural and residential development on aquatic macrophytes in the New Jersey Pine Barrens. Biol. Conserv., 35:143-158.

Moser, F. C. 1997. Sources and sinks of nitrogen and trace metals, and benthic

macrofauna assemblages in Barnegat Bay, New Jersey. Ph.D. Thesis, Rutgers University, New Brunswick, New Jersey.

Mountford, K. 1965. A late summer red tide in Barnegat Bay, New Jersey. Underw. Nat., 3:32-34.

Mountford, K. 1969. A seasonal plankton cycle in Barnegat Bay, New Jersey. M.S. Thesis, Rutgers University, New Brunswick, New Jersey.

Mountford, K. 1971. Plankton studies in Barnegat Bay. Ph.D. Thesis, Rutgers University, New Brunswick, New Jersey.

Mountford, K. 1984. Phytoplankton. Pp. 52-77 *in* Kennish, M. J. and R. A. Lutz (eds.), *Ecology of Barnegat Bay, New Jersey*. Springer-Verlag, New York.

Moyle, P. B. 1986. Fish introductions into North America: patterns and ecological impact. Pp. 25-43 *in* Mooney, H. A. and J. A. Drake (eds.), Ecology of Biological Invasions of North American and Hawaii. Springer-Verlag, New York.

Mulligan, P., R. Kent, and D. Joslyn. 1990. Mosquito production on dredge spoil sites: a comparison of pyramid traps vs. soil sampling for eggs. Proc. N. J. Mosq. Control Assoc., 77:117-120.

Nichols, T. C. and P. M. Castelli. 1997. Waterfowl hunting in Barnegat Bay and Little Egg Harbor Bay, New Jersey. Pp. 309-327 *in* Flimlin, G. E. and M. J. Kennish (eds.), *Proceedings of the Barnegat Bay Ecosystem Workshop*, Rutgers Cooperative Extension of Ocean County, Toms River, New Jersey.

Nixon, S. W. 1982. The ecology of New England high salt marshes: a community profile. U.S. Department of Interior Fish and Wildlife Service, Biological Services Program, FWS/OBS-81-55, Slidell, Louisiana.

Nol, E. and R. C. Humphrey. 1994. American oystercatcher (Haematopus palliatus). *In* Poole, A., P. Stettenheim, and F. Gill (eds.) The Birds of North America, No. 2. The Academy of Natural Sciences, Philadelphia and the American Ornithologists' Union, Washington,

D. C.

Olsen, P. S. 1997. Development and distribution of phytoplankton blooms causing brown water in the Barnegat Bay system. Pp. 253-266 *in* Flimlin, G. E. and M. J. Kennish, M. J. (eds.), *Proceedings of the Barnegat Bay Workshop*. Cooperative Extension of Ocean County, Toms River, New Jersey.

Olsson, H. 1979. Vegetation of the New Jersey Pine Barrens: a phytosociological classification. Pp. 245-263 *in* Forman, R. T. T. (ed.), Pine Barrens: Ecosystem and Landscape. Academic Press, New York.

Orth, R. J. and H. L. J. Heck. 1980. Structural components of eelgrass (*Zostera marina*) meadows in the lower Chesapeake Bay-fishes. Estuaries, 3, 278-288.

Ostergaard, R., R. Murphy, and D. K. Auten. 1961. Aedes sollicitans breeding in freshwater. Proc. N. J.

Mosq. Exterm. Assoc., 48:121-122.

Phillips, F. X. 1972. The ecology of benthic macroinvertebrates of Barnegat Bay, New Jersey. M.S. Thesis, Rutgers University, New Brunswick, New Jersey.

Post, W. and J. S. Greenlaw. 1994. Seaside sparrow (*Ammodramus maritimus*). *In* Poole, A. and F. Gill (ed.), The Birds of North America, No. 127, The American Ornithologists' Union, Washington, D. C.; The Academy of Natural Sciences, Philadelphia.

Pulliam, H. R. 1988. Sources, sinks, and population regulation. Am. Nat., 132:652-661.

Rappole, J. H., E. S. Morton, T. E. Lovejoy III, and J. S. Ruos. 1983. Nearctic avian migrants in the neotropics. Technical Report, U.S. Department of the Interior, Fish and Wildlife Service, Washington, D. C.

Redfield, A. C. 1972. Development of a New England salt marsh. Ecol. Monogr., 42:201-237.

Rich, A. C., D. S. Dobkin, and L. J. Niles. 1994. Defining forest fragmentation by corridor width: the influence of narrow forest-dividing corridors on forest-nesting birds in southern New Jersey.

Richards, A. G. 1938. Mosquitoes and mosquito control on Long Island, New York, with particular reference to the salt marsh problem. N. Y. State Mus. Bull., 316:85-185.

Richards, B. R., R. E. Hillman, and N. J. Maciolek 1984. Shipworms. Pp. 201-225 *in* Kennish, M. J. and R. A. Lutz (eds.), *Ecology of Barnegat Bay, New Jersey*. Springer-Verlag, New York.

Robbins, C. S. 1979. Effect of forest fragmentation on bird populations. Pp. 198-212 *in* DeGraaf, R. M. and K. E. Evans (eds.), Proceedings of the Workshop Management on North Central and Northeastern Forests for Nongame Birds. GRT NC-51, U.S. Department of Agriculture, Forest Service, St. Paul, Minnesota.

Robbins, C. S., J. R. Sauer, R. S. Greenberg, and S. Droege. 1989a. Population declines in North American birds that migrate to the Neotropics. Proc. Natl. Acad. Sci. 86:7658-7663.

Robbins, C. S., D. K. Dawson, and B. A. Dowell. 1989b. Habitat area requirements of breeding forest birds of the Middle Atlantic states. Wildlife Monogr., 103:1-34.

Rogers, Golden, and Halpern. 1990. Profile of the Barnegat Bay. Final Report for the Barnegat Bay Study Group, New Jersey Department of Environmental Protection and Energy, Trenton, New Jersey.

Roman, C. T. and R. E. Good. 1983. Wetlands of the New Jersey Pinelands:

values, functions, and impacts. Technical Report, Division of Pinelands Research, Center for Coastal and Environmental Studies, Rutgers University, New Brunswick, New Jersey.

Roman, C. T., R. A. Zampella, and A. Z. Zaworski. 1985. Wetland boundaries in the New Jersey Pinelands: ecological relationships and delineation. Wat. Res. Bull., 21:1005-1012.

Roman, C. T., R. E. Good, and S. Little. 1990. Ecology of Atlantic white cedar swamps in the New Jersey Pinelands. Pp. 163-173 *in* Whigham, D. F., R. E. Good, and J. Kvet (eds.), Wetland Ecology and Management: Case Studies. Kluwer Academic Publishers, Dordrecht, Netherlands.

Rountree, R. A. and K. W. Able. 1993. Diel variation in decapod crustacean and fish assemblages in New Jersey polyhaline marsh creeks. Est. Coastal Shelf Sci., 37:181-201.

Sandine, P. H. 1984. Zooplankton. Pp. 95-134 in Kennish, M. J. and R. A. Lutz, (eds.), *Ecology of Barnegat Bay, New Jersey.* Springer-Verlag, New York.

Sanderson, G. C. (Ed.). 1977. Management of migratory shore and upland game birds in North America. Technical Report, International Association of Fish and Wildlife Agencies, Washington, D. C.

Sauer, J. R., J. E. Hines, G. Gough, I. Thomas, and B. G. Peterjohn. 1997. The North American breeding bird survey results and analysis. Version 96.4, Patuxent Wildlife Reseach Center, Laurel, Maryland.

Schaffner, L. C. and R. J. Diaz. 1988. Distribution and abundance of overwintering blue crabs, *Callinectes sapidus*, in the lower Chesapeake Bay. Estuaries, 11:68-72.

Schoelkopf, R. 1975-1999a, b. Observations compiled for stranding database by Marine Mammal Stranding Center.

Schoelkopf, R. and E. Stetzar. 1995a. Marine turtles. Pp. 305-309 *in* Dove, L. E. and R. M. Nyman (eds), Living Resources of the Delaware Estuary. Delaware Estuary Program, U. S. Environmental Protection Agency, New York.

Schoelkopf, R. and E. Stetzar. 1995b. Marine mammals. Pp. 503-506 *in* Dove, L. E. and R. M. Nyman (eds), Living Resources of the Delaware Estuary. Delaware Estuary Program, U. S. Environmental Protection Agency, New York.

Schoelkopf, R. and S. P. Feehan. 1998.

Seitzinger, S. P. and I. E. Pilling. 1990. Eutrophication and nutrient loading in Barnegat Bay: initial studies of the importance of sediment-water nutrient interactions. Report No. 90-14, The Academy of Natural Sciences, Philadelphia, Pennsylvania.

Seitzinger, S. P. and I. E. Pilling. 1992. Eutrophication and nutrient loading in Barnegat Bay: importance of sediment-water nutrient interactions. Report No.

92-24F, The Academy of Natural Sciences, Philadelphia, Pennsylvania.

Seitzinger, S. P. and I. E. Pilling. 1993. Eutrophication and nutrient loading in Barnegat Bay: sediment-water phosophorus dynamics. Report No. 92-33F, The Academy of Natural Sciences, Philadelphia, Pennsylvania.

Shafto, S. S. 1974. The marine boring and fouling invertebrate community of Barnegat Bay, New Jersey. M.S. Thesis, Rutgers University, New Brunswick, New Jersey.

Shirley, M. A., A. H. Hines, and T. G. Wolcott. 1990. Adaptive significance of habitat selection by molting adult blue crabs *Callinectes sapidus* (Rathbun) within a subestuary of central Chesapeake Bay. Journal of Experimental Marine Biology and Ecology, 140:107-119.

Shisler, J. K. 1977. Mosquito breeding associated with dredge spoil deposition areas in New Jersey. Proc. N. J. Mosq. Control Assoc., 64:196-208.

Shoemaker and Widjeskog. 1977. (bottome of page 47)

Silva, E. S. 1967. *Cochlodinium heterolobatum* n. sp. - structure and some cytophysiological aspects. J. Protozool., 14:745-754.

Smith, J. B. 1905. Vitality of mosquito eggs. Science, 21:266-267.

Sneddon, L. A., K. J. Metzler and M. Anderson. 1995. A classification and description of natural community alliances and selected community elements of the Delaware Estuary. Pp. A-3-90 *in* Dove, L. E. and R. M. Nyman (eds), Living Resources of the Delaware Estuary. Delaware Estuary Program, U. S. Environmental Protection Agency, New York.

Snyder, D. B. and V. E. Vivian. 1981. Rare and endangered vascular plant species in New Jersey.

Technical Report, The Conservation and Environmental Studies Center, Pemberton, New Jersey.

Sogard, S. M. and K. W. Able. 1991. A comparison of eelgrass, sea lettuce macroalgae, and marsh creeks as habitats for epibenthic fishes and decapods. Est. Coastal Shelf Sci., 33:501-519.

Stechert, R. 1992. Distribution and population status of *Crotalus horridus* in New York and Northern New Jersey. In T. G. Tyning, (ed.), Conservation of the timber rattlesnake in the northeast. Technical Report, Massachusetts Audubon Society, Lincoln, Massachusetts.

Sutton, C. C., J. C. O'Herron, II, and R. T. Zappalorti. 1996. The Scientific Characterization of the Delaware Estuary. The Delaware Estuary Program (DRBC Project No. 321; HA File No. 93.21), U.S. Environmental Protection Agency, New York.

Szedlmayer, S. T. and K. W. Able. 1996. Patterns of seasonal availability and habitat use by fishes and decapod crustaceans in a southern New Jersey estuary. Estuaries, 19:697-709.

Tatham, T. R, D. J. Danila, D. L. Thomas, and Associates. 1977. Ecological

studies for the Oyster Creek Generating Station. Technical Report, Ichthyological Associates, Inc., Ithaca, New York.

Tatham, T. R, D. J. Danila, D. L. Thomas, and Associates. 1978. Ecological studies for the Oyster Creek Generating Station. Technical Report, Ichthyological Associates, Inc., Ithaca, New York.

Tatham, T. R., D. L. Thomas, and D. J. Danila. 1984. Fishes of Barnegat Bay, Pp. 241-280 in Kennish, M. J. and R. A. Lutz, (eds.), Ecology of Barnegat Bay, New Jersey. Springer-Verlag, New York.

Tennant, A. 1997. A Field Guide to the Snakes of Florida. Gulf Publishing Company, Houston, Texas.

Terres, J. K. 1980. Audubon Encyclopedia of North American Birds.

Tiner, R. W. 1974. The ecological distribution of the invertebrate macrofauna in the Cottrell marsh, Stonington, Connecticut. M.S. thesis, University of Connecticut, Storrs.

Tiner, R. W. 1985. Wetlands of New Jersey. Technical Report, Department of Interior, U.S. Fish and Wildlife Service, Region 5, Newton Corner, Massachusetts.

U.S. Fish and Wildlife Service. 1996. Significant habitats and habitat complexes of the New York Bight watershed: complex 6 - Barnegat Bay complex. Technical Report, U.S. Fish and Wildlife Service, Southern New England-New York Bight Coastal Ecosystems Program, Charlestown, Rhode Island.

U.S. Fish and Wildlife Service. 1996. Piping plover (*Charadrius melodus*). Atlantic Coast population, revised recovery plan, Hadely, Massachusetts.

U.S. Fish and Wildlife Service. 1999. Jersey Coast Refuges Draft Comprehensive Conservation Plan: Edwin B. Forsythe and Cape May National Wildlife Refuges. U.S. Fish and Wildlife Service, Hadley, Massachusetts.

Vernberg, F. J. (Ed.). 1975. Physiological Ecology of Estuarine Organisms. University of South Carolina Press, Columbia, S. C.

Vickery, P. D., M. L. Hunter, Jr., and S. M. Melvin. 1997. Effects of habitat area on the distribution of grassland birds in Maine. Pp. 137-152 *in* Vickery, P. D. and P. W. Dunwiddie (eds.), Grasslands of Northeastern North America. Center for Biological Conservation, Massachusetts Audubon Society.

Viscido, S.V., D. E. Stearns, and K. W. Able. 1997. Seasonal and spatial patterns of an epibenthic decapod crustacean assemblage in North-west Atlantic continental shelf waters. Est. Coastal Shelf Sci., 45:377-392.

Vouglitois, J. J. 1983. The ichthyofauna of Barnegat Bay, New Jersey: relationships between long-term temperature fluctuations and the population

dynamics and life history of temperature fluctuations and population dynamics and life history of temperature estuarine fishes during a five-year period, 1976-1980. M.S. Thesis, Rutgers University, New Brunswick, New Jersey.

Vouglitois, J. J., K. W. Able, R. J. Kurtz, and K. A. Tighe, K. A. 1987. Life history and population dynamics of the bay anchovy in New Jersey. Trans. Am. Fish. Soc., 116:141- 154.

Wilson, K.A., K. W. Able, and K. L. J. Heck. 1987. Juvenile blue crab,*Callinectes sapidus*, survival: an evaluation of eelgrass, *Zostera marina*, as refuge. Fish. Bull., 85:53-58.

Wilson, K.A., K. W. Able, and K. L. J. Heck. 1990a. Habitat use by juvenile

blue crabs: a comparison among habitats in Southern New Jersey. Bull. Mar.

Sci., 46:105-114.

Wilson, K.A., K. W. Able, and K. L. J. Heck. 1990b. Predation rates on juvenile blue crabs in estuarine nursery habitats: evidence for the importance of macroalgae (*Ulva lactuca*). Mar. Ecol. Prog. Ser., 58:243-251.

Wilson, K. A. and K. W. Able. 1997. Shallow water habitat use by juvenile fishes and crabs in Barnegat Bay marinas and adjacent areas. Pp. 193-208 *in* Flimlin, G. E and M. J. Kennish (eds.), *Proceedings of the Barnegat Bay Workshop*. Cooperative Extension of Ocean County, Toms River, New Jersey.

Windham, L. M. and R. G. Lathrop. 1999. Effects of *Phragmites australis* (common reed) invasion on aboveground biomass and soil properties in brackish tidal marsh of the Mullica River, New Jersey. Estuaries (in press).

Witting, D.A., K. W. Able, and M. P. Fahay. 1999. Larval fishes of a Middle-Atlantic Bight estuary: assemblage structure and temporal stability. Can. J. Fish. Aquat. Sci.

Wolgast. L. J. 1979. Mammals of the New Jersey Pine Barrens. Pp. 443-455 *in* Forman, R. T. T. (ed.), *Pine Barrens: Ecosystem and Landscape*. Academic Press, New York.

Wood, R. 1995. (middle of page 67)

Yearicks, E. F., R. C. Wood, and W. S. Johnson. 1981. Hibernation of the northern diamondback terrapin, *Malaclemys terrapin terrapin*. Estuaries, 4:78-80.

Zampella, R. A. 1991. New Jersey Pinelands Commission manual for identifying and delineating Pinelands area wetlands. Technical Report, New Jersey Pinelands Commission, New Lisbon, New Jersey.

Zampella, R. A., G. Moore, and R. E. Good. 1992. Gradient analysis of pitch pine (Pinus rigida Mill.) Lowland communities in the New Jersey Pinelands. Bull. Torrey Botan. Club, 119:253-261.

Zampella, R. A. and R. G. Lathrop. 1997. Landscape changes in Atlantic white

cedar *(Chamaecyparis thyoides*) wetlands of the New Jersey Pinelands. Landscape Ecol., 12:397-408.

Zampella, R. A. and J. F. Bunnell. 1998. Use of reference-site fish assemblages to assess aquatic degradation in Pinelands streams. Ecol. Appl., 8:645-658.

Zappalorti, R.T. 1983. A Management Plan for Endangered Amphibians and Reptiles on the Jake's Branch Section of the Davenport Basin. Technical report submitted to Hovsons, Inc., Toms River, New Jersey. HA File No. 83.03, pp. 1-27.

Zappalorti, R. T. and H. K. Reinert. 1989. Revised final report on habitat utiliztion by the timber rattlesnake, *Crotalus horridus* (Linnaeus) in southern New Jersey with notes on hibernation part one). Unpublished Report submitted to the New Jersey Department of Environmental Protection, Division of Fish, Game and Wildlife, Engangered Species Program, Trenton, New Jersey.

Zappalorti, R. T. and R. R. Sykes. 1998. Amphibians and reptiles of the Barnegat Bay drainage basin with life-history notes of selected species. Unpublished report to the Center for Remote Sensing and Spatial Analysis, Rutgers University, New Brunswick, New Jersey.

I. INTRODUCTION

One of the major topics of focus of the Barnegat Bay Estuary Program is the impact of habitat loss and alteration on this rich and diverse ecological system. To assist in developing the Comprehensive Conservation and Management Plan (CCMP), a variety of satellite imagery, aerial photography, digital land use/land cover data and historical maps has been analyzed to document existing conditions, as well as to assess long-term trends of habitat loss and alteration in Barnegat Bay and its watershed. As with many coastal ecosystems, the Barnegat Bay region contains a wide diversity of natural vegetation communities and habitats, vastly complicating the mapping, monitoring, and communication process. One objective is to simplify the analysis of status and trends in habitat loss and alteration by focusing on a few key components of the bay's watershed that are critical to the larger functioning of the bay ecosystem. A set of landscape level environmental indicators are developed to provide quantitative estimates of the watershed-estuarine resource condition (Table 1). This paper describes the results of this habitat mapping and monitoring effort and summarizes the observed trends in loss and alteration of several key landscape indicators. For more information on the methods used in this analysis, consult Lathrop et al. (1999). The relative impact of existing land-use planning jurisdictions on the spatial distribution of habitat loss and alteration is also evaluated.

II. UPLAND LAND COVER CHANGES

A. Trends in Development and Habitat Loss

While development of the barrier islands and the nearshore mainland areas has had the most direct impact on Barnegat Bay proper, land-use change and development in the upland watershed also has had an important role. Development in the Barnegat Bay watershed during the 19th Century centered on a few established villages on the mainland. This pattern followed through the first half of the 20th Century with most of the development focused on the northern part of the watershed around the established towns of Toms River, Lakewood, and Bay Head. In the 1960's and 1970's, large-scale suburban-style residential and retirement communities began to spring up in the upland Pine Barrens of the Toms River watershed (e.g., Manchester Township). The threat of massive development in the Pine Barrens helped to spur the establishment of the Pinelands National Reserve and the New Jersey Pinelands Commission which instituted regional land-use planning and rigorous control of future development (Collins and Russell, 1988). The Pineland Land Management Area (PLMA) includes much of the upland portions of the Barnegat Bay watershed (Figure 1). Continued development in the upland-coastal fringe during the 1970's led to the establishment of the Coastal Area Facilities Review Act (CAFRA) of 1973 with the intent of regulating large-scale (25 unit +) residential and industrial/commercial development. The CAFRA jurisdictional area ranges in width from 5 to 25 km inland from the bay shoreline (Figure 1). Approximately 66,250 ha (46%) of the bay watershed (including barrier islands) lies within CAFRA, and 54,970 ha (38%) lies within the PLMA. The remaining 23,630 ha (16%) falls within neither.

Analysis of the land-use/land-cover change detection data set provides some insight into land-use/land-cover changes over the past 25 years, both before and after the implementation of the aforementioned policies. Between 1972 and 1984, there was approximately 4,800 ha of new development (i.e., residential/commercial/industrial development, not including sand/gravel mining) in the upland portions of the bay watershed, which represents a 19% increase (Table 1). The change between 1984 and 1995 was nearly twice as great with approximately 9,550 ha of new development (an approximate 31 %

increase). Overall, there has been a gradual increase (18% to 21% to 28%) in the area of the bay watershed (excluding the bay proper) that is developed (1972, 1984, and 1995 respectively) (Figure 2). Because there is comparatively little agricultural land in the Barnegat Bay watershed due to its sandy, nutrient poor soils, most of the new development has taken place on forested land. While there was a net loss of 13,731 ha or 20% of upland forest between 1972 and 1995, the comparative loss of freshwater wetlands was much less during this period, amounting to 1875 ha or approximately 6%.

Spatial analysis of the 1972-1984 changes shows the new development was split between the coastal areas (1630 ha or 34% was located in the CAFRA zone) and the northern section the watershed (2403 ha or 50% was located in the non-CAFRA/non-PLMA zone) with the remainder in the Pinelands (764 ha or 16%). As the 1972-1984 analysis includes both pre- and post-Pinelands legislation time periods, it does not provide a good test of the efficacy of these pieces of legislation in affecting development. The 1984-1995 analysis includes only those changes occurring in the post-Pinelands legislation time periods. Analysis of the 1984-1995 changes shows a concentration of development in the CAFRA area with 5560 ha or 58% of the new development. New development in the northern watershed area that is neither under Pinelands or CAFRA control remained steady at 2460 ha (but represented a smaller percentage of overall development at 26% of the new development). Development in the Pinelands Reserve portions of the upper bay watershed increased to 1524 ha (but represented the same percentage of overall development at 16% of the new development). Approximately 61% of the new development in the PLMA is in the designated growth management areas (including Rural Development, Regional Growth, Pinelands town and Pinelands Village Land Management Capability Areas), which represents only 28% of the PLMA area within the Bay watershed.

Development trends were evaluated for the major subwatersheds of the Barnegat Bay basin, to further elucidate spatial patterns of development. Thirteen subwatersheds were evaluated for the 1972-1984-1995 time periods (Table 2). The north-south development gradient of higher development intensity in the northern portion of the Barnegat Bay watershed is clearly evident. Development has intensified in the northern watersheds with the consequent loss of open space and wildlife habitat. Cedar Creek remains the least heavily developed of the Barnegat Bay subwatersheds. The headwater regions of Union Branch, Forked River, Oyster Creek, Westecunk and Tuckerton Creek are still largely undeveloped and contain extensive areas of typical Pinelands upland and wetland forest habitat. These headwater areas are within the Pinelands Reserve Forest or Preservation land management areas and thus receive some measure of protection.

Based on the land-use/land-cover change detection and interpretation of earlier USGS mapping efforts, it appears that development in the bay watershed grew rapidly in the 1950's-early 1960's, slowed somewhat in the 1970's, but continued at a steadily increasing rate through 1980's into the mid-1990's. The bulk of new development should be located in the CAFRA zone, closer to the amenities of Barnegat Bay, if existing trends continue. By 1995, the barrier islands fronting Barnegat Bay were almost completely developed. As the northern CAFRA zone (e.g., north of Toms River) appears to be reaching buildout, the southern CAFRA zone along the Route 9 corridor would appear to be a logical target for new development. This southern CAFRA zone has a comparatively low percentage of wetlands (at least west of Route 9) with a significant acreage of developable upland forest land. Thus, the remaining areas of open space/wildlife habitat in this southern CAFRA zone are especially vulnerable. If existing trends continue, steady growth in the PLMA managed growth areas and slow growth in Pinelands Preservation and Forest areas are expected. Trends in future development of the upper Metedeconk and Toms River subwatersheds (i.e., non-CAFRA/non-PLMA) are more uncertain. While showing steady growth in the 1972-1995 time period, this area is in a position for expanded development spurred by the completion of Interstate 195.

It is unclear what effect CAFRA has had on development within the Barnegat Bay watershed. While the

percentage of the watershed in the CAFRA zone that is developed has substantially increased (30% to 33% to 41% for the years 1972, 1984 and 1995 respectively), it can be argued that the rate of development could have been potentially much higher without CAFRA. Clearly, development in coastal wetland areas has been largely curtailed through the Coastal Wetlands Law. The Pinelands Land Management Act appears to have been successful in limiting development in the Preservation and Forest zones and shunting the development to the regulated growth areas. The initiation of new "mega" developments that were converting large chunks of upland forest prior to the enactment of Pinelands Reserve Act and CAFRA has been largely curtailed.

B. Riparian Corridors

In the Pinelands, there is close coupling between the shallow groundwater aquifers and the region's surface water supplies. Due to the high porosity of the Pineland's soils, most of the precipitation quickly infiltrates into the soil, enters the shallow groundwater system, and then discharges directly into adjacent streams and wetlands (Ballard , 1979; Rhodehamel, 1979). This tight linkage between the region's groundwater aquifers and stream systems, makes it highly likely that contaminated groundwater is a major source of surface water contamination (Vowinkel and Siwiec, 1991). Morgan and Good (1988) and Zampella (1994) have shown that watershed disturbance through either agricultural or residential and urban development have substantial effects on Pinelands stream water quality. Watershed disturbance due to human development also has been shown to affect the species composition of Pinelands aquatic and wetland communities (Hastings, 1984; Morgan and Philipp, 1986; Ehrenfeld and Schneider 1991, 1993; Zampella and Laidig, 1997).

The many streams and rivers that drain the Barnegat Bay watershed serve as vital habitat for a freshwater-dependent flora and fauna that are unique to the Pinelands ecosystem. The low nutrient, high acid waters of undisturbed Pinelands stream systems support a distinctive fish fauna characterized by 13 native species and the absence of non-native species (Hastings 1984, Zampella and Bunnell, 1998). Sections of the Metedeconk and Toms Rivers, while not considered strictly Outer Coastal Plain-Pinelands streams, are classified as trout streams with a put-and-take trout fishery stocked by the New Jersey of Department of Fish, Game and Wildlife. This freshwater stream-and-river network also links human activities in upland areas and Barnegat Bay proper. The use of protected buffer strips where human development is excluded or minimized is one "best management practice" (BMP) that is often advocated as a means of reducing the impact of human development on adjacent riparian zones (NJDEPE, 1993; Zampella et al., 1994). In addition to reducing nonpoint source pollution, protected riparian buffers serve as vital habitat for both upland and wetland-dependent species. These riparian zones serve as important corridors for wildlife movement and dispersal, linking the coastal bay and interior Pinelands habitats.

Data on freshwater streams and rivers were derived from the NJDEP 1:24000 scale digital GIS data set for the Barnegat Bay watershed. A 90-m buffer out from both sides of all mapped stream/rivers was delineated to create a 180-m wide riparian corridor zone. When evaluated on a watershed-wide basis, approximately 20% of the riparian zone (as of 1995) is in altered land uses (i.e., developed, cultivated/grassland, or barren), 50% is in wetlands, and the remaining 30% in upland forest (Figure 3). To more clearly examine spatial patterns in riparian zone alteration, the percentage of altered riparian zone was calculated for each of Barnegat Bay's 13 subwatersheds (see Table 3). In addition, the percentage of Barnegat Bay's total inventory of altered riparian zone represented by each subwatershed was also calculated. As expected, the more highly developed northern watersheds exhibit the highest

percentage of altered riparian zone. The Metedeconk River subwatershed stands out as having the largest riparian zone. Because a large percentage is altered, the Metedeconk River subwatershed represents a significant portion (> one-third) of the Barnegat Bay watershed's total inventory of altered riparian zone. Due to the intensity of development in the relatively small subwatersheds of Kettle Creek, Silver Bay and Stouts Creek, the riparian zone habitat in these subwatersheds are significantly degraded. The potential for non-point source pollution runoff problems and associated degradation of Barnegat Bay water quality would appear to be high for these subwatersheds due to their close proximity to the bay. In contrast, more than 90% of the riparian zones of the Cedar Creek, and to a lesser extent, the Union Branch, Forked River, and Westecunk Creek subwatersheds, is unaltered. The exceptionally high water quality in Cedar Creek is largely due to the low percentage of development in nearby watershed areas. Hence, the Cedar Creek subwatershed should serve as a reference for comparison of other subwatersheds (Zampella, 1994). Cedar Creek should be further targeted for conservation to protect the integrity of its water quality and riparian habitat and to maintain its value as a "pristine" Pinelands-Barnegat Bay tributary.

C. Habitat Fragmentation

The conservation of large tracts of contiguous Pinelands habitat and the minimization of fragmentation are issues of concern to the Barnegat Bay Estuary Program (Forman, 1979; Good, 1982). Human development has the direct impact of removing existing natural habitat as well as fragmenting the habitat that remains into smaller pieces. Paved roads, as well as residential and industrial/commercial development often serve as barriers or hazards to wildlife movement and native plant dispersal. It also alters "natural" disturbance regimes. Within the Pinelands, there is some thought that fragmentation has decreased the frequency, intensity, and spatial pattern of the wildfire regime (Forman and Boerner, 1981). It has been suggested that changes in fire regime related to more effective fire control may result in changes in landscape patterns, including a gradual transition from pine to oak-dominated forests (Little, 1979; Forman and Boerner, 1981). Human development also causes "indirect" effects by creating a number of different types of intrusions with varying depth of impact into adjacent natural habitat. Examples of these intrusions are increased air, water, and noise pollution; changes in microclimatic conditions due to higher sunlight and wind levels; increased populations of invasive "weed" species; and increased frequency of disturbance due to direct contact with humans, human pets, and associated "rural/suburban pest" species. The border area affected by these disturbances is labelled **edge**, as compared to the undisturbed **interior** habitat (Zipperer, 1993).

A number of passerine songbirds such as warblers and vireos, that breed and forage in forested uplands and wetlands are strongly associated with forest interior as compared to edge habitat. A recent decline in the breeding populations of these migratory songbirds has been linked to the effects of forest fragmentation (Bohning-gaese et al., 1993; Robinson et al., 1995). Fragmentation has resulted in isolation of interior forest habitat (Whitcomb, 1977; Butcher et al., 1981; Blake and Karr, 1984), increased pressure by nest predators (Wilcove, 1985), and brood parasitism by cowbirds which shows higher frequency closer to the forest edges (Brittingham and Temple, 1983). In addition to forest interior nesting songbirds, there are a number of other so-called area-sensitive species that depend on large tracts of undisturbed interior habitat to maintain viable populations. Large raptors, such as red-shouldered hawks and barred owls, are area-sensitive species that require large blocks of mature forested wetlands and adjacent upland forest.

Many characteristic amphibian and reptilian species in the Pine Barrens are sensitive to habitat

fragmentation and human disturbance through a variety of mechanisms. Certain characteristic Pine Barrens frogs (e.g., Pine Barrens tree frogs) have higher abundance in watersheds with low levels of human development; conversely, as human disturbance activity increases, there is an increase in the abundance of non-Pine Barrens frog species (Bunnel and Zampella 1999). Slow moving amphibians and reptiles are especially susceptible to road-kill and are therefore impacted by an increasing density of roads and traffic volumes (Zappalorti and Sykes, 1998).

A species of particular concern in the Pine Barrens, the timber rattlesnake, is considered a restricted range species because it relies on winter denning sites in Atlantic white cedar swamps. During the periods immediately before and after hibernation, the snakes congregate around these sites. This makes the snakes particularly susceptible to human disturbance.

GIS analysis was used to examine the present status and recent trends of forest interior in the Barnegat Bay watershed because it is a key habitat type. All forest habitat types, including both wetland and upland forest, were aggregated into a simple forest-nonforest binary map for both the 1984 and 1995 time periods. The 1992 time period was not investigated due to the great difference in spatial resolution of the 1972 data. Paved roads and existing developments were used as a boundary to fragment or demarc the individual patches of contiguous forest habitat. A GIS spatial analysis procedure called "clump analysis" was used to determine spatially contiguous tracts of forest habitat. Tracts smaller than 40 ha (~100 acres) were deemed to be too small to contain significant interior habitat. Hence, they were excluded from the analysis. Using a GIS spatial analysis procedure called "buffering," a 90-m buffer was delineated inside the boundary of every area of forest habitat patch to exclude the edge zone and leave only interior forest habitat. In 1984, there were approximately 87,750 ha of forest. Of this total, 55,050 ha or 63% were classified as interior forest habitat. As of 1995, there were approximately 81,630 ha of upland and wetland forest, with 52,800 ha (~65%) consisting of interior forest habitat. While there has been a 7% overall decline of forest habitat, the loss of interior forest habitat has been slightly less at 4% over the 10-year period. It appears that most of the forest loss and fragmentation has occurred in the northeastern quadrant of the watershed where the forest cover has been greatly fragmented.

Contiguous forest areas (i.e., not subdivided by roads) were delineated to further examine the issue of forest fragmentation. This analysis involved assessment of two components: 1) forest fragments as defined by all types of roads, including non-paved sand roads (Figure 4a); and 2) forest fragments as defined only by major roads, such as interstates, as well as state and county level roads (Figure 4b). The analysis was conducted for both the all roads and major roads only scenarios, because it was thought that the all roads scenario, with its inclusion of even relatively insignificant sand roads, may underestimate the size of Afunctional@ forest patches. The forests of the eastern half of the Barnegat Bay watershed are severely fragmented, contrasting very strongly with the largely unfragmented forests of the upper watershed regions. The Barnegat Bay watershed contains several individual forest tracts of large size (> 1000 ha) that are of statewide significance (Table 4). Some of these forest tracts rival in size those found in Wharton State Forest (the core of the Pinelands Preservation Area) as well as those in the New Jersey Highlands region (Lathrop, 1996). Some of the more notable interior tracts include the Forked River Mountains, the Berkeley Triangle, Greenwood Forest Wildlife Management Area/Double Trouble State Park, the Heritage Minerals tract, Bass River State Forest/Stafford Wildlife Management Area, and Maple Root Branch/Long Brook tract in Jackson Township. Though not quite as large in size, there are several large tracts of mixed wetland forest east of Route 9 that directly border Barnegat Bay (e.g., Manahawkin-Gunning River and Mill/Westecunk Creek areas) and serve as significant wildlife habitat for resident and migratory wildlife (e.g., nesting and migrating neotropical songbirds). These larger tracts, especially when found as contiguous clusters, serve to protect the integrity of Pinelands natural communities by reducing human-induced edge effects and protecting area-sensitive native fauna (e.g., timber rattlesnakes). The protection of large contiguous tracts of unfragmented forest habitat will help to minimize conflicts between forest land management practices, including enhancing the potential

for the restoration of more natural fire disturbance regimes, and adjacent human development. Smaller fragmented forest patches may still have significant conservation value, especially in urban/suburban areas where they may serve as the only available wildlife habitat over large areas.

III. HUMAN ALTERATION OF SHORELINE HABITATS

Large portions of the Barnegat Bay shoreline and adjacent shallow water habitats have been altered by bulkheading and nearshore development. The impact of bulkheading on estuarine ecological communities has not been thoroughly investigated; however, there are some obvious effects. Bulkheading deepens water depths, thereby reducing the areal extent of shallow water near-shore habitats such as intertidal flats and associated submerged aquatic vegetation beds, which are important habitats for a variety of fishes and estuarine invertebrates (Able et al., 1996). Bulkheading eliminates shoreline beach habitat important for shorebirds and terrapin turtles. In addition, the wooden timbers used in bulkheading are generally treated with toxic materials that may have negative impacts on the estuarine biota (Weis and Weis, 1996). Bulkheading is usually associated with marsh infilling/lagoonal development and other types of nearshore development. Bulkheading of the shoreline stabilizes the fill and provides mooring facilities for watercraft. Nearshore development (with or without bulkheading) directly impacts habitat value of the bay/upland by displacing native plant vegetation communities that may serve as feeding, nesting, and migrating habitat. It also indirectly impacts the habitat value of adjacent shallow water, shore, or salt marsh communities by increasing human/pet-wildlife encounters leading to a chronic disruption of feeding, resting, or nesting activity. In addition, human development and its associated impervious surfaces and horticultural practices directly upland of the bay tend to exacerbate runoff, sedimentation, and nonpoint source pollution. Thus, there is great value in protecting bay shorelines and adjacent uplands as a buffer zone.

Approximately 36% of the bay's shoreline (including fringing salt marsh, tidal creeks and bay islands) is bulkheaded (Figure 5a). When mapped tidal creeks are excluded, the length of manmade shoreline increases to 45%. To examine the composition of the upland shoreline zone more closely, the spatial analytical capabilities of the GIS were used to evaluate the composition of a 150-m-wide buffer of lands directly adjacent to Barnegat Bay and its fringing salt marshes (Figure 5b). The land cover within this upland buffer zone was classified as either natural vegetation (e.g., upland forest, wetland forest, beach, or freshwater emergent wetland) or developed/altered (e.g., developed, cultivated, or bare). Bulkheading, as derived from digital USGS topographic maps, was included in the altered land category. The results of the shoreline buffer analysis show that 71% (4,224 ha or 10,729 acres) of the shoreline buffer zone is presently developed/altered, leaving only 29% (1734 ha or 4,406 acres) in natural land covers. The bay can be divided into three general zones: (1) the northern section (north of the Toms River outlet) where both the barrier island and bayshores are largely developed with accompanying bulkheading; (2) the central section (south to Barnegat Inlet) which has extensive lagoonal development/bulkheading on the bayshore, while the barrier island shore is completely undeveloped (due to Island Beach State Park); and (3) the southern section (south to Little Egg Harbor Inlet) which has extensive development/bulkheading on the barrier island shore, while the bayshore is largely undeveloped.

IV. LOSS AND ALTERATION OF SALT MARSH

A. Loss Due to Development

Barnegat Bay is a shallow back-bay, lagoon-type estuary that was once nearly completely fringed by tidal salt marshes. Salt marshes and shallow water estuarine habitats provide food and refuge for many fishes and crustaceans of recreational and commercial value (Boesch and Turner, 1984; Able et al., 1996). They also serve as important habitat for birds, mammals, and other organisms (Daiber, 1974; Burger et al., 1982). About 14,850 ha of the watershed were mapped as tidal salt marsh in 1888. The present extent of tidal salt marsh is estimated to be 9,940 ha (Lathrop et al., 1999), which equates to a decrease of approximately 4,910 ha (33%) of tidal salt marsh area over the last century. Differences in estimates of salt marsh area during the past century may reflect: (1) real loss of wetland; or (2) differences due to classification/mapping accuracy (e.g., mapping of tidal creeks/ponds as separate from the marsh proper varies across the different maps). The positional accuracy of the 1888 maps, while surprisingly good, is still suspect in some places. These maps were produced entirely by plane table without the aid of aerial photographs or modern surveying equipment.

Closer examination of the data shows that probably only 3100-3200 ha of salt marshes have been directly lost due to development (dredging and infilling). When the 1888 maps are cross-tabulated against the 1995 land-use/land-cover maps, it is evident that approximately 3250 ha originally mapped as salt marsh in 1888 are now mapped as developed (including associated lagoons, as derived from the USGS digital hydrography data). Similar results are obtained when comparing the land-use/land-cover maps with maps generated by the Ocean County Soil Survey. Approximately 4,220 ha were mapped in the Ocean County Soil Survey (Soil Conservation Service, 1980) as fill material over tidal salt marsh (PO-Psamments, sulfidic substratum, as extracted from the NJDEP ITU data) (Figure 6a), which represents a 28.4% loss of original salt marsh area. When the maps are overlaid, approximately 3,460 ha mapped as salt marsh in 1888 are now mapped as fill (including associated lagoons, as derived from the USGS hydrography data). When the 1995 land cover and soil survey maps are combined, the composite loss estimate is 4190 ha. The original estimated loss of 4,910 ha of coastal wetlands area would therefore appear to be an overestimate. A more conservative estimate of the areal loss of coastal wetlands to the direct impacts of human development is 4190 ha, or approximately 28.2% of the original 1888 wetlands estimate. This leaves approximately 1160 ha (4910 - 4190 = 720 ha) that was mapped as salt marsh (in 1888) but is now mapped as some other category (other than salt marsh or development, e.g., water or mudflat). It is difficult to judge whether this additional 720 ha represents a real loss of wetlands, presumably due to natural or possibly indirect human disturbance processes, or is simply due to differences in classification or mapping accuracy. Although Barnegat Bay as a whole has lost slightly more than 25% of its salt marshes during the past century, some areas (most notably in the vicinity of the Barnegat Inlet) have actually experienced an increase in salt marsh area, presumably due to the stabilization of the inlet earlier earlier in the 20th century. Since the major modification of Barnegat Inlet in 1991, the salt marsh near Barnegat Inlet has undergone further change, including the loss of existing marsh area at some locations.

Most of Barnegat Bay's wetland loss appears to have occurred during the 30-year period between World War II and impletmentation of the Coastal Wetlands Law of 1970. Earlier work by Ferrigno et al. (1973) examined the loss of tidal marsh areas by diking, filling, and development for all of Ocean County between 1953 and 1973. Their results showed a 29.5% (221.1 ha/yr^{-1}) loss of tidal marsh area from 14,976 ha (37,007 acres) in 1953 to 10,553 ha (26,078 acres) in 1973. While this study encompassed all of Ocean County with portions of the Manasquan River estuary as well as Barnegat Bay, these results are very similar to the findings of Lathrop et al. (1999). Comparison of the 1972, 1984, and 1995 land-use/land-cover maps of Lathrop et al. (1999) shows that there has been comparatively little loss of tidal marsh habitat as a result of human development during the last 25 years. While the area mapped as tidal

wetland has decreased from 10,472 ha in 1972, to 10,380 ha in 1984, and to 9,941 ha in 1995, some of this change is ascribed to the natural dynamics in the marsh, as some of the emergent wetlands area is alternately mapped as open water or unconsolidated shore. Only a smaller fraction of the loss is directly attributable to development, with 50 ha (0.5% or 4.2 ha/yr-1) lost between 1972 and 1984 and 117 ha (1 % or 10.6 ha/yr-1) lost between 1984 and 1995. The Coastal Wetland Law of 1970 appears to have been largely responsible for halting the high rate of loss of tidal salt marsh habitats due to human development. While the loss rate of the tidal marshes has drastically declined, there still appears to be a small but steady loss of existing habitat to development. Hence, coastal zone management agencies must continue to be vigilant in protecting existing salt marshes from development pressure.

B. Alteration Due to Mosquito control

Early mosquito control in Ocean County began with source reduction. No chemical methods were used in the earliest years. From the very beginning the State Entomologist, Dr. J. B. Smith, recommended a unique method of eliminating mosquito breeding in salt marsh and dune areas of Barnegat Bay. The same Dr. J. B. Smith who would be instrumental in solving the mosquito problems during the building of the Panama Canal, had mosquito workers hand-dig permanent sink holes 8' X 8' and connect them with ditch systems that would intersect breeding areas on the marsh (Smith, 1907; Cranmer, 1919). These early Apond and radial@ systems supported tremendous populations of fish which would devour the mosquito larvae. This technique, first attempted at Beach Haven in 1907, would eventually become a major component of Open Marsh Water Management (OMWM), today's "state of the art" source reduction system (Daiber, 1986).

The 1930's brought the depression and then the "New Deal" which radically changed the face of mosquito control in the area. From 1933 to 1938, Ocean County utilized the services of various relief labor, such as the WPA and the CCC. By 1936, the work of this relict labor force created and maintained most of the more than 2,500 km (1,600) miles of drainage ditching in the area. Unfortunately, almost all of this work resulted in straight-line "grid" ditches whose purpose was to drain the marsh. While some mosquito control may have been accomplished at first, the ditches sealed off over time, and the marsh surface and potholes once again began to hold water (even as close as a few meters from a grid ditch), leading to renewed breeding of mosquito populations. Almost all of the grid ditches seen today were originally installed during those federal work project days. Very little "new work" on mosquito control was conducted between 1940 amd 1965. During this period, water management consisted only of maintaining and dredging the grid ditches to try and keep the systems functional.

