THE ECOLOGY OF THE WAQUOIT BAY

NATIONAL ESTUARINE RESEARCH RESERVE

COVER PHOTOGRAPH

Barrier Beaches of Waquoit Bay. WBNERR archives, photographer unknown

WAQUOIT BAY NATIONAL ESTUARINE RESEARCH RESERVE

EDITOR
Margaret A. Geist

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CHAPTER I

AN INTRODUCTION

TO THE WAQUOIT BAY RESERVE

Washburn Island beach with breach in the distance. Photograph by Richard E. Crawford.

INTRODUCTION

The Waquoit Bay National Estuarine Research Reserve (WBNERR) is located within the towns of Falmouth and Mashpee on the southern shore of Cape Cod (Fig. 1.1). Like many embayments located on glacial outwash plains, Waquoit Bay is shallow, fronted by large barrier beaches and backed by salt marshes and upland forests. The main bay is connected to brackish ponds and fresh water tributaries. Two permanent inlets connect Waquoit Bay to Vineyard Sound. (Waquoit Bay is located at the margin of Vineyard Sound and Nantucket Sound. In this volume, we will use Vineyard Sound.) A third opening is a breach created during Hurricane Bob in August, 1991.

To the south, the barrier beaches of South Cape Beach and Washburn Island protect the Bay from the waters of Vineyard Sound. To the west lies Washburn Island with low, steep bluffs and forested uplands. The west coast of Washburn Island faces Eel Pond and the Seapit River and marks the western boundary of the Reserve. At the northern end of the Bay, where the Reserve Headquarters is located, steep coastal bluffs constitute the highest altitude within the Reserve (15.25 meters or 50 feet above sea level). The eastern shore of the Bay and the tributaries to the east are the most developed areas within the Reserve with both seasonal and permanent residences. Densely developed peninsulas to the west along Eel Pond and Childs River are outside of the Reserve boundaries, but land use on these peninsulas affects the functioning of the Waquoit Bay ecosystem complex.

Within the Waquoit Bay National Estuarine Research Reserve are many diverse waters including: Waquoit Bay itself, a shallow embayment; Hamblin and Jehu Ponds, brackish ponds connected to the Bay by Little and Great rivers, respectively; Sage Lot Pond and Flat Pond, brackish waters connected to each other and to the Bay via sections of the Quashnet/Moonakis River; and Bourne, Bog, and Caleb ponds, freshwater kettle hole ponds on the north shore of the Bay (Fig. 1.2).

The largest source of freshwater to Waquoit Bay is the Quashnet/Moonakis River which originates in Johns Pond and traverses Reserve lands, forests, cranberry bogs, residential areas, and a golf course before joining the Bay near its head. (Technically, "Quashnet" applies to that portion of the river within the town of Mashpee, and "Moonakis" refers to the portion of the river lying in the town of Falmouth. Both terms are used in this volume.) The Childs River, which also originates in Johns Pond, is the second largest source of freshwater to Waquoit Bay. The Childs River runs through densely developed residential areas and joins the Reserve waters near the head of the Bay. Another source of freshwater is Red Brook which supplies a minor amount of freshwater via Hamblin Pond. Additional freshwater enters the Bay through groundwater seepage, precipitation and smaller stream flows. The high percolation rates of Cape Cod's sandy soils result in little surface water runoff into the Bay.

WBNERR includes 910 hectares (2,250 acres or 3.5 square miles) of open water, barrier beaches and sand dunes, fresh and salt water marshes, and uplands. Approximately 58% of this area is open water, 13% is brackish and salt marsh, and 29% is grassy and forested upland. The area within the Reserve boundary extends 4.5 kilometers (2.7 miles) from north to south, and averages 3.3 kilometers (2.0 miles) from east to west. Public facilities within the Reserve include South Cape Beach State Park which comprises 175 hectares (432 acres), Washburn Island which encompasses 133 hectares (330 acres), and the Reserve Headquarters with 11.3 hectares (28 acres) at the head of the Bay. The Reserve Headquarters is also known as the Sargent Estate. In addition to land within its boundaries, the Waquoit Bay Reserve also manages 146 hectares (361 acres) of land along the Quashnet River, a revitalized trout stream. The Quashnet River and adjoining woodlands, while very close to major highways, remain a secluded, quiet haven for many birds, mammals and occasional human visitors.

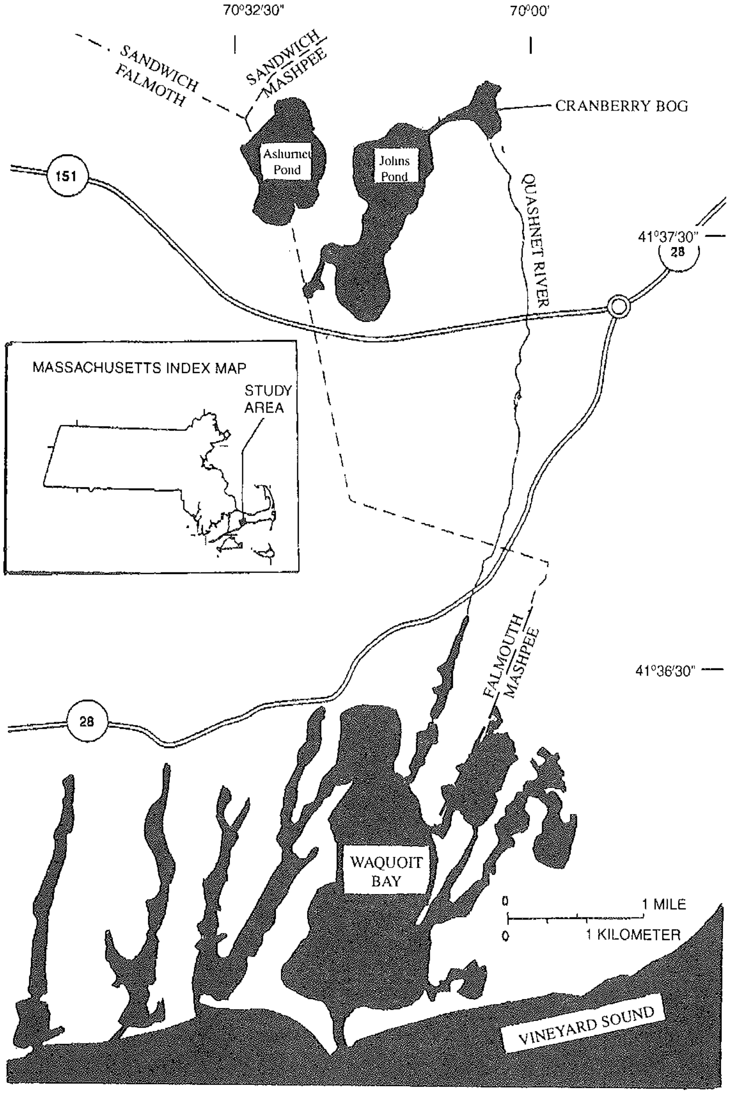

FIGURE 1.1
Location of the Waquoit Bay National Estuarine Research Reserve on the south coast of Cape Cod, Massachusetts.

For designation as a National Estuarine Research Reserve, an area must be considered a "natural ecological unit" and be relatively undeveloped. The Waquoit Reserve boundaries exclude many surrounding areas with extensive residential and commercial development. Waquoit Bay was designated in 1988 and is representative of the New England (Cape Cod to Sandy Hook, New Jersey) portion of the Virginian biogeographic province. WBNERR is the northernmost estuarine research reserve within the Virginian province and is located within the transitional border between the Virginian and the Acadian biogeographic provinces.

About 8,000 people now live in Waquoit Bay's watershed, which covers parts of the towns of Falmouth, Mashpee and Sandwich. The sea-

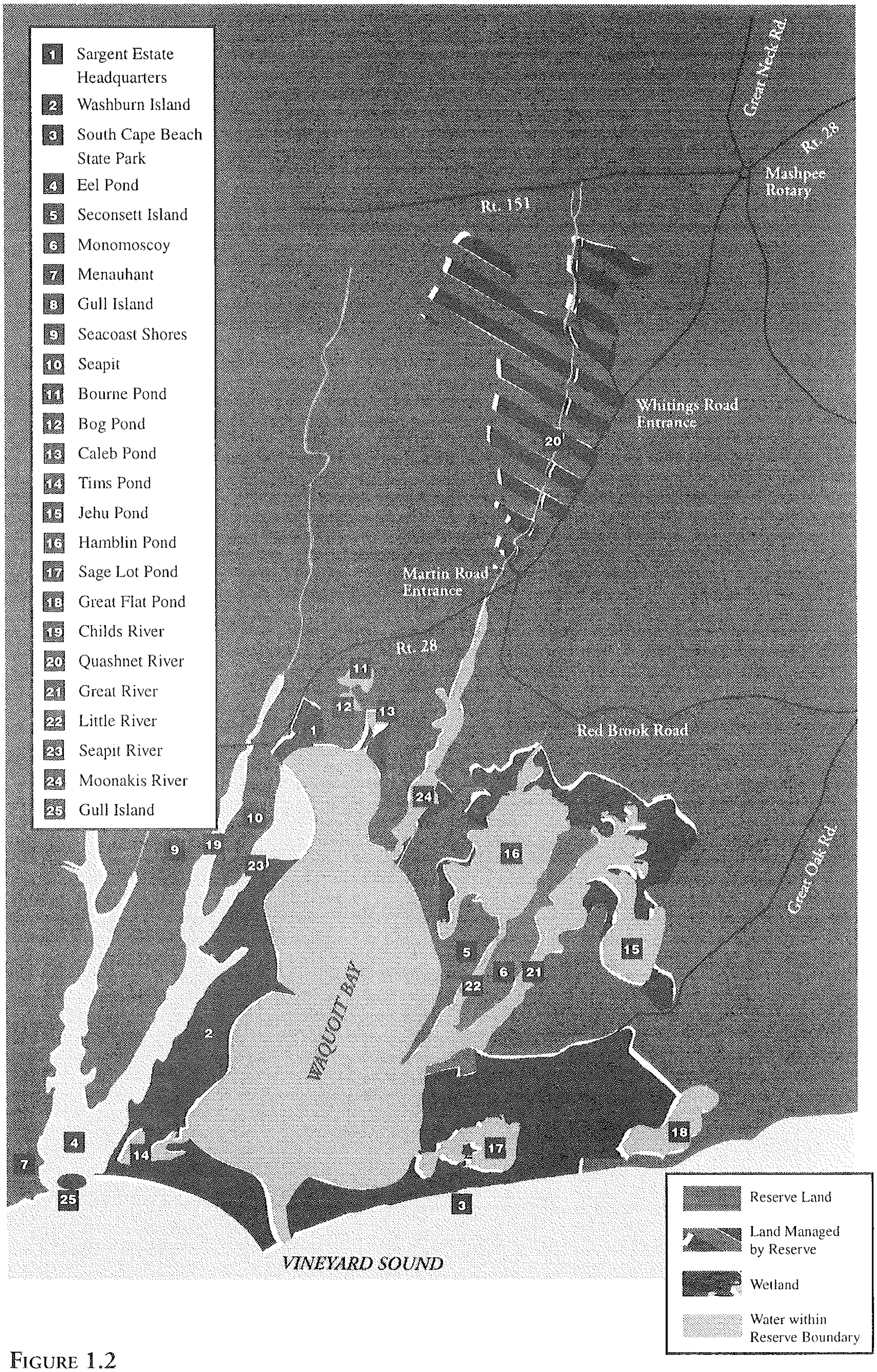

FIGURE 1.2

Boundary of the Waquoit Bay National Estuarine Research Reserve.

sonal influx of tourists swells the population during the summer months. The Bay area is close to Route 28, a major road linking the most highly populated areas of Cape Cod. Several public boat landings make this a popular location for boaters. Located just 70 miles from Boston, Massachusetts, and Providence, Rhode Island, Waquoit Bay is only an hour and a half driving distance from two of New England's largest metropolitan areas.

The Reserve also benefits from its proximity to the scientific community of Woods Hole where the Marine Biological Laboratory, the Woods Hole Oceanographic Institution, the National Marine Fisheries and the U.S. Geologic Survey, Branch of Atlantic Marine Geology, are located. Scientists from these and other institutions make use of the Bay and the Reserve's facilities for their research.

HUMAN HISTORY

PREHISTORIC NATIVE AMERICAN SETTLEMENT

Unlike other areas of New England, there are few artifacts from Cape Cod that predate the Early Woodland Period (2600—1500 years before present) (Gallagher 1983). The evidence there is suggests that human habitation was scattered, with small locally dense sites separated by large uninhabited areas. It may be that prehistoric settlements were near the seashore and that the rising sea level has eradicated any evidence of their existence (Gallagher 1983).

Most artifacts found in the Reserve area date from the Late Woodland Period (1000 – 450 years before present). Many of the Late Woodland sites are shell heaps on or near slightly elevated rises overlooking salt water. (Gallagher 1983). Many projectile points of the Late Woodland period have been found near the mouth of the Childs River; two jasper hammer flakes and a blue felsite hammer flake were found on a cliff on the eastern shore of Washburn Island; and a possible prehistoric shell midden was discovered on the northwest side of the Island (Gallagher 1983). Artifacts are still found on the eastern shore of Washburn Island, particularly after storms.

WBNERR's South Cape Beach property has features that are similar to a prehistoric site in the National Seashore in Eastham on the Outer Cape; like the Eastham site, South Cape Beach is coastal and has a high diversity of natural resources, with upland areas, salt and freshwater marshes and nearby barrier beach. However, no direct evidence of occupation has been found at South Cape Beach. Shoreline accretion in the western portion of the barrier beach and storm activity along the eastern section may have flooded the area below the upland margin eradicating any artifacts (Gallagher 1983).

HISTORIC WAMPANOAG SETTLEMENT

The written record of Wampanoag life and settlements comes from European settlers. The Waquoit Bay area was part of Wampanoag tribal lands at the time of immigration of English settlers in 1620, who bought land from the Wampanoags with the consent of the Court of Plimoth Colony (Gallagher 1983). The name "Waquoit" appeared in print as early as 1674 when it was listed as one of John Eliot's famous "praying villages." Eliot was called "the Indian Apostle" because of his missionary work, and was the first translator of the Holy Bible into a native language (Lynch et al. 1986). Early drawings depict mapping efforts and the variable spellings of common place names (Fig. 1.3).

An early missionary's impression in 1757 included the following description of the area:

> "There is no place I ever saw, so adapted to an Indian town as this. It is situated on the Sound, in sight of Martha's Vineyard; is cut into necks of land, and has two inlets by the sea; being well watered by three fresh rivers, and three large fresh ponds lying in the center of the plantation. In the two salt water bays [Waquoit and Popponesset, a large Bay to the east of Waquoit] are a great plenty of fish of every description; and in the rivers are trout, herring, etc. In the woods, until lately, has been a great variety of wild game, consisting of deer, etc.; and adjacent to the rivers and ponds, otters, minks, and other amphibious animals whose skins have been sought for, and made a valuable remittance to Europe ever since my knowledge of these Indians." (Freeman 1965).

In 1834 Josiah J. Fiske, appointed by the governor to visit the Wampanoag tribe and inquire into the state of affairs, reported to the Massachusetts State Senate:

> "It is hardly possible to find a place more favorable for gaining a subsistence...than the territory of Mashpee. It is situated on a sound, cut into necks of land with inlets from the sea, being well watered with beautiful ponds and fresh water streams running from the central parts of the plantation. On the sea shores are sea-fowl, shell fish, and lobsters in abundance. The salt water bays abound in fish of a larger kind, and the fresh water streams and ponds in trout and herring and small fish of every variety. Great Neck, which has sometimes been called the metropolis of Mashpee, is famous for eels which have been easily taken in large quantities by torch light. In the woods, till lately, wild game has been plenty; and in places adjacent to the streams and ponds, amphibious animals have been easily taken when furs were valuable. The natives are dexterous whalemen. In latter years, the business of pursuing whales has been open to all the able-bodied Indians who have been disposed to embark in the numerous whale ships which sail from the various seaports in the vicinity of Mashpee. This delightful territory has been preserved to the Indians through the guardian care of the government, until the standing wood, with a ready market, has become worth from 50 to $100,000, in addition to all the grants which have been made from time to time to the inhabitants for purposes of education and religious improvement. All were comfortably and decently clad, many of them occupying frame houses, and a few of them dwelling in wigwams. They owned cows and swines, tilled the land for raising corn, rye, etc. Some owned oxen and some owned horses, the fodder for cattle coming from the marshes and pastures. The plantation consists of about 10,500 acres, three quarters of which are covered with wood" (Freeman 1965).