There are approximately 950 km of parallel grid mosquito control ditches in Barnegat Bay salt marshes (Figure 6b). Using a 90-m buffer as the approximate zone of influence around a mosquito ditch, the amount of ditched marsh in the system is estimated to be 5,890 ha, which amounts to about 66% or two-thirds of the existing tidal salt marsh. The only extensive areas of unditched marsh are the Tuckerton Peninsula, the Gunning River area, and the Sedge Islands of Little Egg Harbor and Barnegat Inlets. However, the first two of the above sites have recently been altered by OMWM activities and are not considered in the above analysis.

In the 1960's and early 1970's, the OMWM system of source reduction was developed by Coastal County Mosquito Commissions, the New Jersey Division of Fish, Game and Wildlife, and Rutgers University (Ferrigno and Jobbins, 1968). This system was implemented and refined during the 1970's. In

1980, a set of "standards" was published (Bruder, 1980) These standards were developed to meet the three major objectives of OMWM: (1) to control mosquitoes; (2) to eliminate the use of insecticides; and (3) to enhance the tidal food web (Ferrigno et al., 1975). There are two basic habitat alterations used in OMWM: (1) tidal ditches; and (2) ponds and pond radials. Unlike the "grid" ditch systems of the 1930's era, drainage is no longer the objective of these systems. One of the major objectives is to increase the amount of surface water so that native fishes will increase in abundance and devour the mosquito larvae. Ponds serve as reservoirs for native killifish during times of low water, and the radial ditches provide access for the fish to areas that breed mosquitoes. No habitat alteration is made except directly where mosquito breeding occurs, thus limiting the actual amount of disturbance on the marsh. This method has also been shown to benefit certain aspects of the salt marsh habitat. Because this technique has been so effective in meeting all mosquito control objectives while having little detrimental effects on the tidal marsh, it has been adopted by the U. S. Fish and Wildlife Service as the technique of choice for mosquito source reduction on their wildlife refuges (Taylor, 1998).

The "Standards for Open Marsh Water Management" have been adopted by both state and federal regulatory agencies for use when evaluating applications for water management projects on salt marshes. This is the technique utilized by the Ocean County Mosquito Commission since 1970 for it's source reduction program in the Barnegat Bay region.

In the early days of mosquito control, water management was the mainstay of control efforts. No specific insecticide treatments were used until after World War II. Some applications of oil were made before then to control mosquito larvae and pupae; however, these were limited and made by hand. In July 1945, the military made the first applications of the insecticide DDT as an adulticide on Island Beach State Park (Candeletti et al., 1977). The Ocean County Mosquito Commission believed that more studies should be conducted on both the use of this insecticide and the use of adulticides in general. After a period of time, however, the commission started to use DDT. Use of the insecticide was slow at first, with Ocean County making limited application, and various municipal governments developing their own ground-fogging programs.

In 1959, New Jersey experienced an eastern equine encephalitis epidemic (Kandle, 1960) In Ocean County, there were 18 cases which resulted in 10 deaths. This precipitated a coordinated mosquito larvicide and adulticide effort in the Barnegat Bay region, including state, county, and municipal government initiatives (Potter et al., 1960). Ten years later and three years before DDT was banned by state and federal governments, the Ocean County Mosquito Commission discontinued all use of DDT for mosquito control in the Barnegat Bay-Little Egg Harbor estuary. Subsequently, all insecticide applications consisted of low persistence, short-lived, highly specific products. The larviciding agents used today are not typical chemical insecticides. They are third generation products such as biologicals and insect growth regulators. These are highly specific for mosquito larvae and have been extensively tested against non-targets with little or no effect.

The primary focus of mosquito control in the Barnegat Bay region over the last thirty years has been to moderate adult mosquito populations to tolerable levels and keep the threat of disease to a minimum by utilizing an integrated program of the latest techniques. Today, mosquito control in the Barnegat Bay-Little Egg Harbor estuary utilizes an "Integrated Management" program based on the Pesticide Environmental Stewardship Program adopted by the New Jersey Mosquito Control Association (Bruder 1998). A comprehensive surveillance system monitors adult mosquito populations and vector potential. This guides a coordinated chemical control, biological control, and source reduction system. The primary method of chemical control at the Ocean County level is larviciding. Two Bell Jetranger 206B helicopters are utilized to cover the 11,340 ha of salt marsh. Several truck mounted hydraulic sprayers are used to reach areas inaccessible to helicopters. They also handle upland mosquito larviciding. The helicopters inspect the salt marsh areas at least twice a week during the mosquito breeding season and

treat any larvae found. The trucks make a continuous circuit through all parts of Ocean County starting early in the spring and continuing into October. The control agents used are the latest highly specific, non-persistent, and most environmentally sound available. State-of-the-art insect growth regulators and biological agents are presently used. Larviciding is the method of choice because very small amounts of these very low toxicity insecticides can be used at limited breeding sites to keep the adult mosquitoes from emerging and spreading over a large area. If the adult mosquito populations attain an extraordinary high abundance level or there is disease potential, then a request is made of the State Mosquito Control Commission to perform. an aerial adulticide. Once again, the safest and most effective materials available are used.

Since the inception of Open Marsh Water Management in Barnegat Bay in 1970, several thousand hectares of salt marsh have been treated and no longer require any more larviciding. This is the direction that the Ocean County Mosquito Commission is progressing. Water management is a slow process, accomplishing approximately 203 ha annually. However, the commission has made a commitment to gradually replace continued temporary larvicide treatments with the more permanent and habitat friendly system of Open Marsh Water Management. Until such time that a given section of mosquito breeding salt marsh is subjected to this system, the Commission is committed to using larvicides that are recommended by the Agricultural Experiment Station at Rutgers University and the New Jersey Department of Environmental Protection for use in the salt marsh. The commission has initially targeted some of the most prolific mosquito breeding areas for Open Marsh Water Management, so that the greatest reduction in larvicide concentrations is achieved. Projects in Lacey Township, Barnegat Township, and Little Egg Harbor Township are now being conducted. Near future work is anticipated in Berkeley, Stafford, and Eagleswood Townships. The majority of this work will be accomplished on the Edwin B. Forsythe Refuge.

V. CHANGES IN SUBMERGED AQUATIC VEGETATION

Submerged aquatic vascular plants occur along the shallow margins of the estuary, generally in waters less than 1 m in depth. Eelgrass (*Zostera marina*) is the dominant seagrass species in Barnegat Bay, forming dense beds particularly on sandflats along the backside of the barrier island system (Macomber and Allen , 1979). Widgeon grass (*Ruppia maritima*) is of secondary importance, also attaining highest concentrations on the eastern sand flats. Locally dense beds of sago pondweed (*Potamogeton pectinatus*) appear north of Toms River, with lesser quantities of horned pondweed (*Zannichellia palustris*), widgeon grass, and eelgrass. Submerged aquatic vegetation (SAV) has several functional roles in the Barnegat Bay-Little Egg Harbor estuarine system. It serves as critically important habitat for benthic epifauna and infauna (Good et al., 1978). Some organisms graze on SAV (e.g., gastropods, fish, ducks, muskrats). Some benthic macrovegetation (e.g., *Zostera marina*) also represents valuable spawning, nursery, and feeding grounds for finfish populations in the estuary. They likewise stabilize the benthic habitat by baffling waves and currents and mitigating substrate erosion.

Mapped information on the spatial distribution of SAV beds for Barnegat Bay was derived from several sources. The first mapped survey was undertaken in 1968 (U.S. Army Corps of Engineers, 1976). The methods for this study were not detailed, but is presumed to have been a boat-based survey. The Earth Satellite Corporation produced a 1:24,000 scale map series for the entire bay based on the interpretation of black and white aerial photography and low altitude sea plane reconnaissance during the summer of 1979 (photos were taken in June and August, and field checked July through September) (Macomber and Allen, 1979).The U.S. Fish and Wildlife Service (USFWS) incorporated the Earth Satellite

Corporation maps into the National Wetland Inventory (NWI) for the State of New Jersey. The Bureau of Shellfisheries of the New Jersey Department of Environmental Protection and Energy collected information on eelgrass distribution, water depth, and bottom sediments in conjunction with an estuarine shellfish inventory of the Barnegat Bay-Little Egg Harbor estuarine system conducted between 1985 and 1987 (Joseph et al., 1992). Paul "Pete" McLain conducted a field survey of SAV during the summers of 1996, 1997, and 1998 (McLain and McHale, 1997). The various maps were digitized, superimposed, and analyzed to examine the consistency in mapping interpretation as well as possible changes in the spatial distribution of the SAV between the 1960's, 1970's, 1980's, and 1990's.

The 1968 survey (U.S. Army Corps of Engineers, 1976), which included the area of Barnegat Bay north of the Route 72 bridge, mapped 6,823 ha (16,847 ac) of SAV dominated by either *Zostera marina* or *Ruppia maritima* (Figure 7a). The 1979 SAV survey (Macomber and Allen,1979) mapped 10,783 ha (26,647 ac) of SAV of varying density (Figure 7b). Excluding areas mapped as general undifferentiated or low density SAV, 8,512 ha (21,033 ac) were mapped as dominated (> 80%) by either *Zostera marina* or *Ruppia maritima*. The 1980's survey (Joseph et al., 1992) mapped approximately 8,800 ha (21,745 ac) as eelgrass-dominated SAV beds (Figure 7c). The later 1990's survey of McLain mapped only 5,677 ha (14,029 ac) of eelgrass or widgeon grass-dominated SAV beds (Figure 7d). A GIS spatial comparison of the changes observed between the 1960's, 1970's and 1980's surveys reveals minor shifts in the spatial distribution that might be due to real changes in SAV distribution or purely artifacts of differences in the survey and mapping methodologies. Comparison of these earlier maps with the 1990's survey shows an overall decrease of eelgrass beds amounting to approximately 3,000 ha (7,400 ac) (Table 1).

The SAV beds in the far northern portion of Barnegat Bay and in the Metedeconk River have shown the greatest change over time. The 1968 survey revealed that the Metedeconk River portion of the bay was dominated by extensive beds of sea lettuce (*Ulva lactuca*), whereas the 1979 survey showed that the area was dominated by *Zostera* though with significant component of *Ulva*. Results of the 1990's surveys suggest that there has been a loss of SAV in the deeper waters of the bay, resulting in the contraction of the beds to the shallower subtidal flats (< 2 m depth) since the 1960's. From the Metedeconk River south to Toms River, this contraction appears to have been especially severe with the outright loss of beds by the time of the 1990's survey. There is also some indication of the loss of beds in southern Little Egg Harbor. SAV beds mapped in the 1970's were absent in surveys conducted in the 1980's and 1990's. However, examination of the survey conducted by Good et al. (1978) for this same study area did not map extensive beds in the southern Little Egg Harbor region. In addition, there are questions regarding labelling in the 1970's surveys, leading to uncertainty as to whether these beds were *Zostera*-dominated or general SAV. Due to the great difference in mapping methods, we must be cautious in directly attributing the decrease in eelgrass acreage to a large-scale dieback of eelgrass. The 1970's survey (Macomber and Allen,1979) relied on aerial photography complemented by float plane-assisted field checking. The 1980's survey (Joseph et al., 1992) relied on a boat-based systematic grid sampling (one-quarter mile interval), whereas the 1990's survey (McLain and McHale, 1997) was a more informal boat-based survey. The 1970's and 1980's surveys might be expected to provide a more complete coverage of the bay, especially along the western bayshore which was not exhaustively inventoried during the 1990's survey.

While it is difficult to conclusively establish that there has been a major dieback and loss of eelgrass acreage, there is reason for concern over the status of eelgrass beds in Barnegat Bay. SAV beds are an important component of the bay ecosystem and can serve as as sensitive indicator of the bay's overall health. The status of Barnegat Bay's SAV beds takes on larger regional significance, when one considers that Barnegat Bay-Little Egg Harbor contains over 75% of New Jersey's SAV habitat. The temporal and spatial shifts of SAVs in the Barnegat Bay ecosystem likely result from naturally-occurring cycles (Loveland et al., 1984), although anthropogenic activities such as dredging and nutrient loading may be detrimental. Disease is responsible for significant declines of SAV during certain years. For example,

McClain and McHale (1997) showed that wasting disease, presumably caused by the protist *Labyrinthula zosterae*, destroyed about 400 ha of eelgrass beds in Barnegat Bay in 1995. Less disease and SAV destruction occurred in 1996, although as much as 50% of eelgrass leaves exhibited wasting disease at this time. To further elucidate spatial and temporal patterns of SAV decline and regrowth, as well as potential causal factors such as disease or infestations of epiphytic algae, a SAV monitoring program based on aerial photography and field sampling using consistent methodology should be initiated and continued on a regular basis (i.e., 5-10 year intervals).

VI. ANALYSIS OF GAPS IN CONSERVATION PROTECTION

By digitally overlaying (on a GIS) the maps showing the spatial location of salt marsh, undeveloped shoreline buffer, and interior forest with maps of public conservation ownership (Figure 8), Lathrop et al. (1999) conducted a "gap" analysis to determine gaps in the conservation protection of these high value habitat areas. Table 5 shows the amount and percentage of each Barnegat Bay subwatershed that is presently in some form of public ownership, primarily as conservation/open space (though, these figures do include military reservations).

Gap analysis of salt marsh habitats reveals that approximately 90% (8894 ha) of Barnegat Bay's salt marshes are presently protected in some form of public conservation ownership (e.g., national wildlife refuge, state game management area, state/local park, private conservation land trust) (Figure 8). The salt marsh habitat GIS model was constructed to rank areas as to their importance as feeding habitat for selected fish-eating bird species, namely black skimmers (*Rynchops niger*), Forster's terns (*Sterna forsteri*) and assorted herons and egrets based on the work of Burger et al. (1982) and Burger (1997). Salt marsh areas that have undergone extensive modification by parallel ditching were ranked as having lower habitat value. Parallel ditching drains the surface water (mosquito breeding habitat), and it is generally accepted that parallel ditching has a variety of negative impacts on marsh ecological community structure (Whigham et al., 1982). Salt marsh with a high proportion of open water (i.e., fish habitat) due to ponds, small embayments or tidal creek were ranked as having higher habitat value. Salt marshes with neither ponds/creeks/embayments nor parallel mosquito ditching were ranked as having medium habitat value. Over 99% of the highest value unditched marsh is presently in public ownership (Figure 9). Recently, the Trust for Public Land has purchased several of the larger tracts of remaining undeveloped wetland areas along the western shore of central and northern Barnegat Bay as part of their Century Plan effort (Blanchard, 1995, 1997).

With over 70% of Barnegat Bay shoreline already developed, the remaining undeveloped shoreline areas are especially valuable as open space. These undeveloped shorelines serve to buffer the bay from upland development, and they provide valuable wildlife habitat. Approximately 70% of the remaining undeveloped shoreline is in some form of public conservation ownership. These shoreline buffer areas with their expansive waterfront or marsh views represent some of the more valuable real estate in the Barnegat Bay region and are therefore under heavy development pressure. Unlike other estuaries, such as the Chesapeake Bay, where there are strict buffer or setback requirements, the Barnegat Bay shoreline is not specifically protected under present state land use regulations. The largest stretch of unprotected shoreline buffer area is along the western shore of Little Egg Harbor in the Mill Creek/Westecunk Creek and Tuckerton Creek subwatersheds. The salt marsh land in this area has been largely preserved as part of Forsythe National Wildlife Refuge. These areas should receive priority in future U.S. Fish and Wildlife Service acquisition efforts. Without an aggressive program to specifically protect these critical buffer lands through conservation easements or fee simple purchase, it is likely that there will be

continued conversion and habitat loss.

A number of Barnegat Bay islands serve as nesting places for a variety of shorebirds and colonial nesting birds. Colonial nesting birds such as common terns (*Sterna hirundo*), black skimmers (*Rhynchops niger*) and Forster's terns (*Sterna forsteri*) normally build their nest on the ground. These colonial nesting birds nest almost exclusively on salt marsh or dredge spoil islands to minimize disturbance by mammalian predators (Burger, 1997). Sixty-one Barnegat Bay islands were ranked as to their importance as nesting habitat for common terns (*Sterna hirundo*), black skimmers (*Rhynchops niger*) and Forster's terns (*Sterna forsteri*) based on more than a 20-year record (from the mid-1970's to the present) of personal observations (Joanna Burger, Rutgers University, personal communication, 1999). The following ranking system was devised:

1) islands with no recorded nesting activity;

2) islands with low nesting activity (< 1/4 yrs of record);

3) islands with medium nesting activity (< 1/2 yrs but

> 1/4 yrs of record or currently active 2 out last 3 yrs);

4) islands with high nesting activity (> 1/2 yrs of record); and

5) islands with high nesting activity of 2 or more species.

In Addition, a subset of Barnegat Bay islands used as nesting sites for wading birds (herons, egrets, and ibises) and listed by Burger (1997) was included. Table 6 lists the 61 islands/island groups evaluated and their ranking, as well as their protection status. Lathrop (see Blanchard 1997) conducted a gap analysis of Barnegat Bay islands in conjunction with the Trust for Public Land to prioritize acquisition efforts as part of the Century Plan (Blanchard, 1995). The results of this Barnegat Bay island gap analysis is displayed in Figure 10.

Approximately 44% of the crucial interior forest (both upland and wetland) areas in the Barnegat Bay watershed are presently protected by some form of public conservation ownership (Figure 11). A significant portion of the three largest tracts (> 1000 ha) of contiguous, un-roaded forest are protected. There are still extensive areas of contiguous forest land within the watershed that are presently unprotected. Some of the more notable, largely unprotected tracts include the Forked River Mountains, the Berkeley Triangle, the Heritage Minerals tract and Maple Root Branch/Long Brook tract, in Jackson Township. The fact that most of the larger tracts are within the Pinelands Reserve and thus receive some form of protection is encouraging. However, Pinelands jurisdiction does not preclude future low-density development, which would still have a fragmenting impact on these forests. The best long-term solution to maintaining large tracts of contiguous Pinelands forest in the Barnegat Bay watershed is through some form of public ownership or conservation easement. These areas are included in the Trust for Public Land's (TPL's) Century Plan (Blanchard, 1995), and should receive priority in future public open space acquisition efforts.

Other critical wildlife habitat areas that should receive special consideration are coastal dune scrub/shrub and large areas of cultivation/grassland. A gap analysis was not specifically conducted for these habitats. While extensive remnants exist at Island Beach State Park and at the Holgate section of Forsythe National Wildlife refuge (and to a lesser extent at Barnegat Light State Park), the dune scrub/shrub and woodland communities of the barrier islands fronting Barnegat Bay have largely been destroyed or substantially altered. The natural dune system has been obliterated along great stretches of New Jersey's Atlantic shoreline. Dune grass and shrub vegetation serves a useful role in stabilizing dunes and protecting beaches against wind and wave erosion. Where feasible, dunes are being reconstructed and re-vegetated to help impede beach erosion. However, more could be accomplished by encouraging homeowners in the lower density residential areas of the barrier islands to preserve the natural dune grass and scrub vegetation. These maritime shrublands and woodlands provide important stop-over habitat for numerous species of songbirds and raptors migrating along the Atlantic Coastal Flyway. Large contiguous areas of active or abandoned farmland and grassland habitat are not common in the Barnegat Bay region. Several threatened birds, such as grasshopper sparrows (*Ammodramus savannarum*), can be found on the few remaining areas of pasture/hay fields or unmanaged grasslands which are used as nesting habitat. This type of habitat is largely restricted to the upper reaches of the Metedeconk and Toms River subwatersheds where some of these open habitat areas have been conserved through farmland preservation programs (e.g., Plumsted Township). Other important grassland habitats are associated with the region=s airports (e.g., Lakehurst Naval Air Station) and abandoned gravel pits (e.g., Heritage Minerals tract). Where feasible, these tracts should continue to be managed with the objective of maintaining grassland-dependent nesting birds.

VII. SUMMARY

The Barnegat Bay-Little Egg Harbor estuary and its upland watershed represent a rich diversity of coastal and Pinelands habitats. While significantly altered by human land-use activities, many of these habitats are still largely intact functioning natural communities. Through government legislation and regulation, some of the most destructive past practices, such as dredging and filling of coastal salt and freshwater marshes, have been largely eliminated. However, development and the consequent loss of upland forests proceed apace. While large expanses of upland and wetland habitats are presently protected as public open space, additional open space acquisition is justified on the following grounds: 1) for watershed protection to insure high quality inflow to Barnegat Bay; 2) for protection of habitat for commercially, recreationally and ecological important flora and fauna; and 3) for protection of open space for human recreation and aesthetic enjoyment. While this project has been successful in mapping and quantifying the present status and trends of many important Barnegat Bay habitats, there are still many unanswered questions. The apparent decline in submerged aquatic vegetation (SAV) beds, a critical benthic habitat, is a cause for concern and deserves further investigation. The critical thresholds which, when exceeded, cause habitat loss and fragmentation and the decline of species are not well understood. Similarly, while there is a clear indication that human development leads to declining freshwater tributary water quality due to non-point source pollution, quantifying this impact and developing direct causal relationships between upland development and consequent degradation of water quality and aquatic habitats in the estuary is more difficult. Much more research also must be conducted on the relationship between loss and alteration in the estuary watershed and impacts and impacts on nesting birds in the system.

Literature Cited

Able, K. W., D. A. Witting, R. S. McBride, R. A. Rountree, and K. J. Smith. 1996. Fishes of polyhaline estuarine shores in Great Bay-Little Egg Harbor, New Jersey: a case study of seasonal and habitat influences. Pp. 335-353 *in* Nordstrom, K. F. and C. T. Roman (eds.), *Estuarine Shores: Evolution, Environments ans Human Alterations*. John Wiley & Sons, New York.

Ballard, J. T. 1979. Fluxes of water and energy through the Pine Barrens Ecosystems. Pp. 133-146 *in* Forman, R. T. T. (ed.), *Pine Barrens: ecosystem and landscape*. Academic Press, New York.

Blake, J. G. and J. R. Karr. 1984. Species composition or bird

communities and the conservation benefit of large versus small forests. Biol. Conserv., 30:173-187.

Blanchard, P. P. 1995. The Century Plan. Tech. Rept., Trust for Public Land. Morristown, New Jersey.

Blanchard, P. P. 1997. Beyond the Century Plan. Tech. Rept., Trust for Public Land. Morristown, New Jersey.

Boesch, D. F. and R. E. Turner. 1984. Dependence of fishery species on salt marshes: the role of food and refuge. Estuaries, 7:460-468.

Bohning-gaese, K., M. L. Taper, and J. H. Brown. 1993. Are declines in North American insectivorous songbirds due to causes on the breeding range. Conserv. Biol., 7:76-86.

Bontempo, K. W. 1980. The economic importance of encephalitis in New Jersey. Proc. N. J. Mosq. Exterm. Assoc., 47:155-158.

Bourne, W. S. and C. Cottam. 1950. Some biological effects of ditching tidewater marshes. Res. Rept. 19, U. S. Fish and Wildlife Service, Washington, D.C.

Brittingham, M. C. and S. A. Temple. 1983. Have cowbirds caused forest songbirds to decline? Bioscience, 33:31-35.

Bruder, K. W. 1980. THe establishment of Unified Open Marsh Water Management Standards in New Jersey. Proc. N. J. Mosq. Cont. Assoc., 85 (in press).

Bruder, K. W. 1998. The Pesticide Environmental Stewardship Program. Proc. N. J. Mosq. Cont. Assoc., 85 (in press).

Burger, J., J. Shisler, and F. H. Lesser. 1982. Avian utilization on six salt marshes in New Jersey. Biol. Conserv., 23:187-212.

Burger, J. 1997a. An evaluation of nearshore and island sites for the Trust for Public Land. Final Report of the Habitat Research Component of the Barnegat Bay Initiative, Institute of Marine and Coastal Sciences, Rutgers University, New Brunswick, New Jersey.

Burger, J. 1997b. Identification of habitat use and prey selection dynamics as indicators of high quality habitat in estuarine systems. Final Report of the Habitat Research Component of the Barnegat Bay Initiative. Institute of Marine and Coastal Sciences, Rutgers University, New Brunswick, New Jersey.

Butcher, G. S., W. A. Niering, W. J. Barry, and R. H. Goodwin. 1981. Equilibrium biogeography and the size of nature preserves: an avian case study. Oecologia, 49:29-37.

Bunnel, J. F. and R. A. Zampella. 1999. Acid water anuran communities along a regional forest to agro-urban ecotone. Copeia, 1999:614-627.

Candeletti, R., Candeletti, T., and Kent, R. 1988. The Amphibious Rotary Excavator: new equipment for salt marsh management in New Jersey. Proc. N. J. Mosq. Cont. Assoc., 75:102-108.

Candeletti, T. and H. Lesser. 1977. Mosquito control techniques on Island Beach State Park. Proc. N. J. Mosq. Cont. Assoc., 64:39-42.

Collins, B. R. and E. B. Russell (Eds.). 1988. Protecting the New Jersey Pinelands: A New Direction in Land-use Management. Rutgers University Press, New Brunswick, New Jersey.

Cranmer, C. H. 1919. Ocean County report. Proc. N. J. Mosq. Exterm. Assoc., 6:47-50.

Daiber, F. C. 1974. Salt marsh plants and future coastal salt marshes in relation to animals. Pp. 475-508 *in* Reimold, R. J. and W. H. Queen (eds.), *Ecology of Halophytes*. Academic Press, New York.

Daiber, F. C. 1986. Conservation of Tidal Marshes. Van Nostrand Reinhold, New York.

Dobson, J. E., E. A., Bright, R. L. Ferguson, D. W. Field, L. L. Wood, K. D. Haddad, H. Iredale, J. R. Jensen, V. V. Klemas, R. J. Orth, and J. P. Thomas. 1994. NOAA Coastal Change Analysis Program (C-CAP): guidance for regional implementation. NOAA Technical Report NMFS 123, National Oceanic and Atmospheric Administration, Seattle, Washington.

Ehrenfeld, J. G. and J. P. Schneider. 1991. *Chameacyparis thyoides* wetlands and suburbanization: effects on hydrology, water quality, and plant community composition. J. Appl. Ecol., 28:467-490.

Ehrenfeld, J. G. and J. P. Schneider. 1993. Responses of forested wetland vegetation to perturbations of water chemistry and hydrology. Wetlands,

13:122-129.

Ferrigno, F. and D. M. Jobbins. 1968. Open Marsh Water Management. Proc. N. J. Mosq. Exterm. Assoc., 55:104-115.

Ferrigno, F., L. Widjeskog, and S. Toth. 1973. Marsh destruction. P. R. Project W-533-R-1, Job I-G.

Ferrigno, F., P. Slavin, and D. M. Jobbins. 1975. Salt marsh water management for mosquito control. Proc. N. J. Mosq. Cont. Exterm. Assoc., 62:30-38.

Forman, R. T. T. 1979. The Pine Barrens of New Jersey: an ecological mosaic. Pp. 569-585 *in* Forman, R. T. T., (ed.), Pine Barrens: Ecosystem and Landscape. Academic Press, New York.

Forman, R. T. T. and R. E. Boerner. 1981. Fire frequency and the Pine Barrens of New Jersey. Bull. Torrey Bot. Club, 108: 34-50.

Garcia, A. A. and W. J. Crans. 1989. A geographic distribution of eastern equine encephalitis epidemic and epizootics in New Jersey from 1975 to 1988. Proc. N. J. Mosq. Cont. Assoc., 76:100-105.

Good, R. E., J. Limb, E. Lyszczek, M. Miernik, C. Ogrosky, N. Psuty, J. Ryan, and F. Sickels. 1978. Analysis and delineation of submerged vegetation of coastal new Jersey: a case study of Little Egg Harbor. Tech. Rept., Center for Coastal and Environmental Studies, Rutgers University, New Brunswick, New Jersey.

Good, R. E. (Ed.). 1982. Ecological solutions to environmental management concerns in the Pinelands National Reserve. Tech. Rept., Center for Coastal and Environmental Studies, Rutgers University, New Brunswick, New Jersey.

Hastings, R. W. 1984. The fishes of the Mullica River, a naturally acid water system of the New Jersey Pine Barrens. Bull. N. J. Acad. Sci., 29:9-23.

Headlee, T. J. 1945. The Mosquitos of New Jersey and Their Control. Rutgers University Press, New Brunswick, New Jersey.

Joseph, J., K. Purdy, and B. Figley. 1992. The influence of water depth and bottom sediment on the occurrence of eelgrass in Barnegat, Manahawkin, and Little Egg Harbor Bays. Tech. Rept., Marine Fisheries Administration, Division Fish, Game and Wildlife, New Jersey Department of Environmental Protection and Energy, Nacote Creek, New Jersey.

Kandle, R. P. 1960. Eastern encephalitis in New Jersey, 1959. Proc. N. J. Mosq. Exterm. Assoc., 47:11-15.

Lathrop, R. G., J. A. Bognar and A. C. Hendrickson. 1999. Data synthesis effort for the Barnegat bay Estuary Program: habitat loss and alteration in the Barnegat Bay region. Tech. Rept., Barnegat Bay Estuary Program, Toms River,

New Jersey.

Lathrop, R. G., Jr. 1996. Assessing the status of fragmentation in the New York-New Jersey Highlands. Pp. 316-324 *in* Proceedings of Eco-Informa '96, Lake Buena Vista, Florida.

Little, S. 1979. Fire and plant succession in the New Jersey Pine Barrens. Pp. 297-314 *in* Forman, R. T. T. (ed.), Pine *Barrens: Ecosystem and Landscape*. Academic Press, New York.

Loveland, R. E. and J. J. Vouglitois. 1984. Benthic fauna. Pp. 135-170 *in* Kennish, M. J. and R. A. Lutz (eds.), *Ecology of Barnegat Bay, New Jersey*. Springer-Verlag, New York.

McClain, P. and M. McHale. 1997. Barnegat Bay eelgrass investigation 1995-96. Pp. 165-171 *in* Flimlin, G. E. and M. J. Kennish, (eds.), *Proceedings of the Barnegat Bay Workshop*. Cooperative Extension of Ocean County, Toms River, New Jersey.

Macomber, R. T., and D. Allen. 1979. The New Jersey submerged aquatic vegetation distribution atlas final report. Tech. Rept., Earth Satellite Corporation, Washington, D. C.

Meredith, W. H., D. E. Saveikis, and C. J. Stachecki. 1985. Guidelines for "Open Marsh Water Management" in Delaware's salt marshes - objectives, system designs, and installation procedures. Wetlands, 5:119-133.

Morgan, M. D. and K. R. Philipp. 1986. The effect of agricultural and residential development on aquatic macrophytes in the New Jersey Pine Barrens. Biol. Conserv., 25:143-158.

Morgan, M. D. and R. E. Good. 1988. Stream chemistry in the New Jersey Pinelands: the influence of precipitation and watershed disturbance. Water Resourc. Res., 24:1091-1100.

NJDEPE. 1993. A watershed management plan for Barnegat Bay. Tech. Rept., New Jersey Department of Environmental Protection and Energy, Trenton, New Jersey.

NJDEP. 1996. New Jersey Geographic Information System CD-ROM Series 1, Vol. 4, October 8, 1996, New Jersey Department of Environmental Protection, Trenton, New Jersey.

Potter, D., W. D. Henderson, F. A. Reiley, B. M. Lafferty, and A. Levich. 1960. Summary of Ocean, Burlington, Atlantic, Cape May, and Cumberland County Mosquito Commission Control operations during the 1959 eastern viral encephalitis outbreak. Proc. N. J. Mosq. Exterm. Assoc., 47:76-80.

Rhodehamel, E. C. 1979. Hydrology of the New Jersey Pine Barrens. Pp. 39-60 *in* Forman, R. T. T. (ed.), *Pine Barrens: Ecosystem and Landscape*. Academic

Press, New York.

Robbins, C. S., D. K. Dawson, and B. A. Dowell. 1989. Habitat area requirements of breeding forest birds of the Middle Atlantic states. Wildlife Monogr., 103:1-34.

Robinson, S. K., F. R. Thompson, T. M. Donovan, D. R. Whitehead, and J. Faaborg. 1995. Regional forest fragmentation and the nesting success of migratory birds. Science, 267:1987-1990.

Soil Conservation Service. 1980. Soil Survey of Ocean County. Tech. Rept., U. S. Department of Agriculture, Soil Conservation Service, New Brunswick, New Jersey.

Smith, K. J. and K. W. Able. 1994. Salt-marsh tide pools as winter refuges for the mummichog, *Fundulus heteroclitus*, in New Jersey. Estuaries, 17:226-234.

Schulze, T. L. 1992. Malaria in New Jersey-1991. Proc. N. J. Mosq. Cont. Assoc., 79:123-129.

Smith, J. B. 1907. Pp. 524-531 *in* Report of the Department of Entomology. Tech. Rept., New Jersey Agricultural Experiment Station, Rutgers University, New Brunswick, New Jersey.

Taylor J. 1998. Guidance for meeting U. S. Fish and Wildlife Service resource needs when conducting coastal marsh management for mosquito control on Region 5 national wildlife refuges. U. S. Fish and Wildife Service, Region 5, Boston, Massachusetts.

Tiner, R. W. 1985. Wetlands of New Jersey. Tech. Rept., U. S. Fish & Wildlife Service, National Wetlands Inventory, Newton Corner, Massachusetts.

U. S. Army Corps of Engineers. 1976. Aquatic Plant Control Project for the State of New Jersey: Design Memorandum No. 1. U. S. Army Corps of Engineers, Philadelphia District, Philadelphia, Pennsylvania.

U. S. Fish and Wildlife Service. 1997. Significant habitats and habitat complexes of the New York Bight watershed. Tech. Rept., U. S. Fish and Wildlife Service, Coastal Ecosystems Program, Charlestown, Rhode Island.

Vowinkel, E. F. and S. F. Siwiec. 1991. Plan to evaluate the effects of hydrogeologic conditions and human activities on water quality in the coastal plain of New York and New Jersey. Water Resources Investigations Report 91-4091, U. S. Geological Survey, West Trenton, New Jersey.

Weis, J. S. and P. Weis. 1996. The effects of using wood treated with chromated copper arsenate in shallow-water environments: a review. Estuaries, 19:306-310.

Whigham, D. F., J. O'Neill, and M. McWethy. 1982. Ecological implications of

manipulating coastal wetlands for purposes of mosquito control. Pp. 459-476 *in* Wetlands: Ecology and Management. Proceedings of the First International Wetlands Conference, New Delhi, India, September, 1980.

Whitcomb, R. F. 1977. Island biogeography and "habitat islands" of the eastern forest. I. Introduction. Am. Birds, 31:3-5.

Wilcove, D. S. 1985. Nest predation in forest tracts and the decline of migratory songbirds. Ecology, 66:1211-1214.

Zampella, R. A. 1994. Characterization of surface water quality along a watershed disturbance gradient. Water Resourc. Bull., 30:605-611.

Zampella, R. A., R. G. Lathrop, J. A. Bognar, L. J. Craig, and K. J. Laidig. 1994. A watershed based wetland assessment method for the New Jersey Pinelands. Tech. Rept., New Jersey Pinelands Commission, New Lisbon, New Jersey.

Zampella, R. A. and K. J. Laidig. 1997. Effect of watershed disturbance on Pinelands stream vegetation. J. Torry Bot. Soc., 124:52-66.

Zampella, R. A. and J. F. Bunnell. 1998. Use of reference-site fish assemblages to assess aquatic degradation in Pinelands streams. Ecol. Appl., 8:645-658.

Zappalorti, R. T. and S. A. Sykes. 1998. Amphibians and reptiles of the Barnegat Bay drainage basin with life history notes of selected species. Unpublished Report to the Center for Remote Sensing and Spatial Analysis, Rutgers University, New Brunswick.

Zipperer, W. C. 1993. Deforestation patterns and their effects on forest patches. Landscape Ecol., 8:177-184.

Tables

Table 1. Area Estimates For Level I 1972, 1984 and 1995 land Use/Land Cover Maps

Table 1a. 1972 Level I Land Use/Land Cover

Table 2. Development trends for the 1972-1984-1995 time periods by Barnegat Bay sub-watershed, expressed in area (ha) and as % of sub-watershed (excluding Barnegat Bay proper).

Development by time period						
Sub-Watersheds	1972		1984		1995	

	(ha)	%	(ha)	%	(ha)	%
Metedeconk River	6184	27	8117	36	10362	46
Toms River	1099	7	2066	13	3831	25
Union Branch	1468	9	1817	11	2592	16
Kettle Creek	1820	40	1976	44	2656	58
Silver Bay	5052	58	4918	56	5856	67
Wrangle Br/Jake=s Branch	2068	16	3445	27	4263	34
Potters Creek	787	32	705	29	937	39
Cedar Creek	537	4	615	4	987	7
Stouts Creek	572	27	418	20	500	24
Forked River	944	14	955	14	1109	17
Oyster Creek	1356	13	1398	13	1854	18
Mill Cr/Westecunk Creek	2607	13	2776	14	3458	18
Tuckerton Creek	1216	12	1306	13	1651	17

Table 3. Riparian buffer zone analysis including % of individual sub-watershed freshwater riparian zones that are in human altered land covers and the % of Barnegat Bay=s total inventory of altered riparian zone represented by each sub-watershed. The riparian zone represents a

90 m buffer (total 180 m width zone) around all freshwater streams/rivers.

Sub-watersheds	Area (ha) R. Zone	% of Sub-watershed Riparian Zone Altered	% of Total Bay Altered Riparian Zone

Metedeconk River	4677	28	36
Toms River	2888	14	11
Union Branch	3224	7	6
Kettle Creek	547	52	8
Silver Bay	429	38	4
Wrangle Br/Jake=s Branch	2630	19	14
Potters Creek	129	15	<1
Cedar Creek	3004	3	2
Stouts Creek	56	46	1
Forked River	1401	7	3
Oyster Creek	1792	13	6
Mill Cr/Westecunk Creek	2725	9	7
Tuckerton Creek	478	19	2

Table 4. Size Distribution of Forest Fragments.

Table 4a. With All roads as boundaries.

All Roads	50-100 ha	100-250 ha	250-500 ha	500-1000 ha	1000-5000 ha	>5000 ha
# Tracts	159	128	42	11	3	
Area	11,377	20,030	15,111	7,425	3,997	

Table 4b. With only Major Roads as boundaries.

Major Roads	50-100 ha	100-250 ha	250-500 ha	500-1000 ha	1000-5000 ha	>5000 ha
# Tracts	39	28	16	14	15	2
Area	2,701	4,567	5,578	10,348	34,904	19,649

Table 5. Publicly-owned land within the Barnegat Bay region, by sub-watershed.

Sub-watershed	Area (ha)	% Area
Metedeconk River	1506	6.7
Toms River	1291	8.3
Union Branch	8474	51.8
Kettle Creek	778	17.1
Silver Bay	745	8.6
Wrangle Br/Jake=s Branch	1759	13.8
Potters Creek	940	39.1
Cedar Creek	7294	51.5
Stouts Creek	1460	69.3
Forked River	1834	27.6
Oyster Creek	3877	37.0
Mill Cr/Westecunk Creek	10427	53.8
Tuckerton Creek	4658	47.4

Table 6. Barnegat Bay island gap analysis with bird nesting habitat ranking and protection status.

List of Figures

Figure 11. Interior Forest Gap analysis for Barnegat Bay Watershed

I. INTRODUCTION

New Jersey contains an array of productive aquatic ecosystems, including many lakes, rivers, estuaries, nearshore coastal areas, and offshore waters. Estuaries are particularly important systems for fish due to the availability of habitats and access to both freshwater and marine systems. Barnegat Bay is utilized, to varying degrees, by 107 species of fish (See Chapter 7), many of which are sought by commercial and/or recreational fishermen. As a result, the estuary is an important location for commercial and recreational fishing in New Jersey and a significant factor in the state's economy.

The economic value of commercial fisheries in New Jersey exceeds that of key agricultural products. For example, in 1994, the value of all commercial fisheries statewide substantially exceeded that of all fruit crops, including cranberries, blueberries, peaches, apples, and strawberries . Despite their relative economic importance, commercial and recreational fisheries receive far less support from the state than does agriculture . Consequently, numerous gaps exist in basic knowledge related to fisheries in New Jersey, notably those related to adequate stock assessments, which provide vital information on the status of fished populations (see Table 1). Such data are critical to establishing sustainable fishing practices.

The objectives of this chapter are: (1) to provide relevant natural history information on key commercial and recreational fisheries species; (2) to examine the statewide commercial and recreational landings of several selected fisheries species; and (3) to describe, where possible, the degree to which Barnegat Bay contributes to these fisheries. We focus on seven commercially important finfish species, including the American eel (*Anguilla rostrata*), alewife or river herring (*Alosa pseudoharengus*), bluefish (*Pomatomus saltatrix*), striped bass (*Morone saxatilis*), summer flounder (*Paralichthys dentatus*), winter flounder (*Pseudopleuronectes americanus*), and weakfish (*Cynoscion regalis*). In addition, we investigate three shellfish species, namely the blue crab (*Callinectes sapidus*), horseshoe crab (*Limulus polyphemus*), and hard clam (*Mercenaria mercenaria*). Five of these species (bluefish, striped bass, summer flounder, winter flounder, and weakfish) also are examined for their recreational importance, along with the black sea bass (*Centropristis striata*) and tautog (*Tautoga onitis*). These species were chosen because of their relative economic importance and the availability of landings data on them. We acknowledge that there are other species that are commercially and/or recreationally important, such as croaker, spot, and white perch. However, the amount of data available to adequately characterize the commercial and/or recreational landings of these species, either statewide or specifically in Barnegat Bay, is limited.

II. SPECIES DESCRIPTIONS AND HABITAT ASSOCIATIONS

A. Finfish

Except where noted, finfish life history information is taken from recent National Marine Fisheries Reports (NMFR) on essential fish habitat for bluefish (Fahay, in press), summer flounder (Packer and Griesbach, in press), and winter flounder (Pereira et al., in press), as well as from the Delaware Estuary Program's Scientific Characterization of the Delaware Estuary (Sutton et al., 1996) for striped bass, weakfish, eel, and river herring. For most species, data on distribution and abundance in Barnegat Bay are dated, limited, or lacking. One source presented below is a compilation of information and expert opinions on the distribution and abundance of fish and invertebrates in Mid-Atlantic estuaries (Stone et al., 1994) collected under the National Oceanic and Atmospheric Administration's (NOAA) Estuarine Living Marine Resources Program. Categories of relative abundance defined by Stone et al. (1994) and used below include: (1) "rare" = present but not frequently encountered; (2) "common" = frequently encountered but not in large numbers; (3) "abundant" = often encountered in substantial numbers relative to other species; and (4) "highly abundant" = numerically dominant relative to other species.

Unless otherwise cited, information on status and trends in regional landings and stock sizes is derived from Clark (1998), and includes landings data through 1996 and preliminary data for 1997. Data for New Jersey and Barnegat Bay are from the New Jersey Department of Environmental Protection (NJDEP).

1. American eel (*Anguilla rostrata*)

American eels require estuaries to complete their life cycle. The American eel is catadromous, meaning spawning is in the ocean (in this case the Sargasso Sea, in midwinter) and later stages are found in estuaries or fresh water. The eggs hatch into leptocephali (ribbon-like, transparent larvae) that drift with ocean currents for a year or so toward the North American coast. As they approach coastal waters, the larvae metamorphose into "glass eels," which have the typical eel form but are still transparent. These glass eels are highly valued in Japanese markets. Shortly after entering estuaries, they acquire pigmentation and transform into elvers. In the Delaware estuary, 5 to 8 cm (2 to 3 in) long elvers appear in February-March, when they concentrate in tidal creeks of the lower estuary. They reach the middle estuary in April-May, and the upper estuary in May-June. Females travel farther toward fresh water than do males. Both sexes tend to occur in deeper or fresher water in the colder months, returning to coastal areas in the spring.

Except for the aforementioned seasonal movements, eels are quite sedentary and usually remain in home territories. Males mature at 28 to 30.5 cm (11 to 12 in) long, and rarely exceed 60 cm (24 in). Females mature at about 46 cm (18 in), often attaining lengths of 60 to 90 cm (24 to 36 in) (Bigelow and Schroeder, 1953). In estuaries, juveniles and adults primarily feed on crustaceans, bivalves, and polychaetes. At 5 to 20 years, adults leave the estuary and return to the Sargasso Sea to spawn in the spring, after which they die. Stone et al. (1994) reported that elvers were common in Barnegat Bay from February through April. Later juveniles were common year-round, while adults were rare.

2. Alewife (*Alosa pseudoharengus*) and Blueback Herring (*Alosa aestivalis*)

These two species are collectively called "river herring." They are anadromous, entering brackish to fresh water to spawn and then migrating back to coastal areas. Alewife ranges from Labrador to South Carolina, and is most abundant in Mid-Atlantic and New England waters. Blueback herring occurs from Nova Scotia to Florida, most commonly from Chesapeake Bay south. Alewifes usually spawn in mid-spring at water temperatures of 16-19°C. Blueback herring spawn later in spring, at temperatures of ~5°C warmer. Both species enter the Delaware estuary as early as February and begin spawning runs. Adult alewifes are reportedly abundant in Barnegat Bay, and they spawn there in April and May, a time when eggs and larvae are also abundant. Adults are common in March and June, and juveniles are abundant year-round.

Adult blueback herring are common from March through June. Spawning takes place from April through June, and eggs and larvae are generally observed during these months. Juveniles are common year-round (Stone et al., 1994).