European Colonization and Early Settlement

Europeans settled Waquoit village as an agricultural and whaling village. For 150 years, only light agriculture and animal husbandry were practiced (Faught 1945). The few settlers were outnumbered by the Wampanoags. As late as the early 1800s, some Wampanoags still camped near Caleb and Bourne ponds, where a spring supplied fresh water to the settlers as well as native Americans. According to Lynch et al. (1986):

> "one of Waquoit's retired seafaring men, Ichabod Childs, would drink from no other source and walked miles from his home to fill his pail at this Indian spring. He lived to be almost 100 years old, probably due to the good exercise as much as to the purity of the water."

In 1725 the town of Falmouth incorporated the section of Waquoit containing the Moonakis River, (removing it from Mashpee) to take advantage of the River as a source of water power for local industry. Allen

Green built the first grist mill when the Moonakis was damned. Farmers brought corn to the mill from many outlying areas (Lynch et al. 1986).

By 1800, 200 to 300 houses existed in the town of Falmouth, but only a few were located in the Waquoit section, where some people lived off the land, hunting for deer and ducks and fish. Other Waquoit residents raised livestock (cattle, sheep and hogs), planted gardens, and preserved vegetables and fruits (Faught 1945). In the winter, many sold wood from large tracts of land they purchased for as little as 50 cents an acre (0.4 hectare) (Faught 1945).

After the Revolutionary War and the War of 1812, farming, fishing, shipbuilding, trading and whaling became major enterprises in Waquoit (Faught 1945). Between 1812 to 1865 more than 100 ships were built in Falmouth; some of those were constructed at White's Landing on the Childs River (presently Edward's Boatyard). Peter Lewis, born in 1793, captained trading ships which docked at Peter's Wharf on the west side of Metoxit and Meadowneck roads near the Moonakis River. Lewis also owned a market and a ship's chandlery. Because Falmouth had no harbor at this time, lumber and firewood were shipped from Waquoit to Nantucket, which had been deforested in previous decades (Lynch et al. 1986). In the 1840s, saltworks became another significant industry.

Agriculture expanded as strawberry and cranberry industries developed at the close of the nineteenth century (Smith et al. 1986). Hundreds of acres of salt marsh hay were harvested for cattle feed; more hay was cut in Waquoit than in any town on Cape Cod (Faught 1945). Dried eelgrass also was valued as a fertilizer by the farmers.

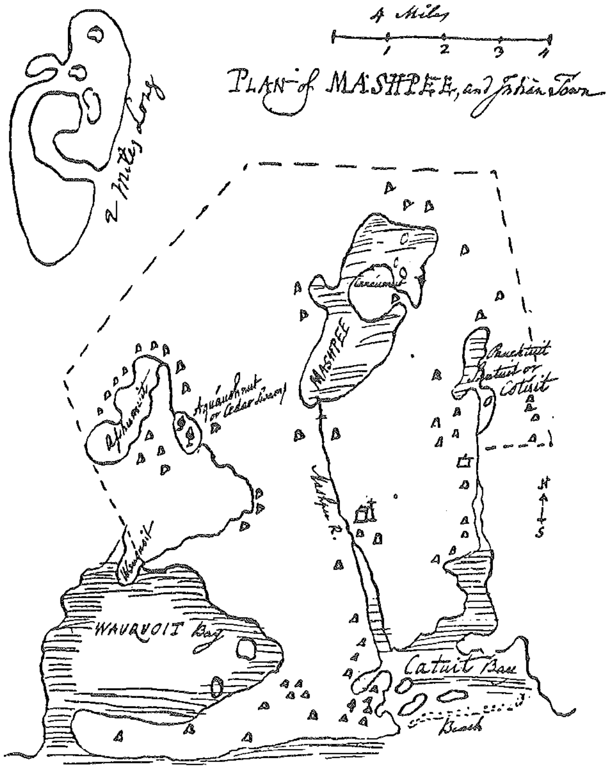

FIGURE 1.3

Map of Mashpee from the middle 1700's reproduced from "Extracts from the Itineraries and other Miscellanies of Ezra Stiles," (Yale University Press 1916).

The bounty of shellfish within the Bay was not unrecognized. Quahogs, bay scallops, soft-shelled clams and blue crabs were taken in abundance (Lynch 1986). Also renowned throughout New England was the abundance of trout in the lower reaches of the Childs and Quashnet rivers. President Grover Cleveland, the actor Joe Jefferson, and Daniel Webster were all regular anglers at these sites (Lynch et al. 1986).

Water from the Moonakis River was used to power a grist mill, saw mill and carding mills. In 1832 a shingle mill was built beside the grist mill. It was converted to a woolen mill in 1840 and operated until it burned down in 1894. Some time after the fire, the mill pond was drawn down and converted to a cranberry bog. To support the cranberry industry, the Waquoit

Company supplied barrels and boxes from their building on Carriage Shop Road, named for a carriage-building industry located there (Faught 1945; Lynch et al. 1986).

The first Waquoit Post Office opened in 1849. Mail for Martha's Vineyard and Nantucket came to Waquoit by stage from Sandwich once a day and was loaded at Peter's Wharf, along with passengers and other supplies for shipment (Lynch et al. 1986).

A weir placed outside the inlet to Waquoit Bay was the focus of an early dispute about resource allocation. The weirs were set for a few months in the spring of the year and there was a great deal of confusion and disagreement about effects on herring as well as on other fish. According to Lyman (1871) the 1870 Massachusetts State Legislature heard a debate between about 3,000 opponents and 8,000 proponents of the use of such contrivances for fishing. The proponents—mainly fishermen who sold the weir catch for bait for the mackerel fishery—claimed the weirs caught only those fish that did not breed "in the neighborhood." The opponents claimed the weirs prevented alewives from entering the rivers. Lyman's report "On the Possible Exhaustion of Sea Fisheries" does not conclude in favor of one or the other antagonist. He calls for careful observations, saying that

> "observations...by men of learning and impartiality, are the only means to real knowledge in this perplexed question."

This may be the first recorded request for the kind of research that is conducted today at the Waquoit Bay National Estuarine Research Reserve.

In an eloquent passage, Lyman (1871) describes Waquoit Bay as follows:

> "Waquoit Bay is one of the most singular of the land-locked fjords on the south shore of Cape Cod—an irregular, many-lobed body of salt water, which is rendered in its upper part brackish by fresh streams, and which empties in the sea only through a very narrow cut in the low sand barrier which shuts out the ocean. The influent brooks, dignified by the names of Quoshnet (sic) and Child's River, are of the clear cold water peculiar to that sandy country, which everywhere pours out its springs near the surface. It is these spring brooks and these extensive shallows of salt or brackish water, protected from the ocean and teeming with small crustacea, that render this region so renowned for its trout, which there get a size, fatness and flavor rarely found anywhere else. For similar reasons the alewives here find a proper breeding ground, by passing through the sheltered bay and ascending the brooks to the ponds at their sources. The scup, too, and the striped bass, eminently estuary fished, delight in the grateful cover and the abundant food."

DEVELOPMENT OF THE LOCAL RESORT AND TOURISM INDUSTRY

The increase in leisure time and extension of railroad service contributed to the development in the late 1800s of the resort economy on Cape Cod (Faught 1945). The "Flying Dude," a special train that ran from Boston to Woods Hole, about 12 miles west of Waquoit, in 1 hour, 48 minutes, was inaugurated by the Old Colony Railroad. Ferry service increased from Woods Hole to Martha's Vineyard and Nantucket to meet demand, and distinct summer "colonies" evolved as families visited year after year (Smith et al. 1986).

Some of these early summer colonies were located on the shores of the Waquoit Bay area. Menauhant, on the western shore of Eel Pond, was the site of the first resort, bought in 1870 as a camp by a group of Universalists. In 1874 the Menauhant Land & Wharf Company bought land and divided it into tiny 30 by 36 foot property lots; in 1928 alone, ten new summer houses were built (Faught 1945). The Menauhant Hotel was built around 1880 (it burned in 1922); the Menauhant yacht club boasted a club house (casino), tennis courts, and boats as well as a rudimentary and "challenging" golf course (Faught 1945). Most of these facilities still remain today.

According to some, Menauhant was also the name given to what we now call Washburn Island. In addition to a name change, Washburn Island has not always been an island! The narrow barrier spit comprising the southwest section of the present-day island has repeatedly breached and filled back in from natural causes and from the acts of humans.

Although uninhabited today, the Island was not always so. As described earlier, artifacts from native peoples have been found there, and in the latter 1800s and early 1900s, there were several homes and farms. On the northern end of the Island one can still see rubble from a 1850s farmhouse owned by J. Bournson. On the west side was another farmhouse owned by Sylvester Bourne. In the 1890s Henry Bryant, a ship's captain, bought the Island. He was the son of the founder of Bryant and Sturges—a shipping firm that was instrumental in opening the western United States to commerce. Bryant contracted Ignatius Sargent to build a large house and other buildings on the Island. Bryant died in 1904; in 1914 the Island was sold to Albert Henry Washburn (who became Ambassador to Austria after World War I). At this time, Washburn Island was connected to the Menauhant mainland by a sandy causeway. The Washburns built a large and gracious summer home where they spent much time (Fig. 1.4), but in 1926 a fire destroyed their home. Falmouth firefighters had trouble traversing the sandy causeway with their trucks and their efforts were further impeded by lack of water. After the fire, the Washburns did not rebuild. Another home on the Island, built on a mound of glacial outwash on the barrier beach by Fred B. Collins, was later moved to the mainland.

On the mainland, a Brooklyn doctor, William Fairley, built the first summer home in Waquoit in 1895. As time passed, many professional families summered in Waquoit where dinner-dances and picnics on Washburn Island were all part of the social activities.

FIGURE 1.4.
The Washburn Family home on "Washburn's Island."

Interestingly, Ignatius Sargent, who built Henry Bryant's house on Washburn Island, was the builder and owner of the properties that now comprise the Waquoit Bay National Estuarine Research Reserve Headquarters. The original mansion, a summer home called the Ignatius Sargent House, was built around 1890 in the shingle style. Other buildings were the Gate House which housed servants, the Carriage House for vehicle storage and the Boat

House. Sargent sold the property to a Norman Rutherford, an Australian, who disappeared without a trace years later, but left behind one amusing story. Norman Rutherford was the first treasurer of the Waquoit Bay Yacht Club and so, one would assume, was a seaman. According to a local story, Rutherford once launched a boat from the Boat House. A large crowd, assembled to watch the proceedings, instead watched the boat sink immediately, as Rutherford had neglected to put in the plug (Lynch et al. 1986). The estate later passed to Charles Swift.

After the loss of the Washburn family island home and the death of their caretaker, Washburn Island was uninhabited, but was a popular recreation area until World War II when it was taken over as a training ground for amphibious landings. To facilitate its use, a breach in the barrier island caused by the 1938 hurricane was filled in and a road built across to the Island. A second access road was built connecting the western part of the island to the Seapit area. About half of the forests were cut down and buildings and tent platforms were constructed. Amphibious vehicles were docked off the east side of the island. Washburn Island was not the only site of wartime activities; Falmouth's second air observation post was also located in Waquoit and the identification cards of Seapit residents were regularly checked. In 1944, Washburn Island's wartime mission was changed to a recreation facility for rehabilitating war veterans. After the soldiers left Washburn Island, the Washburn family did not return. By the 1950s, people living in the Waquoit Bay area used the island increasingly for camping and recreation (Lynch et al. 1986).

History of the Designation of Waquoit Bay as a National Estuarine Research Reserve

In 1979, the Commonwealth of Massachusetts designated Waquoit Bay as an Area of Critical Environmental Concern (ACEC) in recognition of its significant natural resources. The designation provides a statewide umbrella of protection and oversight under the existing regulations of different state agencies which include higher standards of protection for ACEC's. The Waquoit Bay ACEC includes the Bay proper—except for the central channel—parts of the Childs, Quashnet and Red Brook rivers, and Bog, Bourne, Caleb, Hamblin, Flat, Jehu, and Sage Lot ponds. Great and Little river are excluded. Altogether the ACEC covers 1,020 hectares (2,522 acres) including Washburn Island and South Cape Beach and their respective barrier beaches up to the 11- foot contour above mean sea level (which also is the 100- year storm level) (Fig. 1.5).

In the early 1980s a group of people concerned about the future of Waquoit Bay and its surroundings formed the "Citizens for the Protection of Waquoit Bay." This very active and dedicated group campaigned for state acquisition of land around the Bay. Their efforts resulted in the acquisition by the Commonwealth of Massachusetts of South Cape Beach State Park in December of 1982 and Washburn Island in July of 1983. In 1988, Waquoit Bay was added to the National Estuarine Sanctuary Program, since renamed the National Estuarine Research Reserve System (NERRS).

THE NATIONAL ESTUARINE RESEARCH RESERVE SYSTEM

The National Estuarine Research Reserve System (NERRS), a joint federal–state partnership, originated with the Coastal Zone Management Act of 1972. The federal partner is the Sanctuaries and Reserves Divi-

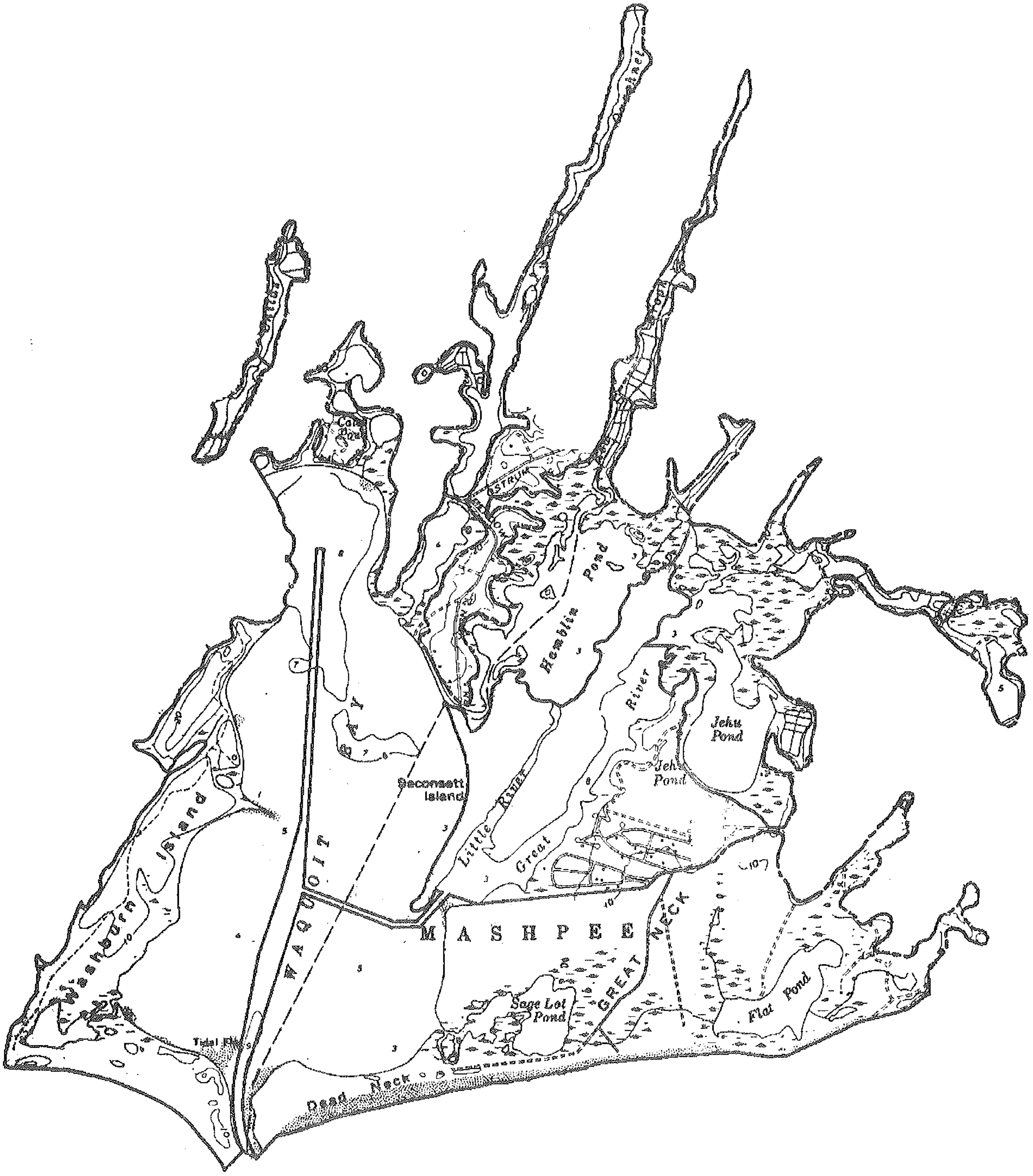

FIGURE 1.5

Boundary of the Area of Critical Environmental Concern.

sion of the U.S. Department of Commerce, National Atmospheric and Oceanic Administration. The state partner of the Waquoit Bay Reserve is the Forests and Parks Division—Region 1 of the Massachusetts Department of Environmental Management. In addition to land within the Reserve boundary, the Reserve also manages a large tract of land along the banks of the Quashnet River, a restored trout stream. The boundaries of the Reserve are almost identical to those of the ACEC.

Each reserve in the national system was selected to serve as a natural laboratory for conducting field research and monitoring activities while protecting the existing ecological, economic, recreational and aesthetic values, and to reflect regional differences and a variety of ecosystem types. Each site provides habitat for a variety of ecologically and commercially important species of fish, shellfish, birds, and other aquatic and terrestrial wildlife. Reserves are designed to ensure their effectiveness as conservation units and as sites for long-term research and monitoring. As part of a national system, the Reserves collectively provide an excellent opportunity to address research questions and estuarine management issues of national significance.

Beginning in 1997, the NERRS will institute the National Estuarine Research Reserve Graduate Research Assistantship Program, through which as many as 40 qualified graduate students will conduct high quality research under the joint guidance of a graduate program advisor at the sponsoring institution and the Research Coordinator or Reserve Manager at one of the Reserves. Research supported by this program will adhere to the NERRS agenda of addressing nationally significant issues as well as those of regional concern.

MISSION OF THE WAQUOIT BAY NATIONAL ESTUARINE RESEARCH RESERVE

The mission of the Waquoit Bay National Estuarine Research Reserve is to protect the resources of Waquoit Bay and surrounding areas, to preserve the area as a natural estuarine ecological laboratory, to support the conduct of research that will further our understanding of the ecosystems of temperate shallow coastal estuaries, and to facilitate the incorporation of research findings into the fabric of cogent coastal management decisions. As such, research at the Reserve, NERRS-sponsored or otherwise, is encouraged to address management oriented priorities such as those of the NERRS program or those which may be of more regional or local concern.

RESEARCH EFFORTS AT THE WAQUOIT BAY RESERVE

A broad range of questions has been studied at Waquoit Bay. Most of this effort has been directed at the impacts of nutrient loading of coastal waters (i.e., eutrophication processes and ecosystem response), a pervasive problem that is particularly evident in the bays of Cape Cod. Some of the other studies related to coastal zone management that are or have been under examination at WBNERR are loss of eelgrass beds; protection of drinking water; ecological impacts of boats, docks and piers; pathogens in the estuarine water; erosion of coastlines and barrier beaches; protection of endangered species and biodiversity; and upland issues (i.e., habitat loss and fragmentation). These issues are overviewed briefly below and in detail in other parts of this volume.

ECOLOGICAL EFFECTS OF EUTROPHICATION

Nutrient loading to the shallow, semi-enclosed Bay has multiple effects which begin with the increase in growth of algae (both phytoplankton and macroalgae or seaweed) that reduces light penetration, contributing to the loss of eelgrass beds—prime habitat for numerous vertebrate and invertebrate species. The large biomass of macroalgae also has been implicated in large fish and shellfish kills that have occurred when the supply of dissolved oxygen has been depleted under certain biological and meteorological conditions. Of commercial importance is the decline in scallops.

Drinking Water Contamination

Nitrogen is also a potential human health hazard. The EPA drinking water standard is 10 parts per million; local communities can enforce stricter standards. As drinking water on Cape Cod comes almost entirely from groundwater, and all of Cape Cod is considered a sole source aquifer, protection of the drinking water supply is of paramount concern.

Impacts of Boats, Docks and Piers

Along with the increase in residential and commercial development on the entire Cape, there has been an increase in the recreational use of the waters. For example, the number of boats moored in Waquoit Bay has increased sharply in recent years, rising from 285 to 400 between 1988 and 1989 alone (Richard Crawford, WBNERR, pers. comm.), and many off-Cape day-trippers use public landings to access the Bay and its tributaries. Unplanned construction of docks adds to congestion on the water as boats and people and docks compete for space. Shading from docks can reduce the productivity of underlying eelgrass. Chemical pollutants from boating activities include oil, and nonconsumed fuel, paint toxins from antifouling bottom paints, and toxic leachates from pressure treated wood used in dock and pier construction.

Other Chemical Contaminants and Pathogens

Chemical contaminants from the adjacent land include components of storm water runoff, pesticides associated with cranberry culture, and the possible future arrival of toxic pollutants from the Massachusetts Military Reservation, a Superfund site several miles north of the Bay.

Closure of shellfish beds due to high fecal coliform levels is a recurring problem near the mouth of the Moonakis River in Waquoit Bay. The source of contamination may be older residences that still use cess pools—on-site wastewater disposal systems that do not remove pathogens from the waste stream. Untreated sewage released by boaters on the Bay is another source of pathogens. Designation of Waquoit Bay as a Federal No-Discharge Zone in 1994 prohibited the release of treated or untreated wastes from boats in Waquoit Bay; however, practical problems exist with enforcement.

Armored Coastlines and Barrier Beaches

The armored south coast of Cape Cod is similar to other areas where attempts to stabilize the coast and ensure navigational channels have created new problems. Coastal jetties and groins interrupt normal sediment transport processes with the result that some beaches are robbed of sand. The impacts of dredging navigational channels and siting of dredge spoils also are ongoing problems.

Luckily, the barrier beaches of Waquoit Bay are not inhabited so management issues are not complicated by direct homeowner concerns. However, the Washburn Island breach caused by Hurricane Bob in 1991 has altered circulation, currents, and navigational channels in the Eel Pond portion of the Waquoit Bay system. Another potential concern is the effects of off-road vehicles on beaches and dune erosion in these fragile habitats.

ENDANGERED SPECIES AND BIODIVERSITY

The Waquoit Bay watershed is home to some federally designated endangered species including the endangered roseate tern and threatened piping plover, which are found on the Reserve's barrier beaches, along with the least tern which is listed as of special concern by the State of Massachusetts. The piping plover and least tern nest on South Cape and Washburn Island beaches (Fig. 1.6), while the roseate tern forages along the beaches. Plant species include the federally endangered sandplain gerardia, a flower found in only 8 locations worldwide, and the threatened bushy rockrose.

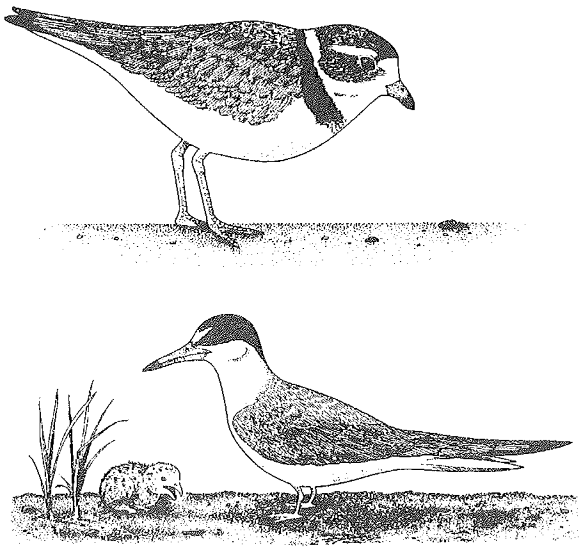

FIGURE 1.6

Piping Plover (top) and Least Tern (bottom), two species that nest on Waquoit Bay barrier beaches. Drawings by Bob Golder.

UPLAND ISSUES

Around the turn of the century, herring runs and trout spawning grounds were obstructed by construction of cranberry bogs along rivers. Restoration efforts on the Quashnet River have resulted in a self-sustaining brook trout population. However, increased development may well increase the demand for water and threaten the future viability of the river.

NATIONAL ESTUARINE RESEARCH RESERVE MONITORING PROJECTS

The National Monitoring Program of the NERRS was established in 1994 to identify and track short-term variability and long-term changes in the integrity and biodiversity of representative estuarine ecosystems and coastal watersheds for the purposes of contributing to effective national, regional, and site-specific coastal zone management. The goal of the program is to collect, analyze, and to distribute via the Internet data sets that are meaningful within the context of pressing coastal management problems. As Reserve sites were selected as representative ecosystems, information gained from monitoring programs should have broad applicability to other places.

NATIONAL WATER QUALITY MONITORING PROGRAM

The NERRS has implemented a long-term water quality monitoring program directed by each Reserve's Research Coordinator. Each Reserve has deployed data loggers that record water temperature, conductivity (salinity), pressure (depth), pH, dissolved oxygen and turbidity at 30 minute-intervals. Beginning in the summer of 1996, each Reserve will also monitor wind speed and direction, air temperature, rainfall, baro-

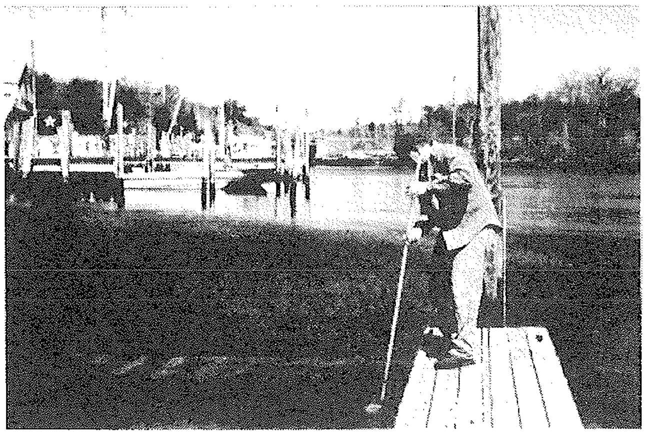

FIGURE 1.7

The Waquoit Bay Reserve depends on a group of volunteers, the WBNERR Bay Watchers, who monitor water quality in Waquoit Bay, its tributaries and adjacent coastal ponds. Here Bay Watcher, Bob Costello, uses a Secchi disk to measure water transparency.

metric pressure, and photosynthetically active radiation. These data will become part of a central data base available via Internet.

WAQUOIT BAY MONITORING PROJECTS

The WBNERR Research Coordinator also carries out other monitoring activities that address specific issues at Waquoit Bay including: monitoring the changing morphology of the barrier beach in the aftermath of Hurricane Bob in 1991; morphometric studies of coastal ponds adjacent to Waquoit Bay, plankton sampling, especially ichthyoplankton; and wetland and eelgrass mapping.

CITIZEN MONITORS

In addition to water quality data gathered with automated data loggers, the Waquoit Bay Reserve also has a dedicated group of citizen monitors who monitor water quality at various sites in Reserve waters (Fig. 1.7). Other volunteer efforts have yielded a botanical survey of the Reserve that has also led to the identification of state and federal-listed rare plants. In addition are two specific bird monitoring programs. Each spring, volunteers patrol the barrier beaches to count the numbers of piping plovers and their eggs and hatchlings, and to construct enclosures to protect them from humans and predators. The numbers of nesting least terns are also monitored.

The Reserve maintains a small library of research on the Waquoit Bay area and related topics and also prints annual Research and Policy Bulletins, Technical Papers and Occasional Papers. Contact the Reserve for access to these documents.

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CHAPTER II

THE PHYSICAL ENVIRONMENT OF WAQUOIT BAY

Waquoit Bay and surroundings. Photograph by Richard E. Crawford.

GEOLOGY AND GLACIATION

Many thousands of years ago, the familiar peninsula we recognize as Cape Cod did not exist. Glaciers covered large areas of the Earth, locking up a great deal of the oceans' waters. Consequently, sea level was much lower than at present and the east coast of North America extended as a broad coastal plain much farther into the Atlantic (Fig. 2.1) (Oldale 1992). Much of the appearance of Cape Cod today is attributable to the action of glaciers, followed by increases in the level of the sea.

Glaciers and the Formation of Cape Cod

Cape Cod is composed of relatively young glacial sediments that were deposited on top of bedrock during the final stage of the last great glacial epoch, the Wisconsinan Stage which lasted from about 75,000 years to 10,000 years before present (Oldale 1992). The glacier did not extend as far south as present-day Cape Cod until about 25,000 years ago. Then, three lobes of the Laurentide ice sheet spread over Cape Cod reaching their southern limits about 21,000 years ago at today's islands of Martha's Vineyard and Nantucket (Fig. 2.2) (Oldale 1990). As the glacier advanced it scraped and scoured the underlying sediments and bedrock, entraining loose soil and rocks in the base of the ice sheet (Fig. 2.3). These materials, called glacial drift, were transported great distances and then deposited by different mechanisms, either as moraines or as outwash plains, as the Earth warmed and the glaciers retreated.

Some moraines form when drift is deposited at the margin of a melting glacier (Fig 2.4a, 2.4b) (Strahler 1966). Oldale (1990; 1992) proposed that moraines on Cape Cod formed when an advancing glacier pushed and thrust existing unconsolidated material before it (Fig. 2.5). Moraines contain sediment made up of particles of many sizes, called unstratified drift or till.

Outwash plains form when water from melting ice at the glacier margin transports sediment from the base of the glacier and carries it along in braided meltwater streams. The running water sorts the sediment by size as it is transported. As the glaciers retreated from the Cape Cod area beginning about 18,000 years ago, the "stratified" drift was deposited forming broad outwash plains (Fig. 2.4b). The Waquoit Bay drainage area is located within one such plain, the Mashpee outwash plain. This plain, shaped like a large fan, radiates from its highest point near the conjunction of the Buzzard's Bay and Sandwich moraines south toward Vineyard Sound. The outwash plain is a mixture of sand and gravel layers, with some clay and silt lenses; finer grained sediments predominate in deeper layers and to the south (Guswa and LeBlanc 1985).

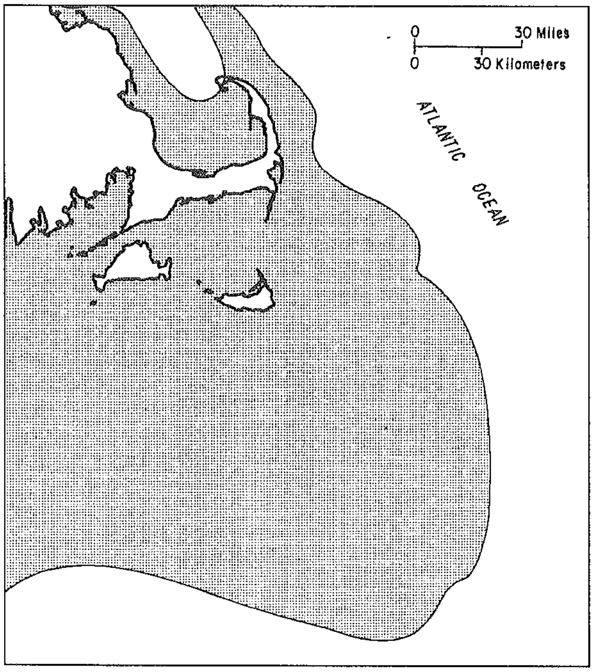


FIGURE 2.1
Present-day Cape Cod and southeastern New England superimposed on map (stippled) showing the extent of broad coastal plain during the Wisconsinan Ice Age (reprinted with permission from Oldale, 1992).

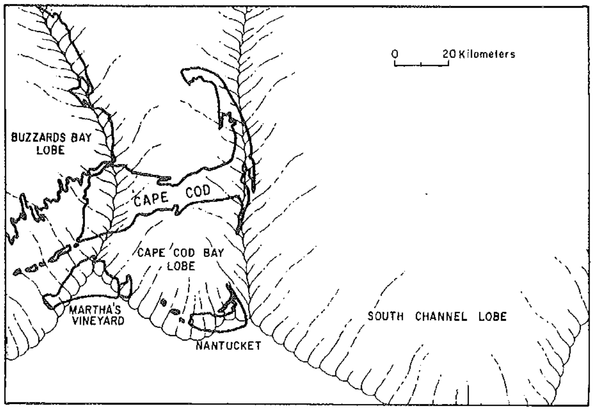


FIGURE 2.2
Maximum advance of the Laurentide ice sheets; the Cape Cod Lobe and Buzzards Bay Lobe formed the Upper Cape (reprinted with permission from Oldale, 1992).