Spawning usually begins at age 3, preferably in shallow areas. Blueback herring favor areas with hard substrates and fast currents, whereas alewifes use a variety of habitats, typically with slower currents. Many historical spawning areas are not presently available due to dams and/or pollution. Loss of these spawning and nursery areas has undoubtedly been a major factor in the decline of herring stocks. However, where upstream habitats are suitable (e.g., good water quality), the installation of fish ladders at dams can effectively enhance the stocks of these important forage species. Alewifes live as long as 10 years and reach 36 cm (14 in) in length. Blueback herring live 7 to 8 years and reach a maximum length

of 33 cm (13 in).

Larvae of both species transform to juveniles at ~2 cm (0.8 in) in length, and juveniles become similar to adults in appearance at ~3 cm (1.2 in). Larval river herring are planktivores, feeding selectively on small copepods and cladocerans. Juveniles consume larger plankton. The diet of adults includes fish eggs, small fish, plankton, bottom invertebrates such as amphipods, and insects. When abundant, all life stages of river herring are important in food webs. Adults are a preferred prey of birds, whales, and many fish species, notably bluefish, striped bass, and weakfish.

3. Bluefish (*Pomatomus saltatrix*)

In the western Atlantic, bluefish range from Nova Scotia to Argentina. Bluefish occurring off the Mid-Atlantic and southeast U.S. coasts are considered a single genetic stock. These fish spawn in offshore waters from March through August. Most bluefish are capable of spawning by age 2. Eggs and larvae generally remain in oceanic waters. Early juveniles (2 to 5 cm; 1 to 2 in long) move toward coastal and estuarine nursery areas by active swimming and/or passive movement with currents. The numbers of larvae reaching these nursery areas are quite variable and may be a key determinant of the subsequent abundance of larger juveniles and adults. Early-spawned fish enter Mid-Atlantic estuaries in late May to mid-June, at an average length of 6 cm (2.4 in). Fish spawned in summer either remain in coastal waters or enter estuaries in August when they are ~4.6 cm (1.8 in) in length.

Bluefish are fast-growing. Young-of-the-year fish may be 25 cm (10 in) long by fall, and are the basis of the popular "snapper" fishery. Maximum size is ~1.1 m (3.5 ft) long and 12.3 kg (27 lb), and maximum age ~12 years. This predatory fish is usually found in schools of similar-sized individuals. There are seasonal migrations, with movement into Mid-Atlantic coastal and estuarine waters in spring, and back southward or offshore in fall. The larger fish tend to move farther north in summer and perhaps not as far south in winter. In Barnegat Bay, adults are common, and juveniles are abundant, from about May to November (Stone et al., 1994).

Larval bluefish consume mostly copepods. Fish appear in the diet when the larvae are slightly over 2.5 cm long, and soon dominate the typical diet. However, young bluefish may prey more on invertebrates, such as crustaceans and polychaetes, in some areas or seasons. Atlantic menhaden (*Brevoortia tyrannus*) is a very important prey for larger individuals. Mature bluefish are in turn eaten by sharks, tunas, and billfish. Oceanic birds are major predators of young-of-the-year bluefish. Some cannibalism has been reported.

The importance to bluefish stocks of specific estuarine habitats, and of estuaries in general, is not known. Since the egg and larval stages develop at sea, estuarine dependence is undoubtedly less than for species in which these sensitive stages occur inshore. The pelagic bluefish also is not closely tied to particular water depths, bottom types, or aquatic vegetation, though young-of-the-year tend to congregate in shallow nearshore areas. It is not known to use the marsh surface. Estuaries, and specific estuarine features such as marsh creeks, probably do provide benefits in terms of shelter and abundant forage that leads to rapid growth, especially among young-of-the-year fish.

4. Striped Bass (*Morone saxatilis*)

The striped bass, one of the largest fish species inhabiting estuaries, is a very popular gamefish. It also is highly valued commercially. Although this species has a natural range from the Gulf of St. Lawrence to the Gulf of Mexico, it has been successfully introduced elsewhere. Being anadromous, the striped bass lives in coastal and estuarine areas and enters fresh or low salinity waters for spawning, as well as egg

and larval development. There are both migratory and non-migratory stocks, with the former predominating in the Mid-Atlantic. Most of the Mid-Atlantic fish originate in Chesapeake Bay. The Hudson River also has an important spawning stock. Migrating stripers move north in the spring; many find their natal estuary to spawn, and then resume their northward coastal migration. The return migration occurs in the fall, and individuals overwinter in coastal areas from New Jersey to North Carolina, and in Chesapeake Bay.

Striped bass are not very abundant in Barnegat Bay. Stone et al. (1994) reported that adults and juveniles are rare in the bay from March through December. There are reports of stripers overwintering in the bay and in areas just outside of the bay, especially in the discharge canal of the Oyster Creek Nuclear Generating Station. Some striped bass have been counted in fish kills at the power plant.

There are no records of striped bass spawning in the Barnegat Bay watershed. In the Delaware River estuary, spawning is from early April to June at temperatures of 10-25°C, with the peak generally from late April to early May at temperatures of 15-18°C. The semi-buoyant eggs are released over various substrates in shallow waters (< 6 m; 20 ft) with moderate flow rates ($\geq$ 0.3 m/s; 1 ft/s). Eggs and larvae are often concentrated in channels, whereas juveniles disperse throughout the estuary and use all depths as nursery areas, moving toward deeper, more saline areas as they grow. Most young-of-the-year (and some adults) overwinter in the estuary; however, fish greater than 2 years of age often spend the winter in adjacent coastal waters. Most stripers reach sexual maturity at age 5.

Striped bass may grow to ~10 cm (4 in) in length by the end of their first summer, and 30 cm (12 in) or more by their second summer. They can grow to great sizes, with the maximum on record being over 1.8 m (6 ft) long and 56 kg (125 lb). Most fish larger than 13.5 kg (30 lb) are females (Bigelow and Schroeder, 1953). The diet of small stripers is often dominated by amphipods and shrimp, whereas larger bass consume a wide variety of fish as well as worms, crustaceans, squid, and clams (Bigelow and Schroeder, 1953).

Commercial and recreational catches of striped bass declined drastically in the Mid-Atlantic region during the mid-1970s (Clark, 1998). The decrease in abundance was largely due to the very low production of juveniles in Chesapeake Bay from the early 1970s through the late 1980s. After a coastwide moratorium on commercial harvesting was declared, juvenile production increased. This led to 1993 and 1996 juvenile indices that were the highest on record. When the moratorium ended, commercial landings had rebounded to 2.2 million kg (4.8 million lb) in 1996. The stock was declared restored in 1995, and it is now considered fully exploited. In New Jersey, commercial fishing for striped bass is currently prohibited. There are no data on recreational landings of striped bass in Barnegat Bay.

5. Summer Flounder (*Paralichthys dentatus*)

The summer flounder (or fluke) is one of the most popular sportfish in the Mid-Atlantic region, and it is commercially important. The species ranges from estuaries to the outer continental shelf, and from Nova Scotia to at least as far south as Florida. Its center of abundance occurs between Cape Cod (MA) and Cape Hatteras (NC). It is unclear if summer flounder in the Mid-Atlantic constitute a single stock; there may be a separate stock in the vicinity of Cape Hatteras and another in the South Atlantic Bight. There are pronounced seasonal migrations, with most adults inhabiting inshore waters during the warmer months and wintering well offshore, to depths as great as 150 m (500 ft). In subsequent years, individuals tend to return to the same estuary, or move north and east. Older fish may remain offshore year-round. Females reach sexual maturity at a size of ~28 cm (11 in), and males at a size of ~25 cm (9.8 in). The median age of sexual maturity in both sexes is 1.5 years (Packer et al., in press). The species attains a maximum size of ~0.9 m (3 ft) and 6.7 kg (15 lb); the largest individual on record is

11.7 kg (26 lb).

Spawning takes place offshore, peaking in October and November, with females capable of producing more than 4 million eggs. The total number of eggs produced is size- and age-dependent. Eggs are pelagic and buoyant, and early larvae are planktonic. Later stage larvae and postlarvae migrate to coastal and estuarine nursery areas from October to May, where they complete metamorphosis to the typical flatfish form. Metamorphosis involves the migration of the right eye across the top of the head, and the widening and flattening of the body. It typically occurs when the larvae are between 0.64 cm (0.25 in) and 1.91 cm (0.75 in) long. After this transformation, they move to the bottom, bury in the sediment, and complete development to the juvenile stage. According to Stone et al. (1994), juveniles and adults are common in Barnegat Bay from May through September, and juveniles are present but rare the remainder of the year. Larvae are rare, occurring in the bay from October through May.

Barnegat Bay and other Mid-Atlantic estuaries are valuable sources of shelter and food for intermediate stages of the species, especially metamorphosing larvae and early juveniles. Juveniles usually are found in sandy areas, adjacent eelgrass beds, among macroalgae, and in marsh creeks. Since these areas are vulnerable to perturbations, they have been identified by the Mid-Atlantic Fishery Management Council as habitat of particular concern in summer flounder management (Packer and Hoff, 1999).

The larval diet is dominated by immature copepods, and also includes tintinnids, bivalve larvae, and copepod eggs and adults. Toward the end of metamorphosis, the diet shifts toward bottom-living invertebrates. Small juvenile flounder less than ~10 cm (4 in) long feed opportunistically on whatever suitable prey is available, eating mostly crustaceans and polychaetes. Fish are more prominent in the diet of larger juveniles. For young-of-the-year summer flounder in marsh creeks of the Great Bay-Little Egg Harbor, the most important prey are silversides, followed by mummichogs, grass shrimp, and sand shrimp. In other estuaries mysid shrimp also are commonly consumed. Adults may eat larger fish such as spot and pipefish. Probable predators on larval flounder include mummichogs and sand shrimp, and juvenile and adult flounder are probably eaten by blue crab, spiny dogfish, goosefish, cod, sea raven, longhorn sculpin, fourspot flounder, as well as silver, red and spotted hake.

6. Winter Flounder (*Pleuronectes americanus*)

The winter flounder is a small-mouthed, right-eyed flatfish. It is valuable in both commercial and recreational fisheries of northwest Atlantic estuaries and continental shelf areas. The species prefers cool temperatures; its range is from Labrador to Georgia, with highest abundances in Canadian waters. The federal fishery management plan for winter flounder considers the species to consist of three stocks: Gulf of Maine, Southern New England/Middle Atlantic, and Georges Bank.

Except for Georges Bank fish, adults migrate inshore in fall and early winter, and spawn in late winter and early spring. In the Mid-Atlantic, the peak of spawning is February and March. Most adults return to offshore waters after spawning. Migrating adults sometimes travel long distances. In one tagging study, the average distance was ~65 km (40.4 mi), and in another study, a fish tagged in the inner New York Bight was recovered ~315 km (195.8 mi) away near Nantucket, Massachusetts. South of Cape Cod, females become sexually mature at 3 years of age and an average length of 27.7 cm (10.9 in), and males at 3.3 years of age and an average length of 29.0 cm (11.4 in). Maximum length is ~63.5 cm (25 in), and the maximum age is more than 15 years. Stone et al. (1994) state that in Barnegat Bay, adults are abundant from November through April, and spawning occurs from January through March, with eggs and larvae being abundant at this time. Juveniles are considered abundant year-round.

Except for the Georges Bank stock, the species is estuarine-dependent, requiring shallow, lower-salinity

waters to spawn. Eggs adhere to various substrates including mud, sand, gravel, and vegetation. Eggs are ~0.3 cm (0.125 in) in diameter when they hatch, typically in two to three weeks, with faster hatching times occurring at higher temperatures. Larvae are negatively buoyant. This probably enables them to be retained in greater numbers in suitable estuarine nursery areas rather than being swept out to sea. As they approach metamorphosis (which usually occurs 5 to 8 weeks after hatching), the larvae become increasingly bottom-oriented, feeding on copepods, copepod and barnacle nauplii, polychaetes, and invertebrate eggs. Metamorphosing larvae settle on the bottom when they are ~1.3 cm (0.5 in) in length.

Young-of-the-year winter flounder inhabit shallow waters, feeding on polychaetes and crustaceans, especially amphipods. Here, they may grow to 10 to 18 cm (4 to 7 in) in length during the first year. Most of these fish overwinter in estuaries, but they also are commonly found in adjacent coastal waters. In some estuarine areas, including the Oyster Creek Channel in Barnegat Bay, there are restrictions on dredging from January 1 through May 31 to protect spawning and early life stages in these important habitats. Since winter flounder are visual feeders, they may be adversely affected by natural or anthropogenic factors which reduce water clarity. Large docks and other platforms also may impair feeding, perhaps by blocking or decreasing available light (Duffy-Anderson and Able, 1999).

7. Weakfish (*Cynoscion regalis*)

Weakfish range from Nova Scotia to Florida, with their center of abundance in Chesapeake Bay and Delaware Bay. This species is relatively estuarine-dependent, since all life stages are found in this environment. Spawning begins at water temperatures of ~15°C, and it generally peaks from mid-May through mid-June. Spawning occurs in 1-3 batches per season, on sand and hard substrates throughout the lower estuary. Some spawning also occurs in coastal waters. Young-of-the-year weakfish appear by June, and occupy nursery habitats in a wide range of temperatures and salinities, in both the mainstem estuary and smaller tributaries and creeks.

The diet of young-of-the-year forms includes mysid shrimp, crabs, worms, and clams. Most weakfish mature by their second summer, when males are 12.7 to 15.2 cm (5 to 6 in) long and females 15.2 to 20.3 cm (6 to 8 in) long. A 30.5 cm (1 ft) long fish is probably 2 years of age, and a 61 cm individual may be 9 years old. The largest weakfish on record is 7.9 kg (17 lb, 8 oz), but fish heavier than 5.4 kg (12 lb) or longer than 1 m (3.3 ft) are rare (Bigelow and Schroeder, 1953). Adults are most abundant in lower estuarine areas, in depths < 9 m (30 ft) and salinities ≥ 15 ‰. Weakfish tend to occur in schools of like-sized individuals. Juveniles begin to migrate out of the estuary in August, and by mid-November both juveniles and adults have left the bay. They travel south to overwinter off Virginia and North Carolina. In Barnegat Bay, adults are common from April through October, and then rare through November. Spawning, eggs and larvae are all rare from May to August. Juveniles are common from May to November (Stone et al., 1994).

B. Shellfish

1. Blue Crab (*Callinectes sapidus*)

Blue crabs are abundant and ubiquitous members of estuarine ecosystems along most of the East Coast of the United States . The life cycle is approximately two years from egg to adult, with an average lifespan of about three to four years. In the Mid-Atlantic region, mating occurs during the summer (June-September) throughout bays and estuaries. Males may mate more than once within a mating season and may go through at least two seasons. In contrast, females have a single opportunity to mate, immediately after their final (terminal) molt to maturity , and most of them mate with only a single male . After mating, females migrate to higher salinity waters near the estuary mouth to overwinter and

eventually spawn . Adult males and immature crabs remain in brackish waters of estuaries, burying in bottom sediments during the winter.

In the Mid-Atlantic region, spawning typically begins the following spring and may continue into the early fall, with females producing what appears to be two or three broods of eggs . However, if mating occurs in the late spring or early summer, females may be able to produce one brood of eggs later that same summer or fall . Individual females can produce between 700,000 and 2,000,000 eggs per brood, with larger females typically exhibiting greater fecundity . Larvae are released into the water column and are transported out of the estuary by tidal flow to develop offshore over the continental shelf .

On the continental shelf, blue crab larvae from different estuaries may mix before being transported back to the estuaries by wind and water circulation patterns . Once the first-stage crabs settle onto the bottom, they seek protective habitats such as seagrass beds . Juvenile crabs molt and grow rapidly, migrating away from high salinity waters into brackish waters, where they eventually mature (after 12-18 months) and mate.

2. Horseshoe Crab *(Limulus polyphemus)*

Horseshoe crabs are found along the East Coast of North America from the Gulf of Maine to the Yucatan Peninsula . The largest populations occur in the Mid-Atlantic region, particularly in Delaware Bay . Adults are dispersed within the estuary and along the continental shelf . In the Mid-Atlantic region, mating begins in late April during the new and full-moon high tides . Males locate a female offshore, grasp her from behind with specialized appendages, and the pair crawl toward the high-tide line of a sandy beach . The female digs a nest in the sand into which she deposits approximately 4,000 eggs, while her attached mate releases sperm to fertilize the eggs externally . A female may lay about 20 broods of eggs during the spawning season, which peaks between mid-May and mid-June . Approximately four weeks later, the larvae hatch, emerge from the sand, and enter the water. However, some larvae overwinter in the beach sediments and emerge the following April . Shallow water areas of the estuary are important nursery grounds for young horseshoe crabs, and as they grow, the crabs move to deeper water areas of estuaries and out to the continental shelf. Sexual maturity is reached in ~9-11 years, with an average lifespan of ~18-20 years .

3. Hard Clam (*Mercenaria mercenaria*)

Hard clams occur in coastal embayments and estuaries from the Gulf of St. Lawrence to the Gulf of Mexico . They are filter-feeding, infaunal bivalves distributed in intertidal and subtidal zones. In most regions, hard clams become sexually mature in about two years . Sexes are separate, and spawning is external. In most areas, spawning takes place from spring to fall when water temperatures exceed 20 ^{o}C . In Barnegat Bay, the peak in spawning occurs at water temperatures between 24^{o}C and 26^{o}C .

Females release from 8 million to 39.5 million eggs per spawning season, with larger females being more fecund . Larvae are planktonic for approximately one to four weeks depending on food supply, water temperature, and larval physiology . There are four planktonic larval stages before the larvae become affixed to the benthic substrate. Larvae prefer to settle on silt or sand, and subsequent growth is most rapid in these substrates . After settling, juveniles burrow into the sediment and grow ~10 mm per year for the first three years . Recently settled clams are subject to intense predation by a variety of predators, including crabs, gastropods, and fish , but as clams grow and their shells thicken, predation decreases. At approximately 3-5 years of age and 3-4 cm in length, they are large enough to be harvested.

III. STATEWIDE LANDINGS

Commercial and recreational fishing are important components of the New Jersey economy. The economic value of all commercially harvested species in New Jersey has risen from approximately $19.8 million in 1975 to just over $100 million in 1997 (Figure 1). Since 1980, New Jersey has ranked second in the combined value of all commercially harvested species as compared with New York, Connecticut, Delaware, Maryland, and Virginia (Figure 1). Since 1965, New Jersey also has ranked second in the combined amount of commercially harvested biomass as compared with these five states (Figure 2). In addition to more than 2,800 commercial fishermen, the industry includes more than 40 fish and seafood processors, 130 wholesalers and distributors, and more than 300 fish and seafood retailers .

The statewide commercial landings of seven finfish species are examined below, specifically those of the American eel (*Anguilla rostrata*), alewife or river herring (*Alosa pseudoharengus*), bluefish (*Pomatomus saltatrix*), striped bass (*Morone saxatilis*), summer flounder (*Paralichthys dentatus*), winter flounder (*Pseudopleuronectes americanus*), and weakfish (*Cynoscion regalis*). The statewide landings of three shellfish species also are investigated, notably those of the blue crab (*Callinectes sapidus*), horseshoe crab (*Limulus polyphemus*), and the hard clam (*Mercenaria mercenaria*). These species were chosen because of their relative economic importance and the availability of landings data on them. The combined annual value of these species represents 11% to 26% of the total value of commercial landings in New Jersey. There are other species that are commercially and/or recreationally important, including tautog, black sea bass, and white perch. However, the amount of data available to adequately characterize the commercial and/or recreational landings of these species is limited.

A. Finfish Landings

1. American eel (*Anguilla rostrata*)

New Jersey landings of the American eel from 1970 through 1993 ranged from ~36,000 to 243,000 kg/yr (~80,000 to 540,000 lb/yr), with no clear trends over time (Fahay, 1995). Since 1989, annual commercial landings of the American eel have fluctuated somewhat, with peaks of over 94,500 kg (210,000 lb) in both 1991 and 1996, followed by declines (Figure 3). The value of the American eel was consistently low between 1989-1995; however, its value increased more than 6.5 times between 1995 and 1996 (from $307,491 to $2,011,104), and then nearly doubled to its maximum value in 1997 ($3,749,078) (Figure 3). Commercial landings were 52,520 kg (116,713 lb) in 1997, of which ~5,300 kg (11,800 lb) were glass eels. Recreational landings were less than 13,500 kg (30,000 lb). Prior to 1994, the American eel was the third most landed species commercially in Barnegat Bay; since then, no landings have been reported. No recreational landings data are available for the bay.

2. Alewife or river herring (*Alosa pseudoharengus*)

Since 1950, the annual commercial landings of alewife in New Jersey have varied considerably (Figure 4). They have typically decreased precipitously, dropping to as low as ~135 kg (~300 lb), following years when annual landings were at least 9,000 kg (20,000 lb). The peak in annual landings occurred in 1990, when over 18,900 kg (42,000 lb) were harvested. The economic value of alewife is relatively low, varying annually - almost identically - with the annual variation in landings (Figure 4). The maximum annual value of $4,173 was recorded in 1990. No commercial, recreational, or bait fishery landings data are available specifically for Barnegat Bay.

3. Bluefish (*Pomatomus saltatrix*)

The annual commercial landings of bluefish in New Jersey consistently increased from a minimum of ~40,500 kg (~90,000 lb) in 1958 to a peak of just over 1.35 million kg (3 million lb) in 1986 (Figure 5). Since 1986, the annual landings have shown a general decline, with landings in 1995 (381,557 kg; 847,905 lb) just below that in 1973 (399,375 kg; 887,500 lb). Abundance is now well below that needed to produce a maximum sustainable yield. The economic value of bluefish is moderate, varying annually - almost identically - with the annual variation in landings (Figure 5). The maximum annual value of $663,497 was reported in 1987, with a maximum annual value of 2.4% (in 1951) of the total value of commercial fisheries in New Jersey. In 1997, the commercial catch from Barnegat Bay amounted to 4,156 kg (9,235 lb). No data on recreational landings are available specifically for Barnegat Bay, although the recreational catch for New Jersey was ~1.0 million kg (2.2 million lb).

4. Striped bass (*Morone saxatilis*)

There have been three peaks in the annual state commercial landings of striped bass since 1950: (1) (240,975 kg; 535,500 lb) in 1952; (2) (448,020 kg; 995,600 lb) in 1964; and (3) (344,835 kg; 766,300 lb) in 1973. These peaks were followed by three periods (lasting at least 7 years) of rapid decline to relatively low catches (Figure 6). After the peak in 1973, the commercial fishery essentially crashed, leading to the release of the Interstate Fisheries Management Plan for Striped Bass by the Atlantic States Marine Fisheries Commission. The plan mandated a target fishing mortality designed to allow the stocks to recover. The commercial striped bass fishery has varied annually - almost identically - with the annual variation in landings (Figure 6), bringing in as much as $210,872 (in 1973) with a maximum annual value of 1.8% (in 1964) of the total value of commercial fisheries in New Jersey. Commercial fishing for striped bass is no longer permitted in New Jersey.

5. Summer flounder (*Paralichthys dentatus*)

In terms of both biomass and value, the commercial summer flounder fishery is one of the most important finfish fisheries in New Jersey. Since 1950, commercial landings of summer flounder have gone through two periods of increase each followed by periods of decline (Figure 7). The first peak in commercial landings occurred in 1958 (> 3.6 million kg; > 8 million lb), followed by a steady decline to their lowest level in 1969 (450,000 kg; just over 1 million lb). Commercial landings rose subsequently and fluctuated around 2.25 million kg (5 million lb) from 1978 until 1988, after which time a sharp drop occurred. The landings have remained relatively low during the 1990s. From 1953 to 1974, the annual value of summer flounder averaged ~$1 million despite relatively high landings. However, the value steadily increased to a peak of over $7 million in 1989 for equivalent levels of biomass (Figure 7). The commercial summer flounder fishery has represented from 2.0% (in 1997) to 13.3% (in 1958) of the total value of commercial fisheries in New Jersey. There are no stock size or landings data available for Barnegat Bay, where there is a substantial recreational fishery.

6. Winter flounder-(*Pseudopleuronectes americanus*)

From 1953 to 1966, commercial landings of winter flounder in New Jersey steadily increased, then following three years of high levels, declined until 1971 (Figure 8). They steadily increased again until 1981, and subsequently fluctuated around 135,000 kg (300,000 lb) until 1995, after which they showed a

sharp decline. As with the value of the commercial summer flounder fishery, that of the commercial winter flounder fishery remained relatively low (~$10,000) until 1980, despite strong landings. Since 1980, the value has steadily risen to a maximum of $72,887 in 1995 (Figure 8). At its maximum value, the commercial winter flounder fishery represented only 0.76% of the total value of commercial fisheries in New Jersey.

7. Weakfish (*Cynoscion regalis*)

In the early 1990s, the weakfish was considered overexploited and at a low level of abundance coastwide. Between 1989 and 1994, the commercial landings of weakfish in New Jersey steadily declined from a peak of 656,325 kg (1,458,500 lb) to a low of 312,876 kg (695,280 lb). They subsequently increased to present levels of 450,000 kg (just over 1 million lb) (Figure 9). In 1997, 0.81 million kg (1.8 million lb) were landed recreationally. The economic value of weakfish is moderate, varying annually - almost identically - with the annual variation in landings (Figure 9). This species returned over $1 million in 1989, which represented its maximum annual value of 1.3% of the total value of commercial fisheries in New Jersey. No commercial landings have been reported specifically for Barnegat Bay in the past several years.

B. Shellfish Landings

1. Hard clam (*Mercenaria mercenaria*)

From 1950 to 1978 (except for a six year period starting in 1962), annual hard clam commercial landings in New Jersey declined from a maximum of 2,288,115 kg (5,084,700 lb) to a minimum of 362,160 kg (804,800 lb) (Figure 10). Subsequently, annual hard clam landings generally showed a slight increase to present levels of nearly 0.9 million kg (2 million lb). Until 1978, hard clam landings fluctuated around $1 million; however, they then increased dramatically to a maximum of over $7 million in 1996. Commercial hard clam landings represent from 2.8% (in 1978) to 17.8% (in 1950) of the total value of commercial fisheries in New Jersey, making it the most important commercial fishery in the state. Because of the economic importance of the hard clam and the need to maintain high water quality to ensure significant recruitment to the fishery, NJDEP has relayed or transported clams from low water quality areas to high water quality areas (e.g., Swan Point, Laurel Harbor, and Tuckerton). Since 1986, the number of clams relayed has ranged from 104,715 kg (232,700 lb) in 1987 to more than 4.5 million kg (10 million lb) in 1991.

2. Blue crabs (*Callinectes sapidus*)

Annual commercial landings of blue crabs in New Jersey fluctuated around 450,000 kg (1 million lb) from 1950 to 1980, and then steadily increased to more than 3.15 million kg (7 million lb) in both 1993 and 1995 (Figure 11). Recent landings have decreased to ~1.35 million kg (~3 million lb). The economic value of commercial blue crab landings remained under $1 million until 1984. Subsequently, the economic value followed that of the annual landings, reaching a high of $6,251,843 in 1995 (Figure 11), which represented its maximum value of 6.5% of the total value of commercial fisheries in New Jersey.

3. Horseshoe crab (*Limulus polyphemus*)

From 1989 to 1996, the commercial landings of horseshoe crabs steadily increased in New Jersey to

their maximum levels of 813,869 kg (1,808,598 lb). They then decreased in 1997 (Figure 12). The variation in economic value of commercial horseshoe crab landings has followed that of the annual landings, reaching a high of $277,182 in 1996 (Figure 12), which represented its maximum value of 0.29% of the total value of commercial fisheries in New Jersey.

IV. BARNEGAT BAY LANDINGS

In this section, the commercial landings of finfish and shellfish in Barnegat Bay are examined. Among the finfish species investigated are the American eel *(Anguilla rostrata)*, bluefish (*Pomatomus saltatrix*), winter flounder *(Pseudopleuronects americanus*), and weakfish (*Cynoscion regalis*). Three shellfish species also are investigated, including the blue crab (*Callinectes sapidus*), horseshoe crab (*Limulus polyphemus*), and hard clam *(Mercenaria mercenaria*). Commercial landings data specifically for Barnegat Bay on three of the species examined in the previous section (i.e., alewife, striped bass, and summer flounder) are currently unavailable. There are additional species that are commercially and/or recreationally important in Barnegat Bay. However, data to adequately characterize the commercial and/or recreational landings of these species were either limited or non-existent for the bay.

A. Finfish Landings

1. American eel (*Anguilla rostrata*)

American eels are harvested commercially, primarily with baited traps, along the Atlantic and Delaware Bay coasts of New Jersey. In Barnegat Bay, commercial fishing begins around April and continues into the fall. Landings are typically highest between April and June . From 1950 through 1963, landings from Barnegat Bay remained under 5,850 kg (13,000 lb), then gradually increased to a maximum of 31,311 kg (69,579 lb) in 1971. They have subsequently declined. From 1950 to 1977, landings of American eel in Barnegat Bay represented approximately one-third of the total American eel landings in New Jersey . More recent commercial landings for American eel in Barnegat Bay are available from 1989 to 1994. During that period, annual commercial landings of the American eel in Barnegat Bay declined from 17,303 kg to 4,095 kg (9,100 lb to 38,450 lb) (Figure 13), representing a decrease from 19.8% to 5.4% of the total weight of American eel landed in the state. From 1989 to 1994, the annual value of American eel in Barnegat Bay also declined from $62,857 to $17,150 (Figure 13), representing a decrease from 20.6% to 5.6% of the total value of American eel in New Jersey.

2. Bluefish (*Pomatomus saltatrix*)

Commercial landings for bluefish in Barnegat Bay are only available for 1997. In Barnegat Bay, 4,156 kg (9,235 lb) of bluefish were landed in 1997 for a value of $3,694. This represents 0.74% and 0.77% of the total weight and total value, respectively, of bluefish landed in New Jersey.

3. Winter flounder (*Pseudopleuronectes americanus*)

Commercial landings for winter flounder in Barnegat Bay are available from 1989 to 1994. Between 1989 and 1991, a rapid decline occurred in winter flounder landings from 2,671 kg to 1,175 kg (5,935 lb to 2,610 lb), followed by a relatively strong recovery to levels consistently near 1,800 kg (4,000 lb) (Figure 14). The commercial winter flounder fishery in Barnegat Bay represents between 1.0% and

1.9% of the total winter flounder fishery in New Jersey. The annual variation in the value of winter flounder in Barnegat Bay follows that of landings; however, winter flounder are becoming relatively more valuable, as seen in 1993 and 1994 (Figure 14). The annual value of the winter flounder fishery in Barnegat Bay represents between 1.1% and 1.8% of the total value of the winter flounder fishery in New Jersey.

4. Weakfish (*Cynoscion regalis*)

Commercial landings for weakfish in Barnegat Bay are only available for 1993. In Barnegat Bay, 253 kg (563 lb) of weakfish were landed for a value of $1,126. This represents 0.7% and 0.16% of the total weight and total value, respectively, of weakfish landed in New Jersey.

B. Shellfish Landings

1. Hard clams (*Mercenaria mercenaria*)

Commercial landings for hard clams in Barnegat Bay are available from 1989 to 1997. A nearly three-fold drop occurred in hard clam landings between 1989 and 1990, from 370,090 kg to 133,533 kg (822,423 lb to 296,740 lb), representing a decrease from 70.1% to 23.9% of the total hard clam landings in New Jersey. Since 1990, landings have slowly declined to their present level of 29,691 kg (65,981 lb) (Figure 15), representing only 3.8% of the total landings in New Jersey. A nearly three-fold increase occurred in the value of hard clams between 1989 and 1990 (from $415,868 to $1,089,591), representing an increase from 9.3% to 25.0% of the total value of hard clams in New Jersey (Figure 15). Since 1990, the annual value of hard clams in Barnegat Bay has steadily declined to the present value of $281,258, representing 4.2% of the total value of hard clams in New Jersey.

2. Blue crabs (*Callinectes sapidus*)

Blue crabs are an important component of both the recreational and commercial fisheries of Barnegat Bay. The commercial fishery extends from March through December, with the majority of crabs captured between May and August . During the warmer months when crabs are actively feeding, baited traps are used. During the late fall and early winter, crabs are dredged from the bottom sediments. Commercial landings for blue crabs in Barnegat Bay recorded from 1989 to 1997 indicate considerable variation in annual landings, with peaks in 1991 (526,478 kg; 1,169,950 lb) and 1993 (627,404 kg; 1,394,230 lb) (Figure 16). After 1993, landings in Barnegat Bay dropped steadily to a low of 207,423 kg (460,939 lb) in 1996. However, they increased to 352,066 kg (782,369 lb) in 1997. From 1989 to 1997, blue crab landings in Barnegat Bay represented between 8.4% and 23.5% of the total blue crab landings in New Jersey. Between these years, the value of blue crab landings in Barnegat Bay ranged between $281,800 and $634,745, representing between 8.5% and 22.5% of the total value of blue crabs in New Jersey.

3. Horseshoe crabs (*Limulus polyphemus*)

Commercial landings for horseshoe crabs in Barnegat Bay are available from 1993 to 1997. Since 1995, the annual landings of horseshoe crabs in Barnegat Bay have increased steadily from 339 kg to 2,322 kg (753 lb to 5,161 lb) (Figure 17), representing between 0.05% and 0.47% of the total landings of horseshoe crabs in New Jersey. The value of horseshoe crabs in Barnegat Bay has increased from $52 to $795 since 1995 (Figure 17), representing between 0.03% and 0.52% of the total value of horseshoe

crabs in New Jersey.

V. RECREATIONAL FISHING: NEW JERSEY

New Jersey is one of the most popular places for recreational fishing along the Mid-Atlantic coast. As compared with other Mid-Atlantic states from Connecticut to Virginia, New Jersey had the greatest number of marine anglers from 1981 to 1998 except in 1982, 1983, and 1989 (Figure 18 [E.B.-Figure 1]) (NMFS MRFSS). The total number of fishing trips by New Jersey anglers ranged from 3,865,158 in 1989 to 7,751,600 in 1986. In 1998, New Jersey anglers took 4,307,924 trips. From 1981 to 1998, New Jersey fishermen made more fishing trips than anglers from Connecticut to Virginia, except for 1984 when New Jersey was second only to New York (Figure 19 [E.B. Figure 2]) (NMFS MRFSS). Due to the extensive fishing effort in New Jersey, the National Marine Fisheries Service has estimated that New Jersey fishermen annually harvest 20-30% of the total Mid-Atlantic recreational catch and approximately 6-7% of the entire marine recreational catch along the Atlantic and Gulf Coasts. Based on these estimates, the economic value of the recreational fishery in New Jersey ranks third among 14 East Coast states (Powell, 1996).

The many rivers, estuaries, and miles of coastline and offshore waters in New Jersey offer recreational fishermen a myriad of fishing opportunities. Sport fishermen pursue these fishing opportunities from beaches, piers, docks, and jetties as well as from boats. The boats range in size from less than 3.3 m (10 ft) to well over 15 m (50 ft). There are slightly over 400 charter/party boats operating from New Jersey ports (McCay et al., 1999). In 1989, there were about 81,000 private boats fishing in New Jersey's marine and coastal waters (Figley, personal communication, NJDEP). Between 1981 and 1997, the number of fishing trips (from shoreline, charter, and privately owned and/or rented boats) in the estuaries and coastal bays of New Jersey averaged around 500,000 per year.

Based upon the National Marine Fisheries Service (NMFS) MRFSS, the number of New Jersey marine recreational anglers fluctuates substantially from year to year, with the lowest estimated number of anglers in 1982 (654,317) and the highest number of anglers in 1985 (1,332,857) (NMFS, MRFSS). In 1998, there were an estimated 785,887 saltwater anglers fishing New Jersey's marine and coastal waters, with 45.5% of anglers from out-of-state and 54.5% from in-state. Recreational fishing is highly seasonal; the peak in the average number of fishing trips occurs at the height of the tourist season in July-August (1,102,739), being nearly twice the average number in May-June (559,652), and more than twice the average number in September-October (463,232). The average number of people fishing recreationally in New Jersey also peaks in July-August (Figure 20), as does the average percentage of out-of-state fishermen (Figure 21), indicating that recreational fishing has a positive influence on tourism in the state.

VI. RECREATIONAL FISHING: BARNEGAT BAY

Barnegat Bay is an important recreational fishing area with anglers pursuing striped bass, bluefish, summer flounder (fluke), winter flounder, weakfish, black sea bass, and tautog. In 1997, charter boat captains targeted summer flounder (N=84), bluefish (N=62), striped bass (N=47), tuna (N=37), weakfish (N=33), winter flounder (N=11), and shark (N=11) (McCay et al., 1999). However, one of the most popular species targeted in Barnegat Bay during late spring through early fall by both tourists and residents is the blue crab. In 1995, 5,139 recreational crab pot licenses were sold in New Jersey (Joseph, personal communication, NJDEP). However, a crabbing license is not needed to harvest crabs without a pot. No recreational catch data are available for any species caught by anglers fishing specifically in Barnegat Bay.

Hard clams also are sought by recreational fishermen, and Barnegat Bay is a popular clamming location from late spring through fall. Since 1983, New Jersey residents clamming recreationally have accounted for the majority of clamming licenses issued by the state (Figure 22). In 1995, 6,920 resident, 765 nonresident, and 824 juvenile recreational clam licenses were issued (Joseph, personal communication, NJDEP). There are ~10,000 senior citizen recreational clammers (26 N.J.R. 3040).

A. Fisheries

1. Bluefish (*Pomatomus saltatrix*)

The bluefish is a recreationally important species in Barnegat Bay. Recreational fishermen catch many young bluefish, called "snappers," in the estuary. New Jersey usually ranks second in total annual landings of bluefish among states from Connecticut to Virginia. In 1992 and from 1996 to 1998; however, New Jersey ranked first in total landings. Bluefish total landings for all states (CT-VA) fluctuate substantially from year to year (Figure 23 [E.B.Figure 9] NMFS MRFSS). Mean lengths of bluefish for all states ranged from ~280 to 620 mm (11.0 to 24.4 in) (Figure 24 [E.B.Figure 10] NMFS MRFSS).

2. Striped bass (*Morone saxatilis*)

Striped bass also are caught recreationally in Barnegat Bay. Among states from Connecticut to Virginia, New Jersey generally ranks in the middle of the range for the annual catch of striped bass. However, New Jersey ranked first for the total catch of striped bass in 1988. New Jersey landings were highest in 1997. All landings have increased since about 1992 (Figure 25 [E.B.Figure 11] NMFS MRFSS). For all states from Connecticut to Virginia, the mean lengths of striped bass have fluctuated greatly through the 1980s, but have varied less so in the 1990s. Anglers from Connecticut, New Jersey, and New York usually catch larger fish than those from Delaware, Maryland, and Virginia (Figure 26 [E.B.Figure 12] NMFS MRFSS).

3. Summer flounder (*Paralichthys dentatus*)

Summer flounder are harvested by anglers in Barnegat Bay and other New Jersey waters from about May to October. Based upon NMFS MRFSS data, New Jersey ranked first in total recreational landings of summer flounder in 1981 and from 1984 through 1998, for states from Connecticut to Virginia. The lowest recorded landings for all of the states from Connecticut to Virginia occurred in 1989. The highest New Jersey catches were reported in 1993. There is great year-to-year variation in catches (Figure 27 [E.B. Figure 3] NMFS MRFSS). NMFS MRFSS annual mean lengths of summer flounder from Connecticut to Virginia are shown in Figure 28 [E.B. Figure 4] (NMFS MRFSS). All states appear to catch similar sized summer flounder, with mean lengths between ~300 and 450 mm (~11.8 and 17.7 in).

4. Winter flounder (*Pseudopleuronectes americanus*)

Winter flounder are usually caught in Barnegat Bay and other coastal bays in late winter and early spring. New Jersey ranked second to New York for states from Connecticut to Virginia in landings of winter flounder in 1981, 1983 through 1986, 1988, 1990-1992, 1995 and 1996. However, New Jersey ranked first in 1982, 1993, 1994, 1997, and 1998. Recreational landings have remained low in most states since about 1986 (Figure 29 [E.B. Figure 5] NMFS MRFSS). For most states, the mean length of winter flounder is between ~280 and 350 mm (11 in to 13.8 in) (Figure 30 [E.B.Figure 6] NMFS MRFSS).

5. Weakfish (*Cynoscion regalis*)

Recreational anglers catch weakfish in Barnegat Bay and other waters from spring through fall. There appears to be some annual variation in total catches for all states from Connecticut to Virginia. However, New Jersey anglers usually catch more weakfish than anglers in other states. New Jersey landings peaked in 1983, 1986, and 1996 (Figure 31 [E.B. Figure 7] NMFS MRFSS). The mean length of weakfish fluctuated from year to year and generally ranged from ~298 to 780 mm (~11.7 to 30.7 in) (Figure 32 [E.B.Figure 8] NMFS MRFSS).

6. Black sea bass (*Centropristis striata*) and Tautog (*Tautoga onitis*)

Both black sea bass (*Centropristis striata*) and tautog (*Tautoga onitis*) are caught near structures in certain parts of Barnegat Bay. When considering the total landings of tautog from Connecticut to Virginia, New Jersey consistently ranked first or second to New York in 1982 and from 1984 through 1997. The lowest total catches for New Jersey were recorded in 1981. The highest landings for the state occurred in 1986. For most years, the total landings for Connecticut, Delaware, Maryland, and Virginia are usually much lower than those of New Jersey and New York (Figure 33 [E.B.Figure 13] NMFS MRFSS). The mean length of tautog ranged from ~48 to 490 mm (1.8 to 19.3 in). New Jersey anglers appear to catch smaller fish than those of most of the other states from Connecticut to Virginia (Figure 34 [E.B.Figure 14] NMFS MRFSS).

The annual total landings for black sea bass appear to fluctuate for most of these states. The highest annual landings for New Jersey occurred in 1986. New Jersey ranked first in total landings in 1983, 1985, 1986, 1989, and from 1991 through 1997. For most years, the total catch was less than 500,000 fish (Figure 35 [E.B.Figure 15] NMFS MRFSS). The mean lengths generally ranged from ~240 to 350 mm (~9.4 to 13.8 in) (Figure 36 [E.B.Figure 16] NMFS MRFSS).

7. Inland Landings

No recreational catch data are available for any species caught by anglers fishing specifically in Barnegat Bay. However, NMFS MRFSS does list total landings by inland areas. Inland areas represent saltwater or brackish waters except for the ocean and include sounds, inlets, tidal sections of rivers, bays, estuaries and other salt or brackish regions. The annual total catch of bluefish in New Jersey's inland areas ranged from 402,628 fish in 1997 to 2,065,971 fish in 1986. In 1998, recreational anglers caught 521,401 bluefish. For black sea bass, the total annual inland area catches ranged from 72,597 fish in 1987 to 4,070,748 fish in 1986. The total catch of striped bass in inland areas remained low from 1981 to 1998, with catches under 445,000 fish. Summer flounder are caught in large numbers in these areas. For example, catches of this species ranged from a low of 2,026,118 fish in 1989 to a high of 6,626,258 fish in 1993. Tautog also are caught in inland areas, but in lower numbers than some of the other species. Numbers of tautog were never greater than 559,000 fish. Weakfish likewise are caught in these inland regions, with catches ranging from a low of 34,698 fish in 1982 to a high of 2,254,283 in 1996. Landings of winter flounder ranged from 403,192 fish in 1992 to 6,020,921 fish in 1985 (Figure 37 [E.B.Figure 17] NMFS MRFSS).

A creel census of summer flounder in Great Bay, New Jersey was conducted from 1967 through 1976. Seasonal catch per angler trip of summer flounder ranged from a low of 0.26 in 1970 to a high of 3.81 fish in 1975. The total summer harvest in Great Bay was estimated and ranged from 7,811 fish weighing 6,210 kg (13,800 lb) in 1970 to 169,095 fish weighing 51,120,000 kg (113,600,000 lb) in 1975. Anglers fishing from small private and rental boats accounted for the majority of fishing effort. There was a fleet of four to six charter boats that occasionally fished in the bay. As the summer flounder started to migrate

out of inland bays in August, fishing effort shifted more to inlet areas (Festa, 1979).

VII. ECONONMIC IMPACTS OF RECREATIONAL FISHING

The number of recreational fishing trips to New Jersey's inland areas ranged from 1,124,337 trips in 1984 to 3,320,853 in 1986. In 1998, 2,154,524 fishing trips were made to inland areas by New Jersey anglers (Figure 38 [E.B.Figure 18] NMFS MRFSS). In 1991, freshwater and marine recreational fishing in New Jersey had a total economic impact of $1.33 billion, which supported 16,754 jobs and generated $630.9 million in retail sales to fishermen, $402.2 million in salaries and wages, $50.3 million in state tax revenues, and $46.4 million in federal income tax revenues (Fedler and Nickum, no year). There were 841,372 New Jersey saltwater anglers age 16 and older who fished during the 1996 season; most (63.3%) were state residents, and the remainder (36.7%) nonresidents. These fishermen made 9,892,030 fishing trips. They spent 10,366,335 days fishing in saltwater. Economic impacts of saltwater fishing in 1996 were estimated at $1.484 billion in total output, $746.9 million in expenditures, $414.5 million in earnings, and 16,112 jobs related to saltwater fishing. Total output consists of impacts on retailers and on the suppliers of goods and services to retailers, wholesalers, and manufacturers, plus indirect and induced impacts from all of these activities (Maharaj and Carpenter, no year).