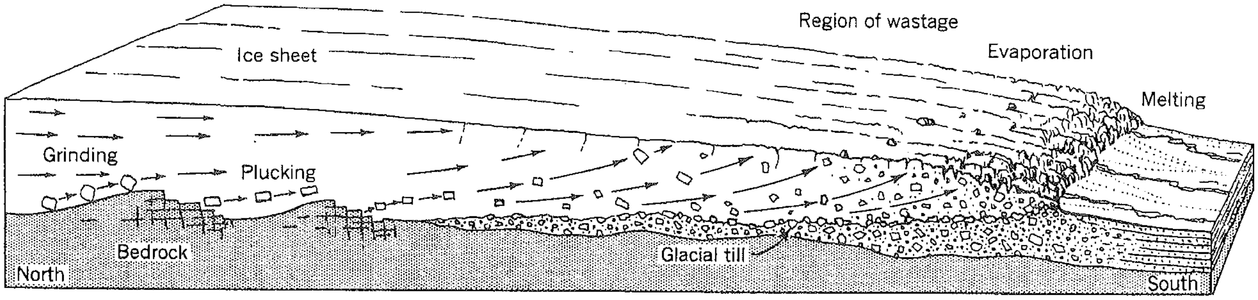


FIGURE 2.3
The figure depicts the scouring action of an ice sheet. As the ice sheet moves it plucks and entrains the underlying bedrock. The debris is deposited in the region of wastage as glacial till (Strahler, 1966). Copyright © by Arthur Strahler.

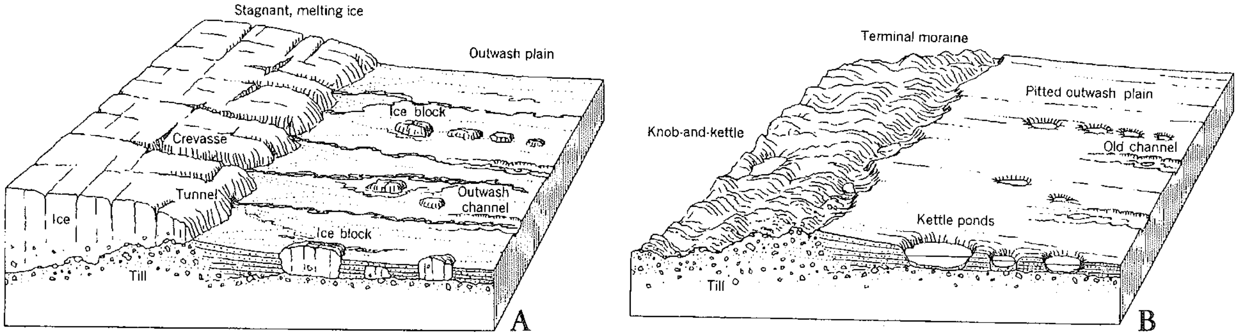


FIGURE 2.4A-B

Formation of a terminal moraine according to Strahler (1966). Figure 2.4a shows stagnant ice sheet; Figure 2.4b shows area after all ice has melted resulting in moraine and outwash plain. Copyright © by Arthur Strahler.

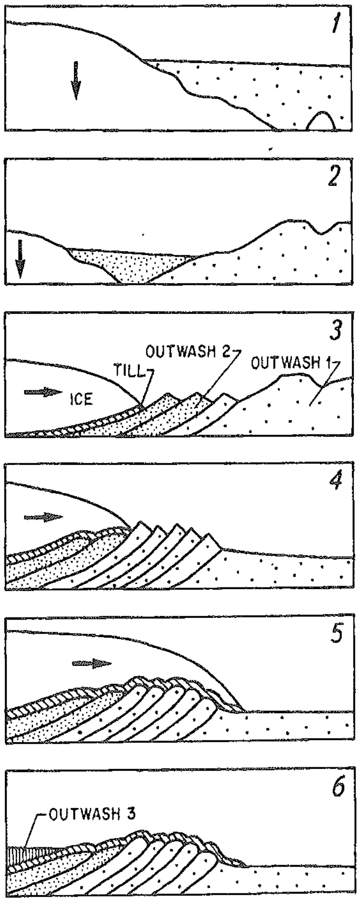


FIGURE 2.5

Mechanism of moraine formation on Cape Cod according to Oldale. 1 and 2 show outwash plains forming beyond a wasting ice front; 3 and 4 show another advancing glacier thrusting the unconsolidated sediments up in front of its advance. 5 shows the glacier overriding the moraine leaving a thin band of till; 6 shows the completed moraine following ice retreat (reprinted with permission from Oldale, 1992).

The Mashpee outwash plain is sometimes called the "pitted" outwash plain due to the presence of numerous depressions called kettles. Kettles formed when blocks of glacier ice were buried under flowing outwash sediments; over time the blocks melted and the overlying ground collapsed, giving it a pitted appearance. Numerous kettle holes deep enough to intercept the groundwater table eventually filled with water to form ponds and lakes.

Another feature associated with kettle holes are kames. These are flat topped or conical hills that originated when sediments filled gaps or holes in the glacier. A small kame deposit, with coarser sands and larger boulders than the Mashpee pitted outwash plain deposits, borders the north side of Flat Pond at South Cape Beach.

Many of the coastal salt ponds seen on Cape Cod, including Waquoit Bay, originated either as kettle ponds, as the lower extreme of outwash plain valleys, or as kettle ponds that intercepted an existing valley (Robert Oldale, U.S.G.S., Woods Hole, MA, pers. comm.). The southern extremes of these valleys were flooded by sea-level rise and are now coastal salt ponds.

According to Oldale (1992) these outwash plain valleys probably did not result from the action of fast-moving meltwater streams; they do not resemble stream-cut valleys which typically have a dendritic appearance and they originate well distant from the meltwater source. Rather, their origin may be from surface springs whose water source originated in a glacial lake north of Cape Cod (Oldale 1992). Glacial lakes were temporary features produced during the retreat of the Laurentian ice sheet, where the drainage of low lying areas was blocked by ice or deposits of glacial drift. The glacial lake was dammed by unconsolidated sediments that formed the northern extent of the outwash plain. Due to the porous sandy nature of the dam sediments, water may have seeped through the dam and traveled south and eventually intercepted the sloping outwash plain surface as a spring. Flowing water from these springs may have created the outwash valleys (Oldale 1992).

Bedrock is not exposed at the surface anywhere on Cape Cod; it lies buried beneath glacial sediments hundreds of feet below sea level. In the Waquoit Bay region, bedrock lies 122 meters (400 feet) below sea level (Oldale 1969); at other locations on Cape Cod, the depth to bedrock varies from about 60 meters to 300 meters (about 200 to 1000 feet) below sea level (Fig. 2.6). The bedrock beneath Cape Cod is more than 150 million years old (Oldale 1990).

SOILS

The parent materials for most of the Mashpee outwash plain soils are the sands and gravels mixed with some pebbles and small boulder gravel that were deposited by meltwater streams. Because the Cape Cod region is geologically young, the parental material has not been significantly altered, with the result that the soil horizons are weakly developed (Brownlow 1979). Rain water percolates rapidly through the surface organic matter and topmost layers of these highly porous, sandy soils. This rapid leaching of moisture and nutrients from the top soil horizons forms the podzolic soils commonly found in the Waquoit Bay region. Cape Cod's podzolic soils are only a few inches to several feet thick (less than six inches in most places) and generally do not support a rich flora and fauna. These soils are highly acidic in nature and are classified as dry, coarse, sandy soils with slopes of less than 15% (Brownlow 1979).

Other soils found in the coastal areas of the Reserve include the saltmarsh soils subjected to regular tidal flooding and the muck deposits found in surface depressions where the water table generally is at or near the surface. Marsh and swamp deposits contain decaying estuarine marsh plants mixed with sand and clay. Beach materials that form the bars and spits off the South Cape Beach and Washburn Island barrier beach complex are composed primarily of sand, but contain some cobbles and pebbles as well. Dune materials, composed of quartose sands, that have been rounded by wind and wave action, are very young (between ten years and several hundred years old), and are generally less than 6.1 meters (20 feet thick).

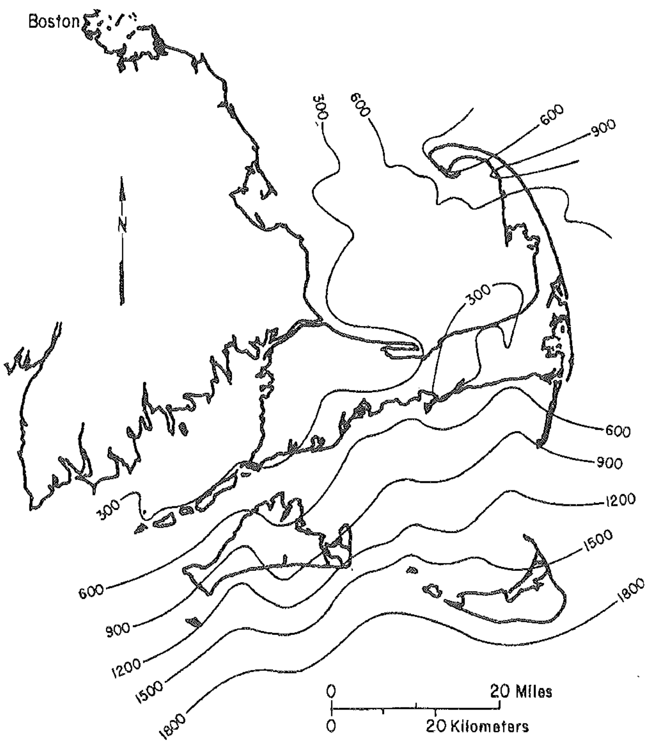


FIGURE 2.6
Contour map (300-foot intervals) showing depth to bedrock below Cape Cod (reprinted with permission by Oldale, 1992).

Rising Sea Levels and Coastal Submergence

As the glaciers retreated, leaving behind the kettles, kames, and outwash plains of the Cape Cod landscape, sea level rose rapidly and submerged the coastal lands, further transforming the landscape. About 5,000 to 7,000 years ago, the rising sea separated Martha's Vineyard, Nantucket and Cape Cod from one another and by about 2,000 years ago Cape Cod looked somewhat as it does today although the shoreline still extended further seaward (Oldale 1992). Sea level rise was rapid at first, slowing to 3.3 meters (11 feet)/1,000 years between 6,000 and 2,000 years ago. For the past 2,000 years sea level has been rising approximately 0.9 meters (3 feet)/1,000 years along the northeast coast of the United States (Nixon 1982; Oldale 1992).

Global or eustatic sea level reflects changes in the volume of the oceans due to the relative degree of glaciation. Eustatic sea level is modified by local changes in the height of the land. Subsidence of land can result from changes in weight of a landmass. Massachusetts is located at one end of a large land mass whose other end is weighted down by glaciers. As the glacier melts, weight is released from that end causing the Massachusetts and therefore, Cape Cod, end to subside (Mah et al. 1993). The term "relative sea level" describes the combined effects of eustatic and isostatic changes.

The relative rate of sea level rise has increased in the more recent past. In Massachusetts, the annual rate of sea level rise over the past 40 years has been approximately 3 millimeters (0.12 inch); about one-third of that increase is from global sea level rise. The remaining two-thirds results from land subsidence (Giese and Aubrey 1987).

Additional evidence for this relative sea level rise is found in the high zone of salt marshes, where salt marsh peat accumulations exist many feet below the sea level at which they were formed. By determining the age of salt marsh peat at different depths, one can track the peat accumulation rate and infer the rate of change in

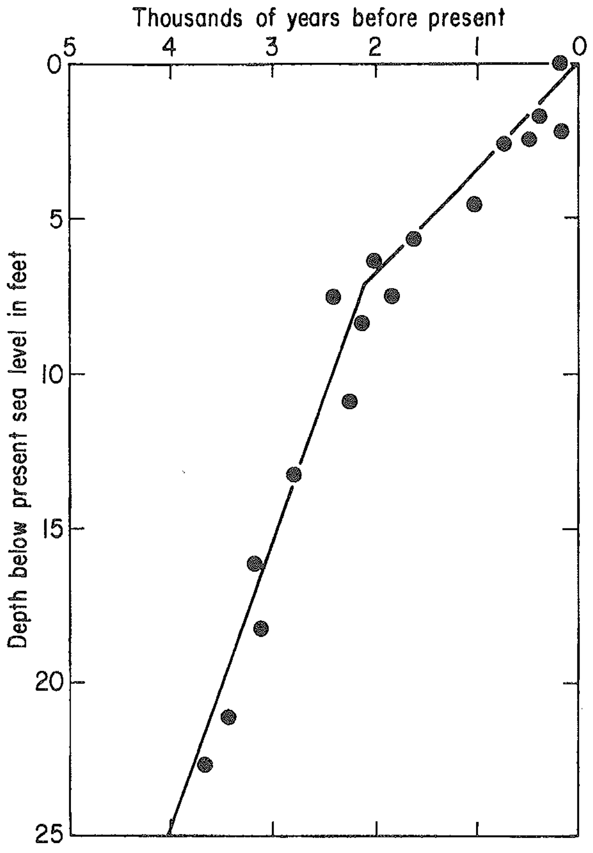


FIGURE 2.7
Sea-level rise curve constructed by Alfred C. Redfield from radiocarbon-dated peat samples from Barnstable's Great Marshes. Redrawn by Oldale (1992) and reprinted with permission.

past sea levels (Redfield and Rubin 1962). Peat accumulation rates in Barnstable, Massachusetts, record the continuous rise in relative sea level from approximately 3,700 years before present, with the average rate of rise decreasing around 2,100 years before present (Fig. 2.7). Orson and Howes (1992) also examined sea level rise and sediment accumulation in salt marshes at Waquoit Bay. Over the past 4,000 years marsh accretion rates were approximately 0.96 mm per year (0.04 inch per year), comparable to measurements from other New England sites (Hicks 1978). During the past 50 years accretion rates at Waquoit Bay have ranged from 2.8 to 4.6 mm per year (0.11 to 0.18 inch per year or approximately 0.01 foot per year); this value agrees with published values for recent sea level rise in Woods Hole, 12 miles from Waquoit Bay (Teal and Howes 1990).

Rising sea levels also were responsible for the formation of freshwater swamps and bogs. The elevation of the sea creates hydraulic pressure in the wedge of saline groundwater along the shoreline, which in turn controls the level of fresh groundwater (Guswa and LeBlanc 1985). As sea level rises, the fresh groundwater level rises in turn, creating greater areas of saturated soil, or freshwater swamps and bogs, such as those found at South Cape Beach off of the Flat Pond Trail (Orson and Howes 1992).

Over the long term, sea level rise has slowly inundated coastlines, erasing some features while exposing new ones. On a shorter time frame, coastal sediments have been reworked by wind and waves. Coarse sediments deposited by longshore currents created barrier beaches and sand spits such as those found on South Cape Beach and Washburn Island. Fine sediments carried by currents and tides were deposited in the quieter, low energy areas behind the barrier beaches within the Bay.

COASTAL DYNAMICS

The landforms common to the Cape Cod coast—sandy beaches, dunes, barrier spits and cliffs—are dynamic features that have been and continue to be shaped by sea level rise and the action of waves, currents, winds and tides. The overwash of sand by winds and waves allows the barrier beach to keep pace with sea level rise; as sand is removed from the forebeach it is redeposited on the back beach causing a slow landward migration of the barrier beach. The marshes that form behind the barrier migrate landward along with the barrier beach. Waquoit Bay has two barrier beaches, one extending westward from South Cape Beach and one that forms the southern end of Washburn Island, extending eastward toward South Cape Beach and westward toward Menauhant. Together they nearly enclose Waquoit Bay and Eel Pond. These barrier beaches have a long and active history that began shortly after the Bay itself came into existence. At present there are three openings to Waquoit Bay (two permanent inlets maintained and stabilized, and one recent breach), but this has not always been the case.

SEDIMENT TRANSPORT AND BARRIER BEACH FORMATION

As discussed above Waquoit Bay may have originated as sea-level rise drowned a kettle pond or outwash valley (Oldale 1992). Then, long finger-like projections or spits began to form as sediment-laden longshore currents encountered the particular morphometric features of the area. When a longshore current intercepts an indentation in the coast, such as an embayment, the current is deflected and its velocity decreased. The slower current loses its capacity to carry sediment and deposits it, beginning the formation of a spit (Magee and Long 1979). As the spit grows, the entrance to the bay narrows creating a tidal inlet (Fig. 2.8). The spit can continue to build across the inlet until the embayment is completely enclosed, or the spit's progression can be halted when the amount of sediment delivered to the inlet area is equalled by the amount of sediment scoured out by inlet currents (Fitzgerald 1983). The shape and appearance of the barrier spits at Waquoit Bay as well as other coasts are continuously refined by longshore currents that rob some areas of sands while depositing sands in other areas. Physical processes are not the only factors responsible for the shape of a barrier beach. Vegetation on the backshore of a sand bar stabilizes the sands, promoting further deposition and an increase in the height of the beach, eventually resulting in the development of dunes. Dunes raise the level of the beach up above the level of the highest tide, thereby reducing the risk of overwash.

Longshore currents transport and deposit sediments, depending on the direction of approaching winds and waves. In the Waquoit Bay area, Martha's Vineyard interrupts the fetch (the distance the wind travels over water without interruption) from the south and intercepts larger offshore waves that would otherwise break along the Waquoit Bay coast. Southwest and southeast of Waquoit Bay there is a long seaward fetch with no protection from larger, offshore waves, a circumstance that is augmented by the prevailing west–southwest

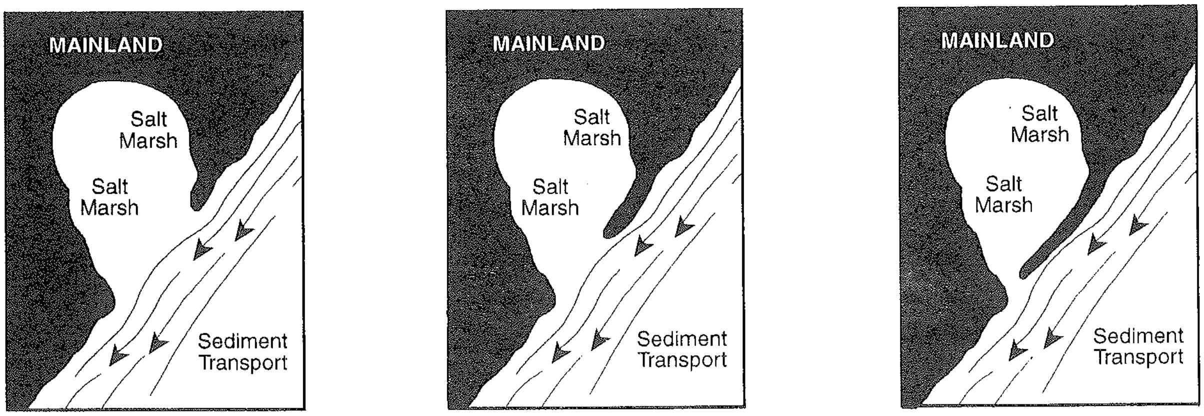


FIGURE 2.8

Mechanism of spit formation in response to dynamics of sediment transport. The panels show a spit forming as sediments are deposited at the entrance to a bay. The arrows denote the direction of sediment transport. Drawings by Karen Holmes.

winds. In general the long seaward fetch results in a net movement of sand from west to east with the sediment supply coming from the erosion of glacial deposits at Nobska Point and Falmouth Heights located to the west of Waquoit Bay (DeWall et al. 1984).

However, the uneven shoreline around Waquoit Bay and the presence of sand bars, shoals and subtidal bars alter incoming waves and their energy with the result that the direction of sediment movement varies in the vicinity of Waquoit Bay. According to DeWall et al. (1984), the observed tendency of inlets to migrate from east to west in the Waquoit Bay area suggests that the net transport of sediment is from east–to–west, supporting Strahler's (1966) view that Succonnesset Point (east of Waquoit Bay) is a null point of divergence. However, aerial photographs support a net west–to–east sediment transport direction. DeWall et al. (1984) interpret the landward migration of the western Washburn Island spit as indicative of a local reversal in net transport east of Eel Pond. They suggest that a nodal point of divergence exists east of the Eel Pond inlet on Washburn Island (Fig. 2.9) where there is an eroding glacial bluff, called Till Hill, that once was fronted by an extensive beach. (Graham Giese, Woods Hole Oceanographic Institution named this glacial bluff, Till Hill, because it is composed of upland rather than dune deposits.)

When left in a natural state, barrier beaches breach, change size, shift orientation and migrate landward. Following an overwash, barrier beaches usually rebuild themselves. The southwest spit on Washburn Island has a history of breaching and rebuilding. A Barnstable County atlas map from 1908 is the first record showing a breach there. The breach filled in but the spit was breached again during hurricanes in1938 and 1944. Jetties, groins, and other armaments are attempts to stabilize the coast and maintain navigational channels. However, because these structures interrupt the normal transport of sediments along the shore, the overall result of armoring is destabilization of the coast.

Inlet Dynamics and Coastal Armament

Armoring of Waquoit Bay barrier beaches began in 1918 when a stone jetty was constructed on the east side of the inlet to the Bay. In 1937, a second jetty was constructed on the west side of the inlet. Both jetties have since been lengthened and reinforced. Sediment moving along the beach is caught by these jetties, building up the adjacent beaches. Also in 1937, a groin was placed on Menauhant Beach on the west side of Waquoit Bay where Washburn Island was connected to the mainland by a narrow spit. In September of 1938 a hurricane caused a breach in the spit, separating it from the mainland and creating an island. Although the breach occurred during a hurricane, the placement of the groin may have accelerated the process of beach thinning that led to

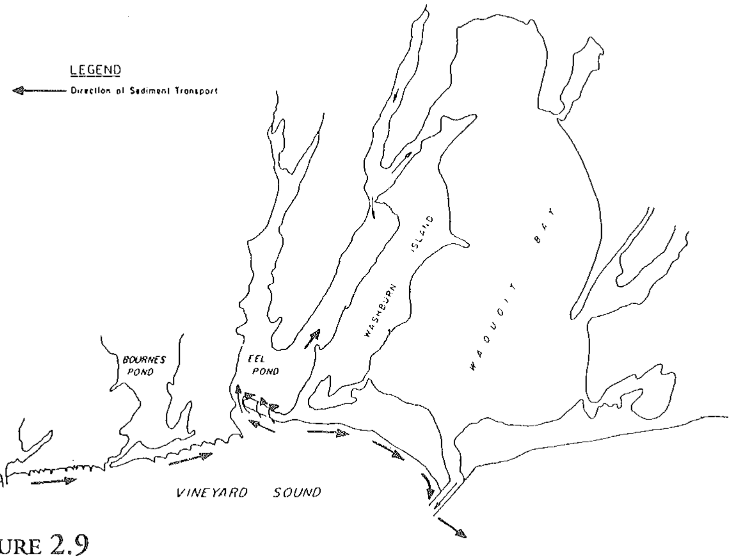


FIGURE 2.9
Localized sediment transport reversal in area of Waquoit Bay (DeWall et al. 1984).

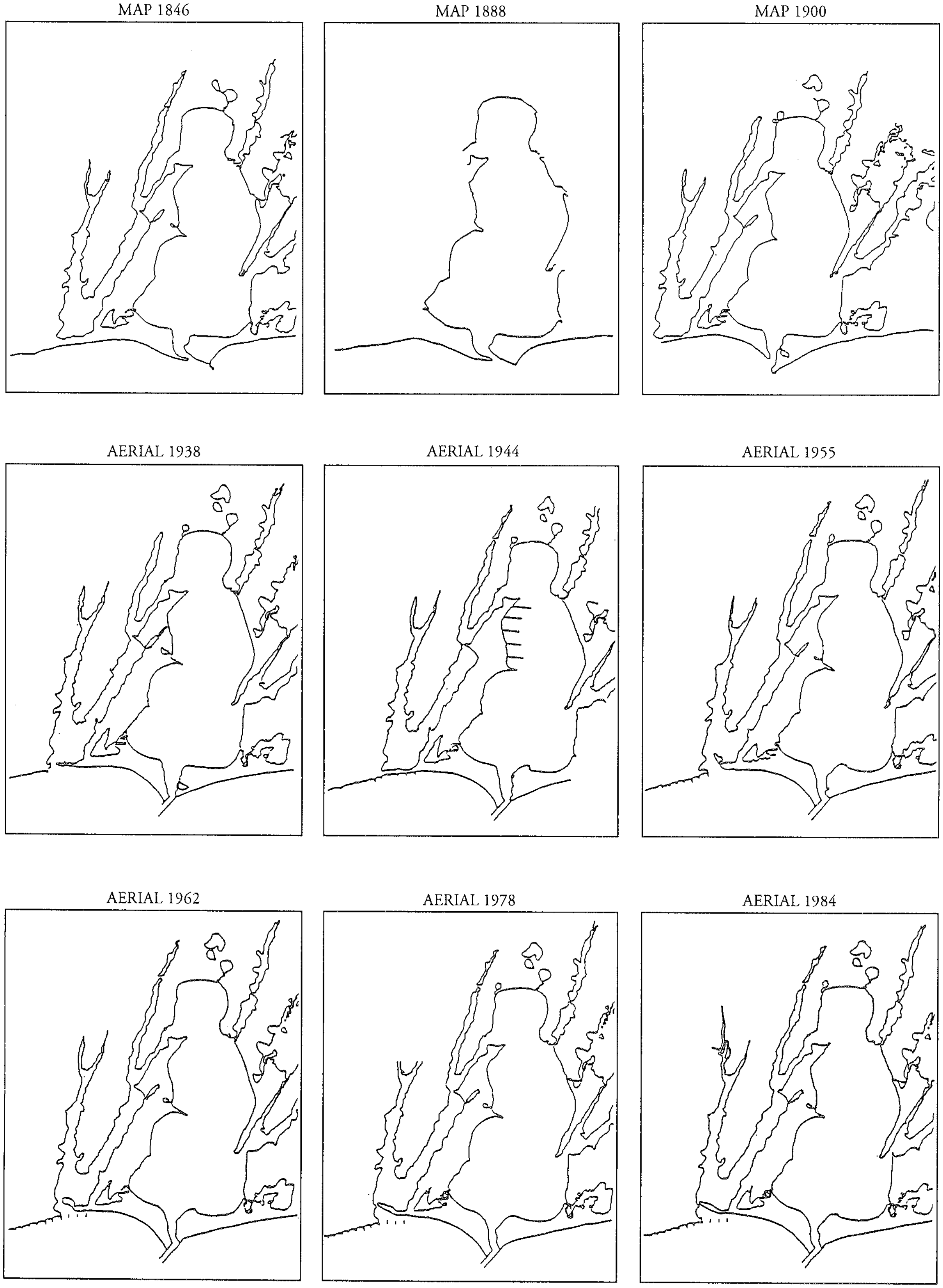
the breach (Eliet 1990). Breach formation may also have been assisted by sand removal by local residents, a practice known to occur even recently.

The 1938 Menauhant inlet remained open until it was artificially closed in 1941. Sand dredged from the flood tidal delta of the inlet was used to fill the breach in preparation for wartime use of Washburn Island by the U.S. Army (DeWall et al. 1984). An access road to the island was built along the newly filled section of barrier beach. Although attempts were made to stabilize this section of the beach with additional groins, another hurricane in 1944 created another breach in the same location as the previous inlet by Menauhant Beach.

Aerial photographs record changes in the appearance of the spit over time (Fig. 2.10) (Eliet, 1990). Between 1944 and 1962 the spit had curved northward and separated from most of the groin field, probably as a result of reduced sediment supply (Aubrey et al. 1993); by 1984 the spit had thinned and straightened but was oriented to the northwest and the groins were stranded about 100 meters offshore (Fig. 2.10). An analysis of changing morphometry of the entire barrier beach system between 1938 and 1984 shows that the Washburn Island barrier beach retreated 180 meters during this time, eroding along its western side while accreting along its eastern side. At the same time the South Cape Beach barrier beach also eroded along its western margin but remained stable on its eastern margin (Eliet 1990).

On August 19, 1991, Hurricane Bob pummeled Cape Cod (Valiela et al. 1996) and the narrow western spit of Washburn Island breached about 1,000 feet east of the Menauhant Beach inlet. This new opening created a new island (so-called "Gull Island") and Waquoit Bay now had a third inlet (Fig.2.11). The inlet formed where an eelgrass bed occurred in the Bay, adjacent to the sand spit. Sand from the remaining portion of the sand spit and from Gull Island washed through the new inlet and quickly covered the bed, resulting in a loss of valuable habitat.

In an unaltered system, the hurricane damage to the barrier beach would presumably be "repaired" by the influx of sediments from the upland pitted plain deposits at Nobska, Falmouth Heights, and Till Hill. But because coastal armoring has reduced the supply of sediment from Nobska and Falmouth Heights, Till Hill has relatively recently become a valuable sediment source for Waquoit Bay barrier beaches (McCormick 1994). During storms, hurricanes and otherwise, the sediments that are washed from the exposed face of this hill may travel east or west, depending on prevailing conditions at the nearby nodal point of divergence. Whatever the case may be, Till Hill sediments contribute to the local longshore drift and slow the alteration of the beaches. However, this sediment source is becoming depleted. The rate of erosion along the Washburn Island barrier beach for much of this century has ranged between 0.3–1.8 meters (1–6 feet) per year (DeWall et al. 1984). From 1975 to 1994, the beach face of the hill eroded about 36.6 meters (120 feet), equivalent to roughly 7,360 cubic meters (260,000 cubic feet) of sediment. As of fall, 1994, about 1160 cubic meters (41,000 cubic feet) of sediment remained. This is not to imply that at current rates of erosion, Till Hill will be washed away by 1998. After Hurricane Bob, Till Hill and Gull Island eroded rapidly. During the first half of 1993, the eastern end of Gull Island regressed at a rate of about 24.4 meters (80 feet) per year. The rate of erosion slowed to about 6.1 meters (20 feet) per year in the latter half of 1993 and during 1994, a period of frequent, violent winter storms (Richard Crawford, WBNERR, pers. comm.). Hurricanes rarely strike this area and the pattern and intensity of winter storms is unpredictable. Because of these and other uncertain-



MAP 1846

MAP 1888

MAP 1900

AERIAL 1938

AERIAL 1944

AERIAL 1955

AERIAL 1962

AERIAL 1978

AERIAL 1984

FIGURE 2.10

Maps and reconstructions from aerial photographs of breaches and migration of the barrier beach from 1846 to 1984 (Eliet 1990).

ties, it is difficult to project how long it will be before Till Hill is a minor factor in the maintenance of the Waquoit Bay barrier beach.

INLET STABILITY

The stability of the eastern or main inlet to Waquoit Bay suggests that the rate of sediment deposition was equalled by erosion from the inlet currents. Although the eastern inlet has remained opened, its orientation changed between 1846 and 1900, presumably due to a change in the direction of net sediment transport. Figure 2.10 shows the eastern Waquoit Bay inlet trending eastward in 1846 and 1888, followed by a reorientation in 1900.

By the middle of 1995, the Hurricane Bob-induced inlet had migrated west and narrowed to about 60% of its original width (Richard Crawford, WBNERR, pers. comm.). The fate of this third inlet is unknown. It may migrate to the west, eventually joining the Eel Pond inlet or it may persist due to the decreased longshore transport in the area (Aubrey et al. 1993).

FIGURE 2.11

Breach migration in the aftermath of Hurricane Bob, August of 1991. Top photograph is March, 1994; bottom is May 1995. Arrows show locations of Tims Pond and Till Hill. The stranded groin field, referred to in the text, is also visible in these photographs. (Aerial photos by Richard Crawford).

SEASONAL CHANGES IN THE WAQUOIT BAY SHORELINE

In addition to catastrophic hurricanes, intense storms can have tremendous impacts on low lying coastal areas. The Waquoit Bay coastline is susceptible to damage from southeastern winter storms, when large, oceanic waves alter the speed and direction of sediment transport, and lead to dramatic changes in the shape of shoreline. Often a storm berm will mark the site where waves have sliced away layers of sand. Even without large storms the erosive force of big winter waves causes a net transport of sand offshore, producing a "winter" beach with a short, steep profile. During the summer the beach is replenished by the gentler summer waves.