A comparison of the 1991 and 1996 National Survey of Fishing, Hunting and Wildlife Associated Recreation was reported by Maharah and Carpenter (no year) for combined saltwater and freshwater fishing (Table 2 [E.B. Table 1]). The number of anglers, days fished, output, expenditures, wages and earnings increased from 1991 to 1996. Output increased from $1,524,924,150 in 1991 to $2,029,864,199 in 1996. In New Jersey, the 1993 recreational striped bass fishery alone generated $43 million in economic output, $20.2 million in angler expenditures, $13.6 million in personal income, $1.1 million in state sales tax, $1.7 million in federal income tax, and $230,000 in state income tax. Six hundred full-time equivalent jobs were associated with this fishery (American Sport Fishing Association, 1995).

In 1997, the charter/party boat industry consisted of about 400 boats that made approximately 900,000 fishing trips (McCay et al., 1999, includes some NMFS MRFSS data). Many of these charter/party boats have home ports in Barnegat Bay, such as Point Pleasant, Point Pleasant Beach, Barnegat Light, Barnegat Inlet, Beach Haven, Forked River, Manasquan, Oyster Creek, Tuckerton, and Waretown. This industry provides a considerable economic gain for these communities. In 1997, the total mean annual fixed costs for charter/party boat operators were $87,353 and included such expenditures as haul-outs/overhauls, food for resale, booking fees, telephone fees, repairs, mooring/dockage fees. Average variable costs for oil, ice, bait and fuel for charter/party boat operators were $16,297 (McCay et al., 1999).

LITERATURE CITED

American Sportfishing Association. July 1995. An economic assessment of marine recreational fishing in New Jersey. 7 p.

Table 1.

Data gaps including the availability of stock assessments and the stock status of key fisheries species in Barnegat Bay.

Species	Stock Assessment	Stock Status	Population Characters	Movements of life stages	Reproduction	Habitat Use	Human Impacts

Finfish							
American eel	None	Unknown	Growth rate	Adults		Spawning	Fishing mortality
Alewife	None	Declining				Spawning Nursery	Contamin: Migration impedime
Bluefish	None currently	Over exploited	Growth rate Age and Size	Larvae	Age at maturity Fecundity	Spawning	Contamin:
Striped Bass	Yes	* Fully exploited				Overwintering	Effluent u: for overwinte
Summer Flounder	None currently	Rebuilding	Age and Size		Fecundity	All life stages	
Winter Flounder	None currently	Over exploited	Age and Size	Larvae-Adults	Age at maturity	Spawning Nursery	Habitat lo:
Weakfish	None currently	Fully exploited		Larvae-Adults			Fishing mortality
Shellfish							
Hard Clam							
Blue Crab	None currently	Unknown	Growth rate Age and Size	Larvae-Adults	Fecundity	Spawning	Fishing mortality
Horseshoe Crab							

*Target fishing mortality (0.31) exceeded in 1997

Table 2.

The state of sport fishing in New Jersey: A comparison of 1991 and 1996 National Survey of Fishing, Hunting and Wildlife Associated Recreation for both saltwater and freshwater fishing (Maharaj and Carpenter, No year)

Item	**1991**	**1996**
Anglers	962,800	1,058,672
Days	11,718,000	16,125,449
Expenditures	$725,569,500	$1,025,230,011

Output	$1,524,924,150	$2,029,864,199
Wages	$462,480,550	$566,132,532
Jobs	16,750	21,910

I. STREAM AND GROUND WATER SOURCES

A. Point and Nonpoint Sources

Changes in water quality resulting from human activities at the land surface in the Barnegat Bay watershed can be broadly characterized as resulting from either point sources or nonpoint sources of contamination. Point sources are commonly localized and originate from one specific source, such as wastewater discharges, leaky underground storage tanks, landfills, pipelines, and surface impoundments. Nonpoint sources of contamination do not result from activities in only one specific point. Rather, they are the cumulative effect of similar activities taking place at a number of locations within a given watershed, which together result in degradation of water quality within the watershed. Nonpoint sources of contamination can occur at widespread locations extending up to hundreds of square miles and over broad geographic areas. Nonpoint sources of contamination include activities occurring on agricultural, residential, and commercial properties to which fertilizers and pesticides have been applied, atmospheric inputs of airborne pollutants, animal feedlots, and right-of-ways (e.g., highway and railway borders) where deicing salts and pesticides are applied. On-site septic systems in residential areas, when in large numbers and closely spaced, also can be considered nonpoint sources of contamination (Vowinkel and Siwiec, 1991).

The aggregate effect on water resources of different human activities occurring in common land-use categories can be evaluated by examining the relations between observations of water quality of streams and ground water, associated constituent loadings, and the land-use composition of corresponding source areas. This approach has been used in many water resource investigations in southern New Jersey and surrounding areas.

The distribution of land use in 1994/95 within the Barnegat Bay watershed was determined to be the following: forested, 45.9%; wetlands (both tidal and freshwater), 25.2%; urban/residential, 19.5%; agricultural land/grasslands, 6.6%; barren lands, 1.9%; and water bodies (lakes, impoundments, reservoirs), 0.9%. These land-use percentages were determined in part by the use of a Geographic Information System and categories defined by Fegeas et al. (1983).

B. Residential and Commercial Nonpoint Source Pollution

Potential pollutants associated with residential and commercial uses within the 447.91 mi2 (1160 km2) Barnegat Bay watershed include nutrients, sediment, organic wastes, petroleum products, pathogens, metals, and halogenated hydrocarbons. The potential pollutant inputs are associated with the type and density of land use, depth to the ground water table, and the degree of impervious surfaces within the watershed. Tables 1 and 2, taken from Rogers et al. (1990), describe the designation of land use and extent of the impervious surfaces within the Barnegat Bay watershed area. (Refer to Appendix A for a breakdown of the residential and commercial land use by municipality within Ocean County as well as the number of new lots for the period from 1987 to 1997.)

1. Impact of Impervious Surfaces on Watersheds

Impervious surfaces directly affect watersheds. The process of urbanization has a profound impact on the hydrology, morphology, water quality, and ecology of surface waters (Schueler, 1998). Impervious cover, which is greatest in urban areas, is a useful indicator with which to measure the impacts of land development on aquatic systems. It directly influences streams through the increase in surface runoff during storm events. Some of the influences of impervious cover on the annual water balance are described in Table 3.

A stream classification system, developed by the Center for Watershed Protection in Elliott City, Maryland, evaluates a watershed according to the degree of impervious surfaces. The classification system is comprised of three components. These are:

(1)Sensitive watersheds with less than or equal to 10% imperviousness. They are represented by a stable channel, excellent biodiversity, and excellent water quality.

(2)Impacted watersheds with impervious surfaces between 10-25%. They arerepresented by a channel becoming unstable, fair to good biodiversity, and fair to good water quality.

(3)Non-supporting watersheds with impervious surface areas greater than 25% imperviousness. They are represented by poor to no biodiversity and poor water quality.

Impervious surfaces significantly influence the quantity and quality of stormwater runoff from urban and suburban areas. Runoff from lands modified by human activities can harm surface water resources in two ways: (1) by changing the natural hydrologic patterns; and (2) by elevating pollutant concentrations and loadings. Stormwater runoff may contain or mobilize high levels of contaminants, such as sediment, suspended solids, nutrients, heavy metals, pathogens, toxins, oxygen-demanding substances, and floatables. (From USEPA web site - http://www.epa.gov/owmitnet/pipes/3.htm).

The U.S. Environmental Protection Agency is proposing amendments to Section 401 of the Clean Water Act for municipalities with populations exceeding 10,000 persons and population densities greater than 1,000 persons per square mile. In Ocean County, there are 25 municipalities that fall into this category. (Refer to Appendix B for a breakdown of the 33 municipalities in Ocean County by population, land area, and population density.) Municipalities within these categories will be required to obtain National Pollutant Discharge Elimination System (NPDES) permits.

The proposed regulations will require the implementation and development of a cost-effective operation and maintenance program with the ultimate goal of preventing and reducing pollutant runoff from municipal operations. The minimum operation and maintenance components for inclusion in the program are described as follows:

(1)Maintenance activities, maintenance schedules, and long-term

inspection procedures for structural and other stormwater controls

to reduce floatables and other pollutants discharged from the

storm sewers.

(2)Controls for reducing or eliminating the discharge of pollutants from

streets, roads, highways, municipal parking lots, maintenance and

storage yards, and waste transfer stations.

(3)Procedures for properly disposing of waste removed from streets, roads, highways, municipal parking lots, maintenance and storage yards, and waste transfer stations.

(4.)Ways to insure that new flood management projects assess the

impacts on water quality and examine existing projects for incorporating

additional water quality protection devices or practices.

2. Impervious Surfaces and Stormwater Runoff Management

Rain drops fall on the soil in a generally vertical direction, and flowing water moves horizontally over the landscape creating runoff. The roughness and slope of the landscape greatly influence the amount and speed of the runoff. When the rate of the runoff exceeds the absorptive capacity of the soil and land cover, runoff occurs.

Ocean County has seen the installation of more than 1000 stormwater basins to help reduce the peak discharge from changing land uses. These basins should be viewed for multiple purposes, such as, water quality and ground water recharge. There is a need to encourage stormwater basin design, which minimizes natural processes.

Ocean County soils are very sandy. These well-drained soils, in a natural wooded condition, normally do not exhibit any runoff. Much of the rainfall is absorbed in the leaf duff and soaks into the sandy soil. It then reaches shallow ground water, which supplies base flow for the streams in the county.

During colonial times, the streams feeding Barnegat Bay were shallow and narrow. Vegetation impinged on the stream banks, and sponge-like soils soaked up nearly all of the rainfall. Only during a hurricane or other intense storm event did runoff occur.

Sandy soils and natural riparian buffers act to slow runoff and maintain flood plains. These natural buffer zones lessen the amount of pollution entering streams in the watershed. Tree and shrub roots hold the stream banks in place, thus minimizing erosion and sedimentation. The vegetation also slows the flow of the runoff, enabling sediment to settle and runoff to percolate and filter through the soil. This process recharges the ground water.

Currently, vegetation has been removed along many of the stream banks, and subwatersheds have been altered by changes in the landscape. The addition of impervious surfaces, together with compacted soils, has greatly increased the amount of runoff. As pitch pine and other native vegetation are stripped away from the land, pervious areas, which naturally act like sponges to recharge ground water and filter pollutants, are converted to impervious surfaces. Pollutants come into contact with the impervious surfaces and are quickly washed off of the land into the streams. With the construction of roads, roofs, and parking lots, rainwater that once recharged the aquifers of Ocean County, instead becomes runoff. These changes in the land use increase the demand for water and, reduce with every home, the ability of the watershed to recharge its ground water. As a result, many private wells must be drilled deeper to compensate for the reduced ground water recharge.

3. Nutrients

a. General

Nutrients are necessary for vegetative growth. The primary nutrients that can impact the environment are nitrogen, phosphorus, silicon, and potassium. The nutrients in residential and commercial areas are usually applied in inorganic or organic fertilizers. When applied in excess of the needs of lawns or gardens, nutrients may run off into surface waters or leach into ground water.

In the case of deep on-lot sewage disposal systems, nutrients from human wastes may enter the shallow ground water table. Nitrates in excess of 10 mg/l can cause human infant methemolglobinemia (blue baby syndrome), which can be fatal. Adults are less susceptible to this disorder.

Nutrient availability in excess of plant growth needs can lead to eutrophication problems. Nutrient enrichment often results in excessive aquatic plant growth that interferes with recreational activities, and in extreme cases can seriously deplete dissolved oxygen concentrations. Hypoxia and anoxia greatly impact the quality and diversity of habitats for benthic organisms and finfish populations.

b. Nutrients from Fertilizers

Fertilizers usually contain nitrogen, phosphate, and potash. Nitrogen is the most important lawn nutrient, but it can contaminate groundwater with nitrate. Phosphate can contaminate streams, rivers, ponds, and lakes stimulating excessive growth of algae and rooted aquatic plants. Chloride is often combined with potassium in potash, which can also contaminate ground water.

Lawn fertilizers contribute 5-10 kg/ha/yr of nitrates from typical residential lots (Palone and Todd, 1997). In the Barnegat Bay watershed, there is the potential for 286,580 to 573,200 kg/ha/yr of nitrate washoff from lawns (OCPD, 1998). This washoff rate was determined by taking the 1997 residential population and dividing it by 3.5 persons per household and then multiplying by the unit figures for nitrates from lawn fertilizers.

Residents should compost their yard wastes to minimize the release of nutrients to waterbodies. In addition, residents should test their soil so that they will apply only the fertilizer needed. It has been reported that less than 20% of the residents in Ocean County test their soils (Granden, 1993)

To protect sandy soils such as those in Ocean County, a slow release nitrogen fertilizer should be applied to lawns and gardens. No more than one pound of nitrogen per 1000 ft^2 (~93 m^2) is recommended in any one application (Turner et al, 1995).

c. Nutrients from Septic Systems

The estimated septic effluent flow amounts to 1,328,830 gal/d (5,029,622 l/d) of septic effluent that

recharges the ground water table within Ocean County. This value is calculated by multiplying the total of 8437 septic systems within the Barnegat Bay watershed (Appendix C) by 3.5 persons per system, and 45 gal (170 l) per person per day (not including garbage grinders) (USEPA, 1980). Nitrate loadings from septic systems are estimated as follows: (1) 1/2 ac (0.2 ha) lot septic systems (= 25-35 kg/ha/yr); (2) ≥ 2 acre (0.81 ha) lot septic systems (= 14 kg/ha/yr) (Palone and Todd, 1997). Hence, with the 8437 septic systems, the range of nitrates for 1/2 ac (0.2 ha) lots can range from 216,930 to 295,300 kg/ha/yr.

d. Nutrients from Pet Wastes

In regard to pet waste, if each licensed dog and cat within Ocean County contributed an average of 0.33 lb (151.2 g) of waste daily, the quantity of pet wastes would be ~10,800 lb (~4860 kg) per day or ~4 x 106 lb (1.8 x 106 kg) of waste per year from the licensed pets only (Dane County, Wisconsin) (Appendix D). It would be difficult to extrapolate this for a full year, since it is difficult to determine how many of the pets are seasonal. However, the number of unlicensed pets during the summer months could be significantly larger due to the resort nature of certain Ocean County areas.

4. Sediment

Sediments from the watershed (sand, silt, clay and organic matter) are transported into the Barnegat Bay-Little Egg Harbor estuary and distributed from one point to another by waves and currents generated by winds and storms. Some of the sediment sources include stream banks, construction sites, and agricultural lands. Bottom sediments in the estuary provide habitat for benthic flora and fauna. Fine-grained sediments (clay and silt) tend to retain contaminants that enter the estuary (e.g., trace metals, hydrocarbons, and other toxic chemicals). (Refer to Appendix E for water quality and suspended solids information from Ocean County demonstration projects.)

5. Organic Wastes

Human wastes are either treated in on-lot sewage disposal systems or community sewage treatment plants. In on-lot sewage disposal systems, the wastes are usually subjected to primary treatment and effluent disposal. This means that the solids settle out of the sewage in a septic tank, and the liquid effluent is filtered into the ground via a leach field. In some cases, an aerobic treatment tank is used, which removes the sediment and some nutrients. The effluent is then discharged to a leach field.

Community sewage disposal systems involve a series of collection pipes to a sewage treatment plant. At the plant, the sewage is subjected to primary treatment (sediment removal), secondary treatment (reduction of the biochemical oxygen demand, and/or tertiary treatment (reduction of nutrients and other toxics). The treated effluent is then discharged to a stream, the estuary, or is applied to the land.

6. Petroleum Products

Stormwater runoff can also transport petroleum products into streams and the estuary via storm drains. These products are residues from vehicles and other motorized equipment. Petroleum hydrocarbons derived from boats, marinas, and land contributions can be assimilated by phytoplankton without necessarily inhibiting their growth. Once contaminated phytoplankton are ingested by herbivorous zooplankton and shellfish, food-chain accumulation may occur and, where there is chronic exposure, the ability of affected organisms to reproduce and feed may be inhibited. (Refer to Appendix E for hydrocarbons discharged from demonstration sites in Ocean County.)

7. Pathogens

The malfunctioning of on-lot sewage disposal systems often releases wastes. When this occurs, pathogens may enter the surface waters (streams, ponds, lakes, and the estuary) and the shallow groundwater table of an area. Appendix C contains a list of the septic systems in Ocean County.

The concentrations of coliform bacteria are used to set standards that regulate surface water quality, swimming, and shellfish harvesting locations within the Barnegat Bay-Little Egg Harbor estuary. Total and fecal coliform bacteria originate from a multitude of sources, including failing on-lot sewage disposal systems, domestic animals (pets), wildlife, and waste disposal from boats and marinas. Appendix D provides a list of the number of licensed dogs and cats in Ocean County.

Beaches have been historically sampled in the Barnegat Bay-Little Egg Harbor estuary for total and fecal coliform bacteria to assess water quality conditions. Total coliform data have been collected, particularly in shellfish harvesting areas, from 1976 though the present. A major concern is for shellfish harvesting areas in the upper portions of the estuary where tidal influences and dilution from the ocean are minimal.

Shellfish growing area classifications have been established based on total and fecal coliform bacteria levels and nonpoint pollution sources. These classifications are:

1. Approved Areas: Waters that have been approved for shellfish harvesting.

2. Prohibited Areas: Areas where shellfish harvesting is not permitted under any circumstance.

3. Special Restricted Areas: Areas from which shellfish must be purified before human consumption. Applications for removal will be considered for transplant, relaying, and controlled purification.

4. Seasonal Area: Waters that are condemned and opened for the harvest of shellfish each year on either January 1 or November 1. All Seasonal Areas close April 30 of each year.

5. Condemned Areas: Waters that are prohibited, special restricted, and seasonal areas.

8. Metals

During the sewage treatment process, sludges are produced from sedimentation. This sludge usually contains heavy metals. These contaminants may pose a problem if the wastes are considered for land-use disposal on edible crops. Appendix E provides information on fecal coliforms at Ocean County demonstration sites.

9. Toxics:

There are household hazardous products that can present a problem if stored in sufficient quantities, and a spill occurs near a storm drain, stream, well, or pond. There are numerous household materials, namely, trash, clothing, and fabric care products, hobby and recreation products, building/wood cleaner and repair products, pesticides, and vehicle maintenance chemicals that may accumulate in streams, lakes, or ponds via storm drains or direct discharge. Lead contamination usually derives from lead-based paint, water from lead pipes, or lead solder. The soil may be contaminated from prior manufacturing activities.

Household and commercial waste control reqirees wise management of trash and other solid waste. Many municipalities have adopted curb-side trash separation programs for glass, papers, cans, cardboard, and other reusables or recyclables.

Over the years, numerous septic tank cleaners have been used. Such chemicals include TCE (Trichloroethylene) and other chlorinated hydrocarbons. Some of these chemicals have been found in surficial ground water.

10. Pesticides

Pesticides include herbicides, insecticides, fungicides, rodenticides, nematocides, algicides, and bactericides used to control pests to human habitation. The most common are the herbicides which prevent weed growth in lawns. Other pesticides are used to control termites, ants, roaches, rodents, and bacteria in swimming pools. Wise use is recommended. The State of New Jersey provides certifications to applicators to ensure that the proper dose is applied to preclude overexposure to humans. Many counties have instituted hazardous waste collection days for receipt of containers of chemicals (e.g., paint, pesticides, cleaners, and other products) at designated locations.

11. Watershed Soils

Many of the soils in Ocean County have been disturbed through cut-and-fill operations (Smith, 1999). Site specific analyses are needed for interpreting residential and commercial applications, such as on-lot sewage disposal systems, basement drainage, surface runoff considerations, and fertilizer and pesticide applications. A runoff curve number analysis is currently being evaluated for the soils in the county both prior to land development and after land development.

With the support of the United States Department of Agriculture and the Natural Resources Conservation Service, the Ocean County Soil Conservation District began conducting soil bulk density tests. Soil bulk density is the ratio of dried soil (mass) to its bulk volume, including the volume of particles and the pore space between the particles. Preliminary findings have shown that typically undisturbed sandy soil has a bulk density of 1.08 g/cc. Following grading activities, bulk densities have ranged from 1.59 to 1.97 g/cc. Regardless of texture, any soil layer with a bulk density greater than 1.65 g/cc is considered root restrictive. Hence, there is an increased amount of surface runoff and surface ponding after storm events. (Friedman, 1999; Smith, 1999)

12. Private Wells

Ocean County has the greatest number of private wells of any county in New Jersey. Most of these wells are in the Kirkwood-Cohansey aquifer. This aquifer is highly vulnerable to activities on the landscape.

When wells are used in conjunction with residential or commercial irrigation systems, backflow prevention devices are effective in preventing cross-connections with the potable water system. This is especially a concern if fertilizers and/or herbicides are incorporated into an irrigation system. Abandoned private wells are a source of pollution if not properly sealed.

13. Well Head Protection

Potential sources of groundwater contamination, which may be present near a home site, include septic tanks, animal waste, pesticides, fertilizers, fuel storage tanks, household chemicals, and used motor oil.

There are six basic principles of well head protection. These are:

1.Proper well siting

2.Proper well construction

3.Keeping contaminants away from the well

4.Use of backflow prevention

5.Sealing abandoned wells

Testing well water

Agricultural Nonpoint Source Pollution: Ground Water and Surface Water

1. Historic Extent of Agriculture in the Barnegat Bay Watershed

To characterize agriculture in the Barnegat Bay watershed, it is necessary to look at past activities and trends, as well as the present and future condition, as they may impact water quality. The information in this section is based on agricultural data compiled for Ocean County and, since nearly all of Ocean County is within the watershed, it provides the most comprehensive way of characterizing the watershed. Prior to 1970, agriculture within the Barnegat Bay watershed was characterized primarily by chicken farms and small cranberry bogs. Table 4 shows the trends in the number of farms and horses in Ocean County since 1930.

Historic impacts of agriculture on current water quality may be significant due to the long residence time of groundwater before it appears as surface water contributions to surface water tributaries and the estuary. Figure 1 shows the extent of agricultural activity, particularly poultry farming, in Ocean County in 1954. Figure 2 illustrates the groundwater residence times for areas of the watershed. These two maps together provide useful information on the nature and degree of historic agricultural impacts on present surface water quality. Potential pollutants associated with agriculture in the Barnegat Bay watershed include nutrients, sediment, pathogens and pesticides.

2. Types of Farming

a. Horse Farming

The 1987 State Equine Survey showed that Ocean County had 1,500 horses, with 1,300 ac (520 ha) dedicated to horse farming (New Jersey, 1987). According to the 1996 State Equine Survey, Ocean County had 1,300 horses on 3,500 ac (1,400 ha). The number of horses appears to have declined considerably when this information is compared to the 1997 agriculture census (Table 5). However, it should be noted that the 1996 State Equine Survey indicates that the total number of horses in the county, including those residing on farmettes, is approximatley twice the number shown for 1997.

b. Poultry Farming

The poultry industry has been a significant part of agriculture in Ocean County for many years. Chicken farms were numerous and produced substantial quantities of both eggs and poultry for the New York and Philadelphia markets during the 20th Century. These operations also produced large quantities of manure high in nitrogen and phosphorus, which was repeatedly spread on sandy, porous soils within the watershed.

Data in Table 6 indicate the trends in the number of farms and number of chickens in Ocean County since 1930. Figure 3 shows the number of chickens that were four months old and older by municipality in Ocean County during 1954. Dover Township had the greatest number of poultry (1,173,908) followed by Jackson (958,411) and Brick/Lakewood (372,487). As is evident in Table 6, the peak year for poultry production in the county was 1969.

Ground water that originates near a stream follows short flow paths that require short travel times prior to seeping into the stream, whereas ground water that originates from distant sources follows relatively long flow paths that require longer travel times prior to entering the stream flow (Modica, 1999). Concentrations of total nitrogen and nitrate in Wrangel Brook, a tributary of the Toms River, were found to be greater during base flow than during storm flow. These nutrients are thought to derive largely from nitrate used in fertilizers for high-maintenance lawns and from agricultural runoff of poultry farms located in the basin almost fifty years ago (1950s) (Hunchak-Kariouk, 1999). As a result, a significant amount of nitrate impacts to the estuary probably reflect poultry farming conditions decades ago. In relative terms, the decline in the number of poultry farms in Ocean County in recent years suggests that they probably have little ongoing impact on water quality, especially when compared to potential contributions from other sources such as lawn fertilization, septic systems, and wildlife.

c. Livestock Farming

Other livestock enterprises also exist in Ocean County, but their impacts on water resources are likely to be less significant than those resulting from horse and poultry farming. Table 7 shows the number of farms and animals for cattle and calves, hogs and pigs, and sheep and lambs in Ocean County. Table 8 indicates the number of farms and number of turkeys and other poultry in the county.

d. Cranberry Farming

The cranberry industry has played an important role in Ocean County agriculture over the years. Acreage devoted to bogs was minimal and the production systems were not high input. Consequently, it is unlikely that water quality was adversely impacted by this type of farming. Table 9 reveals the number of farms and acres in cranberry production in Ocean County since 1930.

C.3. Nutrients

Nutrients are necessary for crop production. Nitrogen and phosphorus are the primary nutrients that can impact the environment. They may originate from inorganic fertilizers, from land-applied animal wastes, or from other organic residuals such as sludge. When applied in excess of crop needs, nutrients run off into surface waters resulting in excessive aquatic plant growth and toxicity to certain fish species. Accelerated plant growth in aquatic systems often interferes with recreational activities and can impact some habitats. Severely depleted dissolved oxygen levels (i.e, hypoxia or anoxia) associated with excessive plant growth reduce the quality of habitats for fish, invertebrates, and other organisms.

Nitrogen losses from manure may be high. For example, volatilization can account for up to a 70% loss of nitrogen from manure as ammonia gas. Nitrogen lost in this way is not available for plant use, runoff, or entry into groundwater. As a result, farmers interested in reducing fertilizer costs and lessening the potential for ground water and surface water impacts inject or incorporate manure into the soil. This keeps volatization losses to less than 5%. If manure is applied in the fall or winter when there is no crop to actively assimilate the nitrogen, particularly on sandy soils, as much as 50% of the nitrogen can be lost through denitrification and leaching into ground water. Denitrification losses can be as high as 20% of manure nitrogen.

a. Nitrate-nitrogen

Nitrate-nitrogen is highly mobile and thus can be leached through the crop root zone to ground water, especially on sandy soils. Nitrate concentrations > 10 mg/l can cause human infant methemoglobinemia, which can be fatal. It can also result in cattle abortion and other livestock disorders. Nitrogen is not routinely evaluated in typical soil tests; however, surveys in this watershed and others in New Jersey show that no more than 10 to 25% of the public test their soil before applying lawn and garden fertilizer (Grandin, 1993; OCSCD, 1995-1997). These same surveys reveal that few lawn service companies test soils prior to fertilizing lawns.

Nitrate is a major constituent in ground water sampled in some residential areas (Watt et al., 1994). Ground water sampled in a number of wells located near streams has exhibited elevated nitrate concentrations. Three samples, collected on Maple Root Branch, Union Branch, and Old Hurricane Brook, exceeded the 10 mg/L MCL (Maximum Contaminant Loading). Median concentrations of total nitrogen were generally highest at sites on the Toms River, downstream on Davenport Branch, Wrangel Brook, and Long Swamp Creek. Figure 4 shows the extent of cropland harvested acres recorded in 1954. Table 10 lists the agricultural land use over time. In 1997, the Census of Agriculture revealed that fertilizer use was reported for 106 farms on 2925 ac (1170) of land in Ocean County (USDA, 1993-1997). Moser (1997) found that ground water contributed about three times as much nitrogen to the northern portion of the Barnegat Bay-Little Egg Harbor estuary as to the southern portion, although the overall contribution is relatively small compared to atmospheric and river nitrogen inputs.

b. Phosphorus

Phosphorus occurs in particulate and dissolved forms in runoff from the watershed. Particulate phosphorus is sorbed to mineral and organic sediment as it moves with the runoff. In general, particulate phosphorus constitutes most (75-90%) of the phosphorus transported in runoff from cultivated land. Dissolved phosphorus comprises a larger portion of the total phosphorus in runoff from non-cultivated lands, such as pastures, fields with reduced tillage, and lawns. Although dissolved phosphorus is 100% bioavailable for plant growth, particulate phosphorus is only 10 to 90% bioavailable because of its association with mineral and organic compounds (USDA, 1994).

Sharpley (1997) noted that all soils do not contribute equally to phosphorus export from watersheds or have the same potential to transport phosphorus to runoff. In their studies, Coale and Olear (1996) observed that soil test phosphorus levels did not accurately predict total dissolved phosphorus. However, they noted that, in all cases studied, soil test phosphorus levels were significantly related to an increase in total dissolved phosphorus. Soil testing is currently the best management tool available to ensure that soils do not become overloaded with phosphorus, which increases the likelihood of their contribution to pollution in surface waters downstream (Norfleet et al., 1996).

Soil test results for the Barnegat Bay region are good indicators of phosphorus availability for movement into surface and ground water of the watershed. A review of soil test results in the Great Swamp watershed in Morris and Somerset Counties found that a large proportion of soil tests had high or very high phosphorus levels (Westfall, 1993). Figure 5 shows the summary of statewide soil test results for phosphorus in soils. A review of the 1997 soil test results from the Rutgers Soil Test Laboratory indicates that 83.9% of soil samples received (801 samples) from around the state had high or very high phosphorus levels.

There are several options available to more effectively manage phosphorus. These include base fertilizer application and placement as well as agronomic considerations. Where soil phosphorus tests are high, applications may be eliminated. Among the agricultural practices which can minimize runoff of phosphorus are subsurface application, conservation tillage, buffer and filter strips, crop rotations with legumes, terracing, contouring, and the use of cover crops (USDA, 1997a). Because agriculture is not a significant land use within the watershed, total phosphorus levels are more likely based on particulate phosphorus derived from barren areas, road ditches, and construction sites, as well as dissolved phosphorus originating from poorly managed lawns.

4. Sediment

Sediments can significantly affect environmental conditions in aquatic systems. For example, sediments in suspension reduce the amount of sunlight available to benthic plants and may clog the gills of benthic animals. Nutrients and chemical contaminants sorbed to sediments often adversely impact water quality. In addition, turbidity commonly creates conditions that are undesirable for swimming, fishing, and other recreational pursuits.

The 1979 State Erosion, Sediment and Animal Waste Study (SESAW) found that on 7,300 ac (2,920 ha) of cropland in the Manasquan-Metedeconk River watershed the average annual sheet and rill erosion rate amounted to 4.8 tons per acre (USDA, 1986). There was an average annual sheet and rill erosion

rate of 5.2 tons per acre on 6,797 ac (2,719 ha) of cultivated cropland. No other information was gathered for the remainder of the Barnegat Bay watershed. The National Resource Inventory, as currently configured, does not provide soil erosion information that is statistically significant at the watershed level. In New Jersey, there are exploratory efforts now underway to determine the level of interest in increasing the sample size of the National Resource Inventory to make it more useful for measurements of the "state of the land" at the watershed level.

5. Pathogens

Pathogens in the form of bacteria and viruses can seriously impact the health of livestock, wildlife, aquatic organisms, and humans. Organic wastes primarily derived from livestock (e.g., dairy cattle, chickens, hogs and horses) are important sources of pathogens (as well as nutrients) to receiving waters in some regions. Wastes from sludges and food processing residuals are also potentially significant sources.

6. Pesticides

Pesticides primarily include herbicides, insecticides, and fungicides. Pesticides, while often providing a substantial benefit to crop production, may impact the environment by adversely affecting non-target organisms. Negative effects are acute or chronic toxicity and accumulation in organism tissues. One study (Wauchope, 1978) has indicated that generally less than 0.5% of the total pesticides applied in the field reach receiving waters. Most pesticides leave the field in soluble form in runoff and not attached to sediment.

Arsenical pesticides were historically applied to cropland, turf, and golf courses between 1900 and 1980. Approximately 100,000 lb (450,000 kg) of arsenic were applied cumulatively in Ocean County (Murphy and Aucott, 1998). Arsenic is not considered to be highly mobile in soils, but its downward migration has been shown to be greater in a sandy soil, such as those prevalent in the Barnegat Bay-Little Egg Harbor watershed, than in a clay loam (Elving et al., 1994).

The 1997 Census of Agriculture shows general agricultural chemical use for control of insects, disease, and weeds (Table 11). Pesticide use in the Barnegat Bay watershed (Managment Area 13) is relatively low when compared to the other watershed management areas in the state (Brown, 1999). Figure 6 illustrates pesticide use by watershed management area.

7. Current Extent and Impact of Agriculture in the Barnegat Bay Watershed

Recent land-use data show that agriculture comprises ~3% of the Barnegat Bay watershed area (USDA, 1997). Farmland assessment data for 1993 (Adams, 1993) and 1996 (Adams, 1997) reveal that there was 5,602 ac (2,241 ha) and 5,488 ac (2,195 ha) of harvested cropland area, respectively, in Ocean County. These harvested areas were located in Barnegat, Berkeley, Brick, Dover, Eagleswood, Jackson, Lacey, Lakewood, Manchester, Ocean, Plumsted and Stafford Townships. Approximately one-half of the acreage is devoted to crop production (grain, vegetables, nursery) and the remainder to horse farms. More than 75% of the agricultural use occurs within the Toms River and Metedeconk River subwatersheds. Table 12 lists the land-use trends in Ocean County over time.

One indicator of the extent of future agricultural land use in Ocean County is farmland preservation. Approximately 1,750 ac (700 ha) of land have been preserved in Plumstead, which is located in the Delaware River Basin. No acres have been permanently preserved in the Barnegat Bay watershed (McKeon, 1999).

Production agricultural fields within the watershed are generally flat and well drained. There is a minimal hazard of runoff and soil erosion under well-managed conditions. The row crops produce only small amounts of sediment, nutrients, and pesticides, with delivery to surface waters limited to headwater drainages. Because of the soils, topography, and limited agricultural acreage within the watershed, significant impacts to the estuary from production agriculture are unlikely.

Livestock acreage, predominantly consisting of small equestrian enterprises, has a slightly greater potential for impact. "Hobby" and commercial horse boarding and riding operations generally share two common characteristics: (1) exercise lots and paddocks that are barren (no vegetation) and possess highly compacted soils; and (2) improper stockpiling of manure. The soils, being bare and relatively impervious, are generators of sediment and excess runoff. The runoff picks up animal wastes in the lot and also may flow through manure stockpiles at the periphery of the property, releasing phosphorus, nitrogen, organic matter, and pathogens to surface waters.

Resource management systems should be developed for all significant horse operations in the Barnegat Bay watershed, and a manure management cooperative should be developed with surrounding row crop farmers and mushroom growers in order to utilize the waste as a resource. These resource management systems would entail, to the greatest extent practical, the exclusion of clean water from roofs and upper lying land from animal use areas. The nature and extent of current riparian buffers adjacent to agricultural and other land uses within the watershed should be inventoried. Riparian buffers should be planted or maintained where agricultural cropland and animal-use areas interface with streams and water bodies.

II. WASTEWATER TREATMENT FACILITIES

This section describes the wastewater collection and treatment facilities within the Barnegat Bay watershed, including a historical look at the situation prior to the implementation of the Ocean County Sewerage (Utilities) Authority regional wastewater treatment system. Since about 1980, all discharges of treated wastewater to the Barnegat Bay watershed have ceased. There are no point source discharges of wastewater into the watershed. For the purposes of this section, stormwater outlets are considered nonpoint sources.

In 1970, the Ocean County Utilities Authority (OCUA) was created to regionalize the treatment of wastewaters generated by residential, commercial, and industrial sources within the service area. Prior to the creation of the regional authority, there were 46 small to medium sized treatment plants operated by municipalities, developers, private sewer companies, and one industry within the OCUA service area. The current OCUA service area also includes certain areas outside the boundaries of the Barnegat Bay watershed, primarily those within the Manasquan River watershed. Prior to the implementation of the regional wastewater system, extensive areas of the watershed were single-family homes utilizing septic systems, many of which were adjacent to Barnegat Bay. Figure 7 shows the locations of the wastewater treatment plants in 1972. Except for wastewater treatment plants on the barrier beaches which discharged into the Atlantic Ocean, all discharges prior to 1972 were to the Barnegat Bay watershed either directly or via streams and rivers. The treatment plants discharging to the Barnegat Bay watershed were generally secondary or higher level treatment with the exception of the U.S. Navy plant at Lakehurst (0.275 MGD; 1.040 MLD) and the Forked River State Marina (0.006 MGD; 0.085 MLD) which provided only primary sewage treatment.

Table 13 indicates the average 1971 summer and winter flows, as well as the level of treatment, and the receiving waters for the treatment plants in the watershed. Based on this data, during the summer of 1971, an average of 6.866 million gallons (25.988 million liters) of effluent per day was discharged to the Barnegat Bay watershed. An additional 13.608 million gallons (52.731 million liters) of effluent per day were discharged to the Atlantic Ocean during the 1971 summer season, which included 5.0 million gallons (18.9 million liters) per day of effluent from the outfall of the Ciba-Geigy chemical plant in Toms River.

Figure 7 indicates the location of the three existing OCUA Regional Wastewater Treatment Facilities and their outfall lines. These outfall lines include 1 mi (1.6 km) of solid pipe that connect to diffuser sections averaging 1400 ft (426.7 m) in length that mix the effluent with the ambient ocean water.

In 1985, the OCUA service area was expanded to include the Manasquan River Regional Sewerage Authority system which encompasses areas of southern Monmouth County that are not part of the Barnegat Bay watershed. During 1998, OCUA treated an average of approximately 52 million gallons (196.8 million liters) per day. However, during rainfall events this volume was significantly higher because some municipal collection systems allow infiltration and inflow of rainwater. The average daily flow increases to approximately 60 million gallons (227.1 million liters) per day during the summer months.

Unlike most estuaries, the Barnegat Bay-Little Egg Harbor stuary does not have any direct input of pollutants from wastewater treatment plants. Nutrient loading and fecal coliform contamination is associated with nonpoint sources of pollution. One concern that has been raised recently is the consumptive use of freshwater by wastewater treatment plants located in the watershed. Because the treatment plant effluents discharge directly into the ocean, significant volumes of freshwater are being exported out of the watershed without any beneficial re-use of the water. The possible impacts to the watershed of this substantial freshwater export is not fully understood. However, the potential for reclamation of wastewater treatment plant effluent to make water available in the watershed for irrigation, cooling water, or groundwater recharge should be investigated.

III. SEPTIC SYSTEMS, UNDERGROUND STORAGE TANKS, AND LANDFILLS

Septic systems, underground storage tanks, and landfills are all potential sources of ground water pollution in the watershed. Cohansey sands, which comprise most of the Barnegat Bay watershed, do little to absorb or breakdown contaminants, which may be intentionally deposited in an individual subsurface sewage disposal systems (i.e., septic system). The relatively short distance between the

bottom of the septic system and the groundwater has led to episodes of ground water contamination.

Homeowners, ignorant of the consequences, have irresponsibly flushed paint thinners, turpentine, household degreasers, cleaners, and detergents into septic systems. Because of the inability of Cohansey sands to filter these chemicals, the contaminants percolate through the soils until they reach the water table where they can ultimately empty into the estuary.

Underground storage tanks, whether housing gasoline or home heating oil, have often leaked their contents into the Cohansey sands. While tanks with a capacity of 2,000 gallons (7,570 liters) are required to be periodically tested and to have leak detection measures, there are no such requirements for the homeowner. These tanks also have been the focus of several investigations of groundwater contamination.

Underground storage tanks all have the potential leak contaminants into the ground water over time. Within Ocean County, a database of underground storage tanks has been developed by the New Jersey Department of Environmental Protection. A number of entities have been identified that contain underground storage tanks (Table 14). Each of these entities may have several tanks. However it is difficult to keep this database up to date, because the tanks are replaced or removed periodically. This list merely indicates that there are a significant number of underground storage tanks within Ocean County, New Jersey. Specific information on the various tanks, such as the material construction, they types of materials stored, and the service life will require an inquiry with the entity involved and/or the New Jersey Department of Environmental Protection.

Sanitary landfills that were constructed in the past were little more than dump sites. They were constructed without liners or caps so that rainwater percolated through the garbage, concentrated sewage and chemical wastes and, ultimately drained down into underlying soils and ground water. Landfills in Ocean County remain potential sources of ground water contamination.

IV. FACTORS AFFECTING GROUND WATER TRANSPORT AND FATE

The fate of contaminants in ground water and whether or not contaminants reach the estuary depends on many factors, notably aquifer characteristics and the chemical characteristics of the contaminant. Aquifer characteristics include whether the aquifer is confined or unconfined, the composition of aquifer material, and the composition of the soils. The amount and quality of water recharging the aquifer is also a factor. Ground water is most vulnerable to contamination in areas that have well-drained (loamy, sandy) soils that are underlain by unconsolidated sand and gravel aquifers where no protective confining layer exists. Fine-grained materials, such as clays and silts, however, act as confining layers that restrict the downward movement of water and contaminants. Clays and silts also enhance chemical adsorption of some contaminants, thereby decreasing the availability of contaminants which could moved through the soils to ground water.

Chemical characteristics are specific to each compound or element, and chemical properties may vary due to chemical composition and form. Water solubility, soil and aquifer sorption, and in the case of pesticides and VOCs, persistence, diffusion, and dispersion, are some of the chemical characteristics that may determine how long and how far a contaminant will travel in the ground water system. For example, a water-soluble organic compound that does not degrade either by chemical, physical, or microbial mechanisms and does not easily sorb to soil or aquifer material, can be very mobile and may be carried a significant distance in a shallow ground water system. Inorganic and organic compounds may be exposed to varying chemical conditions that may change along flowpaths in the aquifer; changes can include the transition from aerobic to anaerobic conditions, changes in pH, and temperature, which

can alter the form of the compound and thus change its chemical properties.

V. SURFACE WATER LOADS

For the time period water years 1987-97, surface-water quality data for nutrients (total phosphorus, nitrogen, nitrate plus nitrite, ammonia plus organic nitrogen, and ammonia) and sulfate were available for 24 stations located on nine of the 12 rivers and streams which flow directly into the Barnegat Bay-Little Egg Harbor (BBLEH) estuary or the Toms River embayment. Surface water quality data were available from the Pinelands Commission, USGS, and the Leeds Point laboratory of the NJDEP for stations on the Toms River, Wrangel Brook, Jakes Branch, Long Swamp Creek, Cedar Creek, Forked River, and Oyster, Mill, and Westecunk Creeks. No water quality data were available for the Cedar Run, or Tuckerton Creek. Some data were available for the Metedeconk River; but for this analysis, these data were insufficient and not comparable to data from the other stations. The station on McDonalds Branch is not within the BBLEH watershed, but was included in the analysis because it represents undeveloped areas within the New Jersey Coastal Plain. Loads for 10 stations on 9 streams draining 266 mi^2 (691.6 km^2) of the 419 mi^2 (1089.4 km^2) BBLEH watershed were calculated for a 6-month, high-flow, nongrowing-season period and a 6-month, low-flow, growing-season period by using the median of the concentrations measured on dates of high and low flows, respectively, and stream flows for the 25% and 75% flow durations, respectively.

Two landscape categories were defined for the watershed based on the percent of urban land cover in 25 watersheds of the New Jersey Coastal Plain. Stations with less than ~10% of urban land cover were designated as Landscape Category I, and stations with more than ~10% of urban land cover were designated as Landscape Category II. Yields ($lb/mi^2/yr$) and loads (lb/yr) for each landscape category were determined as the median of the yields and loads for the stations in each category. In the watershed, 153 mi^2 (397.8 km^2) of the 419 mi^2 (1089.4 km^2) contributing area to the BBLEH were unmonitored. The percent land use was determined for the unmonitored areas downstream of each sampling station in each river basin. These data were used to classify each unmonitored area as either Landscape I or II. The appropriate yields for each landscape were multiplied by the area to determine the loads for each unmonitored area. Annual loads (lb/yr) of total phosphorus, nitrogen, nitrate plus nitrite, ammonia plus organic nitrogen, and ammonia and sulfate to the BBLEH from surface runoff were determined as the sum of the loads from all monitored and unmonitored areas of the watershed.

The load contributed by each river to the BBLEH is dependent on the size of and type of land cover in the basin. Larger basins will contribute larger loads because they have larger annual stream flows; however, the yield from each river basin will depend on the intensity and type of land cover in the basin. The largest basins of the BBLEH watershed are the Toms River (31%, 128 mi^2; 338 km^2), Metedeconk River (18%, 74.5 mi^2; 193.7 km^2), Cedar Creek (13%, 56 mi^2; 145.6 km^2), and Wrangel Brook (8%, 34.6 mi^2; 90 km^2) basins. Urban land cover accounts for 19% of the entire BBLEH watershed. The Long Swamp Creek basin has the greatest percentage of urban land cover (55%). Only about two-thirds of the contributing area (15% urban land cover) to the BBLEH was monitored. Most development in the BBLEH watershed is in the coastal, unmonitored areas (28% urban land cover). The magnitude of loads and yields from unmonitored areas compared to the loads and yields from the rest of the basin varies by constituent.

A. Total Phosphorus

Median total phosphorus (TP) concentrations at the 25 stations during all flows ranged from less than 0.01 to 0.06 mg/l (Table 15). At the 12 stations categorized as Landscape I, concentrations during high and low flows were not significantly different; the median TP concentrations during all flows were 0.01 mg/l or less. For the 13 stations categorized as Landscape II, the median TP concentrations during all flows ranged from 0.01 mg/l to 0.08 mg/l; 7 stations had median concentrations of 0.02 mg/l or greater. Seven of the Landscape II stations had higher TP concentrations during low flows than during high flows. Nonpoint storm runoff does not seem to be a significant source of TP to the bay because concentrations were low, especially in areas of slight urban land cover, and either the same or greater during low flow than high flow in areas of moderate to high urban land cover.

The median yield of TP was higher during high flow than low flow at all stations except those on Wrangel Brook (Table 16). The median TP basin yield during high flow was somewhat greater for Landscape II stations (35 lb/mi2/6 mo) than for Landscape I stations (24 lb/mi2/6 mo). The median TP yield during low flow was similar for Landscape I and II stations (12 and 16 lb/mi2/6 mo, respectively). The basin average annual TP yield for the bay watershed was 55 lb/mi2/yr (Table 16). The highest TP yields were from the Toms River (73 lb/mi2/yr), Wrangel Brook (67 lb/mi2/yr), and Oyster Creek (61 lb/mi2/yr) basins; the lowest yield was from the Jakes Branch basin (33 lb/mi2/yr) (Figure 8 and Table 16). The yield from the total monitored portion of the bay watershed (58 lb/mi2/yr) is higher than the yield from the unmonitored portion (49 lb/mi2/yr).

The annual load of TP to the bay from surface water discharge was estimated to be 23,000 lb/yr (10,350 kg/yr) (Figure 8 and Table 17). The highest TP basin loads were from the Toms River (9,000 lb/yr, 4,050 kg/yr, or 41% of the total annual load), Wrangel Brook (2,300 lb/yr, 1,350 kg/yr, or 10%), and Cedar Creek (2,300 lb/yr, 1,350 kg/yr, or 10%) basins. The load from the Metedeconk River was also high (3,800 lb/yr, 1,710 kg/yr, or 17%), but is entirely estimated. The lowest loads were from the Long Swamp Creek (291 lb/yr, 131 kg/yr) and Jakes Branch (313 lb/yr, 141 kg/yr) basins. The load from Cedar Run is also low (289 lb/yr, 131 kg/yr), but is entirely estimated. About one-third of the load derives from the unmonitored coastal areas of the basin. TP load appears to be related to the type of land cover - basins with greater urban land cover have higher concentrations, yields, and loads of TP to the bay.

B. Total Nitrogen

Median total nitrogen (TN) concentrations at the 25 stations during all flow conditions ranged from 0.18

to 0.99 mg/l (Table 15). At the 12 stations designated as Landscape I, median TN concentrations during all flows ranged from 0.18 to 0.53 mg/l; 8 stations had higher median concentrations during high flow than low flow, and 4 stations had higher median concentrations during low flow than high flow. The overall median concentrations during high, low, and all flows were not significantly different (0.30, 0.29, and 0.27 mg/l, respectively). For the 13 stations designated as Landscape II, median TN concentrations during all flows ranged from 0.35 mg/l to 0.99 mg/l; 3 stations had higher median concentrations during high flow than low flow, and 10 stations had higher median concentrations during low flow than high flow. The overall median concentrations during high, low, and all flows were not significantly different (0.71, 0.79, and 0.80 mg/l, respectively).

TN is a measure of several nitrogen species that can be dissolved or associated with particles. The concentration of TN and the relative importance of nonpoint source constant (ground water) and intermittent (storm runoff) contributions at a site depend on which nitrogen species is predominant. Dissolved species such as nitrite plus nitrate are most likely carried to a stream by ground water and can be in higher concentrations during low flow because the concentration may be diluted during storm flow. Ammonia and organic nitrogen can be associated with particles and can be in larger concentrations during high flow because they may be carried to a stream by surface runoff.

The median yield of TN was higher during high flow than low flow at all stations (Table 16). The median TN yield during high flow was higher for Landscape II stations than for Landscape I stations (1,300 lb/mi2/yr and 700 lb/mi2/yr, respectively), as was the median yield during low flow (740 lb/mi2/yr and 300 lb/mi2/yr, respectively). The basin average TN yield for the bay watershed was 2,000 lb/mi2/yr (Table 16). The highest TN yields were from the Wrangel Brook (2,700 lb/mi2/yr), Toms River (2,600 lb/mi2/yr), and Mill Creek (2,000 lb/mi2/yr) basins; the yield from the Metedeconk River and Tuckerton Creek basins were also high (2,300 lb/mi2/yr, each), but are entirely estimated. The lowest yield was from the Long Swamp Creek basin (600 lb/mi2/yr) (Table 17). The yields from the monitored and unmonitored portions of the bay watershed were very similar (2,000 lb/mi2/yr and 2,100 lb/mi2/yr), respectively).

The annual load of TN to the bay from surface water discharge was estimated to be 870,000 lb/yr (Figure 9 and Table 17). The highest TN loads were from the Toms River (340,000 lb/yr or 38%), Wrangel Brook (93,000 lb/yr or 11%), and Cedar Creek (71,000 lb/yr or 8%) basins. The load from the Metedeconk River basin was also high (170,000 lb/yr or 19%), but was entirely estimated. The lowest loads were from the Jakes Branch (10,000 lb/yr) and Long Swamp Creek (4,000 lb/yr) basins; the load from the Cedar Run basin was also low (8,000 lb/yr), but was entirely estimated.

C. Total Nitrite Plus Nitrate

Median total nitrite plus nitrate ($NO_2 + NO_3$) concentrations at the 25 stations during all flow conditions ranged from 0.01 to 0.65 mg/l (Table 16). At the 12 stations designated as Landscape I, median NO_2 + NO_3 concentrations during all flows ranged from 0.01 to 0.07 mg/l. Three stations had higher median concentrations during high flow than low flow, and 5 stations had higher median concentrations during low flow than high flow. The overall median concentrations during high, low, and all flows were not significantly different (0.02, 0.03, and 0.02 mg/l, respectively). At the 13 stations designated as

Landscape II, median NO2 + NO3 concentrations during all flows ranged from 0.05 mg/l to 0.64 mg/l. Four stations had higher median concentrations during high flow than low flow, and 7 stations had higher median concentrations during low flow than high flow. The overall median concentration during low flow (0.42 mg/l) was greater than during high flow (0.27 mg/l).

Nonpoint, constant-source ground water appears to be a significant source of NO2 + NO3 to the bay because concentrations are higher during low flow than high flow. NO2 + NO3 also seems to be related to land use; concentrations during low flow and high flow are larger in areas with moderate to high urban land cover.

The median NO2 + NO3 yield during high flow at Landscape II stations was higher than for Landscape I stations (447 lb/mi2/yr and 49 lb/mi2/yr, respectively), as was the median yield during low flow (333 lb/mi2/yr and 26 lb/mi2/yr, respectively) (Table 17). The basin average NO2 + NO3 yield for the bay watershed was 859 lb/mi2/yr (Table 16). The highest NO2 + NO3 yields were from the Wrangel Brook (2,000 lb/mi2/yr), Toms River (1,300 lb/mi2/yr), and Mill Creek (2,000 lb/mi2/yr) basins; the yield from the Metedeconk River and Tuckerton Creek basins were also high (840 lb/mi2/yr, each), but are entirely estimated (Table 16). The lowest yield was from the Westecunk Creek basin (86 lb/mi2/yr); the yield from the Cedar Run basin was also low (79 (lb/mi2/yr), but was entirely estimated. The yield from the monitored portion of the bay watershed (920 lb/mi2/yr) was somewhat higher than from the unmonitored portion (750 lb/mi2/yr).

The annual load of NO2 + NO3 to the bay from surface water discharge was estimated to be 360,000 lb/yr (Table 17). The highest NO2 + NO3 loads were from the Toms River (170,000 lb/yr and 45%) and Wrangel Brook (67,000 lb/yr or 19%) basins; the load from the Metedeconk River basin was also high (63,000 lb/yr), but was entirely estimated (Table 17). The lowest loads were from the Long Swamp Creek (2,000 lb/yr) and Jakes Branch (1,000 lb/yr) basins; the load from the Cedar Run basins was also small (700 lb/yr), but was entirely estimated.

D. Total Ammonia

Median total ammonia (NH4) concentrations at the 25 stations during all flow conditions ranged from 0.02 to 0.39 mg/l (Table 16). At the 12 stations designated as Landscape I, median NH4 concentrations during all flows ranged from 0.02 to 0.05 mg/l, and the overall median concentrations during high, low, and all flows were the same (0.05 mg/l). At the 13 stations designated as Landscape II, median NH4 concentrations during all flows ranged from 0.02 mg/l to 0.39 mg/l; the one station on Long Swamp Creek had a higher median concentration during high flow than low flow. The overall median concentrations during high, low, and all flows at these stations were the same (0.05 mg/l).

Nonpoint storm runoff does not seem to be a significant source of NH4 to the bay, except in areas of greater urban land cover. Median concentrations during all flows were low (0.08 mg/l or less), especially in areas of slight urban land. At the two most-downstream stations on the Toms River and Mill Creek, the median concentrations during low flow were the same or larger than during high flow. Only at the Long Swamp Creek station was the concentration during high flow greater than during low flow.

The median yield of NH4 was higher during high flow than low flow at all stations except Mill Creek (Table 16). The median NH4 yield during high flow was higher for Landscape I stations than for Landscape II stations (121 lb/mi2/yr and 93 lb/mi2/yr, respectively), as was the median yield during low flow (59 lb/mi2/yr and 44 lb/mi2/yr, respectively). The basin average NH4 yield for the bay watershed was 271 lb/mi2/yr (Table 16). The highest NH4 yields were from the Mill Creek (700 lb/mi2/yr), Toms River (420 lb/mi2/yr), and Oyster Creek (280 lb/mi2/yr) basins (Table 16). The lowest yield was from the Wrangel Brook basin (81 lb/mi2/yr). The yield from the monitored portion of the bay watershed (340 lb/mi2/yr) was higher than from the unmonitored portion (150 lb/mi2/yr).

The annual load of NH4 to BBLEH from surface water discharge was estimated to be 110,000 lb/yr (Table 17). The highest NH4 loads were from the Toms River (53,000 lb/yr or 48%), Mill Creek (16,000 lb/yr for 14%), Cedar Creek, and Wrangel Brook (3,000 lb/yr or 10%) basins (Figure 10, Table 17). The lowest load was from the Long Swamp Creek (600 lb/yr), which exhibited the highest amount of urban land cover.

E. Total Ammonia Plus Organic Nitrogen

Median total ammonia plus organic nitrogen (TAON) concentrations at the 25 stations during all flow conditions ranged from 0.20 mg/l to 0.74 mg/l (Table 16). At the 12 stations designated as Landscape I, median TAON concentrations during all flows ranged from 0.20 mg/l to 0.52 mg/l; 8 stations had higher median concentrations during high flow than low flow, and 2 stations had higher median concentrations during low flow than high flow. At these stations, the overall median concentration during high flow (0.30 mg/l) was somewhat higher than during low flows (0.23 mg/l); the overall median concentration was 0.25 mg/l. At the 13 stations designated as Landscape II, median TAON concentrations during all flows ranged from 0.23 mg/l to 0.74 mg/l; 9 stations had higher median concentrations during high flow than low flow, and 3 stations had higher median concentrations during low flow than high flow. The overall median concentration during high flows (0.40 mg/l) was higher than during low flows (0.31 mg/l); the overall median concentration during all flows was 0.40 mg/l.

Nonpoint storm runoff is most likely an important source of TAON to the bay because concentrations were higher during high flow than low flow, especially in areas of moderate to high urban land cover. TAON also seems to be related to land use; concentrations tend to be higher in areas with more wetlands.

The median yield of TAON was higher during high flow than low flow at all stations (Table 16). The median TAON yield during high flow was slightly higher for Landscape I stations than for Landscape II stations (790 lb/mi2/yr and 700 lb/mi2/yr, respectively). During low flow, it was slightly higher for Landscape II stations than for Landscape I stations (310 lb/mi2/yr and 270 lb/mi2/yr, respectively). Annual yields for Landscapes I and II were similar (1,110 and 960 lb/mi2/yr, respectively). The basin average TAON yield for the bay watershed was 1,110 lb/mi2/yr (Table 16). The highest TAON yields were from the Mill Creek (1,500 lb/mi2/yr), Oyster Creek (1,300 lb/mi2/yr), and Toms River (1,200 lb/mi2/yr) basins; the lowest yield was from the Long Swamp Creek basin (360 lb/mi2/yr) (Table 16). The yields from the monitored and unmonitored portions of the bay watershed were similar (1,200 and 980 lb/mi2/yr, respectively).

The estimated annual load of TAON to bay from surface water discharge was 460,000 lb/yr (207,000 kg/yr) (Table 17). The highest TAON loads were from the Toms River (160,000 lb/yr, 72,000 kg/yr, or 33%), Cedar Creek (64,000 lb/yr, 28,800 kg/yr, or 14%), and Mill Creek (35,000 lb/yr, 15,750 kg/yr, for 8%) basins. The load from the Metedeconk River basin (72,000 lb/yr, 32,400 kg/yr) was also high. The lowest load was from the Long Swamp Creek (2,400 lb/yr, 1080 kg/yr).

F. Total Sulfate

Median total sulfate (SO4) concentrations at the 25 ranged from 1.0 mg/l to 13.0 mg/l. SO4 was not measured at the stations on Wrangel Brook and Long Swamp Creek (Table 13). At the 12 stations designated as Landscape I, median SO4 concentrations during all flows ranged from 1.0 mg/l to 10.0 mg/l; 7 stations had higher median concentrations during high flow than low flow, and 3 stations had higher median concentrations during low flow than high flow. At these stations, the overall median concentrations during high flows and low flows were similar (5.8 mg/l and 5.0 mg/l, respectively). At the 10 stations designated as Landscape II, median SO4 concentrations during all flows ranged from 5.0 mg/l to 13.0 mg/l; 6 stations had higher median concentrations during high flow than low flow, and 2 stations had higher median concentrations during low flow than high flow. The overall median concentrations during low flows was somewhat greater than during high flows (9.5 mg/l and 8.9 mg/l, respectively).

The median yield of SO4 was higher during high flow than low flow at all stations (Table 16). The median SO4 yield during high flow was higher for Landscape I stations than for Landscape II stations (19,000 lb/mi2/yr and 12,000 (lb/mi2/yr, respectively), as was the median of the SO4 yields during low flows (6,000 lb/mi2/yr and 8,000 (lb/mi2/yr, respectively) for stations with Landscape I and II, respectively. The basin average SO4 yield for the bay watershed was 27,000 lb/mi2/yr (Table 16). The highest SO4 yields were from the Oyster Creek (38,000 lb/mi2/yr) and Toms River (30,000 lb/mi2/yr) basins. Yields from the Metedeconk River, Wrangel Brook, Long Swamp Creek, and Tuckerton Creek basins were also high (30,000 lb/mi2/yr), but they were entirely estimated (Table 16). The lowest yield was from the Jakes Creek basin (19,000 lb/mi2/yr). The estimated yield from the unmonitored portions of the bay watershed (30,000 lb/mi2/yr) was slightly higher than from the monitored portion (26,000 lb/mi2/yr) (Table 16).

The annual load of SO4 to the bay from surface water discharge was estimated to be 11,000,000 lb/yr (4,950,000 kg/yr) (Table 17). The highest SO4 loads were from the Toms River (3,800,000 lb/yr, 1,710,000 kg/yr, or 35%), Cedar Creek (1,200,000 lb/yr, 540,000 kg/yr, or 10%), and Wrangel Brook (1,000,000 lb/yr, 450,000 kg/yr, or 9%) basins (Table 17). The load from the Metedeconk River basin ws also large (1,000,000 lb/yr, 450,000 kg/yr), but is entirely estimated (Figure 11, Table 17). The lowest loads were from the Jakes Branch basin (180,000 lb/yr, 81,000kg/yr); the load from the Cedar Run basin was also low (150,000 lb/yr, 67,500 kg/yr), but was entirely estimated.

VI. GROUND WATER LOADS

Most ground water within basin discharges to gaged streams that flow into the bay. Some ground water does discharge to small ungaged streams near the coast, and some ground water discharges directly to Barnegat Bay. Loadings for three water quality parameters in ground water that discharges directly to the bay or to small unmonitored tributaries were estimated. Values for three variables were needed to calculate a ground water load, the area contributing to direct ground water discharge to the bay and small tributaries, the ground water recharge rate for that area, and a representative concentration.

The area of ground water basins was determined using GIS. The ground water recharge rate was assumed to be 15 in (38.1 cm) per year. This estimated value is based on the recharge rates reported by Watt and others (1994), adjusted downward to account for a relatively high percentage of urban land use, which generally results in lower rates of recharge.

Parameter concentrations used to calculate loads were the median concentration from ground water samples of the 16 wells of various depths within the contributing recharge areas shown in Figure 12. For calculation purposes, data values reported at less than the method detection limit were assumed to equal that limit. Parameter concentrations and medians are listed in Table 18. These medians compare favorably with medians for the same parameters determined by a National Water Quality Assessment (NAWQA) study of shallow, recently recharged ground water from the Kirkwood-Cohansey aquifer system in urban areas (Stackelberg et al., 1997). The medians they report are 2.6 mg/L for NO2+NO3, 22.9 mg/L for SO4, and 2 mg/L alkalinity as CaCO3. Given that the medians used for the loadings are similar in value and come from ground water samples collected in the same aquifer and within urbanized basins, the medians appear to be comparable and reasonable.

The equation to calculate parameter loadings is:

Loading = (Area) x (Concentration) x (Recharge rate) x (Units conversion factor)

Calculated gross loadings are, respectively: 326,488 lb/yr (146,920 kg/yr) NO2+NO3; 1,959,149 lb/yr (881,617 kg/yr) SO4; and 842,644 lb/yr (379,190 kg/yr) alkalinity as CaCO3. An investigation by the USGS National Water Quality Assessment (NAWQA) Program of nitrate concentration in streams predicted from nitrate concentration in shallow ground water through numerical modeling of ground water flow, found that for three different basins in the New Jersey Coastal Plain, the NO2+NO3 concentration measured in streams was consistently about 40% less than the predicted concentration (Leon Kauffman, U.S. Geological Survey, written communication, 1999). Because this NAWQA study was in the same physiographic province and aquifer system as the Barnegat basin, the NO2+NO3 loading was reduced by 40% to 195,892 lb (88,151 kg), while sulfate and alkalinity were assumed to be conservative.

Yields to the bay from the ground water basins were calculated from the loadings, allowing comparison with yields from the surface water basins and ground water yields from other studies. The yields are

2,024 $lb/mi^2/yr$ for NO2+NO3, 20,239 $lb/mi^2/yr$ for sulfate and 8,705 $lb/mi^2/yr$ for alkalinity as CaCO3.

VII. RELATIONS OF NUTRIENT LOADS TO STREAM FLOW AND LAND USE

Contributions of constituents to the bay from rivers can be quantified as concentrations (mass per volume), loads (mass per time) and yields (mass per time per unit area). Some important factors influencing the amount of nutrients that enter the bay via river discharge are: (1) the type of land use in the basin, such as urban/residential, grasslands plus agricultural land, or forested land; (2) the intensity of development in the basin (greater than or less than 10% development); (3) the historical land use in the basin; (4) the relative importance of constant (ground water discharge) and intermittent (runoff) contributions of constituents to the river; (5) the relative importance of ground water discharge to annual stream flow of each river; and 6) the area of contributing drainage (basin size). Concentrations and loads are strongly influenced by stream flow - low concentrations can represent a large instream load during high flow conditions; the magnitude of loads is dependent on the size of the basin – larger loads come from larger basins. Yields, loads normalized to the basin area, are directly comparable between basins because the influences of stream flow and basin size are removed.

The main contributors of water quality constituents to the bay are nonpoint sources in the basin because there are few major permitted point source discharges to the major rivers draining the watershed. Nonpoint source constituents are transported to the bay through ground water, surface water, and direct atmospheric deposition. Nonpoint source contributions of nutrients (total phosphorus, nitrite plus nitrate, and total ammonia plus organic nitrogen) are typically associated with certain types of land cover, such as runoff from agriculture and intensive lawn maintenance. Increased amounts of impervious surfaces and soil compaction during building construction can reduce the infiltration rate of rainfall and increase storm runoff. Forested land and wetlands land cover has greater water retention and less storm runoff than other land covers as a result of ponding and dense vegetation. The presence of some constituents in ground water can be attributed to historical land uses and their concentrations in receiving streams can remain high for many years because of the slow movement of ground water.

The hydrologic conditions under which constituents enter a stream are important when assessing the source of nutrient loads to the bay. Concentrations of constituents in streams of the bay watershed are a summation of the nonpoint source contributions from constant ground water discharge and intermittent storm runoff sources. Ground water contributions to a stream are relatively constant, varying only slightly with season. Concentrations of constituents carried to a stream by ground water can be quantified in samples collected during base flow conditions. Storm runoff, composed of overland runoff and interflow, contributes to a stream intermittently, depending on storm intensity and frequency, and only during high flows. Storm runoff dilutes the ground water contributions to a stream. Constituents intermittently carried to a stream by storm runoff along with the constant contributions from ground water can be quantified in samples collected during storm flow events.

The magnitude or steepness of the regression slope of constituent load to stream flow can be used to indicate the relative contributions of ground water and storm runoff at a river location (Hunchak-Kariouk et al., 1999; Price and Schaefer, 1995). The steeper the slope, the greater the contribution from nonpoint sources during increased stream flow. If the contributions to instream load are predominantly from ground water, instream load will remain relatively constant with increasing stream flow and the regression slope of load to stream flow will be approximately zero. If, however, storm runoff contributes a disproportional amount to instream load, instream load will increase with increasing stream flow and the regression slope of load to stream flow will be greater than zero. Comparison of the relative

magnitude of the load slopes between stations and for different constituents at a station can indicate the relative importance of storm runoff and ground water to instream loads at a station for each constituent.

The amount of total phosphorus (TP) entering the bay via river discharge is small compared to the amount of nitrogen, measured as nitrite plus nitrate and total ammonia plus organic nitrogen. Total phosphorus load appears to be related to the type of land cover - basins with greater urban land and agricultural plus grasslands cover have somewhat larger concentrations, yields, and loads of TP. Yields calculated for monitored basins and estimated for unmonitored areas are larger for basins classified as Landscape II (> 10% development) than as Landscape I (< 10% development). About one-third of the load comes from the unmonitored coastal areas (mostly Landscape II) of the basin. Yields are largest at the most upstream and downstream sites on the Toms River, the downstream site on Wrangel Brook, and the site on Oyster Creek.

Nonpoint storm runoff does not seem to be a significant source of TP to the bay because concentrations are small, especially in areas of slight urban land cover, and either the same or larger during low flow than high flow in areas of moderate to high urban land cover. Using the values presented by Hunchak-Kariouk et al. (1999) for relations between water quality and stream flow at USGS stations in the Atlantic Coastal Plain, the slope of TP load to stream flow was higher at McDonalds Branch than at Toms River near Toms River, which was slightly higher than at Great Egg Harbor near Sicklerville. Storm runoff is a greater contributor to instream load at McDonalds Branch than at Toms River or Great Egg Harbor River. The Great Egg Harbor River Basin is more developed than the basins of Toms River and McDonalds Branch and the concentrations were slightly larger at Great Egg Harbor than at Toms River and McDonalds Branch.

Total nitrogen (TN) is a measure of several nitrogen species that can be dissolved or associate with particles. The concentration and loading of TN in a stream and the relative importance of groundwater and storm runoff contributions depend on which nitrogen species is predominant. About half the TN measured in surface water of the Bay watershed is NO2 + NO3; the other half is organic nitrogen because total ammonia concentrations are small in most basins. The amount of NO2 + NO3 in a stream is strongly related to the intensity and type of land cover in the contributing area basins. Greater urban land and agricultural plus grasslands cover have much larger concentrations, yields, and loads of NO2 + NO3 than less developed basins. Yields calculated for monitored basins and estimated for unmonitored areas are in general an order of magnitude larger for basins classified as Landscape II (greater than 10% development) than as Landscape I (less than 10% development). Yields calculated at all sites on Wrangel Brook were especially large. The most downstream area of the Wrangel Brook basin had nd estimated NO2 + NO3 yield of greater than 1,900 ($lb/mi^2/yr$). Yields from direct groundwater discharge from nearby areas with no major streams are also estimated to be large.

Ground water appears to be a significant source of NO2 + NO3 to the bay because concentrations are larger during low flow than high flow. Concentrations during low flow and high flow are larger in areas with moderate to high urban land cover than in areas with slight development.

The remaining half of the TN in surface water is organic nitrogen; NH4 concentrations were small except at the site on Mill Creek where it was a very large component (more than half of the TN). Nonpoint storm runoff is most likely an important source of TAON to the Bay because concentrations are larger during low flow than high flow, especially in areas of moderate to high urban land cover. TAON also seems to be related to land use; concentrations are larger in areas with moderate to high amounts of urban land cover and wetlands. The yield of NH4 and TAON from the Mill Creek was especially large.

Nonpoint storm runoff does not seem to be a significant source of NH4 to the Bay, except in areas of greater urban land cover. Median concentrations during all flows were low (0.08 mg/l or less) at all sites except 4 of the 10 most developed sites. Of the sites with median concentrations greater than 0.08 mg/l, the median concentrations during low flow were the same or greater than during high flow at the two most-downstream stations on the Toms River and the Mill Creek station.

VIII. TOTAL NITROGEN AND NITRITE PLUS NITRATE LOADS TO THE ESTUARY

Total loads to the BBLEH can be computed as the sum of the surface-runoff loads and the ground water discharge. For NO2 + NO3, the total annual load is 560,000 lb/yr 252,000 kg/yr) -- 360,000 lb/yr (162,000 kg/yr) from surface runoff and 200,000 lb/yr (90,000 kg/yr) from ground water discharge (rounded values).

The overall yield of NO2 + NO3 from surface water and ground water discharge to the BBLEH is estimated to be 1,000 lb/mi^2/yr and the yield from surfacewater discharge was 900 lb/mi^2/yr. The yield of TN from surface water discharge was 2,000 lb/mi^2/yr. About half of the nitrogen load discharged to the BBLEH from rivers is organic nitrogen. This load of organic nitrogen to the BBLEH may be significant.

Yield values of total nitrogen and nitrite plus nitrate from the BBLEH watershed are comparable to those estimated for other Coastal Plain basins. For the BBLEH watershed, nitrite plus nitrate and nitrate yields can be assumed equivalent because nitrite concentrations in surface and ground water were small. Yields of nitrate to the Chesapeake Bay were estimated to be 2,400 lb/mi^2/yr from total flow (total stream flow) and 1,700 lb/mi^2/yr from base flow; total flow, total nitrogen yields were 4,460 lb/mi^2/yr (Bachman et al., 1998). Yield values of total nitrogen were estimated to be 2,900, 1,600, and 4,600 lb/mi^2/yr from three basins in the Patuxent River basin in the Maryland Coastal Plain (Preston, 1996). Base flow yield values of total nitrogen were estimate to be 3,800 and 900 lb/mi^2/yr, depending on the method used (Bachman and Phillips, 1996).

IX. CHANGES TO DESIGNATED HUMAN USES IN THE WATERSHED

Historical increases in population and water demand in the Barnegat Bay watershed have resulted in or contributed to substantial water supply problems, including saltwater intrusion, stream depletion, and concerns about the quality of drinking water. Restrictions on the use of confined aquifers in order to reduce the threat of saltwater intrusion have resulted in an increased reliance on surficial aquifers and surface water to meet increasing water demands. The implementation of these restrictions has raised concern about environmental impacts that can result from excessive stream depletion and the vulnerability of water supplies to contamination.

A. Confined Aquifers

Prior to the development of regional water supplies, water pressure levels in all confined aquifers in the New Jersey Coastal Plain were above sea level. Withdrawals from confined aquifer supply wells located within and outside the project area have produced cones of depression that extend over large parts of the watershed area. Withdrawals from major confined aquifers in the northeastern coastal plain have also resulted in the migration of saltwater into two productive aquifers in northern Monmouth County and in Middlesex County (USGS, 1989).

Withdrawals from confined aquifers in the northeastern coastal plain region have resulted in deep cones of depression in areas where relatively low rates of groundwater flow from adjacent areas and overlying aquifers are available to replace the water withdrawn. By 1983, confined aquifer withdrawals in response to high water demand had caused groundwater pressure levels to decline to more than 200 ft (61 m) below sea level in some areas (USGS, 1995a). If withdrawals had been left unrestricted, groundwater levels would have declined even further.

Saltwater intrusion caused by excessive confined aquifer withdrawals has resulted in elevated chloride concentrations in supply wells in the upper and middle aquifers of the Potomac-Raritan-Magothy Aquifer system to the north of Barnegat Bay. Specific areas where the upper aquifer is affected by saltwater include South Amboy, Keyport, Union Beach, and Keansburg. Specific areas where the middle aquifer is affected by saltwater are Sayreville, South Amboy, Keyport, and Union Beach (USGS, 1996).

In response to a similar saltwater problem in the west-central part of the New Jersey Coastal Plain, the New Jersey Department of Environmental Protection designated Water Supply Critical Areas 1 and 2 (Figure 13), and mandated reductions in confined aquifer withdrawals in these areas. Since reductions in Critical Area 1 were initiated in 1990, groundwater levels in the northeastern coastal plain have substantially recovered, but the threat of saltwater intrusion remains.

Although saltwater intrusion into the major confined aquifers is not known to be a problem for supply wells located in the Barnegat Bay watershed, supply wells located in several areas within the watershed area appear to be potentially threatened by saltwater intrusion in the long term (O. Zapecza, U.S. Geological Survey, written communication, July 6, 1994).

These areas include:

•Long Beach Island (Atlantic City 800-Foot Sand Aquifer);

•Barnegat Light, Seaside Heights, and Seaside Park (Piney Point Aquifer);

•Point Pleasant, Lavallette, and other Monmouth County locations (Englishtown Aquifer system);

•Point Pleasant, Chadwick, and Lavallette (upper aquifer of the Potomac-Raritan-Magothy Aquifer system); and

•Lavallette, Toms River, and other locations in northern Ocean County (middle aquifer of the Potomac-Raritan-Magothy Aquifer system).

Because the major confined aquifers are overlain by thick layers of clay and silt, they are generally less vulnerable than unconfined aquifers to contamination resulting from human activities at the land surface.

B. Unconfined Aquifers

1. Kirkwood-Cohansey Aquifer System

Many municipalities, public purveyors, and private well owners use the unconfined Kirkwood-Cohansey aquifer system. Because of the potential threat of saltwater intrusion in the confined aquifers of the region, it is anticipated that requests for additional withdrawals from the Kirkwood-Cohansey Aquifer system for public supply and irrigation uses will increase. Consumptive withdrawals from the unconfined aquifer system can reduce stream flow (Figure 14), resulting in habitat loss and a reduced capacity of streams to dilute contaminant loads. The unconfined aquifer system is also much more vulerable to contamination due to human activities at the land surface, and numerous instances of shallow groundwater contamination in the Barnegat Bay watershed area have been documented (USGS, 1984, 1997a, b, 1998; Ocean County Health Department, written communication, 1998).

Historic groundwater withdrawals have caused the shifting of flow patterns in parts of the Kirkwood-Cohansey Aquifer system, reducing groundwater discharge to streams and wetlands of significant ecological value. A recent investigation of trends in stream discharge over time concluded that stream flow measured at gaging stations on the North Branch of the Metedeconk River and Toms River decreased periodically between 1970 and 1989 (USGS, 1995b). However, the cause(s) of these declines has not yet been determined. In addition, there has not been a determination of whether ecological resources or shellfish were affected by the reduced flow. Nevertheless, the New Jersey Department of Environmental Protection is presently evaluating actions that should be taken to minimize possible impacts.

Recent hydrogeologic investigations indicate that withdrawals from the Kirkwood-Cohansey have lowered groundwater levels and have caused average reductions in stream flow of up to 11% (USGS, 1997a). Stream flow in some streams during natural low flow periods could decrease by ~26%, if water allocations are fully utilized. Kettle Creek, in particular, could be most affected. Withdrawals have caused the average groundwater level to decline by up to 20 ft (6.1 m) near pumping centers. At full allocation, it is estimated that water levels can decline by an additional 20 ft (6.1 m). These impacts can potentially damage riverine ecosystems and reduce the yields of the surface water supplies of the Metedeconk River (and the Toms River if it is used for water supply purposes in the future).

There are two areas in the region where saltwater intrusion has affected wells withdrawing water from the Kirkwood-Cohansey Aquifer system. Saltwater has adversely affected public supply wells located in Seaside Heights and Point Pleasant Beach, where observed chloride concentrations in groundwater have exceeded the 250 mg/l secondary drinking water standard (Figure 15). There are numerous other public and private wells that are located near brackish water along the coast. Consideration should be given to additional monitoring, where applicable, especially if higher allocations are proposed.

Domestic wells in Berkeley, Dover, Eagleswood, Lakewood, and Stafford produce water with high levels of sodium (Bergman and Associates, 1990). It is unknown if this phenomenon is caused by saltwater intrusion, road salting, or septic systems.

Present and future withdrawals from the region's confined aquifers can also shift groundwater flow patterns and result in stream flow depletion. However, these effects have not been quantified; therefore, the cumulative effects of all pumpage are not well understood.

Ocean County has the largest number of domestic wells of any county in New Jersey. It is thought that large numbers of these wells are used for lawn irrigation. When there are large numbers of domestic wells that are used for this purpose in close proximity to each other, the effects can be similar to a large public well that serves homes and businesses that are in a sewer service area. Much of irrigation water is subject to evaportranspiration and is not "recycled" into the aquifer system. It was estimated that domestic wells in Ocean County used 10.7 MGD in 1990 (Bergman and Associates, 1990). Most of these wells are in the Kirkwood-Cohansey Aquifer system.

X. WATERSHED BIOTIC IMPACTS

The intrinsic link between anthropogenic disturbance and changes in aquatic community structure has been consistently documented over the past decade. Land-use alterations resulting in an increase in impervious surfaces, runoff, suspended sediment, and nutrient loading directly affect the hydrology, geomorphology, and water quality of the Barnegat Bay watershed, and alter the aquatic communities that inhabit this system. Because this link exists, it is possible to assess the severity of anthropogenic disturbances by comparing aquatic communities (for example, aquatic macroinvertebrates) found at specific sampling sites to that expected at reference or minimally impaired sites and by relating measured environmental conditions to aquatic communities that have been modified.

Many state and federal government agencies have initiated biomonitoring programs to assess the effects of anthropogenic disturbances on aquatic communities (e.g., Loeb and Spacie, 1994; Davis and Simon, 1995). In 1992, the New Jersey Department of Environmental Protection (NJDEP) initiated a watershed-based biomonitoring program known as the Ambient Biomonitoring Network (AMNET) to evaluate the biological integrity of aquatic invertebrate communities in New Jersey streams including tributaries of the Barnegat Bay-Little Egg Harbor estuary. This statewide network incorporates regional reference sites, which are minimally disturbed areas organized by selected chemical, physical, and biological characteristics (New Jersey Department of Environmental Protection, 1994; Reynoldson et al., 1997). The goal of the program is to monitor the condition of benthic macroinvertebrate communities every five years. This frequency is considered to be realistic for evaluating environmental changes. Sampling locations were chosen for monitoring mainstem locations above major tributary confluences, assessing the effects of lakes, investigating known sources of contamination, and evaluating the effects of significant natural features such as wetlands, preserves, and wildlife management areas. Concurrently, the U.S. Geological Survey in cooperation with the NJDEP operates a statewide surface water quality monitoring network that provides the basis for the state water quality inventory report to the U.S. Environmental Protection Agency and Congress mandated by the Section 305(b) of the Clean Water Act. Together, these programs maximize the integration of water quality and biological information and provide a solid foundation for statewide water quality planning and management decisions involving surface water quality standards and biocriteria in New Jersey.

The bioassessment method chosen by the NJDEP for evaluating aquatic macroinvertebrate communities was modified from the U.S. Environmental Protection Agency's Rapid Bioassessment Protocol II (Plafkin et al., 1989). Rapid bioassessments are based on a multimetric approach which uses an array of

individual measures (e.g., community, population, structural, and functional) to summarize diverse biological information into a single measure of condition. Individual measures of biological condition (referred to as metrics) for each sampling site are compared to a statewide reference database (New Jersey Department of Environmental Protection, 1994). On the basis of this comparison, a total community "impairment score" is established. Benthic macroinvertebrates are ideally suited for this type of approach because they are sensitive to minor changes in water quality and therefore are useful as indicators of a wide range of environmental disturbances.

Five metrics comprise the NJDEP's rapid bioassessment protocol (total taxa richness, total EPT richness, percent dominance, modified family biotic index, and percent EPT) (Table 18). The primary requirements for inclusion of metrics in the New Jersey RBP are low variability, the demonstrated ability to discriminate non-impaired from impaired conditions, and statistical independence (non-redundancy). A brief description of metrics used in the New Jersey RBP follows. The total taxa richness measures the total number of families identified in the sample. A reduction in richness may indicate environmental stress related to organic enrichment, toxics, and sedimentation. The EPT richness index measures the total number of ephemeropteran (mayfly), plecopteran (stonefly), and trichopteran (caddisfly) families in a sample. These organisms are considered to be highly sensitive to disturbance, and typically, the number of families vary inversely with the magnitude of environmental disturbance. The percent dominance assesses the relative balance within a macroinvertebrate community. Healthy macroinvertebrate communities are often characterized by an equitable faunal assemblage. Degraded streams are commonly dominated by a few highly tolerant taxa or taxa groups. The modified family biotic index (FBI) was developed to evaluate the relative tolerance of benthic macroinvertebrates to organic enrichment (Hilsenhoff, 1988). This index is based on a gradient or continuum of tolerance that ranges from 0 (sensitive) to 10 (tolerant) and typically increases as water quality decreases (Plafkin et al., 1989). The percent EPT provides a measure of the percent abundance of three sensitive aquatic insect families. A high percentage of Ephemeroptera, Plecoptera, and Trichoptera in a sample is associated with good water quality. Percent abundance of these groups often decreases with only minimal increases in environmental degradation.

In the Barnegat Bay watershed, benthic macroinvertebrate samples were collected from August to December 1994. To maintain consistency among sampling sites, a multihabitat sampling approach was used. Benthic macroinvertebrates were sampled with a Surber sampler (box-type sampler) or a rectangular kick net. A grab sampler was used to collect benthic macroinvertebrates located in depositional areas. In addition, a separate sample of coarse particulate organic matter (primarily decomposing leaf litter) was collected by hand. All material from the samples was combined, and a family-level 100-organism subsample was randomly generated from the entire sample. Three condition categories (non-impaired, moderately impaired, and severely impaired) were established to reflect the type and level of macroinvertebrate community impairment in New Jersey streams (see Table 18 for scoring criteria and definition of the three impairment ratings).

Sixty-one sites were sampled within the Barnegat Bay watershed as part of the AMNET program. These sites range in condition from non-impaired to severely impaired (Table 19, Figure 16). Of the 61 sites sampled, 57% were classified as non-impaired, 36% as moderately impaired, and 7% as severely impaired (Figure 17). Three of the four sites classified as severely impaired (AN0525, AN0532, and AN0510; Table 19, Figure 17) are proximally located to hazardous waste sites within the Barnegat Bay watershed.. The percent EPT ranged from zero at AN0525 and AN0532 to 91% at AN0548. The modified FBI, which increases with increasing levels of organic contamination, ranged from 2.02 at AN0548 to 8.91 at AN0525. The most diverse site was AN0507 with 57 different taxa and the least diverse sites were AN0525 and AN0532 with four taxa (Table 16).

Twenty of the 61 benthic macroinvertebrate monitoring sites in the Barnegat Bay watershed were

directly linked to cooperative water quality monitoring stations. Detrended Correspondence Analysis (DCA, an indirect ordination technique) was used to assess potential land-use and water quality gradients in the watershed (Figure 18). DCA is an ordination technique favored by many practical field ecologists for non-linear data analysis of a variety of organisms including plant communities (Chang and Gauch, 1986), benthic organisms (Wright et al., 1984; Leland et al., 1986; Tate and Heiny; 1995), terrestrial vertebrates (Ben-Shahar and Skinner, 1988), and fishes (Edds, 1993; Galacatos et al., 1996; Zampella and Bunnell, 1998). It is considered to be one of the most powerful multivariate tools available for assessing patterns in communities composed of species that vary along compositional gradients (Peet et al., 1988). The underlying assumption of this approach is that species respond unimodally to environmental constraints. More specifically, species abundances tend to increase with an increase in some environmental parameter, reach a maximum at some environmental optimum, and then decrease in abundance at increasing levels of the environmental parameter. Therefore, if any aspect of the environment is greater or lesser than this optimum, the species will perform more poorly (i.e., it will have reduced abundance). This technique effectively summarizes community variation relative to underlying gradients and is scaled in units of average standard deviation (SD) or species turnover (Gauch, 1982). A species appears, rises to its mode, and disappears over a length of approximately 4 SD's, which is equal to one species turnover (beta diversity). This is a measure of how sites differ from each other or, alternatively, it is a measure of the length of an ecological gradient or ordination axis in terms of species composition. An axis or gradient with high species turnover will have completely different species compositions at opposite ends of the ordination diagram. Thus, ordination by DCA arranges sites with similar taxonomic composition to cluster more closely together and sites with dissimilar taxonomic composition to cluster farther apart (Gauch, 1982).

Site scores produced from this ordination procedure can be related to environmental variables. The site scores represent a coordinate along an ordination axis specifying the x-y location of the sample in ordination space. Ideally, site scores represent the position of communities along an important environmental gradient. Each of the DCA axes comprises part of the basic structure of the Cartesian coordinate system, and the axes are usually portrayed as being at right angles to each other (orthogonal; Figure 19). The axes for DCA are obtained by using a statistical procedure known as reciprocal averaging. This technique involves matrix algebra and simultaneously arranges species and sites by calculating the weighted average or centroid of the species and site scores in ordination space. This is an iterative approach which continues for each axis until the scores stabilize (converge to a unique solution). Convergence is relatively rapid; however, this is dependent upon the initial size of the data matrix (Digby and Kempton, 1995). Thus, the scores themselves form a gradient because they are ordered along each axis and the importance of an axis is commonly represented by its eigenvalue. The eigenvalue is actually equal to the maximized dispersion of the species scores along the ordination axis and is thus a measure of the relative strength of the ordination axis (Jongman et al., 1995). Eigenvalues always range between 0 and 1. The first axis of an ordination will have the largest eigenvalue, the second axis the second largest eigenvalue, and so on (Jongman et al., 1995).

AMNET sampling sites were linked with corresponding water quality data and used to assess potential anthropogenic changes in the Barnegat Bay watershed by subsequently comparing the site scores of DCA axes 1 through 4 to environmental variables using Spearman rank correlations (Table 20). Only the first 4 axes of the ordination generally are interpreted because, in practice, they represent or account for most of the variation in the species data. One goal is to determine whether site scores are related to anthropogenic changes in the environment. By using this approach, it is possible to determine indirectly which environmental variables contribute most to the separation of sites along a particular axis (Table 20), that is, which environmental variables exert the greatest influence in structuring the aquatic communities inhabiting tributaries of the Barnegat Bay.

As described earlier, the relative magnitude of the eigenvalues for each DCA axis describes the relative

importance or strength of the environmental gradient and the length of the gradient is a measure of how unimodal the species responses are along an ordination axis. A gradient can be defined as a spatially varying aspect of the environment, which is expected to be related to species composition. It has been suggested that a gradient length of 4 SD's represents a full species turnover, and that sites at the opposite ends of the axis would have few species in common (Jongman et al., 1995). The gradient length for the ordination of sites in the Barnegat Bay watershed was 6.01, representing a strong unimodal response (Figure 18) and more than one species turnover. This suggests a low similarity between sites located at opposing ends of the axes in the ordination diagram (Figure 19).

Twelve environmental variables were found to be significantly correlated with the four DCA axes (Table 20). The first axis of the ordination diagram (x-axis, Figure 20) represents a separation of sites based on the number of taxa present at each site (a diversity gradient). High diversity suggests that niche space, habitat, and food sources are adequate to support the survival and propagation of the endemic fauna. Those sites located on the right side of the ordination diagram have the highest species diversity and those on the left, the lowest.