SALT MARSH DEVELOPMENT AND ACCRETION WITH RISING RELATIVE SEA LEVEL

When sediments are carried from the more energetic, open water environment into the more tranquil bay environment, the finer particles suspended in the water column settle out. Salt marshes form in these quiet, depositional environments through a gradual building process. In the Waquoit Bay area, Flat, Sage Lot, Hamblin, and Jehu ponds—originally kettle holes left in the outwash plain—have partly filled in with fine sediments and organic matter producing a system of tidal mud flats and salt marshes (Fig. 2.12).

FIGURE 2.12

Salt marsh in the South Cape Beach area of the Waquoit Bay Watershed.

In addition to a protected depositional environment, salt marshes require a specific tidal flooding regime to maintain themselves (Teal 1986). Salt marshes are divided into low and high marsh zones with different species dominating the two areas. *Spartina alterniflora* (cordgrass) inhabits the intertidal zone where it is subjected to regular tidal inundation, and *S. patens* (salt marsh hay) inhabits higher elevations where it is inundated only by extreme high tides.

Because salt marshes inhabit low-lying areas they are among the first systems to be impacted by rising sea levels. Indeed, the development and accretion of salt marshes in New England is coupled to rising sea levels (Redfield 1972). Salt marshes form in sheltered areas where sediments have accumulated enough so that salt tolerant marsh species can take hold. Marshes then increase in area as their roots and rhizomes trap sediments and decaying organic matter, a process that elevates the marsh and promotes additional sedimentation and marsh growth on the bay or seaward side. As sea level rises, the marsh can grow also on the landward margin. This explanation of bi-directional growth was proposed by Redfield (1962; 1972) and explains how marshes sustain themselves despite the encroaching sea.

Depending on the conditions, salt marsh growth can keep pace with, be impeded by or accelerated by sea level rise. If sea level rise keeps pace with marsh development, there is no net change in the extent of the marsh, although its position migrates landward. If saltmarsh accretion is slower than the rate of sea level rise, a salt marsh may be flooded, and convert to open water. If sediments accumulate faster than the rise in relative sea level, a salt marsh may expand its area. Human development behind a salt marsh prevents its continued landward migration and results in a narrower marsh which may eventually disappear (Teal and Howes 1990).

SALT MARSH DEVELOPMENT IN THE WAQUOIT BAY AREA

By analyzing the sequences and relative contributions of freshwater, high marsh and low marsh vegetation in sediment cores, Orson and Howes (1992) reconstructed the history of salt marsh development at five sites in the Waquoit Bay area. The analysis indicated several different pathways of development. For instance, salt marshes around Caleb Pond developed by accretion onto adjacent tidal flats under the direct influence of the waters of the Bay beginning about 1,600 years ago. Sediment cores from the Hamblin Pond and Great River areas showed that rising sea levels drowned freshwater swamps leading to their transition to freshwater marshes and then salt marshes about 2,400 years before present (Orson and Howes 1992).

Marsh development within the Hamblin Pond area was not uniform. Above Seconsett Island, evidence of *Spartina alterniflora* directly overlying gray marine clays suggests that a breach between the Bay and Hamblin Pond flooded nearby areas causing a rapid transition to salt marsh; whereas farther from the breach remains of *S. alterniflora* above freshwater species suggest a slower transition to salt marsh. At Great River, the earliest salt marsh cores are dominated by *S. patens* and marsh development was more gradual than at Hamblin Pond. Orson and Howes (1992) speculate that the different development of these two systems at the same time can be explained if Great River were open to Hamblin Pond at the same time that a breach opened Hamblin Pond to Waquoit Bay.

Sediment cores indicate that continuous marsh development around Sage Lot Pond and Washburn Island began about 1,100 years before present. Prior to that time, Sage Lot Pond cores record alternating sequences of salt marsh and sandy overwash deposits (Orson and Howes 1992).

The record of salt marsh development in the Waquoit Bay area reveals relatively long periods of stability (100–1000 years) followed by rapid transitions. Orson and Howes (1992) suggest that hydrodynamic conditions and the physical structure of the Bay have been the major influences on marsh development in this area. The 1938 hurricane provides an example of the effects of hydrodynamics in structuring a marsh system. According to Orson and Howes (1992) most of the marshes in Waquoit Bay were dominated by high marsh (*Spartina patens*) vegetation until 1938 when the hurricane opened a second inlet near Menauhant. The marshes have rapidly converted to low marsh, *Spartina alterniflora* dominated systems. Maintenance of the second inlet with its increased tidal flow and flushing rate, coupled with continued increases in the rates of sea level rise, will probably preserve the system as a low marsh for some time. The authors contrast marsh development in Waquoit Bay with its narrow inlets and restricted flow to that of Barnstable Marsh on Cape Cod Bay where the salt marshes are open to the bay. In Barnstable, hydrodynamics change slowly and salt marsh development is more closely tied to autoecological processes like interspecific competition than to hydrodynamics.

HYDROGRAPHY

TIDAL CYCLE

The morphology of Waquoit Bay is like that of other New England coastal bays which typically feature asymmetric shaped bays, fringing marshes, fronting barrier spits or beaches and inlets (Fitzgerald 1983). The amount of water that enters and exits a bay during its tidal cycle is determined by the magnitude of the tides as well as by the morphology of the bay and its inlets. On Cape Cod there are two high tides and two low tides every 24 hours and 48 minutes, with each high and low tide separated by approximately 6 hours and 12 minutes (Smrcina 1992). Waquoit Bay has a 0.5 meter (1.5 feet) tidal range (Aubrey et al. 1993).

Inlet and bottom morphometry, the extent of tidal flats, and the ratio of the height of the tide to the mean depth of the water can distort the tide such that the duration of the flood and ebb tides are unequal. Waquoit Bay's flood-tide currents are faster and have higher amplitudes than the slower, lower amplitude ebb-tide currents. Near the mouth of Waquoit Bay's main inlet, shoals have developed from the deposition of sediments brought into the Bay on the flood tide.

TIDAL EXCHANGE IN A MULTIPLE INLET SYSTEM

Because of inherent differences in the hydraulic efficiencies of inlets, the flow of water in an embayment with multiple inlets is not uniform, resulting in a net flow that favors one inlet over the other. In the Waquoit Bay estuarine complex, the residual currents are from Eel River to Waquoit Bay (Aubrey et al. 1993). The water travels up Eel River and around the north end of Washburn Island and then southward through the Bay to Vineyard Sound through the main inlet, located in the barrier beach between Washburn Island and South Cape Beach's Dead Neck (Aubrey et al. 1993).

SALINITY STRATIFICATION

Significant freshwater input from rivers creates vertical stratification in some parts of the Waquoit Bay system resulting in large salinity differences between top and bottom waters in the estuarine parts of the rivers (D'Avanzo and Kremer 1994) and a two-layer circulation pattern. The lighter fresh water travels downstream on the surface while the denser salt water moves upstream on the bottom. Salty, dense water enters the Bay on each flood tide from Vineyard Sound, where salinities typically range from 30 to 32 ppt. Salinities in most of the Bay range from 26 to 31 ppt over a tidal cycle (Aubrey and Giese, 1990, unpublished data).

The extent and structure of the low salinity surface layer depend on rainfall and local wind conditions at the time of sampling. In the estuarine reaches of the Childs and Quashnet rivers, wind direction can dramatically alter the salinity structure (Geyer in press). In the Childs River, when the wind blows onshore, the freshwater backs up in the estuary, the water column stratifies and the flushing rate decreases. An offshore wind has the opposite effect; the flushing rate increases, which increases the salinity and decreases the stratification (Fig. 2.13a and b) (in press). Onshore winds are typical of summer conditions, while offshore winds are more common in winter.

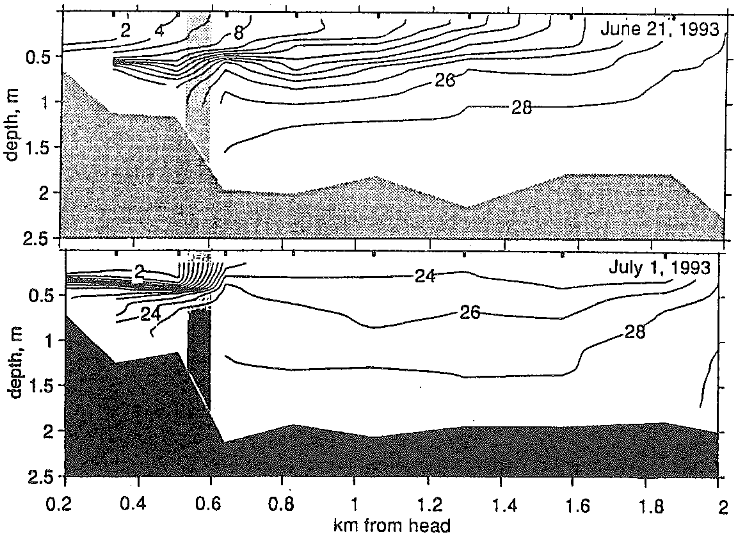


FIGURE 2.13

Influence of wind direction on the salinity structure in the Childs River subestuary. Flushing is impeded by the constriction in the Childs River at 0.6 km from the head. During onshore winds, salinity stratification increases as freshwater accumulates (top). During offshore winds, salinity stratification decreases as freshwater is flushed out the estuary (bottom) (Geyer, in press).

RESIDENCE TIMES

Circulation and mixing in the Eel Pond section of the Waquoit Bay estuarine complex increased and the residence time decreased after the 1938 hurricane created a second opening into Eel Pond (Aubrey et al. 1993). The 1991 hurricane which created the third inlet further increased circulation in the western Eel River system but had only a small effect on the overall circulation of the Waquoit Bay complex (Aubrey et al. 1993; Valiela et al. 1996).

Residence times of water vary in the Waquoit Bay estuarine complex. In the Childs River, residence time ranges 0.8 to 2.6 days with an average of 2 days. The average residence time of the

Quashnet River is 0.5 days. In Sage Lot Pond where there is little freshwater input, residence times are about 2 days. In Waquoit Bay proper, there is a 2 – 3 day flushing rate, mainly due to the influence of freshwater, tides and winds (W.R. Geyer, Woods Hole Oceanographic Institution, pers. comm.).

HYDROGEOLOGY

GROUNDWATER

The source of groundwater is precipitation that falls onto the land and percolates into the soil filling up the spaces between soil particles. Groundwater recharge rates are affected by sediment type. On Cape Cod, the unconsolidated glacial sands and gravels generally promote rapid percolation of water. The glacial moraine deposits of sandy soils interspersed with boulders, gravel lenses, sand, silt and clay are highly permeable and have moderate groundwater recharge rates with little surface, or overland, runoff. The Mashpee pitted outwash plain's highly porous and permeable sand and gravel deposits have high groundwater recharge rates, with negligible surface runoff. However, in places with fine-grained deposits such as a clay lens, water movement and recharge are slower. Salt marsh deposits have low to moderate recharge rates, while the reworked sands and gravels found on beaches have moderate to high recharge rates (Hudak 1979).

Although the sandy soils of Cape Cod promote rapid infiltration of precipitation, less than half of Cape Cod's annual 101.6 to 111.8 centimeters (40 to 44 inches) of rainfall percolates into the soil, recharging the groundwater; the remainder is evaporated or evapotranspired by plants. Evapotranspiration rates are higher in warmer months.

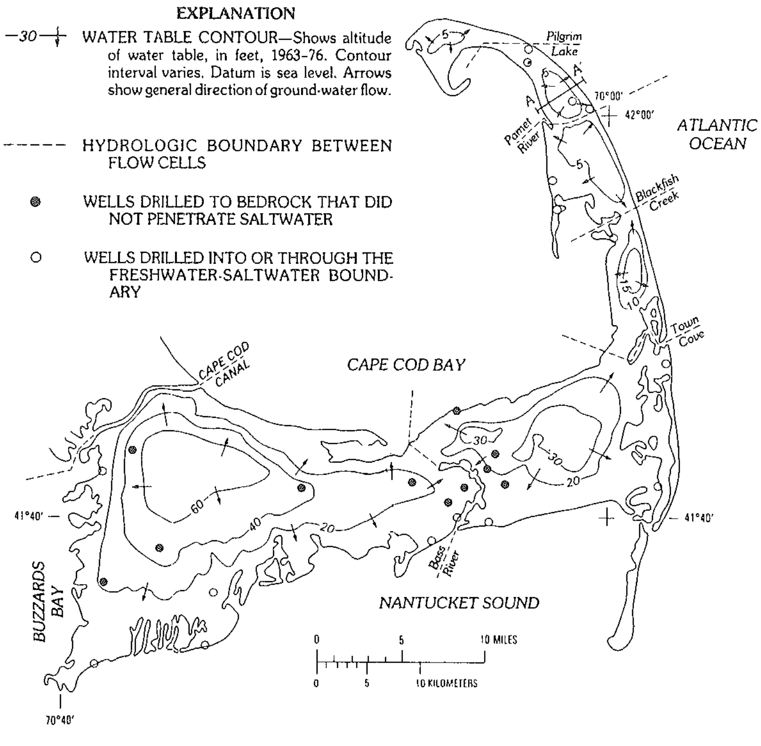


FIGURE 2.14

The six groundwater lenses on Cape Cod; the Waquoit Bay watershed is located in the Sagamore or Western lens (Guswa and LeBlanc, 1985).

The unconsolidated sediments of Cape Cod make ideal aquifers. In recognition of the unique groundwater characteristics of Cape Cod, the United States Environmental Protection Agency declared this region a Sole-Source Aquifer in 1982, a designation designed to facilitate protection of the water supply. In actuality, the Cape Cod aquifer can be subdivided into six groundwater "lenses" or areas of elevated groundwater. Surface features, such as rivers, separate the lenses and generally groundwater does not flow between lenses. The Waquoit Bay watershed lies within the Sagamore or western Cape lens of the Cape Cod Aquifer (Fig. 2.14) (Guswa and LeBlanc 1985).

Looked at in cross-section, the groundwater beneath Cape Cod occurs in a saucer-shaped formation with the depth of

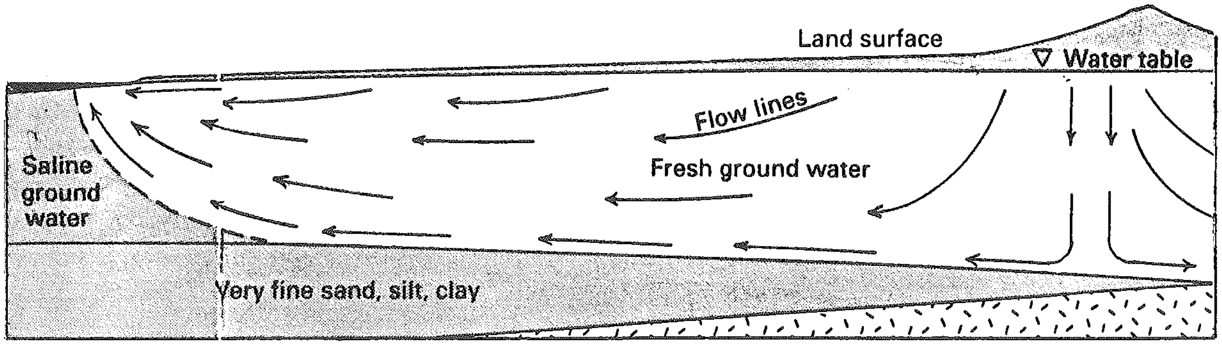


FIGURE 2.15
At the interface of land and sea, fresh groundwater meets saline water. The lighter freshwater floats above the denser saltwater (LeBlanc et al. 1986).

groundwater decreasing toward the margins of the land. Recharge by rainfall and the force of gravity drive groundwater movement downhill toward coastal waters, where it discharges at the edge of the freshwater lens. The volume of water in the aquifer is maintained by a balance between rainfall recharge and discharge to the sea (Guswa and LeBlanc 1985). Because it is lighter than saltwater, the fresh groundwater lens floats on top of the denser salt water wedge near the coast (Fig. 2.15). The extent of saline groundwater at a shoreline is a function of the level of the fresh groundwater table, which in turn depends on the tides, freshwater recharge, and pumping. Too much pumping of a well, especially during periods of low recharge, will shrink the freshwater lens and may cause migration of the brackish zone. This can result in salt water intrusion into wells.

WATER TABLE

The fine scale mapping of the height of the groundwater table in the Waquoit Bay region (Fig. 2.16) shows that the water table ranges from 20.7 meters (68 feet) above sea level near Snake Pond to 0.61 meters (2 feet) above sea level near Waquoit Bay (Cambareri et al. 1992). The steeper hydraulic gradients near rivers indicate that groundwater discharge is the prime source of water to the rivers, which are important drains for the aquifer. The map further shows that ponds and rivers receive groundwater from their upgradient sides and discharge groundwater on their downgradient sides.

THE DRAINAGE BASIN OF WAQUOIT BAY

Although the terms "recharge area" or "drainage basin" correctly describe the land area that contributes runoff or groundwater to a receiving body of water, the term "watershed" has entered the lexicon in recent years as resource protection managers have called for "watershed-wide management plans." The term, watershed, is widely used on Cape Cod by the public, policy-makers and scientists. In this volume, the reader will find the three terms used interchangeably.

The drainage basin of Waquoit Bay was first characterized in two dimensions by Babione (1990) and was refined by Cambareri et al. (1992). It comprises more than 5,000 hectares (12,355 acres) and extends northward approximately 8 kilometers (5 miles) from the head of the Bay to the regional groundwater divide above Snake Pond in the town of Sandwich. Seven subwatersheds were delineated within the Waquoit Bay watershed (Cambareri et al. 1992). Brawley and Sham (in preparation) further refined the watershed delineation using data of Cambareri et al. (1992), United States Geological Survey streamflow data and the finite difference, three-dimensional flow model (MODFLOW) and the particle-tracking model (MODPATH). Their delineation of the watershed is compared to that of Cambareri et al in Fig. 2.17. The two delineations show very good agreement.

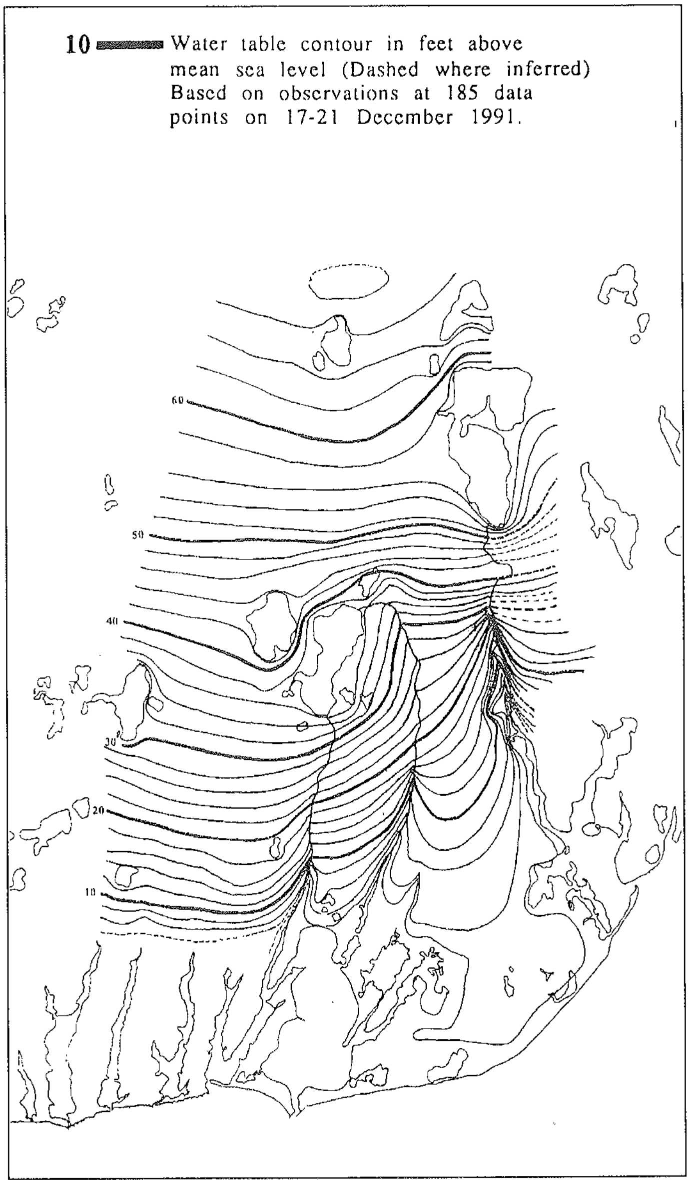


FIGURE 2.16.
Water table elevations in the Waquoit Bay watershed (Cambareri et al. 1992).

Based on a seismic geophysical survey (Oldale 1969), well logs and borings, Cambareri et al. (1992) constructed a transect of Waquoit Bay's subsurface geology. The transect shows layers of outwash plain deposits with depth below the land surface (Fig. 2.18). Each layer has a characteristic composition and corresponding permeability that results in different water storage capacities. Sands and gravels are highly permeable, whereas silts and clays are less permeable. In the Waquoit Bay area, a high permeable and low permeable layer can be distinguished. A soil's permeability is a reflection of its ability to yield water.

As Figure 2.18 shows, the bottom bedrock layer is located at approximately 107 meters (350 feet) below sea level at the head of Waquoit Bay. Above this layer, at about 84 meters (275 feet) below sea level, is a layer of basal till, composed of clay, silt, sand and gravel. The surfaces of these two layers slope downward from Snake Pond in the north to Waquoit Bay in the south. Resting on top of the basal till in the south is a wedge of sand and gravel that is, in turn, overlain by a low-permeable layer of fine sand, silt and clay, that slopes upward from the north to the south. Above this is the permeable, water-bearing sand and gravel layer that is the local aquifer. The permeable aquifer is about 46 meters (150 feet) thick near Snake Pond, about 15 meters (50 feet) thick for much of its length and then thins southward to about 6 meters (20 feet) near Vineyard Sound (Fig. 2.18). The thinning of the permeable aquifer along the groundwater's north to south path forces much of the watershed's groundwater to discharge into the Childs and Quashnet Rivers prior to reaching Waquoit Bay (Cambareri et al. 1992).

The water budget of the Waquoit Bay watershed and its subwatersheds has been examined using calculations of subwatershed recharge rates and measurements of streamflow. The results indicate that 50% of the water

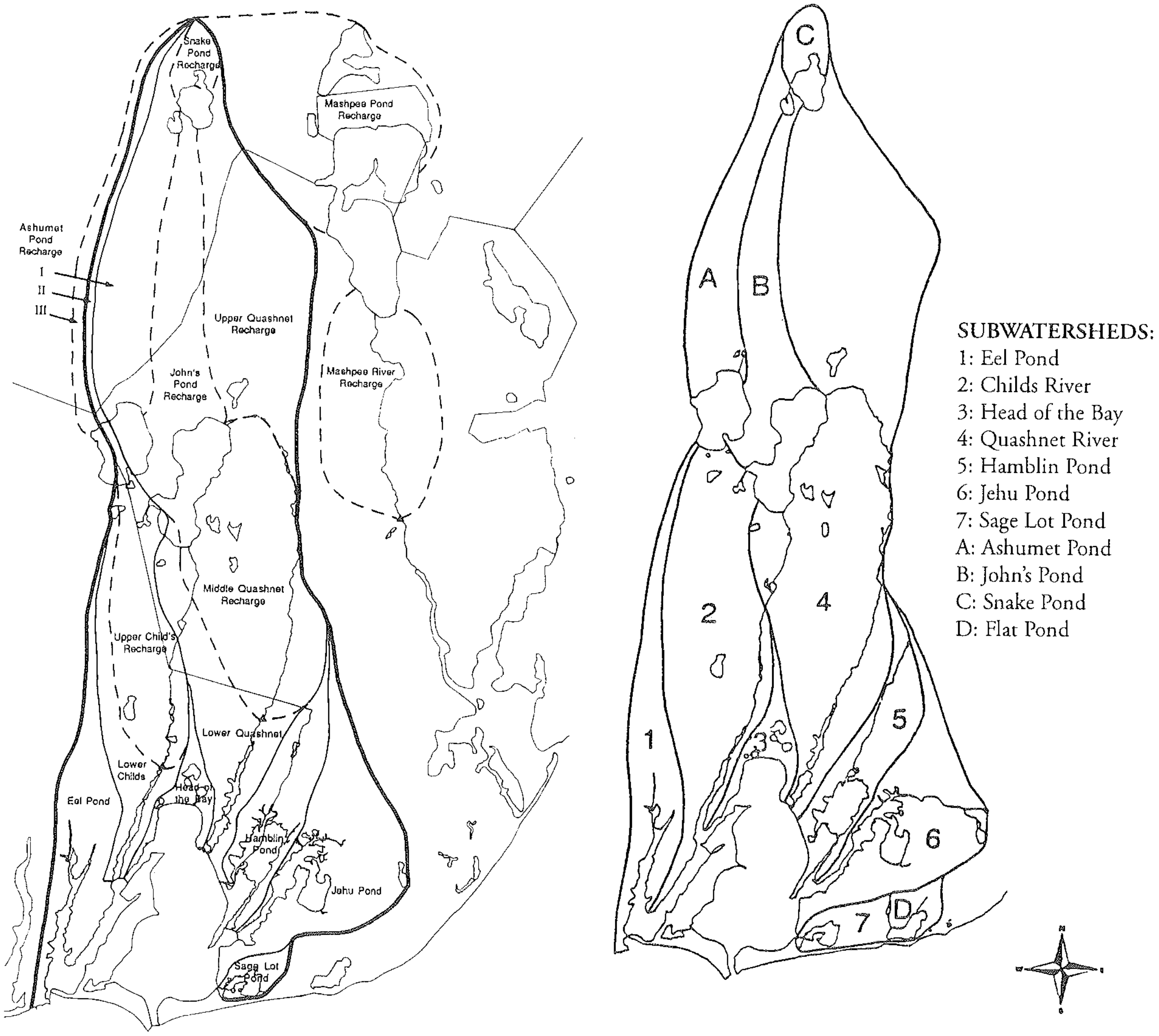


FIGURE 2.17

Waquoit Bay watershed and subwatershed boundaries as delineated by Cambareri et al. (1992) on the left and by Brawley and Sham (in preparation) on the right.

entering Waquoit Bay comes from the Quashnet and Childs rivers; 23% comes from direct precipitation to the Bay and its tributaries, and 27% comes from recharge to groundwater flowing into Waquoit Bay and its tributaries (Cambareri et al. 1992).

THE FRESHWATER-SALTWATER MIXING ZONE

The fresh groundwater in the Waquoit Bay area is bounded by saline surface water at the Vineyard Sound shoreline and by saline groundwater at depth. The exact location of this zone fluctuates with tidal changes and with changes in the movement of freshwater to the sea. In exploring the location and extent of the brackish interface, borings taken in the permeable aquifer beneath the Bay and within 7.6 meters (25 feet) of the shore showed that most of the groundwater was saline (Cambareri et al. 1992).

Borings taken at the head of Waquoit Bay (Fig. 2.19) show that the salt water interface in the upper, permeable layer of the aquifer occurs at the Bay's shoreline. The saltwater interface in the lower, low-permeable layer occurs at about 46 meters (150 feet) below sea level. This deeper, saline groundwater is the transition zone for the regional salt water interface. This transition zone is 15 – 23 meters (50 – 75 feet) thick and extends south under the Bay. There is no knowledge of exactly how far south this fresh groundwater wedge extends underneath Waquoit Bay, but a monitoring well located on the barrier beach at South Cape Beach (see well M-22 on Fig. 2.18) shows saline groundwater from 3 – 27 meters (10 to 90 feet) below sea level (LeBlanc et al. 1986). Therefore, the southern terminus of the saltwater transition zone is located somewhere between the head of the Bay and the Vineyard Sound shoreline (Cambareri et al. 1992).

RIVERS AND GROUNDWATER

Although the Cape is notable for the numerous kettle ponds that dot the landscape, large lakes and extensive river systems are not found. Waquoit Bay is unusual in that it is fed by two rivers—the Childs and Quashnet,

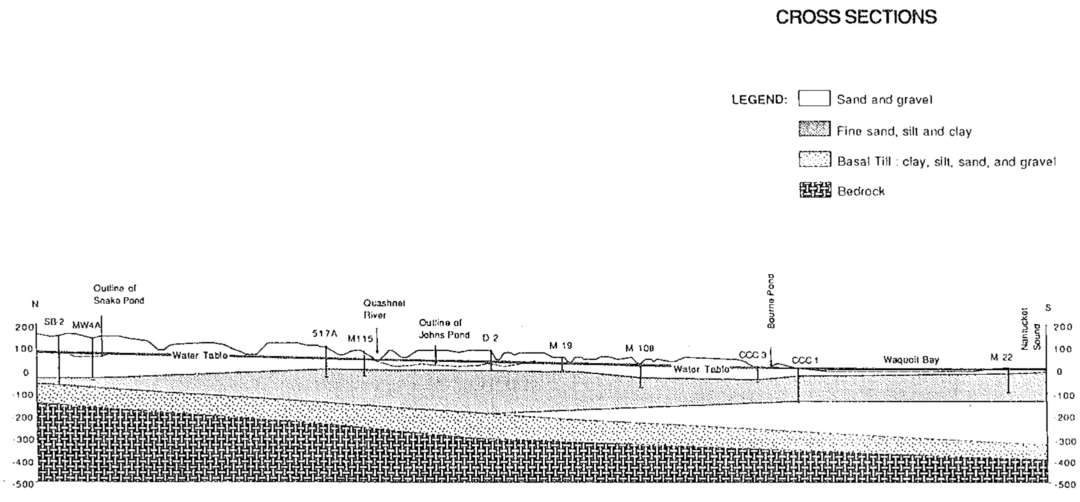


FIGURE 2.18

Hydrogeologic cross section through the Waquoit Bay watershed from Snake Pond in the north to Nantucket Sound in the south. Note the thinning of the permeable aquifer from north to south (Cambareri et al. 1992).

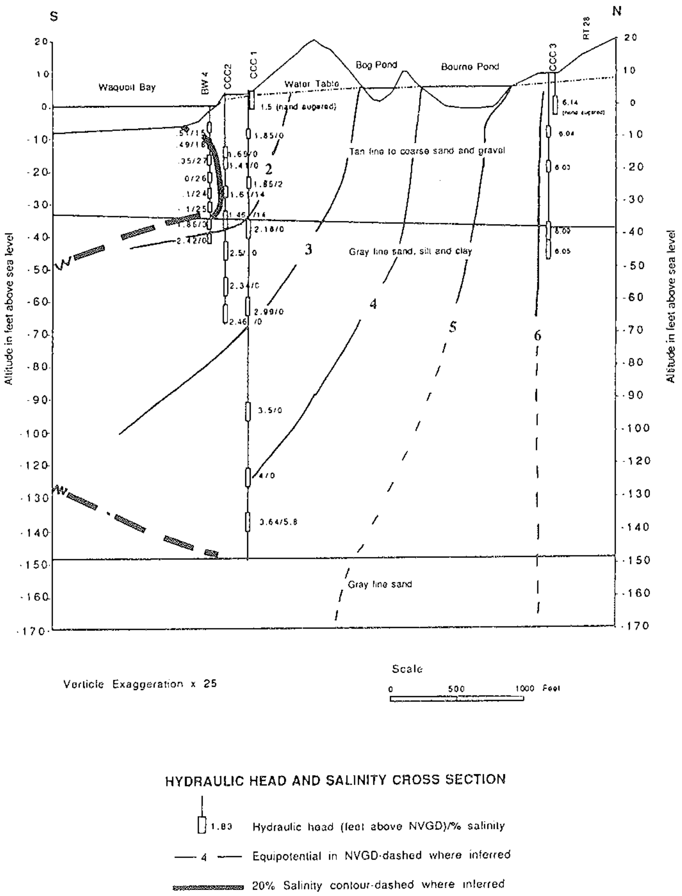


FIGURE 2.19

Saltwater interface in the upper permeable and lower less permeable aquifer in Waquoit Bay (Cambareri et al. 1992).

entering Eel Pond and Waquoit Bay, respectively. Both of these rivers originate in Johns Pond.