The second ordination axis, which runs from the top to bottom of the ordination diagram (y-axis, Figure 19), reflects a strong water quality impairment gradient and separated sites based primarily on community metric criteria. Three variables, the New Jersey Impairment Score (NJIS, which is the numerical sum of all metrics shown in Table 18), FBI, and percent EPT were significantly correlated with the second axis (Table 20). In general, sites located at the top of the second axis are least impaired and those at the bottom are most impaired. The presence of EPT taxa (mayflies, stoneflies, and caddisflies) is strongly associated with good water quality conditions, and it is well established that these three families of aquatic insects typically decrease with only minimal increases in environmental degradation. The premise underlying composition based metrics such as %EPT is that a healthy and stable macroinvertebrate assemblage will be relatively consistent in its proportional representation, though individual abundances may vary. Thus, a high percentage of EPT taxa in a sample would represent sites with good water quality; for example, those sites at the top of the ordination diagram (AN0524, AN0535, AN0523, AN0519, and AN0547) typically exhibit unimpaired conditions and better water quality than those at the bottom of the ordination diagram (AN0510, AN0532, AN0538, AN0509, AN0518). The modified FBI was established to assess the relative tolerance of benthic macroinvertebrates to organic enrichment. This index is based on the premise that some organisms are more tolerant of a variety of stressors than others. Some organisms are considered to be sensitive to contamination, and others are indicative of a highly stressed system. For example, many Ephemeroptera (mayflies) are highly intolerant organisms, and their presence may be indicative of a site that has little organic enrichment. However, the dominance of members of the caddisfly family Hydropsychidae is indicative of a stressed system. AN0548 has the highest percentage of ephemeropteran taxa (91.1%, Table 19) and is located at the top of ordination diagram (Figure 19). AN0532 and AN0510, however, have no ephemeropteran taxa and are nearest the bottom. The NJIS was designed to incorporate the characteristics of benthic macroinvertebrate assemblages that are best able to distinguish water quality impairment. The finding that the second DCA axis is significantly correlated with the NJIS as well as % EPT and FBI (Table 3) further substantiates the strong water quality gradient that exists within the Barnegat Bay watershed.

The third axis (not shown in the ordination diagram) represents a wetland gradient that reflects also a change in pH and flow characteristics. Sites with the highest percentage of wetlands in the watershed appear to have the lowest pH. These factors were found to be strongly influenced by latitude which was also significantly related to the third axis ($R=0.51$, $p=0.02$). This suggests, in general, that sites nearer to the eastern side of the basin and more proximally located to urban areas and the Garden State Parkway have a lower percentage of wetlands and higher pH. It is well documented that changes in pH affect the reproduction and survival of endemic aquatic organisms. Thus, as urban corridors continue to increase in

the Barnegat Bay watershed, changes such as the reduction in the amount of wetlands may produce measurable negative consequences for stream water quality and the aquatic communities that inhabit these systems.

The fourth axis scores were found to be strongly related to median specific conductance (MD_SC), flow, number of individuals (NOINDIV = abundance), the ratio of EPT to the family Chironomidae (EPT/C), latitude, and percent forest (Table 20). This was the weakest of the gradients assessed; however, the eigenvalue for the fourth axis was fairly strong and still accounted for a significant amount of the variance. MD_SC, flow and NOINDIV were the three most strongly correlated environmental parameters with axis four. MD_SC and NOINDIV were negatively correlated, however, flow was positively correlated with the fourth axis. These relations suggest that as flow increases, specific conductance and abundance of aquatic macroinvertebrates in tributaries of Barnegat Bay decrease. Runoff from urban development has been directly linked to changes in specific conductance and stream flow characteristics. Although these factors can vary seasonally, the impact is measurable and can directly affect the abundance of benthic organisms in streams of the Barnegat Bay.

The biological impairment associated with physically degraded sites is clearly related to a change in landuse in the Barnegat Bay watershed. Changes in land-use practices appear to have impaired the physical and biological integrity of many of these streams by decreasing the quality and quantity of specific habitats in the basin. As land is further developed for residential and commercial uses, important basin characteristics (e.g., the amount of area classified as wetlands) are significantly reduced. In addition, development alters flow regimes by straightening, deepening, and diverting natural channels. These changes in conjunction with the reduction in wetland habitat likely explains the strong correlation between the third axis and flow characteristics found for streams in the Barnegat Bay ($R=0.46$, $p=0.04$). Rain falling on vegetated surfaces can be absorbed more rapidly than on paved surfaces, and it is well established that wetlands mitigate flood peaks. Rain falling on impervious surfaces, however, is not absorbed, and thus can sharply increase runoff peaks, which can negatively affect the aquatic communities that inhabit these streams.

Many of the factors linked to the degradation of benthic communities are becoming better understood. Factors such as the amount of impervious area (areas in a watershed covered by asphalt, concrete, buildings, and other compacted surfaces), urban runoff, increased suspended-sediment loads, habitat degradation, sewage effluent, and greater urbanization all have been shown to affect the hydrology, geomorphology, and water quality of stream systems. In the Barnegat Bay watershed, aquatic macroinvertebrate communities appear to be driven by the level of organic enrichment and the percentage of wetlands present in a basin. This is indicated by the strong water quality impairment gradient found along the second ordination axis and the significant correlations with wetlands, stream flow, and pH.

XI. ESTUARINE BIOTIC IMPACTS

A. Introduction

Barnegat Bay, Manahawkin Bay, and Little Egg Harbor comprise a unique lagoon-type estuarine system (Figure 20). An array of environmentally sensitive habitats exists in these shallow bays, such as waterfowl nesting grounds, salt marshes, submerged aquatic vegetation, finfish nursery areas, and

shellfish beds. Biotic communities are replete with rich assemblages of planktonic, nektonic, and benthic organisms that are highly responsive to variations in natural and anthropogenic factors. Some of these organisms (e.g., winter flounder, *Pseudopleuronectes americanus*; hard clams, *Mercenaria mercenaria*; blue crabs, *Callinectes sapidus*) are also of recreational and commercial importance.

Human activities both in watershed areas and on open bay waters have affected sensitive habitats and living resources of the estuary. Many anthropogenic impacts in Barnegat Bay are directly coupled to development in the bay watershed and to activities associated with human habitation, notably construction, land maintenance, agriculture, and vehicle use. Watershed modifications that have particularly affected estuarine water quality include deforestation and infrastructure development together with landscape partitioning and paving. Along the estuarine perimeter, marsh filling and bulkheading, diking and lagoon construction, and dredging and dredge material disposal have disrupted natural habitats and altered biotic communities. Human activities in the watershed significantly alter the timing, magnitude, and nature of material inputs to the estuary.

The Barnegat Bay-Little Egg Harbor estuary is highly susceptible to pollution because of its limited dilution capacity and flushing rate. Major groups of chemical contaminants occurring in sediments, biota, or estuarine waters are halogenated hydrocarbons, polycyclic aromatic hydrocarbons, trace metals, and radioactive substances. These contaminants, which are generally poorly characterized, may derive from both point sources (e.g., industrial wastewater discharges, marinas, and dredged materials) and nonpoint sources (e.g., suburban and construction-site runoff, faulty septic systems, groundwater pollutant transfer, boats, and atmospheric deposition). Their effects on organisms in the estuary have not been addressed. Operation of the Oyster Creek Nuclear Generating Station is not only responsible for biocidal and radioactive contaminant releases into the estuary but also for increased mortality of estuarine organisms due to thermal discharges, as well as impingement and entrainment. Nearly all previous investigations of anthropogenic impacts on biotic communities in the estuary have focused on power plant activities.

Among the highest priority problems encountered in this system are those associated with nutrient and organic loadings. Barnegat Bay is classified as a moderately eutrophic system (Seitzinger and Pilling, 1992, 1993). Nutrient enrichment leads to elevated phytoplankton biomass and production in the summer. Seasonal phytoplankton blooms occur in the estuary, with winter blooms dominated by diatoms (e.g., *Thalassiosira nordenskiolkii* and *Detonula confervacea*) and summer blooms dominated by a nonmotile chlorophycean (green) alga (i.e., *Nannochloris atomus*). Brown tides comprised largely of a coccoid picoplankter, *Aureococcus anophagefferens*, have been documented in the southern part of Little Egg Harbor, most recently during the summers of 1995, 1997, and 1999 (Mahoney et al., 1997; Olsen, New Jersey Department of Environmental Protection, personal communication, 1999). The accumulation and bacterial decay of phytoplankton remains on the estuarine floor during bloom events are a a concern because they may promote hypoxia of estuarine bottom waters that can be detrimental to biotic communities.

Additional impacts are attributable to pathogens (e.g., coliform bacteria) from animal waste washed into the bay along roadways and adjacent lands, from bird droppings, as well as from human waste from faulty septic systems and boats. Elevated coliform bacteria levels periodically result in beach closings and the closure of shellfish beds to harvesting. Apart from these impacts, increased turbidity and siltation levels, particularly in tributaries of the estuary, result from construction, dredging, and bank stabilization projects. Finally, the estuary is frequently littered with floatable debris ascribed to stormwater runoff, beachgoers, recreational boaters, and various illegally dumped sources.

B. The Watershed

The Barnegat Bay-Little Egg Harbor estuary is plagued by many of the same environmental problems found in other coastal bays of the Mid-Atlantic region. Two high-priority problems in this system include nutrient enrichment and pathogens; both directly affect estuarine water quality. In addition, the alteration and loss of sensitive habitat areas threaten the continued health and biodiversity of the system. Water quality and habitat degradation are linked to development in watershed areas which has increased dramatically during the past four decades. Development has been most acute in the northeastern part of the Barnegat Bay watershed along the mainland, as well as on the barrier island complex. Except for Island Beach State Park, a 15.5 km area on Island Beach, and the Holgate Unit, a 3.5 km area of the Edwin B. Forsythe National Wildlife Refuge at the southern extreme of Long Beach Island, natural vegetation has been largely destroyed or substantially altered on the barriers. More than 70% of the Barnegat Bay shoreline is developed (Lathrop et al., Appendix 3).

According to U.S. Census reports, the population of the watershed increased from nearly 40,000 people in 1940 to 108,000 in 1960, 208,000 in 1970, 346,000 in 1980, and 433,000 in 1990, making it one of the most rapidly growing areas in the United States over this 50-year period. The watershed now supports more than 450,000 people year-round, and more than 800,000 people during the summer tourist season (David McKeon, Ocean County Planning Department, personal communication, 1999). The population is concentrated along Island Beach, Long and Beach Island, as well as municipalities in the northeastern and central mainland areas of the watershed. The most heavily populated municipality is Dover Township, with 85,436 residents estimated in 1998. Since 1950, the Barnegat Bay watershed has undergone dramatic development, with land use changing from principally undeveloped and agricultural to suburban sprawl. More than 50% of the development has occurred in the lower watershed in nearshore areas of the estuary, being heaviest along the northern third of the bay (Moser, 1997).

Habitats in the watershed are highly diverse, varying from coastal dunes and low-lying estuarine and freshwater wetlands to upland pine/oak forests. Upland forests and wetlands habitat predominate, comprising 37% and 19% of the watershed, respectively (Lathrop et al., 1999). More than 50,000 ha of estuarine and freshwater wetlands occur in the system, providing valuable habitats for colonial nesting birds, fish, and wildlife. Many rare and endangered species utilize these habitats. In addition, nearly 23,000 ha of open space are associated with the system, including a portion of the Forsythe National Wildlife Refuge and the Manahawkin State Wildlife Management Area. Historically, land-use conversion in watersheds has altered many habitats; the predominant sequence of land-use conversion is from natural land (forest or grassland) to community land (urbanization) and from natural land to agricultural land (agriculturization). These conversions have been shown to directly modify the original patterns of water and material output from watershed areas to streams and rivers discharging to bays (Hopkinson and Vallino, 1995). Due to complex linkages between the watershed and open bay, changes in biotic communities may be expected in the estuary from largescale watershed modifications.

Lagoon and bayfront residential developments of western Barnegat Bay, which bulkhead and drain wetlands, have eliminated important habitat areas and provided numerous sources of road runoff (Sugihara et al., 1979). Although the loss of wetlands is essentially irreversible, the construction of new lagoons and bulkheads for residential development along the bayshore has declined markedly since 1970, because of stricter permitting regulations. State laws (i.e., the Wetlands Act of 1970, the New Jersey Coastal Area Facilities Review Act of 1973, and the Freshwater Wetlands Protection Act of 1986) and federal regulations (i.e., Section 404 of the Clean Water Act of 1977) have greatly curtailed the loss and alteration of wetlands habitat. However, a small, albeit steady loss of existing wetlands area continues to this day (Lathrop et al., 1999).

There is only limited industrial development in the Barnegat Bay watershed, with slightly more than 20 industrial/commercial point source discharge permit holders located within the drainage area (Table 21). Nearly all of these point sources release small discharge volumes to influent systems of Barnegat Bay, and thus are not significant sources of pollution. An exception is the Oyster Creek Nuclear Generating Station, a 630 MW (net) electric generating facility, which discharges 1.74 x 106 l/min of thermal effluent and 0.98 x 106 l/min of dilution water to the discharge canal and Oyster Creek. It is by far the most voluminous source of wastewater in Barnegat Bay (Kennish et al., 1984).

Point source pollution in the estuary improved considerably in the 1970s when the Ocean County Utilities Authority (OCUA) commenced operation of a state-of-the-art wastewater reclamation system. Prior to operation of this system, regional wastewater was treated by about 40 local sewage plants which provided varying degrees of treatment for the region. The discharge of wastewaters from these plants into bay watershed areas, together with leaching from septic tanks into influent systems, impacted water quality in the estuary. Soon after the first OCUA regional wastewater treatment plant went on line more than 20 years ago, water quality in the estuary began to improve. The entire OCUA wastewater treatment system was operational by 1979 and consisted of three secondary treatment plants, 40 pumping stations, and more than 270 km of interceptor pipe lines and three ocean outfall lines discharging 1.6 km offshore in the Atlantic Ocean.

Nonpoint source pollution has become a more serious concern in recent years (Table 22). When sampled, influent systems often have relatively high nutrient concentrations. Diffuse nutrient and organic loadings stimulate algal growth in bay waters which can lead to blooms of toxic or nuisance algae and an accompanying degradation of water quality. A toxic red-tide bloom dominated by a dinoflagellate, *Cochlodinium heterolobatum,* occurred in Barnegat Bay in 1964 (Mountford, 1965). More recently, blooms of a brown-tide phytoplankter, *Aureococcus anophagefferens*, have been observed in Little Egg Harbor as noted previously, and repeated blooms of *Nannochloris atomus* have appeared since 1985 (Olsen and Kurtz, 1989; Olsen, 1997). According to Mountford (1984), the occurrence of *N. atomus* blooms may signal eutrophic conditions in the estuary.

C. The Bay

1. Pollution Concerns

Insidious alteration of estuarine communities and habitats is often linked to nutrient overenrichment, as well as the accumulation of toxic chemical contaminants from industrial and municipal wastes, dredge materials, and various nonpoint sources (Kennish, 1992, 1997). The deterioration of estuarine systems by pollutant inputs can be severe, as manifested by:

•degraded water quality coupled to hypoxia or anoxia over extensive areas;

•disease, abnormalities, reproductive failure, and mortality of fish and shellfish populations;

•changes in abundance, diversity, and distribution of estuarine organisms;

•loss of submerged aquatic vegetation, wetlands, and other critical habitats;

•closure of shellfish grounds and beaches due to chemical or microbial contamination;

•outbreaks of human disease caused by individuals swimming in contaminated marine waters or consuming contaminated shellfish.

All of these effects can greatly limit resource uses in these shallow coastal systems.

Pollution impacts in estuaries are most pronounced in benthic communities because of the accumulation of contaminants in bottom sediments, and the limited mobility of most benthic fauna. When exposed to increased organic loading, for example, estuarine macrobenthic communities commonly exhibit: (1) a decrease in species richness and an increase in total number of individuals attributable to the high density of a few opportunistic species; (2) a general reduction in biomass, although there may be an increase in biomass corresponding to a dense assemblage of opportunists; (3) a decrease in body size of the average species or individual; (4) a shift in the relative dominance of trophic guilds; and (5) a shallowing of that portion of the sediment column occupied by infauna (Weston, 1990).

Various human activities in the open waters and tidal creeks of Barnegat Bay, Manahawkin Bay, and Little Egg Harbor contribute to habitat loss and alteration. Commercial and recreational clamming, operation of personal watercraft (i.e., jet skis), and the use of motor boats can disrupt shallow benthic habitats. Dredging for maintenance of navigation channels, marinas, and lagoons not only destroys benthic habitats but also greatly increases mortality of benthic organisms. In addition, it increases turbidity levels and light attenuation which can decrease primary production in the estuary. Since 1960, federally funded dredging has been conducted at seven locations between Manasquan Inlet and Manahawkin. During the past 50 years, dredge spoils have been dumped either at designated locations in the estuary or at upland sites.

Freshwater entering the Barnegat Bay-Little Egg Harbor estuary contains nutrient and chemical contaminant loads that originate mainly from nonpoint sources in the watershed. These loads, which can impact biotic communities in the estuary, include contributions from surface water, groundwater seepage, and atmospheric deposition. Many factors affect the magnitude, transport, and fate of contaminants in the system. Contaminant levels in surface water, for example, are coupled to contributions from both groundwater influx and atmospheric deposition. Groundwater contaminants may enter at many different locations in the watershed. Atmospheric deposition can be a major source of groundwater contamination which, in turn, may be a primary source of surface water contamination. Alternatively, atmospheric deposition may contribute significant concentrations of contaminants directly to surface waters. Sound assessment of water quality in tributaries of Barnegat Bay, Manahawkin Bay, and Little Egg Harbor requires accurate identification and quantification of the most important sources of contaminant loadings, along with an understanding of the physical, chemical, and biological processes occurring along transport pathways.

2. Point Sources of Pollution

The Barnegat Bay-Little Egg Harbor estuary is most greatly affected by nonpoint sources of pollution such as runoff from agricultural, residential, and commercial properties, inputs from groundwater, and atmospheric deposition. The Oyster Creek Nuclear Generating Station (OCNGS) remains the most significant point source discharger in the system. Other potential point sources of pollution include leaky

underground storage tanks, landfills, and pipeline discharges. Effects of the OCNGS on the estuarine environment have been the focus of many detailed investigation (e.g., Tatham et al., 1977, 1978; Summers et al., 1989). The following discussion focuses on the impacts of the OCNGS on the biotic communities of Barnegat Bay.

a. Oyster Creek Nuclear Generating Station

The Oyster Creek Nuclear Generating Station (OCNGS) is a 630 megawatt nuclear power plant located between Forked River and Oyster Creek approximately 3.5 km west of Barnegat Bay (Figure 21). Consisting of a single boiling water reactor, the OCNGS operates with a nominal thermal efficiency of 32%, rejecting approximately two-thirds of thermal energy produced as waste heat into the environment. During operation, the station uses a once-through cooling system. Four circulating pumps, each with a design capacity of 435 m3/min, deliver a total of 1,739 m3/min of cooling water to the main condenser. This water is drawn from Barnegat Bay via the South Branch of Forked River and the intake canal of the station. Condensation of steam in the main condenser transfers waste heat to the circulating cooling water that flows into the discharge canal, Oyster Creek, and Barnegat Bay.

When all four circulating pumps are operating at full power, the temperature rise across the condenser approaches 12.8°C. The temperature change may increase to 18.3°C during a period when one circulating pump is out of operation. To mitigate the impact of the thermal discharges on aquatic biota in the discharge canal, Oyster Creek, and Barnegat Bay, two axial flow dilution pumps, each with a 983 m3/min capacity, divert water from the intake to the discharge canal to control the temperature level. A thermal plume forms in the bay as the effluent flows out of Oyster Creek. The morphology of the plume varies temporally, being affected principally by winds and tides. The plume is confined to roughly a 1.6-km radius about the mouth of Oyster Creek. On calm days the plume often fans out about the mouth of Oyster Creek, its shape affected by weak tidal currents; however, strong winds from the north or south cause the plume to form a narrow band abutting the shoreline. At times of peak operation, water temperatures rise 3° to 5°C above ambient levels at the mouth of Oyster Creek (Kennish et al., 1984).

Construction and operation of the OCNGS caused the loss and alteration of habitat in Forked River and Oyster Creek. Dredging and construction of the intake and discharge canals destroyed most of the original freshwater and low salinity habitats in the affected portions of the streams. Pumping at the station changed the salinity, temperature, and dissolved oxygen levels in both streams such that they became similar to those of the bay. Water flow in the South Branch of Forked River was reversed, being directed toward the station during operation. As a result of the changing water quality and flow, assemblages of organisms characteristic of Barnegat Bay replaced the typically brackish and freshwater communities in the lower portions of the South Branch of Forked River and Oyster Creek. The estuarine portion of Oyster Creek was expanded. A portion of the freshwater stream was replaced by estuarine habitat, and a new segment of aquatic habitat was created as a connection to Forked River (Summers et al., 1989). The OCNGS was constructed between December 1964 and September 1969, with operational testing commencing in August 1969 and commercial operation in December 1969.

Estuarine organisms are adversely affected by the OCNGS in the following ways: (1) by the calefaction of receiving waters due to waste heat discharges; (2) by the release of biocides and other contaminants; (3) by the impingement of larger organisms on intake screens; and (4) by the entrainment of smaller life forms in the cooling water systems. Calefaction or thermal loading in the discharge canal and Oyster

Creek directly interferes with physiological processes of biota, such as enzyme activity, feeding, reproduction, respiration, and photosynthesis. Less conspicuous, indirect effects, which are difficult to quantify, include greater vulnerability to disease, to changing gaseous solubilities, and to chemical toxicants associated with thermal enrichment. Significant physiological and behavioral responses of organisms affected by the thermal discharges involve: (1) an alteration of metabolic rates leading to a diminution of growth or death; and (2) behavioral adjustment manifested in avoidance or attraction reactions to the heated effluent.

Behavioral changes (e.g., attraction or avoidance responses) are commonly observed in finfish exposed to the thermal discharges. From June through September, for example, Atlantic menhaden (*Brevoortia tyrannus*), bluefish (*Pomatomus saltatrix*), and weakfish (*Cynoscion regalis*) avoid some part of Oyster Creek, and young winter flounder (*Pseudopleuronectes americanus*) avoid most of Oyster Creek because of high water temperatures. From fall through early winter, Atlantic menhaden, bluefish, spot (*Leiostomus xanthurus*), bay anchovy (*Anchoa mitchilli*), weakfish, and several other incidental species are attracted to the discharge canal. Some individuals of these species overwinter in the canal, but they do not show abnormal rates of parasitism or disease, retarded growth, or aberrant reproductive characteristics (Kennish et al., 1984). Large numbers of finfish attracted to the thermal discharges have occasionally experienced heat- or cold-shock mortality in the discharge canal and Oyster Creek (Table 23).

The warm water effluent has attracted some invertebrate populations to the area as well. The establishment of the tropical-subtropical shipworm, *Teredo bartschi*, in Oyster Creek during the mid-1970s and its subsequent spread into Forked River also have been ascribed to thermal discharges from the OCNGS, as well as to changes of salinity and water flow in Oyster Creek and Forked River due to operation of the station. In addition to *T. bartschi*, the occurrence of the tropical-subtropical shipworm, *T. furcifera*, in the Barnegat Bay system during the mid to late 1970s was related to the presence of thermal effluent in the Oyster Creek area. Thermal discharges from the OCNGS have generally extended the breeding season of shipworms, increased their growth rates (and hence the amount of their damage to wooden structures), and reduced their winter mortality rates (Hoagland and Crocket, 1981a,b).

The most notable chemical impacts are associated with power plant biocides. To maintain the design flow and heat exchanger efficiences at the OCNGS, chlorine is injected sequentially into six condenser sections each day to prevent and remove the buildup of bacterial slime and other fouling organisms in the condenser tubes. Maximum chlorination occurs during the summer to compensate for more rapid growth of fouling organisms at this time. Although chlorine destroys bacterial slimes very efficiently when added at regular intervals to condenser cooling water, it does not control macrofouling (e.g., mussels or clams) as well. Chlorine rapidly kills microorganisms directly and hydrolyzes the extracellular polymers that hold biofilms together, thereby preventing their accumulation on heat exchanger surfaces. Phytoplankton and zooplankton are also highly susceptible to power plant chlorination. However, mussels and other large shell-bearing organisms respond to intermittant chlorine dosing by closing their shells until the biocide concentration dissipates.

In general, chlorine begins to be lethally effective on marine fish at concentrations of about 0.01 mg/l (Mattice and Zittel, 1976), but temperature, the presence of other compounds (e.g., nitrogenous substances), and the physiological condition of the animals appear to affect their tolerance (Langford, 1983). When exposed to sufficiently high chlorine levels, juvenile and adult fish eventually die from anoxia as the biocide attacks the gills, resulting in the oxidation of hemoglobin to methemoglobin (Morgan and Carpenter, 1978). One chlorine related fish kill was documented in the discharge canal of the OCNGS in January 1974.

A byproduct of power plant chlorination is the propensity of chlorine to form toxic residual organic compounds (chloramines) which can be hazardous to many aquatic organisms. In addition, some of the organochlorine compounds that form can be highly refractory. The toxicity and fate of many of these persistent chlorinated compounds to estuarine organisms have not been determined.

Waste chlorinated water (< 0.05 mg/l) is rejected to the discharge canal. Biocidal releases have the potential to increase mortality of nontarget organisms in receiving waters, and hence are closely regulated. While low-level radioactive waste is also released to the discharge canal, the concentration of this material is too low to be hazardous to aquatic organisms or humans who consume contaminated seafood from the bay.

Of even greater concern than thermal loading and biocidal releases are impingement and entrainment effects. Impingement is the trapping of large organisms on trash racks and intake screens of the station. Most impinged organisms at the OCNGS are fish and blue crabs too large to pass through the 9.5-mm intake screens. These screens are periodically rotated and washed, with the impinged organisms diverted to the discharge canal through a sluiceway. Smaller organisms, such as the early life history stages of fish and invertebrates (eggs and larvae) which pass through the intake screens, enter the cooling water system. These entrained organisms experience a sudden temperature rise of 12°-13°C, shear and pressure forces, and mechanical stresses from contact with internal structures of the station. They may also be exposed to lethal levels of chlorine and its residuals during periods when the chemical is applied. Other organism are entrained in the dilution pump system. Organisms surviving impingement and entrainment are exposed to elevated temperatures and possibly excess chlorine residuals in the discharge canal. Impingement and entrainment have the potential to reduce the productivity of the system due to the loss of large numbers of organisms at the plant site.

Many factors influence impingement rates. Apart from intake flow velocities, the type of intake screens, the configuration of the intake structure, and the behavior and physiology of the organisms themselves all play prominent roles. Seasonal variations in impingement, which can be substantial, are affected by migration of populations, swimming performance, and changes in water temperature. The ability of an organism to withstand currents and hence impingement on intake screens depends greatly on its condition. The swimming performance of a fish is a function of several important factors, such as its developmental stage and nutritional condition, as well as the occurrence of parasite infestations, the presence of predators or prey, tides, time of day, and season.

Biotic factors must also be considered in entrainment mortality. For example, the seasonal densities of entrainable organisms in impacted systems are closely correlated with observed mortalities. Furthermore, the size, life stage, and relative susceptibility to injury of the entrained organisms play a major role in the observed mortality.

The absolute number of organisms impinged and entrained at the OCNGS is extremely high. The most comprehensive database on impingement and entrainment is for the years 1975-1977 and 1984-1985. From September 1975 through August 1977, about 13 million fish (79% of all individuals) and invertebrates (21%) were impinged on OCNGS intake screens (JCPL, 1978). The most abundant species impinged, in numerical order, were the blue crab (*Callinectes sapidus*), sand shrimp (*Crangon septemspinosa*), bay anchovy (*Anchoa mitchilli*), grass shrimp (*Palaemonetes vulgaris*), Atlantic menhaden (*Brevoortia tyrannus*), spot (*Leiostomus xanthurus*), Atlantic silverside (*Menidia menidia*), smallmouth flounder (*Etropus microstomus*), striped searobin (*Prionotus evolans*), and blueback herring (*Alosa aestivalis*). The estimated total mortality of these species due to impingement was 30%. Population surveys of fishes and macroinvertebrates indicate that the standing crop lost through impingement was <10% for species in central Barnegat Bay. No evidence exists that losses of organisms through impingement on the intake screens have had a discernible effect on invertebrate and fish

communities in the bay.

From November 1984 through December 1985, 22 million organisms were impinged at the OCNGS (EA, 1986). Sand shrimp, grass shrimp, and blue crabs accounted for 94% of the impinged organisms. Finfish represented no more than 2% of the annual impingement catch, with the most abundant species being the Atlantic silverside, bay anchovy, and northern pipefish (*Syngnathus fuscus*). The estimated annual impingement for 1984-1985 was the highest in 9 years of record, due primarily to the high impingement rates of sand shrimp. In December 1985 alone, nearly 7 million organisms were impinged at the OCNGS; most were sand shrimp.

In terms of entrainment, a total of 9.19×10^{13} microzooplankton (organisms <500 µm in size) and more than 4.25×10^{11} macrozooplankton (organisms >500 µm in size) were entrained through the OCNGS during the period September 1975 through August 1977. Most of the microzooplankton (78%) were holoplankton, although significant numbers of meroplankton (22%) also were entrained. Copepods (all developmental stages) accounted for 89% of all of the holoplankton.

Large numbers of organisms also pass through dilution pumps at the OCNGS. For instance, from November 1984 through December 1985, 1×10^{8} organisms were entrained through the dilution pumps. Copepods were the most abundant microzooplankton entrained, mysid shrimp (*Neomysis americana*) the most abundant macrozooplankton, and bay anchovy eggs the most abundant life stage of fish. Survival of the entrained organisms ranged from a low of 42% for the bay anchovy to more than 90% for the sand shrimp, blue crab, Atlantic silverside, northern pipefish, and winter flounder (*Pseudopleuronectes americanus*).

Despite the large numbers of eggs, larvae, and small life forms of Barnegat Bay organisms lost via in-plant passage at the OCNGS, these losses have not resulted in detectable impacts on biotic communities in Barnegat Bay. Effects of operation of the OCNGS on aquatic communities appear to be restricted to the discharge canal and Oyster Creek. Changes in species composition, species diversity, population densities, and primary production have been observed in near-field regions of the OCNGS (i.e., the discharge canal and Oyster Creek). For example, phytoplankton exhibit lower primary productivity, biomass, and diversity in Oyster Creek than other areas of the estuarine system. Mountford (1971) recorded a maximum decrease in gross productivity of 30.3%, a maximum decline in net productivity of 20.1%, and a maximum drop in biomass of 17.7% at the mouth of Oyster Creek when compared to the mouth of Forked River. Loveland et al. (1972) also registered a decrease in gross productivity (35%) at the mouth of Oyster Creek. Mountford (1971) and Hein (1977) documented lower phytoplankton diversity in the discharge canal and Oyster Creek than in the intake canal and Forked River. These differences were attributed to station operation.

Changes in abundance of some microzooplankton, macrozooplankton, and ichthyoplankton have been observed in the discharge canal and Oyster Creek (Tatham et al., 1977, 1978). Microzooplankton found to be less abundant at the mouth of Oyster Creek than at the condenser discharge of the station included barnacle larvae (72% less abundant at the mouth of the discharge canal), polychaete larvae (42%), copepod nauplii (19%), unidentified bivalve larvae (25%), *Acartia tonsa* (57%), and *Acartia* spp. (61%). Other microzooplankton were more numerous at the mouth of Oyster Creek than at the condenser discharge of the station; these included rotifers (103% more numerous at the mouth of the discharge canal), cyphonaute larvae (3,547%), gastropod larvae (70%), and *Mulinia lateralis* larvae (155%). Macrozooplankton showing lower densities in Oyster Creek than Forked River were *Crangon septemspinosa* zoeae; the mud crabs, *Neopanope texana*, *Panopeus herbstii*, and *Rhithropanopeus harrisi; Hippolyte* spp.; the mud shrimp, *Upogebia affinis*; hermit crabs, *Pagurus* spp.; and spider crabs, *Libinia* spp. The density of eggs, larvae, and juveniles of the bay anchovy (*A. mitchilli*), larvae of gobies (Family Gobiidae), and larvae of juveniles of the northern pipefish (*Syngnathus fuscus*) were lower in

Oyster Creek than Forked River.

Summers et al. (1989) employed three impact assessment models to estimate the fractional reduction in representative important species populations due to the OCNGS: the equivalent adult model, production foregone model, and spawning/nursery area of consequence model. The equivalent adult model was applied to populations of the winter flounder, bay anchovy, opposum shrimp (*Corophium* sp.), sand shrimp, hard clam (*Mercenaria mercenaria*), and blue crab. Results of this model showed that the equivalent adult losses for all these species, with the exception of the winter flounder, did not exceed the average commercial fishery for Barnegat Bay during the period 1975-1980.

The production foregone model was used to estimate the proportional decline in annual net production lost from bay anchovy, opossum shrimp, and sand shrimp populations due to impingement and entrainment at the OCNGS. Based on this model, the relative net production losses for these three forage species represented larger portions of the forage population production. The absolute magnitude of the losses was small except for the sand shrimp which lost 748,428 kg. Predator losses associated with this reduced forage production were estimated to be 7,484.3 kg.

The spawning/nursery area of consequence model was utilized to assess relative population losses of the winter flounder, bay anchovy, hard clam, blue crab, sand shrimp, and opossum shrimp as a result of OCNGS operation. Direct population losses were only significant for the sand shrimp (16.6%). Because of the minor role that sand shrimp play in the Barnegat Bay food web, the model projections suggest no direct economic ramifications of the losses and minimal rediversion of ecosystem productivity. The largest contributor to economic losses appears to be potential hard clam fishery losses, which were about 1% of the regional fishery for the study period.

Summers et al. (1989) stated that the OCNGS does not comply with the surface water quality standards for thermal discharges regulated by the New Jersey Department of Environmental Protection. However, discharge effects are small and localized. Changes in species composition, species diversity, population densities, and primary production are essentially confined to near-field regions of the OCNGS. According to Summers et al. (1989), continued operation of the OCNGS will not threaten the protection and propagation of balanced, indigenous populations in Barnegat Bay.

3. Nonpoint Sources of Pollution

Water quality degradation of the Barnegat Bay-Little Egg Harbor estuary is primarily caused by nonpoint sources of pollution. Two high priority management issues relate to nutrient loading and pathogens which are closely coupled to development and associated activities in the watershed, such as deforestation and construction, lawn and garden maintenance, and malfunctioning septic systems. Atmospheric deposition contributes substantially to nutrient input to the estuary. Stormwater discharges deliver significant concentrations of coliform bacteria. Nutrient overenrichment (eutrophication) can lead to several important changes in estuarine dynamics, including increased phytoplankton production and biomass, algal blooms, elevated water column turbidity, a decline in biodiversity, and dissolved oxygen depletion. Excessive nutrient input may shift primary production from an eelgrass-dominated system to a phytoplankton and seaweed-dominated system. This may be facilitated by algal blooms and

high turbidity conditions which reduce light penetration. High coliform bacteria levels, in turn, directly impact water quality and adversely affect human uses of the bay, such as shellfish harvesting, swimming, and boating.

4. Pollutants

a. Nutrients

Seitzinger and Pilling (1990) recorded low concentrations of nutrients in Barnegat Bay waters, with the concentrations of nitrate plus nitrite, ammonium, and phosphate amounting to ≤ 1.0 µM, ≤ 0.6 µM, and ≤ 0.5 µM, respectively. In addition, they estimated that minimal external inputs of inorganic nitrogen and phosphorus to the bay from both point and nonpoint sources were 4 mmol N/m2/d and 0.2 mmol P/m2/d. More recently, the New Jersey Department of Environmental Protection found that concentrations of nitrate and nitrite in the bay ranged from 0 to 200 µg N/L (NJDEP, 1996a). Most nitrogen (87-90%) was in organic form.

Seitzinger and Styles (1999; Appendix 2), assessing the temporal and spatial trends of nutrients in the estuary, showed that the highest concentrations of organic nitrogen (~40 µM) occurred in summer. They also reported that organic nitrogen concentrations were about 10x greater than those of dissolved inorganic nitrogen (i.e., nitrate, nitrite, and ammonium). The mean concentrations of nitrate (NO3-) plus nitrite (NO2-) were <4 µM, with the highest measurements recorded in winter (notably in the northern estuary) due to reduced biotic assimilation of nutrients at this time. Mean ammonium (NH43-) levels, in turn, amounted to < 2.5 µM; highest values likewise were registered in summer. Total nitrogen concentrations ranged from ~20-80 µM. Phosphate (PO43-) exhibited patterns similar to ammonium. Mean concentrations of phosphate were lower than those of the inorganic nitrogen forms, being <1 µM. Highest levels repeatedly developed in summer, a seasonal pattern typically observed in other Mid-Atlantic estuaries.

Moser (1997) showed that nitrogen loading in the northern bay (3.1 x 107 mmol DIN watershed/km2/yr) was substantially greater than that in the southern bay (2.7 x 106 mmol DIN watershed/km2/yr). She also revealed that the total diffuse inputs of dissolved inorganic nitrogen inputs (river = 118 mmol N/m2/yr; groundwater = 13 mmol N/m2/yr) to Barnegat Bay are comparable to the total atmospheric inputs (100 mmol N/m2/yr) to the system. Of much less significance are boat and marina inputs which amount to 10 mmol N/m2/yr.

Most nutrients not assimilated by plants are removed to bottom sediments in the bay or exported to the ocean. Moser (1997) estimated that 70% of the total nitrogen in Barnegat Bay was exported from the system. The predominant direction of nitrogen transport in the bay is from north to south.

Elevated nutrient inputs to the estuary from nonpoint sources can stimulate excessive phytoplankton growth, leading to accelerated bacterial respiration and a depression in dissolved oxygen levels which may culminate in mass mortality of organisms. In addition, greater phytoplankton abundance can reduce light penetration. This "shading effect" can cause the loss of submerged aquatic vegetation, much of which provides important habitat for many animals in the estuary. Hence, it is critical to continually monitor phytoplankton blooms in the system.

Olsen (1997) documented intense picoplanktonic algal blooms in the Barnegat Bay-Little Egg Harbor estuary between 1985 and 1996. These blooms occurred through the summer months each year. Maximum cell counts typically exceeded 106 cells/ml, with highest cell counts (~3 x 106 cells/ml) recorded in lower Barnegat Bay and Little Egg Harbor. Compared to other areas in the estuary, the blooms in the southern estuary began earlier (mid-June), continued with sustained high cell densities (5 x 105 to > 1.2 x 106 cells/ml), and lasted longer (to early October).

Nannochloris atomus, a minute nonmotile chlorophycean (green) alga, dominated the blooms, causing a yellowish to greenish-brown discoloration of the water during peak bloom periods. Other picoplankton comprising the blooms were a few minute flagellates (*Chlamydomonas* and *Micromonas*? sp.), short cylindrical forms (*Stichococcus* or a diatom *Minutocellus* sp.), and a coccoid cyanobacterium. Pennate diatoms (*Phaeodactylum*?, *Nitzschia* sp., and *Pyramimonas micron*), as well as a chrysophyte species (*Calycomonas ovalis*) represented the larger forms. Phytoflagellates (*Chroomonas* spp., *C. minuta*, *Pyramimonas grossii*, and *Chrysochromulina* sp.), diatoms (*Nitzschia*, *Cyclotella* sp. and *Cylindrotheca closterium*), and another chlorophyte (*Chlorella* sp.) were also identified in the blooms.

Blooms of the picoplanktonic chrysophyte, *Aureococcus anophagefferens*, also occurred in Little Egg Harbor during late spring and summer in 1995, 1997, and 1999 (Olsen, New Jersey Department of Protection, personal communication, 1999). Cell counts typically exceeded 106 cells/ml, with peak cell numbers (> 2 x 106 cells/ml) recorded in blooms during 1999. Brown tides of *A. anophagefferens* not only resulted in a distinctive golden-brown discoloration of the water but also caused reduced growth of hard clams (*Mercenaria mercenaria*) in the area. It has been suggested that salinity is a critical factor in brown tide bloom initiation in the estuary (Mahoney et al., 1997).

More extensive *Nannochloris* and *Aureococcus* blooms are a cause of concern because they may indicate increasing eutrophic conditions in the estuary. These blooms must be carefully monitored. A major goal is to delineate the environmental factors responsible for initiating the blooms. Once these factors are determined, remedial actions can be instituted to reduce the probability of future bloom events.

b. Pathogens

The input of pathogens (e.g., bacteria and viruses) from stormwater runoff, malfunctioning septic systems, boats, animals, and other sources can taint shellfish beds and cause the closure of bathing beaches, thereby impairing human uses of the estuary. Several serious human health diseases have been linked to pathogenic exposure in estuarine environments. Examples include dysentery, hepatitis A, and viral gastroenteritis. Although elevated coliform bacteria levels have periodically impaired human use of the estuary due to bathing beach and shellfish bed closures, there is no evidence that the bacteria or other pathogens have adversely affected the abundance, distribution, or diversity of organisms in the system.

New Jersey surface water quality standards support drinking water, recreational contact, and safe shellfish growing water uses (NJDEP, 1995). The maintenance of swimmable conditions for brackish backbay waters, such as the Barnegat Bay-Little Egg Harbor estuarine system, is determined by the levels of fecal coliform (indicator) bacteria recorded in water samples. A direct linear relationship exists between indicator bacteria and the occurrence of specific illnesses resulting from contact with infected water (National Resources Defense Council, 1992). The surface water quality standards in the New

Jersey for recreational contact with saline estuarine waters specify that the fecal coliform level shall not exceed a geometric mean of 50/100 ml within 1,500 ft (457 m) of the shoreline (nearshore). In addition, the fecal coliform level shall not exceed a geometric mean of 200/100 ml at distances between 1500 ft (457 m) and 15,840 ft (4,828 m) from the shoreline (farshore), nor should more than 10% of the total samples taken from these waters during any 30-day period exceed a geometric mean of 400/100 (N.J.A.C. 7:9B).

Carter (1997) compared the geometric means of fecal coliform levels at approximately 700 coastal marine and estuarine stations (including Barnegat Bay) during three time periods: 1974-1978, 1984-1988, and 1989-1992. She determined that 5% or less of these stations violated the nearshore and farshore recreational standards during each sampling period. Based on the survey results, she also concluded that water quality conditions were more degraded during the 1974-1978 and 1989-1992 periods than during the 1984-1988 period. More highly degraded water quality conditions during the 1989-1992 period is surprising considering the tighter pollution management controls implemented at this time.

Table 24 shows the number of Barnegat Bay beach closings recorded over the 1988-1998 period due to elevated fecal coliform bacteria concentrations. These data are based on fecal coliform levels in water samples collected within ~9 m of the shoreline. The highest frequency of violations were recorded after periods of rainfall, reflecting the effect of nonpoint source pollution inputs. For example, 84% of the water samples exceeding the surface water quality standard in 1988 were collected soon after rainfall (NJDEP, 1989). As is evident from Table 24, most of the beach closings were registered in 1989 (175), 1990 (186), and 1994 (127). The majority of these stations were located in the northern part of the bay along the shoreline at Lavellette, Seaside Heights, Seaside Park, Island Beach, Brick, Point Pleasant, Dover, Island Heights, Beachwood, Pine Beach, and Ocean Gate. Since 1995, there have been less than 50 beach closings documented each year in the bay, reflecting improved water quality conditions in recent years. Most of the beach closings over the 10-year period occurred at Windward Beach in Brick (117) and Beachwood Beach in Beachwood (119).

Coliform bacterial concentrations are regularly monitored in Barnegat Bay, Manahawkin Bay, and Little Egg Harbor to compare to standards that regulate surface water quality, swimming, and fishing in the system. Bacterial standards for shellfish harvesting and recreational waters are set by the Interstate Shellfish Sanitation Conference. While New Jersey bases its growing water classifications on the total coliform criterion, it also conducts corresponding fecal coliform determinations for each sampling station in accordance with the National Shellfish Sanitation Program. These fecal coliform data are viewed as adjunct information and are not directly used for classification. The State Shellfish Control Authority also has the option of choosing one of the two water monitoring sampling strategies for each growing area: the Adverse Pollution Condition Strategy or the Systematic Random Sampling Strategy.

The Adverse Pollution Condition Strategy requires that a minimum of five samples are collected each year under conditions that have historically resulted in elevated coliforms in the particular growing area. The results must be evaluated by adding the individual station sample results to the preexisting bacteriological sampling results to constitute a data set of at least 15 samples for each station. The adverse pollution conditions usually are related to tide and rainfall, but can derive from a point source of pollution or variation during a specific time of the year. Under this strategy, the total coliform median or geometric mean Most Probable Number (MPN) of the water does not exceed 70 per 100 ml and not more than 10% of the total samples exceeds an MPN of 330 per 100 ml for the three-tube decimal dilution test. Areas to be approved under the seasonal classification must be sampled and must meet the criterion during the time of the year that it is approved for the harvest of shellfish.

The Systematic Random Sampling Strategy requires the establishment of a random sampling plan before

field sampling begins. It can only be used in areas that are not affected by point sources of contamination. A minimum of six samples per station is collected each year and added to the database to obtain a sample size of 30 for statistical analysis. The bacteriological quality of every sampling station in Approved Areas shall have a total coliform median or geometric mean MPN not to exceed 70 per 100 ml, and the estimated 90th percentile shall not exceed an MPN of 330 per 100 ml. For Special Restricted Areas, the bacteriological quality shall not exceed a total coliform median or geometric mean MPN of 700 per 100 ml, and the estimated 90th percentile shall not exceed an MPN of 3,300 per 100 ml.

In addition to Approved and Special Restricted Areas, shellfish growing waters in Barnegat Bay, Manahawkin Bay, and Little Egg Harbor are classified as Seasonally Approved or Prohibited, depending on coliform bacteria concentrations and/or the presence of pollution sources that may impact water quality. The water quality of each growing area must be evaluated before the area can be classified by one of these designations. Shellfish growing water classifications are defined in the New Jersey Shellfish Growing Water Classification Code as follows:

•Approved Areas - waters approved for shellfish harvesting;

•Prohibited Areas - waters where shellfish harvesting is not permitted under any circumstances;

•Special Restricted Areas - waters where harvested shellfish must be purified before human consumption (applications for removal are considered for transplant, transfer, relaying, and depuration/controlled purification);

•Seasonal Areas - waters condemned and opened for the harvest of shellfish each year on either January 1 or November 1, with all seasonal areas closing on April 30 of each year;

•Condemned Areas - waters that are designated as Prohibited, Special Restricted, Seasonal, and Seasonal Special Restricted.

Applying the aforementioned designations, the general trend in the Barnegat Bay-Little Egg Harbor estuarine system over the past three decades has been toward less restrictive shellfish growing classifications, although local areas of water quality degradation continue that are related to increasing coliform bacteria input from nonpoint pollution sources. The largest areas of harvesting restriction of shellfish occur in tributaries of Barnegat Bay from Toms River northward and along the barrier island in the same portion of the bay. The harvesting of shellfish from all man-made lagoons and marinas is prohibited (USFDA, 1989).

Total and fecal coliform levels are important as indicators of overall water quality and the presence of "hot-spot" pollution sources (e.g., marinas). As noted above, the criterion for Approved Areas of shellfish growing waters includes a median or geometric mean total coliform concentration that does not exceed 70 per 100 ml. Analysis of data for 1976 and 1980 shows that the mean total coliform concentrations exceeded 70 per 100 ml only in the northern portion of Barnegat Bay. By 1987, the area exceeding the total coliform standard had increased slightly over that observed in 1976 and 1980.

The total coliform concentrations peaked during "rain" conditions (defined as ≥ 0.25 cm total rainfall for the sampling day plus two days prior to the sampling day). The area in the bay exceeding the shellfish standard of 70 per 100 ml was five times greater during summer wet weather conditions than during summer dry weather conditions in 1980 and 1987. Persistently elevated total coliform levels above the standard were observed in the northern bay along Island Beach State Park and at several locations along the mainland from Silver Bay to Gulf Point. Likely sources of coliforms include stormwater outfalls,

septic systems, and wildlife.

More recent water quality surveys have been conducted in Barnegat Bay and Little Egg Harbor to assess total and fecal coliform bacteria levels for the determination of appropriate shellfish harvesting classifications in different areas of the estuary. For example, approximately 1,000 water samples were collected between 1990 and 1995 at 41 monitoring stations each year in the Manasquan River and analyzed for total and fecal coliform bacteria concentrations by the three-tube MPN method (NJDEP, 1996b). The primary sources of these bacteria in the Manasquan River include stormwater discharges, boats and marinas, agricultural inputs from upstream areas, and wildlife. During this survey period, the total coliform concentration in the Manasquan River estuary consistently exceeded the shellfish standard of 70 per 100 ml for Approved Areas, whereas the upper reach, upstream of the Route 70 Bridge, frequently exceeded the Special Restricted standard. The area upstream of the Route 70 Bridge continues to exhibit the worst water quality and is now classified as Prohibited. The area between the Route 70 Bridge and the Manasquan Inlet, except for the Manasquan-Point Pleasant Canal and the immediate vicinity of marinas, continues to be classified as Special Restricted. Although water quality appears to be improving here, it is not yet to the point where an upgrade in classification is warranted.

Between June 1988 and April 1991, approximately 1,980 shellfish growing water samples were collected at 44 stations in northern Barnegat Bay between Bay Head and Seaweed Point. They were analyzed for total and fecal coliform bacteria by the three- tube MPN method. Because coliform levels are usually elevated during the summer season, most notably following rainfall, this area of Barnegat Bay was sampled under the Adverse Pollution Condition Strategy. Samples were collected more frequently during the winter in order to verify the Seasonally Approved section of this growing area, which is open for direct harvest and marketing of shellfish from January 1 through April 30 each year.

Results of the aforementioned analysis showed that both total and fecal coliform concentrations were generally higher in summer. The fecal coliform median standard was met at 42 of 44 sampling stations between Bay Head and Seaweed Point. The fecal coliform percentage standard was exceeded, albeit minimally, at 22 stations located north and south of the Swan Point relay waters. The fecal standards were met by both the Swan Point relay waters and adjacent areas. However, shellfish taken from the Swan Point relay lots exhibited a trend toward deteriorating bacterial quality with elevated fecal coliform levels in shellfish tissue. A recommendation was made to remove Swan Point from the relay program in 1992 and to select an alternate site (Laurel Harbor in Barnegat Bay).

Between 1988 and 1996, nearly 6,000 water samples were collected from Toms River and central Barnegat Bay from the Route 37 Bridge to Forked River and analyzed for total and fecal coliform bacteria using the three-tube MPN method. Waters of the Toms River have long been classified as Prohibited for shellfish harvesting. Although recent sampling indicates a potential upgrade of this area to a Special Restricted classification, no change has yet occurred.

The most recent change in classification in the central bay between Route 37 and Forked River occurred in 1994 when 72 ha of bay waters were reclassified from Seasonal (November 1-April 30) to Approved classification as a result of improving bacterial water quality in the area. Based on more than 5,600 water samples, bacteriological data from this area of the central bay complied with their respective National Shellfish Sanitation Program criteria for either Approved, Seasonal, or Special Restricted classification. A relationship also existed in this area for increasing MPN values during rainfall conditions.

More than 3,400 water samples were collected from southern Barnegat Bay to northern Little Egg Harbor during the period January 1, 1992 through December 31, 1994. They were analyzed for total and fecal coliform bacteria using the three-tube MPN method. Approximately 175 stations were monitored

during each year. The sampling area extends from Forked River across the bay to Island Beach State Park then southward approximately 27 km to Spray Beach. Most of the shellfish waters here are classified as Approved, with Seasonal and Special Restricted areas acting as a buffer along the developed sections of the shoreline. The most recent change in shellfish water classification in the area occurred in 1992 when 71 ha of Cedar Run Cove were reclassified from Seasonal to Special Restricted. Results of the water sample analysis indicated that the bacteriological data for each of the sampling stations complied with their respective National Shellfish Sanitation Program criteria for either Approved, Seasonal, or Special Restricted classification standard under the Adverse Pollution Criterion Sampling or Systematic Random Sampling strategies.

From October 1, 1993 through September 19, 1996, a total of 2,391 water samples were collected and analyzed for total and fecal coliform bacteria from shellfish waters of Little Egg Harbor using the three-tube MPN method. The sampling area extended from Long Point to Spray Beach southward approximately 8 km to Little Egg Inlet. Results of the water sample analysis indicated that the bacteriological data for each of the sampling stations complied with their respective National Shellfish Sanitation Program criteria for Approved, Seasonal, or Special Restricted classification designations .

c. Toxic Chemicals

Several classes of toxic chemicals commonly found in estuarine environments are potentially damaging to habitats and hazardous to biotic communities. Among the chemical pollutants of greatest concern are halogenated hydrocarbons, polycyclic aromatic hydrocarbons (PAHs), and heavy metals. Oil, which contains a wide array of toxic substances, also poses a serious threat to these coastal ecosystems. More than 70,000 synthetic chemicals have been introduced into marine environments during the past 50 years, many of which are toxic to marine life even in minute concentrations.

Because of the persistence of numerous toxic chemicals in estuarine environments and their accumulation by successive levels of food chains, a human health risk may exist from ingestion of carcinogen-contaminated seafood products. Estuarine organisms assimilate toxic chemicals via respiratory, dermal, and oral routes. Uptake of the contaminants is strongly dependent on their bioavailability. Accumulation of the contaminants is a function of many factors, such as temperature, salinity, diet, spawning period, and the ability of the organism to regulate chemical contaminants in the body. The toxicity of the contaminants, in turn, is also influenced by environmental factors.

The exposure of estuarine organisms to toxic levels of chemical contaminants elicits a range of pathological responses such as the lack of repair and regeneration of damaged tissue, inflammation and degeneration of tissue, neoplasm formation, and genetic derangement. Growth inhibition may arise, as well as changes in physiology, reproduction, and development. Feeding behavior, respiratory metabolism, and digestive efficiency may also be impaired. At elevated concentrations, death often ensues.

There is no heavy industrial activity, other than the Oyster Creek Nuclear Generating Station, that directly affects the Barnegat Bay-Little Egg Harbor estuary. In addition, this estuarine system is not a major shipping port for oil. Consequently, few studies have targeted toxic chemical contaminants in these waters, or their effects on biotic communities. Nevertheless, it is likely that both Barnegat Bay, Manahawkin Bay, and Little Egg Harbor receive inputs of toxic chemicals from various nonpoint pollution sources. For example, heavy metal contamination has been documented in bottom sediments of some areas of Barnegat Bay. Organochlorine and petroleum hydrocarbon compounds also occur in

the system, but their distributions and concentrations are largely unknown due to the lack of sufficient monitoring and assessment data. The suspected principal sources of hydrocarbons are stormwater discharges, river runoff, atmospheric deposition, boats, and marinas. The use of pesticides and herbicides in the watershed is a likely source of organochlorine contaminants in the system, although only DDT and its metabolites have actually been measured in sediment samples collected from Barnegat Bay.

The database on toxic chemicals in the Barnegat Bay-Little Egg Harbor estuary is not extensive. More data have been collected on metals than any other group of toxic chemicals. Additional studies are needed to determine the concentrations, distributions, and effects of toxic chemicals on biotic communities as well as sensitive habitats in the estuary.

Organochlorine Contaminants

DDT and its metabolites have been measured in muddy sedments collected from a number of stations in Barnegat Bay. The highest concentrations of these contaminants were recorded at stations north and south of the Thomas Mathis Bridge (State Highway 37), the mouth of Toms River, Kettle Creek, Forked River, and Oyster Creek (Rogers et al., 1990). Data on DDT and other chemical contaminants in Little Egg Harbor are lacking.

Metals

The concentrations of trace metals vary widely in estuaries, owing to fluxes of metals from natural sources, pulsed anthropogenic inputs, changes in the extent of weathering, erosion, and runoff, complex biogeochemical processes, and a range of bioaccumulation effects which often differ markedly within these coastal ecotones. Because of large natural inputs of trace metals from the weathering and erosion of rocks, soils, and ore-bearing deposits, as well as from volcanic activity and atmospheric fallout, it is usually difficult to assess the effects of elemental inputs from specific human activities. Anthropogenic enrichment of metals is often most evident where rivers flow through urban or metropolitan centers, and metal burdens are augmented by human wastes and discharges from industrial facilities. The influx of metals from farmlands represents a major route of entry in some rural areas. The fluxes of trace metals from various anthropogenic sources (e.g., metals released from sewages, metals leached from solid waste dumpsites, and metals derived from industrial processing of ores) largely account for the patchy mosaic of metal contamination that characterizes many estuaries. Detailed investigations have shown that trace metals are introduced into estuaries mainly via riverine discharges and atmospheric deposition.

Trace metals may be grouped into two categories: transitional metals and metalloids. Transitional metals (e.g., copper, cobalt, iron, and manganese) include those elements essential for metabolic function of organisms at low concentrations, but may be toxic at high concentrations. In contrast, metalloids (e.g., arsenic, cadmium, lead, mercury, selenium, and tin) are generally not required for metabolic activity, but may be toxic at low concentrations (Clark, 1992; Kennish, 1994). Aside from these trace metals, organometal pollutants (e.g., tributyl tin, alkylated lead, and methylmercury) are of primary concern

because they are particularly toxic to marine organisms and potentially deleterious to humans.

Various mechanisms and processes affecting trace metal-particle associations and dynamics control to a large degree the transport, accumulation, and fate of the metals in estuaries. Trace metal removal during estuarine mixing is accelerated by precipitation, interactions with particle surfaces and flocculating colloids, co-precipitation with organic, iron and/or manganese hydrous oxides, increased affinity of the metals for anions in seawater, and uptake by organisms. The distribution and behavior of dissolved and particulate trace metals are not only contingent on biogeochemical processes occurring during the mixing of river water and seawater in estuaries but also on the magnitude and location of natural and anthropogenic sources of the metals.

Because trace metals are particle-reactive and quickly sorb to suspended particulate matter or particulates at the sediment-water interface, a major fraction is ultimately deposited in bottom sediments. As a result, the concentrations of trace metals range from three to five orders of magnitude greater in bottom sediments than in overlying waters (van den Berg, 1993; Kennish, 1998). Estuarine bottom sediments act as metal repositories and serve as a primary source of these elements for biota and overlying waters (Bryan and Langston, 1992). Only a minor fraction typically escapes to nearshore oceanic environments (Turekian, 1977; Sinex and Wright, 1988).

Analysis of vertical profiles of trace metals in estuarine sediment cores yields valuable information for reconstructing the chronology of contamination problems in an area and for developing historical pollution records. The variation of metal concentrations with depth in estuarine sediment cores can be used to delineate temporal trends in metal inputs and behavior, since bottom sediments are long-term integrators of geochemical processes and metal contamination (Bricker, 1993). Metals accumulating in bottom sediments have both a natural and an anthropogenic signal, although it is often difficult to differentiate the two components (Alexander et al., 1993).

Several studies have examined trace metal concentrations in bottom sediments of Barnegat Bay. Rogers et al. (1990) reported that the levels of cadmium, chromium, lead, mercury, and zinc measured in sediments throughout the bay in 1972 appeared to be sufficiently high to affect estuarine organisms. All of these metals, except chromium, were also found in fish samples, with the highest values being those of lead in fish collected in the Toms River area.

Renwick (1983) investigated trace metal contamination in estuarine sediments along the New Jersey coastline from Monmouth to Cape May Counties. Highest metal concentrations were documented in the most densely populated portions of the study area. The absence of major industrial or harbor facilities near the sampling locations suggested that nonpoint sources (e.g., urban and suburban runoff, atmospheric deposition, and boats) are principally responsible for trace metal accumulation in bottom sediments of these back bay systems.

Within the Barnegat Bay study area, Renwick (1983) measured low levels of trace metals in sediments of Waretown Creek, Mud Channel, and Barnegat Channel. Moderate to high concentrations of trace metals were recorded in sediments of the Manasquan River (arsenic, lead, and zinc), Metedeconk River (arsenic, copper, lead, and mercury), Double Creek Channel (arsenic and lead), and West Creek (arsenic). Koehnken (1990) recorded elevated levels of lead at sampling stations in Toms River, attributing them to urban land uses in the area.

Moser (1997) studied the concentrations of trace metals in recent and historical sediments of Barnegat Bay. She also investigated the spatial and temporal variability of trace metals in the estuary and the possible sources of the contaminants. Sediment cores were collected in the estuary and its tributaries

from 1988-1990 and 1992-1993, and sediment samples were analyzed using atomic absorption spectroscopy and graphite furnace atomic absorption. Analysis of surface sections from the cores showed that copper, lead, and zinc were enriched in bay sediments. The highest concentrations occurred in sediments at or near marinas, where the levels of copper, cadmium, lead, and zinc were enriched above background. These elevated levels are not surprising because marinas are sites where antifouling boat-bottom paints, chromated copper arsenate preservatives, and other trace metal sources are commonly used.

Historical trends of trace metals in sediment cores collected at three sites in the bay indicate that lead concentrations were highest in sediments during the period from the mid-1970s to the early 1980s, and they have subsequently decreased to the present. Moser (1997) attributed the sharp decline in lead concentrations after the 1970s to the removal of lead as an additive in gasoline. The consumption of leaded gasoline peaked in 1975. Elevated levels of trace metals in bottom sediments is a cause of concern because of the potential toxicity of the metals to benthic organisms. In addition, biomagnification of the metals up the food chain may pose a hazard to humans consuming seafood products from the estuary. However, no data are available on the toxicity or biomagnification of trace metals in the Barnegat Bay-Little Egg Harbor estuarine system.

Burger (1997) examined heavy metals in colonial-nesting birds of Barnegat Bay, using concentrations in eggs and feathers as a bioindicators of contamination. The highest levels of mercury in eggs and feathers amounted to 3.8 ppm and 10.3 ppm, respectively. Mercury levels of 1 ppm in eggs and 5 to 40 ppm in feathers are known to produce adverse effects, such as impaired reproduction. The Forster's tern and black skimmer showed high egg levels of mercury, and the great egret, snowy egret, and black skimmer showed high feather levels of the contaminant. Mercury levels in the eggs of some wild birds are within the range known to increase embryo and chick mortality and to decrease hatchability and chick weight. Similarly, mercury levels in the feathers of some wild birds are within the range which may cause lower hatchability of eggs, abnormalities in adult behavior, and sterility.

Oil

The Barnegat Bay-Little Egg Harbor estuary receives waste oil from various nonpoint sources on land and from boats (motors) in the waterbody itself. While the greatest input of oil is presumed to be near marinas because of the large number of vessels anchored there, the waste oil may enter the estuary almost anywhere, since more than 50,000 boats use the estuary over an annual period (Rogers et al., 1990). However, because the concentrations of waste oil and petroleum hydrocarbons have not been quantified in the estuary, it is not possible at present to assess their potential impacts.

The noxious effects of oil pollution on estuarine and marine communities are well chronicled, as are the damaging impacts on sensitive habitats areas (Clark, 1992; Kennish, 1992, 1994, 1997). Oil consists of many chemical compounds that are toxic to marine life. The aliphatic and aromatic hydrocarbon fractions of dissolved oil, for example, can degrade estuarine populations over extensive areas due to their extreme toxicity, rapid uptake by biota, and persistence in the environment. These fractions tend to bioconcentrate in estuarine organisms because of their high lipid solubility, and thus are a concern to humans consuming commercially and recreationally important finfish and shellfish from the estuary. Petroleum hydrocarbons sorb readily to particulate matter and accumulate in bottom sediments, where they may pose a chronic threat to the benthos. Water soluble compounds (e.g., benzene, toluene, and

xylene) can kill meroplankton, ichthyoplankton, or other life stages of organisms exposed to them in the water column, even at concentrations as low as 5 mg/l. Due to the serious hazards posed by oil pollution in estuaries, particularly systems with restricted circulation, it is deemed to be necessary to conduct a future investigation of oil contamination in Barnegat Bay, Manahawkin Bay, and Little Egg Harbor.

Polycyclic Aromatic Hydrocarbons

Among the most ubiquitous organic contaminants in estuaries are the polycyclic aromatic hydrocarbons (PAHs), a group of potentially carcinogenic, mutagenic, and teratogenic compounds. Consisting of hydrogen and carbon arranged in the form of two or more fused benzene rings in linear, angular, or cluster arrangements with substituted groups possibly attached to one or more rings, PAHs encompass a wide range of chemicals from naphthalene ($C_{10}H_8$ two rings) to coronene ($C_{24}H_{12}$, seven rings). PAHs, although observed in estuaries worldwide, are found in highest concentrations in systems near urban, industrialized centers. A concern exists regarding the carcinogenic and mutagenic risks to humans who consume PAH-contaminated estuarine and marine seafood products.

PAH compounds originate from a variety of anthropogenic sources (e.g., municipal and industrial effluents, creosote, oil spills, urban and agricultural runoff, fossil fuel combustion, asphalt production, and waste incineration). Incomplete combustion of organic matter, especially in the high temperature (500-800°C) range, is a primary mechanism for atmospheric contamination by PAH compounds, many of which enter estuarine and marine waters via fallout. The process of thermal decomposition of organic molecules and subsequent recombination of the organic particles (pyrolysis) represents a principal pathway of PAH formation. Hence, natural sources of PAHs (e.g., forest and brush fires and volcanic eruptions) also can be important.

Eisler (1987) estimated that 2.3×10^5 mt of PAHs enter aquatic environments annually, being derived mainly from oil spills (1.7×10^5 mt) and atmospheric deposition (0.5×10^5 mt) (Table 25). Forest and brush fires (0.19×10^5 mt) and agricultural burning (0.13×10^5 mt) are the major sources of PAHs for the atmosphere. Wastewaters, surface land runoff, and biosynthesis supply relatively small quantities of PAHs to marine environments, with each contributing less than 0.05×10^5 mt/yr.

As in the case of polluting oil, PAH contamination has not been investigated in the Barnegat Bay ecosystem. However, because of the broad array of anthropogenic sources of the compounds and their potential toxicity to estuarine and marine organisms, it is important to undertake a study of the levels of the contaminants in both biotic and abiotic media of the estuary. PAHs are relatively insoluble in water, sorb strongly to particulate matter, and accumulate in bottom sediments. Hence, it is likely that benthic organisms are exposed to the highest concentrations of PAH compounds. Future studies of PAHs in Barnegat Bay and Little Egg Harbor should focus on the concentrations of the contaminants in bottom sediments and benthic communities.

5. Other Human Impacts

a. Dredging and Dredge Material Disposal

Both dredging and dredge material disposal affect water quality, as well as benthic communities and habitats. The greatest immediate impacts of dredging on the benthic community and habitat are attributable to sediment removal from the estuarine floor which often kills many of the entrained organisms. Other adverse effects are ascribable to redeposition of suspended sediment subsequent to dredging, increased turbidity at the dredging site, and the release of contaminants from sediments (e.g., trace metals, halogenated hydrocarbons, polycyclic aromatic hydrocarbons, etc.).

Mortality of the benthos occurs from mechanical damage by the dredge itself and from smothering by sediment when the organisms are picked up or deposited at disposal sites. Recovery of the benthic community varies considerably at dredging and dredge material disposal sites, being contingent upon the time of dredging or dredge material disposal relative to the reproductive periods of the benthic populations. The dispersal of larval stages also plays an important role. Complete recovery of the benthic community often requires months or even years to complete, with opportunistic species settling first, followed by equilibrium assemblages in a successional sequence (Rhoads and Boyer, 1982; Kennish, 1990). Effects of dredging and dredge material disposal on mobile species are less clear since many of these forms merely leave the impacted areas until conditions are suitable once again for habitation (Weinstein, 1996).

When turbidity is high at a dredge or dredge material disposal site, primary productivity of phytoplankton and benthic flora can decrease abruptly. However, these effects generally are ephemeral. In contrast, the release of nutrients from bottom sediments during dredging or dredge material disposal can enhance primary productivity, although this process may exacerbate eutrophic conditions in those systems characterized by high concentrations of nitrogen and phosphorus. Dissolved oxygen levels may decline substantially as a result.

Dredging also produces some beneficial effects. For example, dredging improves circulation in the estuary by deepening waterways. As a consequence, there is generally more even distribution of temperature, salinity, dissolved oxygen, and other physical-chemcial factors which may enable organisms to disperse and colonize new habitats. Finfish and invertebrate migrations (e.g., flounder and shrimp) usually are facilitated by the improved circulation and increased depths of waterways. In addition, the increased depths can create important sanctuaries for some species from the extreme low or high temperatures during the winter and summer months, respectively. New spawning grounds may be generated for some species, although these grounds are typically of limited extent.

Most dredging in the Barnegat Bay-Little Egg Harbor estuarine system has historically occurred at the inlets and along the Intracoastal Waterway (Table 26). The amount of sediment dredged over an annual period from the inlets has ranged from ~10,000 m3 to more than 1,000,000 m3. While the volume of sediment removed from the inlets has occasionally been large, these are areas with less extensive benthic communities. Thus, the direct impacts of dredging on biota at the inlets are likely to be less significant than those at dredging sites elsewhere in the estuary. However, because the impacts of dredging on biotic communities in the system have not been quantified, it is not possible to make meaningful comparisons. The U.S. Army Corps of Engineers has dredged at seven locations along the Intracoastal Waterway and Oyster Creek Channel, but dredging is conducted much less frequently at these locations than at the inlets. Dredging maintains the Intracoastal Waterway to a depth of 1.5 to 3.7 m below mean low water and a width of 30 m over most of its length.

Dredged sediment has been dumped at a few disposal sites in the estuary, although most are now abandoned. Dredged spoil islands have been created which serve as valuable habitat for many organisms. Other disposal options that may be considered in the future include ocean disposal and

upland disposal.

b. Boating

The estimated number of boats using Barnegat Bay increased from 30,000 to 53,200 between 1979 and 1988. An estimated 54,635 registered boats are housed in the immediate region of the Barnegat Bay-Little Egg Harbor estuarine system, and an additional estimated 9,320 registered boats are housed in the adjacent Manasquan River watershed. In total, Ocean County currently has 197 marinas with 15,368 slips. Tiedemann et al. (1997) disclosed that the Manasquan Inlet and the Manasquan-Point Pleasant Canal are the most heavily utilized waterways of the Manasquan River estuary, with more than 1,500 vessels passing through the inlet during a 10-hour period on a summer weekend and more than 1,200 vessels passing through the canal during a similar weekend period.

Among the most significant impacts of boating activity in estuaries and coastal marine waters are increased turbulence, enhanced sediment and contaminant resuspension, laceration of submerged aquatic vegetation, decreased substrate stability, loss of benthic habitat, shearing of plankton, disturbance of shorebird populations, and toxic chemical emissions from boat engines (Crawford et al., 1998). In shallow, heavily utilized systems such as the Barnegat Bay-Little Egg Harbor estuary, these impacts can be substantial. Heavy boat use has been coupled to several specific types of pollution, notably sewage, oil, antifouling paints, plastic debris, and litter (Millekin and Lee, 1990; Chesapeake Bay Program, 1991). Aside from impacting water quality, boats can physically disrupt bottom habitats. In the shallow waters of Barnegat Bay and Little Egg Harbor, prop scarring may damage benthic habitats. Submerged aquatic vegetation in the bay and wetlands along the bay perimeter and in tidal creeks are particularly susceptible to boating activity. The use of personal watercraft has increased dramatically during the past few years. Improper handling of personal watercraft can be hazardous to rooted vegetation along the shallow flats, tidal creeks, and wetlands along the perimeters of the estuary. Colonial waterbird nesting and staging areas are easily destroyed by human activities in these areas. Increased turbidity associated with heavy boat traffic in the estuary may reduce primary productivity, although this impact is likely to be ephemeral.

The effects of boating activity and personal watercraft use on biotic communities in the Barnegat Bay-Little Egg Harbor estuary are largely unknown. However, because of the extreme shallowness of the estuary and the heavy boat use in the system, it is highly probable that power boat operation impacts some biotic components. Future research programs must address this largely unresolved issue.

XII. C ONCLUSIONS

Both point and nonpoint sources of pollution affect biotic communities in the Barnegat Bay-Little Egg Harbor estuary. Many of these pollution sources originate from human activities in the watershed, although others derive from multiple uses of the estuary itself. Much of the pollution that potentially

threatens estuarine organisms (e.g., excess nutrients, xenobiotics, organic loading, suspended solids) is closely coupled to ongoing development in the watershed. For example, the increase in impervious cover associated with infrastructure growth has accelerated runoff and inputs of pollutants to the estuary. Where development is most extensive in northern watershed areas and along the barrier island complex, greater nonpoint source pollutant inputs are expected. In these areas, the influx of pathogenic organisms (e.g., coliform bacteria) appears to degrade water quality during some periods of the year.

Notable chemical contaminants occurring in biota, sediments, or overlying estuarine waters include halogenated hydrocarbons, polycyclic aromatic hydrocarbons, trace metals, and radioactive substances. Operation of the Oyster Creek Nuclear Generating Station is not only responsible for low-level radioactive waste in the estuary but also for increased mortality of estuarine organisms due to biocidal releases, thermal discharges, and impingement and entrainment effects of the station's cooling water system. Nearly all investigations of anthropogenic impacts on biotic communities in the estuary have focused on power plant activities. Little, if any, information is available on the influx, accumulation, and effects of toxic substances on organisms in the system, although in many other estuarine and coastal marine waters insidious alteration of biotic communities attributable to such toxicants is well documented.

Aside from adverse environmental effects in the estuary associated with watershed development, activities in the estuary itself (e.g., dredging, jet skiing, and boating) also directly impact organisms and habitats. However, they have not been adequately investigated. More studies must be conducted to determine the magnitude of these anthropogenic impacts on the estuarine system.

Literature Cited

Adams, H. 1993. Farmland assessment summary. Division of Taxation, Trenton, New

Jersey.

Adams, H. 1997. 1996 Farmland assessment summary. Division of Taxation, Trenton,

New Jersey.

Alexander, C. R., R. G. Smith, F. D. Calder, S. J. Schropp, and H. L. Windom. 1993. The historical record of metal enrichment in two Florida estuaries. Estuaries, 16: 627-637.

Anonymous. no date. Wellhead protection project. Better Homes and Groundwater, Stevens Point, Wisconsin.

Bachman, L. J. and P. J. Phillips. 1996. Hydrologic landscapes on the Delmarva

Peninsula. Part 2: Estimates of base flow nitrogen load to Chesapeake Bay. Water Resourc. Bull., 23:779-791.

Bachman, L. J., B. Lindsay, J. Brakebill, and D. S. Powars. 1998. Ground water discharge and base flow nitrate loads to nontidal streams and their relation to a hydrogeomorphic classification of the

Chesapeake Bay watershed, Middle Atlantic Coast. USGS Water Resources Investigation Report 98-4059, U.S. Geological Survey, Washington, D.C. 71 p.

Ben-Shahar, R., and J. D. Skinner. 1988. Habitat preferences of African ungulates derived by uni- and multivariate analyses. Ecology, 69:1479-1485.

Bergman, D. J. and Associates. 1990. Ocean County water supply study: projections of water demands and population. Technical Report, Ocean County, Toms River, New Jersey.

Bricker, S. B. 1993. The history of Cu, Pb, and Zn inputs to Narragansett Bay, Rhode Island as recorded by salt-marsh sediments. Estuaries, 16:589-607.

Bryan, G. W. and W. J. Langston. 1992. Bioavailability, accumulation, and effects of heavy metals in sediments with special reference to United Kingdom estuaries: a review. Environ. Pollut., 76:89-131.

Burger, J. 1997. Avian studies on Barnegat Bay. *In*: Flimlin, G. E. and M. J. Kennish, (eds.), *Proceedings of the Barnegat Bay Ecosystem Workshop*. Rutgers Cooperative Extension of Ocean County, Toms River, New Jersey, pp. 345-350.

Carter, G. P. 1997. Eight characterizing trends in the Barnegat Bay watershed, Ocean County, New Jersey. *In*: Flimlin, G. E. and M. J. Kennish, (eds.), *Proceedings of the Barnegat Bay Ecosystem Workshop*. Cooperative Extension of Ocean County, Toms River, New Jersey, pp. 1-15.

Cavigelli, M. A., S. R. Deming, L. K. Probyn, and R. R. Harwood (eds.). 1998. Field crop ecology: managing biological processes for productivity and environmental quality. Michigan State University Extension Bulletin E-2646, East Lansing, Michigan.

Chang, D. H. S. and H. G. Gauch, Jr. 1986. Multivariate analysis of plant communities and environmental factors in Ngari, Tebet. Ecology, 67:1568-1575.

Chesapeake Bay Program. 1991. Recreational boat pollution and the Chesapeake Bay: a report to the Chesapeake Executive Council. Technical Report, Chesapeake Bay Commission, Annapolis, Maryland.

Clark, R. B. 1992. *Marine Pollution*, 3rd ed., Clarendon Press, Oxford.

Coale, F. J. and J. A. Olear. 1996. The relationship between soil test phosphorus level and the concentration of dissolved and potentially transportable phosphorus in field drainage water. Technical Report, Chesapeake Research Consortium, Inc., Edgewater, Maryland.

Crawford, R. E., N. E. Stolpe, and M. J. Moore (Eds.). 1998. The environmental impacts of boating: proceedings of a workshop held at Woods Hole Oceanographic Institution, Woods Hole, Massachusetts (USA) December 7 to 9, 1994. Technical Report WHOI-98-03, Woods Hole Oceanographic Institution, Woods Hole Massachusetts.

Dane County, Wisconsin. no date. Water watch, 210 Martin Luther King, Jr., Boulevard, Madison, Wisconsin.

Davis, W. S. and T. P. Simon. 1995. Biological assessment and criteria: tools for water resource planning and decision making. Lewis Publishers, Boca Raton, Florida. 415 p.

Digby, P. G. N. and R. A. Kempton. 1995. Multivariate analysis of ecological communities. Chapman and Hall, New York. 206 p.

EA. 1986. Entrainment and impingement studies at Oyster Creek Nuclear Generating Station 1984 - 1985. Technical Report, EA Engineering, Science, and Technology, Inc., Sparks, Maryland.

Edds, D. R. 1993. Fish assemblage structure and environmental correlates in Nepal's Gandaki River. Copeia 1993:48-60.

Eisler, R. 1987. Polycyclic aromatic hydrocarbon hazards to fish, wildlife, and invertebrates: a synoptic review. Biol. Rept. 85(1.11), U.S. Fish and Wildlife Service, Washington, D.C.

Elving, D. C., K. R. Wilson, J. G. Ebel, K. L. Manzell, W. H. Gutenmann, and D. J. Lisk. 1994. Migration of lead and arsenic in old orchard soils in the Georgian Bay region of Ontario. Chemosphere, 29:407-413.

Farifax Soil and Water Conservation Districts 1997. 1997. You and Your Land - A Homeowners Guide for the Potomac River Watershed. Soil and Water Conservation Districts, Fairfax, Virginia.

Fegeas, R. G., R. W. Claire, S. C. Guptill, K. E. Anderson, and C. A. Hallam. 1983. Landuse and land cover digital data. U.S. Geological Survey Circular 895-E, U.S. Geological Survey, Washington, D.C. 21 p.

Friedman, D. B. 1999. Monitoring data and narratives on the Barnegat Bay estuary and watershed demonstration projects data. Ocean County Soil Conservation District, Forked River, New Jersey.

Gauch, H. G. Jr. 1982. *Multivariate Analysis in Community Ecology*. Cambridge University Press, Cambridge, England. 298 p.

Galacatos, K., D. J. Stewart, and M. Ibarra. 1996. Fish community patterns of lagoons and associated tributaries in the Ecuadorian Amazon. Copeia, 1996: 875-894.

Granden, J. 1993. A survey of Ocean County residents performing soil tests. Ocean County Soil Conservation District, Forked River, New Jersey.

Grandin, B. A. 1993. Exploring householder's use of lawn and garden chemicals in a subwatershed of the Great Swamp: preliminary findings. Technical Report, Department of Human Ecology, Cook College, Rutgers University, New Brunswick, New Jersey.

Heckman, J. and J. Murphy. 1994. Fertilizing the home lawn. Rutgers Cooperative Extension of Middlesex County, New Brunswick, New Jersey.

Hein, M. K. 1977. Effects of thermal discharges on the structure of periphytic diatom communities. M.S. thesis, Rutgers University, New Brunswick, New Jersey.

Hilsenhoff, W. L. 1988. Rapid field assessment of organic pollution with a family-level biotic index. J. North Am. Benthol. Soc., 7: 65-68.

Hirsh, R. M. 1982. A comparison of four stream flow record extension techniques. Water Resourc. Res., 18:1081-1088.

Hoagland, K. E. and L. Crocket. 1981a. Ecological studies of woodboring bivalves in the vicinity of the Oyster Creek Nuclear Generating Station. Technical Report NUREG/CR-1855, U.S. Nuclear Regulatory Commission, Washington, D.C.

Hoagland, K. E. and L. Crocket. 1981b. Ecological studies of woodboring bivalves in the vicinity of the Oyster Creek Nuclear Generating Station. Technical Report NUREG/CR-1939, Vol. 3, U.S. Nuclear Regulatory Commission, Washington, D.C.

Hopkinson, C. S., Jr. and J. J. Vallino. 1995. The relationships among man's activities in watersheds and estuaries: a model of runoff effects on patterns of estuarine community metabolism. Estuaries, 18:598-621.

Hunchak-Kariouk, K. 1999. Relation of water quality to land use in the drainage basins

of four tributaries to the Toms River, New Jersey, 1994-95. U.S. Geological Survey Water Resources Investigations Report 99-4001, Prepared in Cooperation with the New Jersey Department of Environmental Protection, U.S. Geological Survey, West Trenton, New Jersey.

Hunchak-Kariouk, K., D. K. Buxton, and R. E. Hickman. 1999. Relations of surface water quality to stream flow in the Atlantic Coastal, Lower Delaware River, and Delaware Bay Basins. U.S. Geological Survey Water Resources Investigation Report 98-4244, West Trenton, New Jersey. 146 p.

Ingenito, R. 1999. Septic systems within Ocean County, New Jersey. Ocean County Health Department, Toms River, New Jersey.

JCPL. 1978. Oyster Creek and Forked River Nuclear Generating Stations 316 (a) and (b) Demonstration, Volumes 1-5. Technical Reports, Jersey Central Power and Light Company, Morristown, New Jersey.

Jongman, R. H. G., C. J. F. ter Braak, and O. F. R. van Tongeren. 1995. Data Analysis in Community and Landscape Ecology. Cambridge University Press, Cambridge, England. 299 p.

Kennish, M. J., M. B. Roche, and T. R. Tatham. 1984. Anthropogenic effects on aquatic communities. *In*: Kennish, M. J. and R. A. Lutz (eds.), *Ecology of Barnegat Bay, New Jersey*. Springer-Verlag, New York, pp. 318-338.

Kennish, M. J. 1990. *Ecology of Estuaries*, Vol. 2, *Biological Aspects*. CRC Press, Boca Raton, Florida. 391 p.

Kennish, M. J. 1992. *Ecology of Estuaries: Anthropogenic Effects*. CRC Press, Boca Raton, Florida. 494 p.

Kennish, M. J. (Ed.). 1994. *Practical Handbook of Marine Science*, 2nd ed. CRC Press Boca Raton, Florida. 566 p.

Kennish, M. J. (Ed.). 1997. Practical Handbook of Estuarine and Marine Pollution. CRC Press, Boca Raton, Florida. 511 p.

Kennish, M. J. (Ed.). 1998. Trace metal-sediment dynamics in estuaries: pollution assessment. Rev. Environ. Contam. Toxicol., 155:73-114.

Koehnken, L. 1990. The composition of fine-grained weathering products in a large tropical river system, and the transport of metals in fine-grained sediments in a temperate estuary. Ph.D. Thesis, Princeton University, Princeton, New Jersey.

Lacombe, P. J. 1996. Water levels in, extent of freshwater in, and water withdrawal from eight major confined aquifers, New Jersey Coastal Plain, 1993. Proceedings of the 1996 Spring Meeting, American Geophysical Union, Estuarine Research Federation, Geochemical Society, and Mineralogical Society, Baltimore, Maryland.

Langford, T. E. 1983. *Electricity Generation and the Ecology of Natural Waters*. Liverpool University Press, Liverpool. 383 p.

Lathrop, R. G., Jr., J. A. Bognar, A. C. Henrickson, and P. D. Bowers. 1999. Data synthesis effort for the Barnegat Bay Estuary Program: habitat loss and alteration in the Barnegat Bay region. Technical Report, Center for Remote Sensing and Spatial Analysis, Rutgers University, New Brunswick, New Jersey.

Leland, H. V., J. L. Carter, and S. V. Fend. 1986. Use of detrended correspondence analysis to evaluate factors controlling spatial distribution of benthic insects. Hydrobiologia, 132:113-123.

Loeb, S. L and A. Spacie. 1994. *Biological Monitoring of Aquatic Systems*. Lewis Publishers, Boca Raton, Florida. 381 p.

Loveland, R. E., E. T. Moul, D. A. Busch, P. H. Sandine, S. S. Shafto, and J. McCarty.1972. The qualitative and quantitative analysis of benthic flora and fauna of Barnegat Bay before and after the onset of thermal addition. Technical Report, Rutgers University, New Brunswick, New Jersey.

Mahoney, J. B., A. Codella, and K. I. Keating. 1997. Occurrence of brown tide, *Aureococcus anophagefferens*, in the Barnegat Bay system. *In*: Flimlin, G. E and M. J. Kennish (eds.), *Proceedings of the Barnegat Bay Ecosystem Workshop*. Cooperative Extension of Ocean County, Toms River, New Jersey, pp. 153-163.

Mattice, J. S. and H. E. Zittel. 1976. Site-specific evaluation of power plant chlorination. J. Wat. Pollut. Cont. Fed., 48:2284-2292.

McKeon, D. 1999. Municipalities within Ocean County with nonpoint source sensitive ordinances. Ocean County Planning Department, Toms River, New Jersey.

Milliken, A. and V. Lee. 1990. Pollution impacts from recreational boating: a bibliography and summary review. Technical Report, Rhode Island Sea Grant College Program, Narragansett, Rhode Island.

Modica, E. 1999. Source and age of ground water seepage to streams. Fact Sheet FS-063-99, U.S. Geological Survey, West Trenton, New Jersey. Morgan, R. P., II and E. J. Carpenter. 1978. Biocides. *In*: Schubel, J. R. and B. Marcy, Jr. (eds.), *Power Plant Entrainment: A Biological Assessment*. Academic Press, New York, pp. 95-115.

Moser, F. C. 1997. Sources and sinks of nitrogen and trace metals, and benthic macrofauna assemblages in Barnegat Bay, New Jersey. Ph.D. thesis, Rutgers University, New Brunswick, New Jersey.

Mountford, K. 1965. A late summer red tide in Barnegat Bay, New Jersey. Underwater Naturalist, 3:32-34.

Mountford, K. 1971. Plankton studies in Barnegat Bay. Ph.D. Thesis, Rutgers University, New Brunswick, New Jersey.

Mountford, K. 1984. Phytoplankton. *In*: Kennish, M. J. and R. A. Lutz (eds.), *Ecology of Barnegat Bay, New Jersey*. Springer-Verlag, New York, pp. 52-77.

Murphy, E. A. and M. Aucott. 1998. An assessment of the amounts of arsenical pesticides used historically in a geographical area. Sci. Tot. Environ., 218:89-101.

Murphy, J. 1995. Turfgrass seed selection for home lawns. Rutgers Cooperative Extension of Middlesex County, New Brunswick, New Jersey.

National Resources Defense Council 1992. Testing the waters: a national perspective on beach closing. Technical Report, National Resources Defense Council, Washington, D.C.

New Jersey Department of Agriculture. 1987. New Jersey equine industry. Technical Report New Jersey Department of Agriculture, Trenton, New Jersey.

New Jersey Department of Agriculture. 1996. New Jersey equine industry. Tech. Rept., New Jersey Department of Agriculture, Trenton, New Jersey.

New Jersey Department of Environmental Protection. 1996. New Jersey statewide water supply plan -- water for the 21st Century. Technical Report, New Jersey Department of Environmental Protection, Trenton, New Jersey.

NJDEP. 1989. Annual report: The Cooperative Coastal Monitoring Program. Technical Report, New Jersey Department of Environmental Protection, Trenton, New Jersey.

NJDEP. 1994. The establishment of ecoregion biological reference sites for New Jersey Streams. Technical Report, New Jersey Department of Environmental Protection, Bureau of Water Monitoring, Trenton, New Jersey.

NJDEP. 1995. New Jersey 1994 state water quality inventory report. Technical Report, New Jersey Department of Environmental Protection, Trenton, New Jersey.

NJDEP. 1996a. New Jersey Statewide Water Supply Plan: The Vital Resource - Water for the 21st Century. Technical Report, New Jersey Department of Environmental Protection, Trenton, New Jersey.

NJDEP. 1996b. Shellfish growing area 6: Manasquan River 1990-1995. Water Monitoring Project Report, New Jersey Department of Environmental Protection, Trenton, New Jersey.

Norfleet, M. L., C. W. Wood, G. L. Mullins, and B. F. Hajek. 1996. Phosphorus in Agriculture. Tech. Pamph. No. 2, Soil Quality Institute, USDA Natural Resources Conservation Service, Auburn, Alabama.

Ocean County Board of Health. 1990. Well and individual sewage disposal system ordinance. Ocean County Board of Health, Toms River, New Jersey.

Ocean County Planning Department. 1998. Demographic profiles of Ocean County municipalities. Ocean County Planning Department, Toms River, New Jersey.

Ocean County Soil Conservation District. 1995-1997. Understanding and

communicating with people about people pollution in the watershed of Barnegat Bay. Technical Report, Ocean County Soil Conservation District, Forked River, New Jersey.

Olsen, P. S. and B. Kurtz. 1989. Annual summary of phytoplankton blooms and related conditions in New Jersey coastal waters, summer of 1988. Technical Memorandum 89-1, New Jersey Geological Survey, Trenton, New Jersey.

Olsen, P. S. 1997. Development and distribution of phytoplankton blooms causing brown water in the Barnegat Bay system. *In*: Flimlin, G. E. and M. J. Kennish, (eds.), *Proceedings of the Barnegat Bay Ecosystem Workshop*. Cooperative Extension of Ocean County, Toms River, New Jersey, pp. 253-266.

Palone, R. and A. Todd. 1997. Chesapeake Bay riparian handbook: a guide for establishing and maintaining riparian forest buffers. USDA, Forest Service, NA-TP-02.97, Radnor, Pennsylvania.

Peet, R. K., R. G. Knox, J. S. Case, and R. B. Allen. 1988. Putting things in order: the advantages of DCA. Am. Nat., 131:924-934.

Plafkin, J. L., M. T. Barbour, K. D. Porter, S. K. Gross, and R. M. Hughes. 1989. Rapid bioassessment protocols for use in streams and rivers: benthic macroinvertebrates and fish. U.S. Environmental Protection Agency Report EPA/444/4-89/001, Office of Water Regulations and Standards, U.S. Environmental Protection Agency, Washington, D.C.

Preston, S. D. 1996. Study of nonpoint source nutrient loading in the Patuxent River

Basin, Maryland. USGS Water Resources Investigation Report 96-4273, U.S. Geological Survey, Washington, D.C., 6 p.

Price, C. V. and F. L. Schaefer. 1995. Estimated loads of selected constituents from permitted and nonpermitted sources at selected surface water quality stations in the Musconectong, Rockaway, and Whippany River Basins, New Jersey, 1985-90. U.S. Geological Survey Water Resources Investigations Report 95-4040, West Trenton, New Jersey. 28 p.

Renwick, W. 1983. Metal and bacterial contamination in New Jersey estuarine sediments. Environ. Pollut., 5:175-185.

Reynoldson, T. B., R. H. Norris, V. H. Resh, K. E. Dey, and D. M. Rosenberg. 1997. The reference condition: a comparison of multimetric and multivariate approaches to assess water quality impairment using benthic macroinvertebrates. J. North Am. Benth. Soc., 16:833-852.

Rhoads, D. C. and L. F. Boyer. 1982. The effects of marine benthos on physical properties of sediments:

a successional perspective. *In*: McCall, P. L. and M. J. S. Tevesz (eds.), *Animal-Sediment Relations: The Biogenic Alteration of Sediments.* Plenum Press, New York, pp. 3-52.

Rogers, Golden and Halpern, 1990. Profile of the Barnegat Bay. Final Report for the Barnegat Bay Study Group, New Jersey Department of Environmental Protection and Energy, Trenton, New Jersey.

Rutgers Cooperative Extension. 1954. Census facts – Ocean County. Extension Service, College of Agriculture, Rutgers University, New Brunswick, New Jersey.

Rutgers Cooperative Extension. 1998. Home*A*Syst for the Barnegat Bay watershed - an environmental risk-assessment guide for the home. Rutgers Cooperative Extension of Ocean County, Toms River, New Jersey.

Schueler, T. 1998. Rapid watershed planning handbook - a comprehensive guide for managing urbanizing watersheds. Center for Watershed Protection, Elliott City, Maryland.

Seitzinger, S. P. and I. E. Pilling. 1990. Eutrophication and nutrient loading in Barnegat Bay: initial studies of the importance of sediment-water nutrient interactions. Report No. 90-14, The Academy of Natural Sciences, Philadelphia, Pennsylvania.

Seitzinger, S. P. and I. E. Pilling. 1992. Eutrophication and nutrient loading in Barnegat Bay: importance of sediment-water nutrient interactions. Report No. 92-24F, The Academy of Natural Sciences, Philadelphia, Pennsylvania.

Seitzinger, S. P. and I. E. Pilling. 1993. Eutrophication and nutrient loading in Barnegat Bay: sediment-water phosophorus dynamics. Report No. 92-33F, The Academy of Natural Sciences, Philadelphia, Pennsylvania.

Seitzinger, S. P. and R. M. Styles. 1999. Barnegat Bay National Estuary Program data synthesis report: water quality and primary production in the Barnegat Bay-Little Egg Harbor estuarine ecosystem. Technical Report, Institute of Marine and Coastal Sciences, Rutgers University, New Brunswick, New Jersey.

Sharpley, A. N. 1997. Dispelling common myths about phosphorus in agriculture and the environment. Technical Report, Watershed Science Institute, USDA Natural Resources Conservation Service, Aiken Center, University of Vermont, Burlington, Vermont.

Sinex, S. A. and D. A. Wright. 1988. Distribution of trace metals in the sediments and abiota of Chesapeake Bay. Marine Pollution Bulletin, 19, 425-431.

Smith, C. 1999. Ocean County soils studies. USDA, NRCS, Somerset, New Jersey.

Stackelberg, P. E., J. A. Hopple, and L. J. Kauffman. 1997. Occurrence of nitrate, pesticides, and volatile organic compounds in the Kirkwood-Cohansey aquifer system, southern New Jersey. U.S. Geological Survey Water Resources Investigation Report 97-4241, U.S. Geological Survey, West Trenton, New Jersey. 8 p.

Sugihara, T., C. Yearsley, J. B. Durand, and N. P. Psuty. 1979. Comparison of natural and altered estuarine systems: analysis. Technical Report, Center for Coastal and Environmental Studies, Rutgers University, New Brunswick, New Jersey.

Summers, J. K., A. F. Holland, S. B., Weisberg, L. C. Wendling, C. F. Stroup, R. L. Dwyer, M. A. Turner, and W. Burton. 1989. Technical review and evaluation of thermal effects studies and cooling water intake structure demonstration of impact for the Oyster Creek Nuclear Generation Station. Technical Report, Versar, Inc., Columbia, Maryland.

Tate, C. M. and J. S. Heiny. 1995. The ordination of benthic invertebrate communities in the South Platte River Basin in relation to environmental factors. Freshw. Biol., 33:439-454.

Tatham, T. R., D. J. Danila, D. L. Thomas, and Associates. 1977. Ecological studies for the Oyster Creek Generating Station. Technical Report, Ichthyological Associates, Inc., Ithaca, New York.

Tatham, T. R., D. J. Danila, D. L. Thomas, and Associates. 1978. Ecological studies for the Oyster Creek Generating Station. Technical Report, Ichthyological Associates, Inc., Ithaca, New York.

Tiedemann, J., M. Danko, and D. McKeon. 1997. Marinas, dockage facilities, and boating in the Barnegat Bay National Estuary Program region. *In*: Flimlin, G. E. and M. J. Kennish (eds.), *Proceedings of the Barnegat Bay Ecosystem Workshop*. Cooperative Extension of Ocean County, Toms River, New Jersey, pp. 283-298.

Turekian, K. K. 1977. The fate of metals in the ocean. Geochim. Cosmochim. Acta, 41:1139-1144.

Turner, T. R. 1995. Lawns and the Chesapeake Bay. Fact Sheet 702, University of Maryland, College Park, Maryland.

Tyson, A. W. 1993. Wellhead protection for private wells. Report C-819-12, University of Georgia, Athens, Georgia.

U.S. Department of Agriculture. 1930-1997. Census of agriculture. USDA National

Agricultural Statistics Service, Washington, D.C.

U.S. Department of Agriculture. 1978. Agricultural waste management handbook. Soil Conservation Service, Washington, D.C.

U.S. Department of Agriculture. 1986. State erosion, sediment, and animal waste

(SESAW study). Soil Conservation Service, Somerset, New Jersey.

U.S. Department of Agriculture. 1992. National engineering handbook: Part 651 agricultural waste management field handbook. U.S. Department of Agriculture, Soil Conservation Service, Washington, D.C.

U.S. Department of Agriculture. 1997a. National resource inventory. USDA Natural

Resources Conservation Service, Washington, D.C.

U.S. Department of Agriculture. 1997b. Water quality and agriculture – status, conditions, and trends. Working Paper 16, USDA Natural Resources Conservation Service, Washington D.C.

U.S. Department of Agriculture. 1998. Conservation programs manual. Part 515. Environmental Quality

Incentives Program, USDA Natural Resources Conservation Service, Washingtion, D.C.

USEPA. 1977. Process design manual for wastewater treatment for small communities. EPA - 625/1-77/009, Cincinnati, Ohio.

USEPA. 1980. Design manual, onsite wastewater treatment and disposal systems. EPA 625/1-80012, Cincinnati, Ohio.

USGS. 1984. Water quality data for aquifers in east-central New Jersey, 1981-82. USGS OF Report 84-821, U.S. Geological Survey, West Trenton, New Jersey.

USGS. 1989. Simulated effects of future withdrawals in the northeastern coastal plain aquifers of New Jersey. USGS WRI Report 88-4199, U.S. Geological Survey, West Trenton, New Jersey.

USGS 1995a. Water levels in major artesian aquifers of the New Jersey Coastal Plain, 1988. USGS WRI Report 95-4060, U.S. Geological Survey, West Trenton, New Jersey.

USGS. 1995b. Statistical characteristics of stream discharge in tributaries of selected estuaries in New Jersey. USGS WRI Report 91-4141, U.S. Geological Survey, West Trenton, New Jersey.

USGS. 1997a. Simulation of groundwater flow in the unconfined aquifer system of the Toms River, Metedeconk River, and Kettle Creek Basins, New Jersey. USGS WRI Report 97-4066, U.S. Geological Survey, West Trenton, New Jersey.

USGS. 1997b. Mercury in groundwater, soils, and sediments of the Kirkwood-Cohansey Aquifer system in the New Jersey Coastal Plain. USGS WRI Report 95-475, U.S. Geological Survey, West Trenton, New Jersey.

USGS. 1998. Radium-226 and Radium-228 in shallow groundwater, sourthern New Jersey. USGS Fact Sheet FS-062-98, U.S. Geological Survey, West Trenton, New Jersey.

USFDA. 1989. FDA guideline: evaluation of marinas by state shellfish sanitation control officials. Technical Report, U.S. Food and Drug Administration, Washington, D.C.

van den Berg, C. M. G. 1993. Complex formation and the chemistry of selected trace elements in estuaries. Estuaries, 16:512-520.

Vowinkel, E. F. and S. F. Siwiec. 1991. Plan to evaluate the effects of hydrogeologic

conditions and human activities on water quality in the coastal plain of New York and New Jersey. U.S. Geological Survey Water Resources Investigations Report 91-4091, U.S. Geological Survey, West Trenton, New Jersey. 42 p.

Wauchope, R. D. 1978. The pesticide content of surface water draining from

agricultural fields: a review. Environ. Qual., 7:459-472.

Watt, M. K., M. L. Johnson, and P. J. Lacombe. 1994. Hydrology of the unconfined

aquifer system, Toms River, Metedeconk River, and Kettle Creek Basins, New

Jersey, 1987-90. U.S. Geological Survey Water Resources Investigations Report 93-4110, U.S. Geological Survey, Washington, D.C. 5 plates.

Weinstein, J. E. 1996. Anthropogenic impacts on salt marshes - a review. *In*: *Sustainable Development in the Southeastern Coastal Zone*, Vernberg, F. J., W. B. Vernberg, and T. Siewicki, (eds.). University of South Carolina Press, Columbia, South Carolina , pp. 135-157.

Westfall, G. 1993. Soil phosphorus levels. A Background Paper for the Great Swamp

USDA Hydrologic Unit Area Project, USDA Soil Conservation Service, Somerset, New Jersey.

Weston, D. P. 1990. Quantitative examination of macrobenthic community changes along an organic enrichment gradient. Mar. Ecol. Prog. Ser., 61:233-244.

Wright, J. F., D. Moss, P. D. Armitage, and M. T. Furse. 1984. A preliminary classification of running-water sites in Great Britain based on macroinvertebrate species and the prediction of community type using environmental data. Freshw. Biol., 14:221-256.

Zampella, R. A. and J. F. Bunnell. 1998. Use of reference-site fish assemblages to

assess aquatic degradation in pineland streams. Ecol. Appl., 8:645-658.

I. INTRODUCTION

This chapter focuses on the historical and current human uses of the environmental resources within the watershed. Colonial land uses caused environmental impacts that were unknown to the early inhabitants, who were mainly concerned with survival, the establishment of their communities, and commerce. These historical pursuits required the use of natural resources that were readily available, through timber cutting, bog iron mining, charcoal making, and the development of other industries (see Chapter 4). Modern human uses are currently influenced by population growth, tourism, and various forms of recreation. In addition to being home to many retirees and other year-round residents, Ocean County is an attractive location for large numbers of tourists who use Barnegat Bay and Little Egg Harbor for numerous activities.

II. HISTORICAL HUMAN USES

As the Wisconsin glacier retreated, New Jersey was in a "pristine" condition, with untapped forest, mineral, clay, silicate, and water resources. Over a period of approximately 10,000 years, the presence of aboriginal hunter-gatherers had very little environmental impact on the land due to their low population size. About 3,000 years ago, the original inhabitants became more skilled at using natural resources for survival, and they began to exploit certain resources, most notably oysters and clams, for food and for production of wampum. These activities involved the use of vast amounts of shells.

Evidence exists that these original inhabitants were concentrated in the western part of New Jersey, near Burlington and Trenton. They traveled to the shore each summer to use their ancestral hunting and fishing grounds. The remains of their summer residences have been found in and around the Toms River and Tuckerton areas. It can be said that they were the first "tourists" in Ocean County.

When the first Europeans settled in Ocean County in the late 1600's, they traded with the original inhabitants and bought their land. The mutually dependent trade relationship produced a demand for furs and pelts that depleted the local stocks of forest animals and forced the Indians to broaden their hunting areas. The widening of the hunting areas caused conflict with other tribes through competition for a dwindling resource. The term "competing uses" has an historical aspect and is not just a contemporary concept. Historical sources document that competition for land and resources has existed in Ocean County for almost 300 years.

Southern New Jersey, which today also encompasses part of the Barnegat Bay-Little Egg Harbor watershed, historically contained a large area of pine barrens which eventually included the more than 1 million ac (400,000 ha) that now comprise the protected Pinelands. For most of the 17th Century, this area remained sparsely settled due to the dense nature of the forests and swamps between the Delaware River and the Atlantic Ocean. By the end of the 17th Century, the towns of Barnegat and Tuckerton had been established and several saw mills existed in Ocean County. Lumbering was so extensive during the first decade of the 18th Century that the New Jersey General Assembly was forced to promulgate regulations restricting the cutting of timber. By the mid-18th Century, conservationists were speaking out against the cutting of large amounts of timber (most notably Benjamin Franklin). Shellfish harvesting was so widespread during the early 1700's that the first oyster law was passed, limiting harvesting to May 10th through September 1st.

The maritime tradition of Barnegat Bay produced a rich history of whaling, boat building, fishing, shipping, commerce, and (during the Revolutionary War) privateering. All of these enterprises added to the economic well-being of the people who chose to settle in the woodlands south of New York and east of Philadelphia. Boat building produced an array of boats particularly suited to the shallow bay: sneakboxes for hunting; garveys for hunting and fishing; catboats for guiding the earliest visitors to the hunting and fishing grounds, and for shipping industrial goods to New York, Philadelphia and points south; sloops and schooners for commerce up and down the Atlantic Coast and to farther ports, such as the West Indies.

Other colonial industries, including lumbering, bog iron manufacture, charcoal production, cranberry cultivation, salt hay and sphagnum moss harvesting, depleted or altered the resources to the extent that some of the industries collapsed. In the case of lumber and bog iron, the environment was transformed when sawmill ponds and clearcut Atlantic white cedar stands were converted to cranberry cultivation after the lumber was depleted. It is evident from historical records that major parts of Ocean County were heavily industrialized from the mid-18th Century to the mid-19th Century. Various historical sources corroborate that there is hardly a forested acre in Ocean County that has not been cut over many times, burned, cleared or otherwise disturbed. By the early 1900's, eelgrass in the bay essentially disappeared due to a blight, although it returned in the 1950's. In addition, the oyster industry was declining in Barnegat Bay.

Natural forces also shaped the land and affected the way of life of the inhabitants. Great fires burned throughout Ocean County and the pine barrens as they had since the last ice age. Violent northeasters and hurricanes opened and closed inlets, swallowed up an entire island, and removed acres of beaches along the oceanfront.

The original inhabitants - the native Americans - also vanished within a short period of time. They had roamed this land for more than 10,000 years, but within the space of 100 years they were gone, nearly without a trace. If the physical remnants of their existence (e.g., their shell middens) and their names (e.g., Manasquan, Manahawkin, Mantoloking, and Metedeconk) had not been preserved, we would hardly know that they once lived here.

When the first settlers arrived in the Ocean County area in the late 1600's, there were approximately 500 million ducks making an annual flight over Barnegat Bay. By 1934, that number had dropped to 30 million ducks. It became increasingly obvious that the wholesale killing of birds by recreational and market hunters threatened to eliminate a number of species. Finally, game limits and hunting restrictions were imposed to mitigate the impact.

The growth of the tourist industry in the later part of the 19th Century and early part of the 20th Century brought the mosquito problem to the attention of the state government, which organized a survey of the meadows along the bay in 1908. This eventually led to a great decline in the mosquito population through the elimination of their habitat and the use of insecticides. These early 20th Century actions had unexpected ecological consequences because the mosquitoes were preyed upon by the dragonflies and damselflies, who were in turn preyed upon by the martins, frogs, and toads. The dragonflies and damselflies declined after the mosquito exterminations, and thereafter a decline occurred in the toad population. The toads were the favorite prey of the hog-nosed snakes that frequented the beaches in the northern portion of the bay, and they eventually disappeared with the decline of their prey species. This anecdotal information is important because it illustrates how species are connected in a complex food web, and it reminds us how actions may have unintended consequences.

With the advent of the first railroads, and then the automobile, tourism became an economic factor in the early 20th Century, as hunting and fishing excursions employed local captains. The popularity of hunting

and bay fishing, along with the benefits of ocean bathing, contributed to the growth of tourism, which had expanded to become a local industry by the end of the 19th Century, both at the head of the bay to the north and along the barrier island to the south. The tourist industry grew in the first half of the 20th century, but declined during World War II due to gas rationing. After the war, when the Garden State Parkway was completed, there was a resurgence of interest in Ocean County. As a result, the county experienced phenomenal growth during the late 1900's. Thousands of shore homes were built, and thousands of new boats appeared on the bay. With this growth came a decline in bay water quality. In the 1970's, many environmental regulations were enacted by the state to control growth, which was perceived as negatively impacting estuarine and freshwater wetlands resources.

The opening of the Point Pleasant Canal in 1926 forever changed the ecology of the upper part of the bay by the introduction of saline water. Certain vegetation preferred by wildfowl, such as wild celery, disappeared completely. Similarly, the change in salinity contributed to the demise of oyster beds in the estuary. Freshwater species of fish disappeared and were replaced by salt water forms.

Human activity in the watershed and estuary have caused ecological impacts through the following:

- Clear-cutting of the forests every 25 to 40 years since the late 1600's to the mid-1800's for timber-harvesting and charcoal-making; the reduction of species diversity caused by poor soil nutrition as a result of so much clear-cutting.
- Elimination of animal species through indiscriminate hunting of animals inhabiting the interior of southern New Jersey.
- Disturbance of rivers, streams, and wetlands via damming for saw mill operations.
- Disturbance of streams and wetlands for bog-iron mining; the depletion of the bog-iron resources by the mid-1800's.
- Near decimation of the duck population due to unrestricted hunting for 200 years.
- Destruction of tidal wetlands as a result of salt hay harvesting, cattle pasture, dock facilities, and development.
- Disturbance of freshwater wetlands for construction of roads and other colonial development.
  - Elimination of freshwater fish species in the northern portion of the bay through construction of the Point Pleasant Canal.
  - Demise of the prolific oyster industry in Barnegat Bay and Little Egg Harbor.
  - Introduction of oil pollution into the estuarine system from motorized vessels during the 20th Century.
  - Disruption of shallow water habitats and colonial nesting bird populations by personal watercraft.

Population growth over the last hundred years has also had an impact on the environment. This growth has been facilitated by:

•Construction of the railroads in the late 1800's.

•Construction of the causeway to Long Beach Island in the early 1900's.

•Construction of the Thomas A. Mathis Bridge in the 1950's.

•Construction of the Garden State Parkway in the 1950's.

•Proximity to major metropolitan areas.

•Construction of the Oyster Creek Nuclear Generating Station in the 1960's.

•Development of the regional sewer system in the 1970's.

First, the location of the bay and the inlets influenced settlement and growth by providing easy access by boat. Then, the modern transportation facilities enabled the growth of seasonal and year-round populations in the Barnegat Bay and Little Egg Harbor area. The regional sewer system provided large areas of the county with sanitary sewerage treatment.

Natural forces have also played a major part in shaping the physical environment by:

•Changing the locations and configurations of inlets and beaches over the centuries.

•Consuming the forest vegetation (via wildfires).

•Eroding beachfront, causing the destruction of Atlantic the White Cedar swamp on Long Beach Island, and eliminating Tucker's Island (via northeasters and hurricanes).

These two elements – human activities and natural dynamic forces - will continue to shape the Barnegat Bay-Little Egg Harbor estuary and watershed in the future.

III. COMPETING MODERN USES

Population growth has accelerated rapidly during the 20th Century, both along the eastern and western sides of the bay. The Ocean County area has become a particularly desirable place to live and work. It is no longer merely a seasonal or retirement destination. It is home to nearly a half million people. This population growth has led to intense competition for resource use and the realization by the federal and state regulatory agencies that ecosystem management is a complex undertaking that must involve diverse groups of people with different attitudes. Population growth and associated human activities have produced significant change in the coastal ecosystem; they can be separated into three general categories to assess impacts on the estuary: (1) land-use activities; (2) competition between recreational and commercial fisheries; and (3) conflicts between boats and personal watercraft.

A. Land Use Activities

Accelerated population growth during the last half of the 20th Century has led to changes in land use for homes and businesses. Since the most populated areas are located in the north-central portion of the county, in Dover, Brick, Lakewood, Manchester, Jackson and Berkeley Townships (Ocean County Department of Planning, 1998), these areas have experienced the most commonly recognized effects of land-use changes:

•Filling of tidal wetlands (prior to 1970) for lagoon developments, which virtually ceased upon enactment of the Wetlands Act of 1970.

•Filling of freshwater wetlands for road construction, commercial development and housing development. As of 1988, freshwater wetlands were jointly regulated by the U.S. Army Corps of Engineers and the New Jersey Department of Environmental Protection (NJDEP). In March 1994, New Jersey assumed jurisdiction of the Federal 404 Program of the Clean Water Act. Between March 2, 1994 and June 30, 1998, 510 ac (207 ha) of freshwater wetlands were impacted by development activities and granted Statewide General Permits under the permit program of the NJDEP Freshwater Wetlands Protection Act Rules. The filling of isolated wetlands totaled 173 ac (70.1 ha) during that same time period, and minor road crossings totaled 65 ac (26 ha) (NJDEP, 1999). Between 1990 and 1998, filling of wetlands for development declined, leaving a total of approximately 300,000 ac (121,500 ha) of freshwater wetlands which remain in the state (New Jersey Future, 1999).

•Stormwater runoff from impervious surfaces (e.g., existing county roads, municipal streets, old pavement, and parking lots) has been linked to the decline in water quality and the decrease in base flow in streams.

•Historic (and some current) septic system failures, which introduce pathogens to groundwater and contribute to groundwater pollution.

•Over-fertilization of residential lawns, which can produce nutrient-loaded

stormwater runoff that can contribute to algal blooms, the decrease of light transmission in the water column, the decline in submerged aquatic vegetation, and the eutrophication of water bodies.

•Pet waste, which can produce high levels of bacteria (e.g., cryptosporidium, giardia, and salmonella) that cause water-borne diseases. Other wildlife, such as waterfowl, can contribute to this problem.

•Improper disposal of sanitation tanks in boats (boaters should dispose of sanitation waste at pump-out stations located throughout the bay).

•Beach closings, which have been linked to precipitation events, high stormwater runoff, and elevated bacterial counts. New Jersey has made great strides in controlling coastal pollution, and beach and bay closings have been dramatically reduced since 1988 (New Jersey Future, 1999).

•Landfills and buried toxic waste, which can leach contaminants into groundwater.

•Leaking underground storage tanks, which can also be a significant source of chemical contaminants in groundwater.

•Increased soil erosion at construction sites, which often generates high suspended solids, increased turbidity, and sedimentation problems in area streams.

•Soil compaction on large construction sites, which can inhibit groundwater recharge and decrease base flows in area streams.

•The cumulative effect of withdrawal of groundwater for public potable water supply, residential well use, irrigation wells, and industrial ground water withdrawal, which has created an estimated deficit in the Metedeconk River and Toms River of about 20 million gallons per day (75.7 million liters per day) that may increase to 34 million gallons per day (129 million liters per day) in the year 2016. Some of the purveyors presently use aquifers that have reduced allocations through NJDEP regulations. Purveyor demand is largely depletive in nature. Groundwater withdrawals can also affect baseflow to local streams and contribute to salt water intrusion in coastal communities (New Jersey Department of Environmental Protection, 1996).

•Riparian construction, such as bulkheads, sea walls, docks, and dredging, which has reduced shallow nearshore habitat area and impacted the benthic environment.

•Dredging of bay bottom that destroys benthic habitat, including submerged aquatic vegetation.

•Petroleum and halogenated hydrocarbons, metals, particulate organic matter, pathogens, and floatables introduced into surface waters at marina sites.

•Reduced public access to the bay due to the lack of public open space along the bay shore.

These are among the most common impacts created by modern land-use changes in the watershed. Some of the categories mentioned are controlled by state environmental regulations (e,g., wetland impacts, soil erosion, and sediment control), whereas others are not. The dredging and filling of wetlands in tidal waters are also regulated by federal agencies. Some of the causes of pollution listed above are not being addressed because of the lack of clean-up funds or reduced enforcement budgets. A number of these impacts can be attenuated by more effective planning and development, but some problems may have no immediate solution and will require an intense public outreach effort aimed at education and personal behavioral modification.

B. Recreational and Commercial Fisheries

Conflicts over fishing rights are generally based on resource availability and natural stock restoration, and they become evident when any economically or recreationally important species suffers an observable decline. These types of conflicts began in colonial times, when the first oyster law in New Jersey was passed in 1720, and they have continued up to the present. The public trust doctrine that protects fishing and navigation rights against privatization became U.S. law through conflicts over oysters in New Jersey (McCay and Jenks, 1998). The conflicts between recreational and commercial fishermen are not Barnegat Bay-Little Egg Harbor specific. They occur in the marine waters of this geographic region because the anadromous, coastal pelagic, crustacean, and shellfish species which inhabit the waters of Ocean County are recreationally and commercially important.

Historical accounts of fishing in Barnegat Bay and Little Egg Harbor are replete with descriptions of the vast amounts of fish available to recreational and commercial fishermen. Based on these descriptions, it is almost inconceivable to think that such vast numbers of fish could be depleted and that human use could outstrip the resource's ability to replenish itself. Yet, that is exactly what is happening to many of the important finfish stocks in coastal waters of the United States (Fowle, 1993). Human exploitation and habitat loss are affecting the abundance of fish and impacting the commercial fishing industry, as well as the recreational angler. Conflicts have arisen over economic interests versus conservation and sustainability of the resources. For many species, fisheries management now regulates the size of the catch, the gear used to catch the fish, the waters that can be legally fished, how the bycatch is to be handled, and a host of other issues pertaining to fishing in the recreational and commercial fishing industry.

The Magnuson Fishery Conservation and Management Act was passed in 1976 (later amended and reauthorized to become the Magnuson-Stevens Fishery Conservation and Management Act, Public Law 94-265) for the purposes of maintaining the viability of U.S. fish populations for the future. The act pertains to ocean species of fish harvested in federal waters, but many of these species use estuaries as nurseries during the juvenile stage. The act has established the Exclusive Economic Zone (EEZ) to exclude foreign vessels without specific permits. It established eight regional fishery management councils that develop Fishery Management Plans (FMPs) for the EEZ (Fowle, 1993). The Mid-Atlantic Fishery Management Council represents the States of New York, New Jersey, Delaware, Pennsylvania, Maryland, Virginia and North Carolina and has authority over the fisheries in the Atlantic Ocean seaward of the states, from 300 to 500 mi (480 to 800 km). Several species managed by the New England Fisheries Management Council can also be found in the waters in and around New Jersey. The 1996 Sustainable Fisheries Act reauthorizing the Magnuson-Stevens Fisheries Management and Conservation Act (MSFMCA) required the identification of "essential fish habitat" (EFH) for all of the species managed by the regional Fisheries Management Councils. The goals of the EFH amendments to the Magnuson Stevens Act include the protection, conservation, and enhancement of the EFH. In Barnegat Bay, Little Egg Harbor and the waters of the Atlantic Ocean off Ocean County, EFH has been designated for 24 species. Offshore management of fish landings can affect bay stocks. The information presented above on the origins of the act illustrates the nature of conflicts between commercial fishermen and recreational anglers.

The management system in place for almost all U.S. marine fisheries is the *open access* system (Fowle, 1993) that results in a cumulative impact from so many fishermen, both recreational and commercial, without providing for any return of the resource. The open access system is a type of fishery which allows anyone wanting to fish who has the appropriate gear to do so. Even when licenses are required, if the number of licenses is not limited and the holder does not have to abide by quotas or other restrictions to access, the fishery is an open access fishery. The open access coupled with technological advances in fishing strategy, such as fish finders, hydraulic gear, spotter planes, on-board processing equipment, and satellite communication systems has given commercial fishermen the ability to find almost all of the fish, making fish vulnerable to overfishing impacts. Certain fisheries are commercially extinct, since

they are depleted to the point where the fishing effort is no longer economically feasible. Not all species have been assessed for a determination of overfishing. The commercial fishing industry has contributed to the increase in the unintended catch, also known as the bycatch, of fish that are killed by non-selective gear use. The bycatch consists largely of juvenile fish, which further limits recovery of depleted species. Although recreational anglers experience bycatch, the numbers of unwanted fish caught by recreational anglers is significantly lower than that experienced by the commercial fishing industry (Fowle, 1993).

It has been estimated that 75% of all commercially valuable fish in the United Sates depend on estuaries and their associated wetlands for some portion of their life cycle (Fowle, 1993). Nursery grounds for juveniles of many marine species are found in these unique inshore habitats. Protection of these habitats in the Barnegat Bay-Little Egg Harbor estuary should be a top priority for any management strategy, since the estuary directly contributes to restoration of the resource. Overfishing increases the impacts resulting from habitat loss, and the combined pressure from overfishing and habitat loss can cause a collapse of fisheries (Fowle, 1993).

Although not specific to Barnegat Bay, conflict arises between the recreational and commercial fisheries due to the dwindling resources and the problems associated with this decline. Recreational fishermen claim that the gear used by the commercial fishing fleets can deplete the resources and limit the recreational angler's ability to retain a catch. They are more vocal in support of conservation, and protest loans and loan guarantees, tax exemptions, and federal subsidies for overcapitalized fisheries (Fowle, 1993).

Overcapitalization pertains to the commercial fishing industry, and occurs when too many boats pursue too few fish, or the total investment in and effectiveness of gear exceeds what is necessary to catch the available fish. Size limits and catch-and-release management policies make it extremely difficult for recreational anglers to retain some species for personal consumption. Commercial fishermen claim, on the other hand, that recreational anglers on party and charter boats land as many fish of some species as commercial boats and that improved harvesting methods are required to keep the industry competitive. The federal fishery management polices, however, have generally been responsive to the voices of the people who have a direct and immediate economic interest in how a fishery is managed and regulated. Commercial fishermen are reluctant to accept increased regulation in a fishery where they are catching less than in previous years, exerting twice as much effort, and losing their jobs in some cases because the fishing is no longer profitable. They consider over-regulation as a threat to their livelihood. The recreational fishermen are concerned that overfishing will destroy their traditional catches and that there will be no more fish left to catch, thereby eliminating an important recreational pursuit and the facilities that support the recreational fishing community. They have an interest in restoring a healthy and productive ecosystem by limiting landings of certain species until the resource recovers. Recreational and commercial interests also clash over how many fish are allocated to each fishing group. Preventing overfishing and restoring depleted fish stocks will provide solutions to the conflict between these two groups of fishermen, but accomplishing this goal will be a long-term task, and no one knows when, or if, the stocks will rebound. For example, the porbeagle shark fishery off the U.S. Atlantic coast was decimated in seven years, and 30 years later, the species still had not recovered (Fowle, 1993).

The Mid-Atlantic Fishery Management Council has a Scientific and Statistical Committee (SSC) and Advisory Panels (APs) to provide expertise for development of Fishery Management Plans (FMPs). Existing FMP's for the Mid-Atlantic, as of March 1993, include those for the surf clam (*Spisula solidissima*), ocean quahog (*Arctica islandica*), Atlantic mackerel (*Scomber scombrus*), butterfish (*Peprilus triacanthus*), long-finned squid (*Loligo pealei*), short-finned squid (*Illex illecebrosus*), summer flounder (*Paralichthys dentatus*), and bluefish (*Pomatomus saltatrix*). FMP's for tilefish (*Lopholatilus chamaeleonticeps*) and spiny dogfish (*Squalus acanthias*) are under development. The New England Fisheries Management Council has FMP's for species found in New Jersey waters, such as the monkfish

(*Lophius americanus*), Atlantic sea herring (*Clupea harengus*), and the northeast multispecies FMP, which includes the winter flounder (*Pseudopleuronectes americanus*). These plans can require size limits, bag limits, quotas, limits on the number of vessels, restriction on net mesh size, closed areas and seasons, or any other measure to control fishing activity. The Mid-Atlantic Fishery Management Council must carry out the objectives of the Magnuson-Stevens Act, one of which requires conservation and management measures to be based on the best scientific information available. In the past, some council members were reluctant to limit fishing if they did not believe the data conclusively proved that a species was in decline (Fowle, 1993).

The only solution that will alleviate many fishing conflicts is a return of the resources to previous levels of abundance. The Barnegat Bay Estuary Program can recommend the formulation of estuary management strategies aimed at protecting the resources that nurture the larval and juvenile species of recreationally and commercially important fish. A resource management strategy based upon the best scientific information available on a probable species decline will be a key element of that solution.

The 1996 amendments to the Magnuson-Stevens Fishery Conservation and Management Act strengthened the ability of the councils to protect and conserve the habitat of marine, estuarine and anadromous finfish, mollusks, and crustaceans. As noted previously, this habitat is called "essential fish habitat" (EFH) and is broadly defined as waters and substrate necessary to fish for spawning, breeding, feeding or growth to maturity. The act has established measures to protect EFH, including summaries of EFH for selected 10' x 10' squares of latitude and longitude along the coast (NOAA/National Marine Fisheries Service, 1999).

There are few written sources of information on the problems of conflicts between commercial fishermen and recreational anglers in the Barnegat Bay-Little Egg Harbor estuary, but there are issues of concern. According to the New Jersey Department of Environmental Protection, Bureau of Shellfisheries, the major conflict is related to boaters, who complain that commercial crab pots interfere with boat navigation in shallow bay areas (James Joseph, NJDEP, personal communication, March 8, 1999). "Commercial crab pot" is a cube or rectangular shaped device not larger than 30 in (76 cm) on a side with openings inward for the entrance of crabs. The buoys and trot lines (a single length of anchored line no longer than 3,000 feet, to which baits or baited barbless hooks are attached) require that boats maneuver around the pots. Boaters complain that they can not navigate in areas where there are many crab pots (Eleanor Bochenek, New Jersey Sea Grant, personal communication, March 4, 1999).

The New Jersey Department of Environmental Protection regulates the blue crab (*Callinectes sapidus*) commercial crabbing industry through regulations administered by the Division of Fish, Game and Wildlife's licensing program (N.J.A.C. 7:14.1-12. Authority: N.J.S.A. 23-2B-6, 23:2B-14, and 50:3-16.13). All provisions of Subchapter 14, Crab Management, were originally adopted pursuant to authority of N.J.S.A. 50:3-20 and became effective June 1, 1977, as R.1977 d.196. Subchapter 14 was amended and adopted as a new rule pursuant to Executive Order No. 66(1978) as R.1985 d.560, effective November 4, 1985. In recent years, blue crab management has made commercial crabbing a "limited entry fishery." The regulatory goal is to reduce the number of crab pot fishermen over time. Those fishermen who drop out of the industry are not replaced. No additional crab pot licenses will be issued until the number of licenses issued decreases below the number issued in 1991 (312 licenses). There are currently still only 312 commercial crabbing licenses for the State of New Jersey, and each license holder in the Barnegat Bay-Little Egg Harbor is limited to no more than 400 crab pots for each license (Bruce Halgren, NJDEP, personal communication, March 8, 1999). License holders can harvest crabs from March 15th to November 30th each year. Hard blue crabs must measure 4.5 in (11.4 cm) across the back from tip to tip of the spikes to be legal. Since the crabs are a limited resource, there have been complaints to the NJDEP from recreational crabbers, who feel that the commercial crabbers take an unfair proportion of available crabs, and that there are not enough crabs left in the bay for them. That

perception has caused recreational crabbers to blame commercial crabbers for a perceived lack of crabs. However, placing blame on the commercial crabbers may not be justified. Local baymen with personal knowledge of the bay have stated that the location chosen for crabbing has more to do with the size of the catch than the number of crabs taken by commercial crabbers (D. Hook, proprietor of Double Creek Fishery, personal communication, April 21, 1999).

According to the NJDEP, conflicts between commercial and recreational clammers in Barnegat Bay-Little Egg Harbor estuary are so minor that they are not perceived to be an issue requiring regulatory action. Clamming conflicts are related to the minimal stocks in the estuary (G. E. Flimlin, Jr., Ocean County Cooperative Extension, personal communication, March 11, 1999). Contemporary clam stocks are much lower than the level of historical resource stocks. There is an effort on the recreational side to have Sunday clamming approved in New Jersey, but the restriction on Sunday clamming may never be lifted due to the limited resources available and the fear by regulators that lifting the limit would further deplete the clam stocks.

Conflicts exist between recreational clammers and boaters when boats speed past people treading for clams. The boaters are not sensitive to the safety issues of overboard treaders in the congested bay. Recreational clammers have complained that the boat traffic is so intense around Swan Point that they can not work the clam beds (G. E. Flimlin, Jr. Ocean County Cooperative Extension, personal communication, March 11, 1999). Commercial clammers complain about the improper use of personal watercraft and inconsiderate boaters (D. Hook, proprietor of Double Creek Fishery, personal communication, April 21, 1999).

C. Boats and Personal Watercraft

Ocean County has a long history of maritime traditions, which began in colonial times. Boats were the basic means of transportation, and the location of the inlets along the Ocean County coast has played a major role in the settlement and development of the watershed. Sail powered vessels were the most common type of vessel on the estuary until the early to mid-20th Century, when the development of the gas-powered engine forever changed the nature of boating in the region. As motorized boats began to gain in favor, the power boats and sail boats on the bay were still able to co-exist peacefully. It was not until the mid-1950's that the numbers of power boats using the bay began to increase substantially, leading to conflicts between the two types of craft. Sailors prefer the experience of using the wind to power a boat. However, sailboats do not have the same maneuverability or speed as power boats and conflicts often arise if proper boating safety practices are not observed, such as giving the right-of-way to boats under sail.

Recreational boating has experienced tremendous growth within the last decade. Many marinas are located on both the east and west sides of Barnegat Bay and Little Egg Harbor, and along the major inland tributaries. The tidal portions of the Manasquan River also provide boating facilities which are connected to Barnegat Bay by the Point Pleasant Canal. Boating, along with its associated facilities and traditions, has been a primary recreational industry since the 1800's and is part of the heritage of Barnegat Bay and Little Egg Harbor (Tiedemann et al., 1996).

Personal watercraft (PWC) are classified as boats in New Jersey, but there are several major differences between boats and personal watercraft, the major one being the depth of water in which the PWC can

operate. The PWC can maneuver in shallow waters that often contain seagrasses, such as eelgrass (Zostera marina) and widgeon grass (*Ruppia maritima*). These are also important habitats for fish and wildlife. The turbulence which results from the operation of the water jet pump can uproot seagrasses, cause shoreline erosion, destruction of larval habitat, and the disruption of colonial nesting birds. The roiling of bottom sediments causes sediment resuspension that limits light penetration and may deplete oxygen. Although no studies have been performed to assess PWC impact on the larvae in Barnegat Bay, the U.S. Fish and Wildlife Service estimates that approximately two-thirds of commercial and recreational species of fish and shellfish rely on estuarine marshes for spawning and as nursery habitat (Chin, 1998). SAV beds have also been designated as a habitat area of particular concern for summer flounder by the Mid-Atlantic Fisheries Management Council. In addition to fish habitat destruction, the PWC can maneuver close to islands where colonial birds nest, disrupting the nesting season and causing abandonment. Other impacts of disturbance on birds include permanent loss of habitat, reproductive problems, interruption of courtship, and behavioral changes (Chin, 1998). Emphasis should be placed on educating PWC users about the sensitive nature of the estuary, and how the use of their craft can impact the estuary on several levels. For example, seagrasses, shallow flats, and wetlands may be adversely affected by PWC users. Burger (1996) has recommended a buffer zone around key nesting islands because she has observed PWCs cutting so close to islands that they keep the birds off their nests for hours. During high tide, they may even run over some nests, as well as eggs and chicks hidden in the grass. PWCs can have a devastating effect on coastal creeks and shallow water habitats of the estuary, especially in areas that other craft have not been able to reach.

A variety of other problems are related to the PWCs, such as noise pollution, water pollution from polycyclic aromatic hydrocarbons released in raw unburned gasoline, air pollution, lack of formal safety education of operators, and reduced enforcement due to budget cuts. All of these factors can lead to conflicts between users of the estuary. PWC manufacturers have attempted to address these problems through education and the development of quieter engines (Chin, 1998). Crabbers, anglers, public officials, and members of the public have expressed concerns about the use of PWCs on Barnegat Bay (Burger, 1996; Barnegat Bay Watershed Association, 1998). Given the popularity of this type of water craft, more research is needed to identify all the specific problems with their use in the Barnegat Bay-Little Egg Harbor area. Conflicts between PWC users, the public, and other boaters will continue to exist until environmental restrictions are developed to protect the estuarine resources.

In 1998, Senator Leonard T. Connors drafted NJ S-556, which would give waterfront towns the authority to issue tickets to boaters and PWC operators who violate state safety regulations, if adopted. This bill would allow municipalities to adopt a resolution or ordinance restricting "...the operation of personal watercraft above idle speed within 100 ft (379 m) of residential units, beaches with swimming areas that have boundaries marked by buoys or signs, the shoreline, persons in the water, fishing piers, or other vessels". It would also allow the Bureau of Marine Law Enforcement, or any other officer of a county or municipal police department, to enforce the provisions of the bill. The bill would allow local regulations to hold operators of PWC's to a higher safety standard, but would not prohibit a legal PWC from operating on state waters. NJ A-419, sponsored by Assemblyman Christopher J. Connors and Assemblyman Jeffrey W. Moran mirrors S-556, with certain additional restrictions (Chin, 1998). The bills proposed by members of the assembly have not yet received the legislature's approval and the ultimate disposition of this legislation is uncertain.

IV. SUMMARY

It is anticipated that the action items included in the Barnegat Bay Estuary Program's Comprehensive Conservation and Management Plan will include specific management recommendations that will:

•Attempt to mitigate water quality impacts and other impacts associated with development in the watershed through education of stakeholders and involvement of the public in resource protection. It is hoped that increased public awareness about ways to protect the environment, while accommodating responsible development, will lead to actions mutually beneficial to the region's economic vitality and the health of the estuary and its watershed.

•Attempt to alleviate the conflicts between crabbers and boaters, recreational crabbers and commercial crabbers, and recreational and commercial fishermen by advocating protection of the estuary's essential fish habitat, providing a forum for exchange of information, and promoting public education about the problems.

•Contribute to development of regulatory guidelines on personal watercraft that will lessen their impact on sensitive habitats in the estuary while still allowing for their proper use.

Literature Cited

Barnegat Bay Watershed Association. 1998. Watershed Waves. Newsletter of the Barnegat Bay Watershed Association, Inc., Toms River, New Jersey

Burger, J. 1997. Avian studies on Barnegat Bay. Pp. 345-350 *in* Flimlin, G. E. and M. J.

Kennish (eds.), *Proceedings of the Barnegat Bay Ecosystem Workshop*. Rutgers Cooperative Extension of Ocean County, Toms River, New Jersey.

Chin, M. 1998. Issues and problems associated with personal watercraft in Barnegat Bay. Cook College Education Program Paper, Rutgers Cooperative Extension of Ocean County, Toms River, New Jersey.

Fowle, S. 1993. Fish for the future: a citizens guide to federal marine fisheries management. Technical Report, Center for Marine Conservation, Washington, D.C.

McCay, B. J. and W. P. Jenks, III. 1997. From the Goose Bar to Swan Point: reflections on Barnegat Bay clamming. Pp. 299-308 *in* Flimlin, G. E. and M. J. Kennish (eds.), *Proceedings of the Barnegat Bay Ecosystem Workshop*. Rutgers Cooperative Extension of Ocean County, Toms River, New Jersey.

New Jersey Department of Environmental Protection. 1996. New Jersey Statewide Water Supply Plan. Trenton, New Jersey.

New Jersey Department of Environmental Protection. 1999. Freshwater Wetlands Rule Development. acreage impacted under general permits since New Jersey assumed the federal wetlands program, March 2, 1994 - June 30, 1998. Internet Site: http://www.state.nj.us/dep/landuse/news/impact.htm

New Jersey Future. 1999. Living with the future in mind. Technical report, State of New Jersey, Trenton, New Jersey.

National Oceanic and Atmospheric Administration. 1999. Guide to essential fish habitat designations in the northeastern United States, Volume IV: New Jersey and Delaware. Technical Report, National Marine Fisheries Service, Gloucester, Massachusetts.

Ocean County Planning Board. 1988. Comprehensive Master Plan: 1997, 1998. Ocean County Data Book, Ocean County Planning Board, Toms River, New Jersey.

Tiedemann, J., M. Danko, and D. McKeon. 1997. From the Goose Bar to Swan Point: reflections on Barnegat Bay clamming. Pp. 283-296 *in* Flimlin, G. E. and M. J. Kennish (eds.), *Proceedings of the Barnegat Bay Ecosystem Workshop*. Rutgers Cooperative Extension of Ocean County, Toms River, New Jersey.