Much of the Quashnet River lies outside of the Waquoit Bay Reserve. However, under the Commonwealth of Massachusetts, the Reserve manages about 140 hectares (350 acres) of land on either side of the River north of the Reserve boundary (Fig. 1.2). In addition to being the largest source of freshwater to Waquoit Bay, the Quashnet is one of the largest rivers on Cape Cod (Barlow and Hess 1993). The Quashnet River originates at Johns Pond; a man-made outlet built to irrigate cranberry bogs controls surface water outflow from Johns Pond (Barlow and Hess 1993). The river winds through bogs to the northeast of Johns Pond and then south to Waquoit Bay. For much of its length the Quashnet is a gaining stream (Barlow and Hess 1993). Groundwater enters the Quashnet through sediments and springs (Baevsky 1991; Barlow and Hess 1993). Many of these springs are visible where the sediment is discolored by the oxidation of metals, such as iron.

Because large amounts of water are stored in the aquifer, streamflow is fairly constant all year despite seasonal differences in recharge. Uniform stream flow is typical of Cape Cod with its highly porous soils in comparison to other parts of New England. Cape Cod's groundwater supplies, which are depleted over the summer by high growing season evapotranspiration rates, begin to be recharged in October. Groundwater levels steadily increase throughout the winter and then increase again in spring as temperatures rise. On Cape Cod, groundwater determines the level of surface waters, so that river discharge is an excellent indicator of ground water levels.

CLIMATE

THE MODERATING INFLUENCE OF OCEAN WATERS

While Cape Cod shares New England's humid, continental climate, the strong maritime influence of the North Atlantic Ocean creates a moderate annual temperature range, producing milder winters and prolonged cooler summers. There is ample rainfall throughout the year which favors the development of forests.

Humidity is often high in the summer and foggy conditions commonly occur in the spring and summer. Fogs, caused by the condensation of warm, moist air near the surface of the cold Labrador Current waters passing to the north of Cape Cod, are relatively frequent and dense (Strahler 1966).

The moderate climate on Cape Cod's southern shores has contributed to its appeal as a vacation resort community. On many summer days the seas are calm, the sky is cloudless and the sun is warm but not hot. On other days fog and humidity can combine to produce uncomfortable weather. However, successive atmospheric highs and lows moving up the Atlantic coast, along with breezes generated by the Cape's shape and location, change the weather patterns daily, so that hot, humid days rarely follow each other (Faught 1945).

January and February are the coldest months on Cape Cod, while July and August are the warmest. The annual growing season is between 180 and 200 days and average annual precipitation is 113 centimeters (44 inches). June and July are somewhat drier than other months, averaging 6.8 centimeters (2.7 inches) of rainfall. Snowfall is highly variable from one year to the next, and averages less than 51 centimeters (20 inches) per year (Strahler 1966).

Winds are generally westerly, with orientation changing with the season; northwest winds are dominant between October and April and southwest winds are common between May and September. Major storms occur in any season, with hurricanes most common in late summer and early fall, and "northeasters" in winter and early spring. Major hurricanes occurred in September of 1938 and 1944, August of 1954 and 1955, September of 1960 and August of 1991. Thunderstorms or squalls occur less frequently than in inland Massachusetts because the cool waters of Vineyard Sound impede the formation of the strong vertical air movements that produce thunderstorms (Strahler, 1966).

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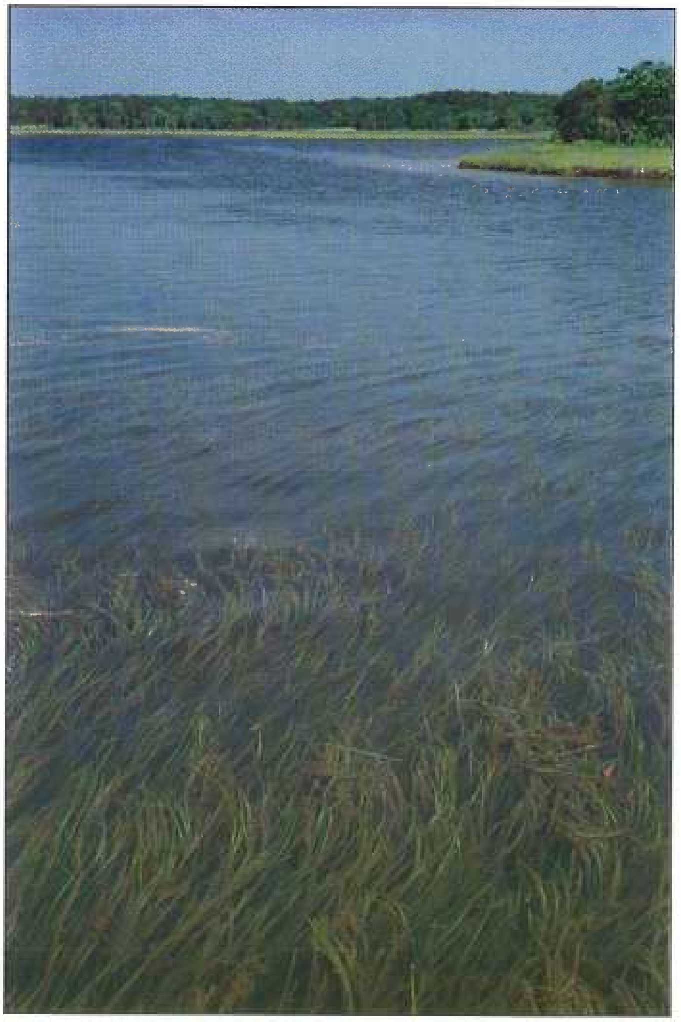
CHAPTER III

HABITATS AND COMMUNITIES OF THE WAQUOIT BAY RESERVE



Eelgrass meadow in Hamblin Pond. Photograph by Richard F. Crawford.

The Waquoit Bay National Estuarine Research Reserve encompasses a broad range of habitats that are the foundation of the biological communities that dwell within them. Described here are the subtidal, intertidal, marsh, dune and upland habitats of the Waquoit Bay region. Although discussed here as discrete units, the communities and habitats described form a continuum of species associations and environments.

ESTUARINE WATERS

The abundance and distribution of organisms in any ecosystem depends on a complex set of interacting physical, chemical and biological factors. In the environment of an estuary these factors can change rapidly and the adaptability of resident organisms is crucial to their survival. Inhabitants of the estuary must respond to daily and seasonal changes that have occurred for thousands of years, as well as to recent changes that have accompanied increased development along the coast.

The coastal waters of Cape Cod are a mixing zone where colder waters of the Gulf of Maine, influenced by the southward flowing cold Labrador current, meet warmer Gulf Stream waters moving northward along the coastline (Fig. 3.1). The result of this physical confluence is a biological transition zone between the Virginian (temperate) and Acadian (boreal) biogeographic provinces (Gosner 1971). Cape Cod waters harbor boreal species from the Gulf of Maine along with warm-water dwellers from the mid-Atlantic. Although many species, such as lobsters *Homarus americanus*), green crabs (*Carcinus maenus*), and bluefish (*Pomatomus salatrix*), are found in abundance both to the north and south, many other organisms reach their northern (e.g., bay scallop, *Argopecten irradians*) or southern (e.g., green sea urchin, *Arbacia punctulata*) extent here (Gosner 1971; Gosner 1978; Buchsbaum 1992). In general, the echinoderm species are more numerous to the north of Cape Cod, while the number of fish species increases to the south of Cape Cod (Ayvazian et al. 1992).

SUBTIDAL ZONE

With an area of approximately 334 hectares (825 acres), Waquoit Bay is the dominant feature of the approximately 910-hectare (2,250 acres) Waquoit Bay National Estuarine Research Reserve. The shallow Bay, with a maximum depth of 2.7 meters (8.9 feet) and a mean depth of 0.8 meters (2.6 feet), is warmer in the summer and colder in the winter than neighboring Vineyard Sound. Salinity ranges from 0 parts per thousand (ppt) in the upper reaches of rivers to

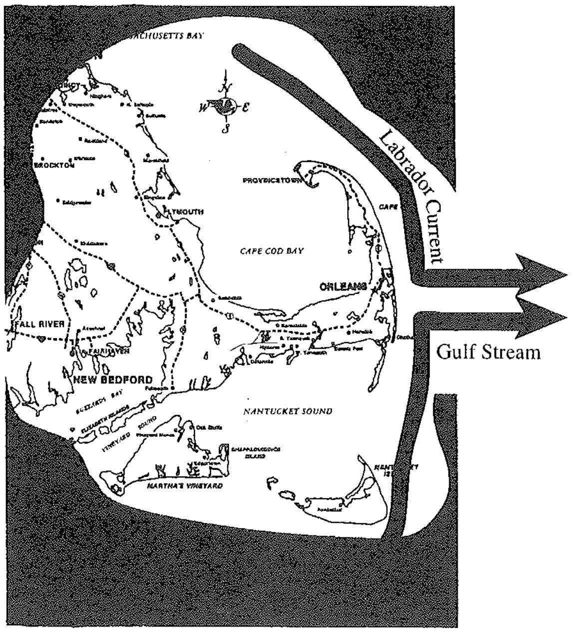


FIG 3.1
The waters of Cape Cod are a transition zone where the Gulf Stream and Labrador currents meet.

about 32 ppt in the open Bay. In the near shore area, the bottom sediments are composed of shells and sands (Ayvazian et al. 1992) while in the deeper, central basins, sediments are primarily fine, organically rich clays and silts (Valiela et al. 1990).

FINFISH

The overlapping biogeographic ranges produce diverse communities, with both year-round residents and seasonal migrants among the finfish (Table 3.1). For example, alewives, *Alosa pseudoharengus*, and blueback herring, *A. aestivalis*, navigate Waquoit Bay on their annual spawning migrations to fresh water, and larger fish such as bluefish, *Pomatomus saltatrix*, and striped bass, *Morone saxatilis*, enter in pursuit of smaller prey fish. Many primarily marine fishes, such as longhorn sculpin, *Myoxocephalus octodecemspinosus*, winter flounder, *Pleuronectes americanus*, and scup, *Stenotomus chrysops*, use the estuary in the winter as a spawning and nursery ground, and as a rich food source. Tomcod, *Microgadus tomcod*, white hake, *Urophycis tenuis*, pollock, *Pollachius virens*, and bluefish inhabit the Bay as juveniles but are rarely present as adults (Curley et al. 1971; Hurley 1990; Ayvazian et al. 1992; Hurley 1992).

A comparison of finfish between Waquoit Bay and Wells Harbor, Maine (250 kilometers or 155 miles north of Waquoit Bay) showed that Waquoit Bay had higher species diversity (48 vs 24 species) and greater abundance of finfish (80,341 vs 22,561) (Ayvazian et al. 1992). Life history groups also differed between estuaries. While resident species were the largest life history group in both estuaries, Waquoit Bay had proportionally more nursery, marine and occasional visitors than Wells Harbor. According to Ayvazian et al. (1992) these results support the assertion that Cape Cod is a transition zone that supports both cold water fish fauna and warm-temperate fish fauna.

INVERTEBRATES

The Bay is the site of an active shellfishery dominated now by quahogs, *Mercenaria mercenaria*, and softshell clams, *Mya arenaria*. In the past, bay scallops, *Argopecten irradians*, were abundant; their declining numbers may be associated with a loss of eelgrass habitat. The blue crab, *Callinectes sapidus*, has been caught recreationally in Waquoit Bay and the adjacent tidal rivers, although its numbers fluctuate. Table 3.2 is a compilation of invertebrate species recorded in Waquoit Bay and its subestuaries. Because of the shallowness of the Bay, most of the open bay bottom invertebrate epifauna and infauna communities are similar to those found in the adjacent nearshore tidal flat and tidal marsh communities and are overviewed in those sections.

Detailed life histories of a few representative estuarine finfish and shellfish (bay scallop, quahog, winter flounder and American eel) are described in Chapter IV to illustrate the importance of the estuarine habitat to its resident and visiting species.

Table 3.1 Finfish species identified in the Waquoit Bay Estuarine Complex.

SCIENTIFIC NAME	COMMON NAME	SOURCE
Estuarine residents		
Opsanus tau	oyster toadfish	A, C
Fundulus heteroclitis	mummichog	A, C, H
Fundulus majalis	striped killifish	A, C
Cyprinodon variegatus	sheepshead minnow	A, C
Lucania parva	rainwater killifish	A, C
Menidia beryllina	Atlantic silverside	A
Menidia peninsulae	tidewater silverside	C
Pungitius pungitius	ninespine stickleback	A, C
Apeltes quadracus	fourspine stickleback	A, C, H
Gasterosteus aculeatus	threespine stickleback	A, C
Gasterosteus wheatlandi	blackspotted stickleback	A, C
Syngnathus fuscus	northern pipefish (in eelgrass)	A, C
Menticirrhus saxatilis	northern kingfish	A, C
Gobiosorna bosci	naked goby	A
Pholis gunnellus	rock gunnel	A, C
Myoxocephalus aenaeus	grubby	A, C
Trinectes maculatus	hogchoker	A
Sphoeroides maculatus	northern puffer	A, C
Estuarine nursery		
Clupea harengus	Atlantic herring	A
Brevoortia tyrannus	Atlantic menhaden	A, C
Anchoa mitchelli	bay anchovy	A
Microgadus tomcod	Atlantic tomcod	A, C
Strongylura marina	Atlantic needlefish	A, C
Menidia menidia	Atlantic silverside	A, C
Pomatomus saltatrix	bluefish	A, C
Tautoga onitis	tautog	A, C
Tautogolabrus adspersus	cunner	A, C
Mugil cephalus	striped mullet	A, C
Pleuronectes americanus	winter flounder	A, C
Urophycis tenuis	white hake	C
Diadromous (anadromous/catadromous)		
Anguilla rostrata	American eel	A, C, H
Alosa aestivalis	blueback herring	A, C
Alosa pseudoharengus	alewife	A, C
Alosa sapidissima	American shad	A
Osmerus mordax	rainbow smelt	C

Table 3.1 cont. Finfish species identified in the Waquoit Bay Estuarine Complex.

SCIENTIFIC NAME	COMMON NAME	SOURCE
Marine, seasonal visitors as adults		
Anchoa hepsetus	striped anchovy	A
Pollachius virens	pollock	A, C
Morone saxatilis	striped bass	A, C
Centropristis striata	black sea bass	A, C
Stenotomus chrysops	scup	A, C
Mugil curema	white mullet	A
Ammodytes americanus	American sand lance	A, C
Prionotus carolinus	northern searobin	A, C
Prionotus evolans	striped searobin	A, C
Myoxocephalus octodecemspinosus	longhorn sculpin	C
Paralichthys dentatus	summer flounder	A, C
Scophthalmus aquosus	windowpane flounder	A
Limanda ferruginea	yellowtail flounder	A
Freshwater sometimes in brackish water		
Fundulus diaphanus	banded killifish	A, C
Fundulus confluentus	marsh killifish	A
Morone americana	white perch	A, C
Notemigonus crysoleucas	golden shiner	C, H
Notropis bifrenatus	bridle shiner	A
Notropis heterolepis	blacknose shiner	A
Catostomus commersoni	white sucker	C, H
Etheostoma olmstedi	tesselated darter	H
Salvelinus fontinalis	"sea run" eastern brook trout	C, H
Salmo trutta	brown trout	
S. fontinalis x S. trutta	tiger trout (hybrid)	H
Ameiurus nebulosus	brown bullhead	H
Lepomis gibbosus	pumpkinseed	H
Micropterus salmoides	largemouth bass	H
Adventitious visitors		
Elops saurus	ladyfish	A
Caranx hippos	crevalle jack	
Hemiramphus brasiliensis	ballyhoo	A
Hyperoglyphe perciformis	barrelfish	A
Gadus morhua	Atlantic cod	C
Cyclopterus lumpus	lumpfish	C

Source: A = Ayvazian et al. 1992, C = Curley et al. 1971, H = Hurley 1990, 1992.

OTHER SPECIES OF THE OPEN WATERS

In the winter months Waquoit Bay is frequented by many sea ducks, such as eiders, *Somateris mollissima*; scoters, *Melanitta* sp.; red-breasted mergansers, *Mergus serrator*; gulls, *Larus* spp.; and buffleheads, *Bucephala albeola*. Harbor seals, *Phoca vitulina concolor*, also visit shallow waters along the open coast, occasionally entering the Bay. Ospreys, *Pandion haliaretus*, return each spring to build large nests on Reserve lands from which they forage for fish to feed themselves and their young (Fig. 3.2).

EELGRASS BEDS

Historically, seagrass beds have been a dominant feature of shallow coastal embayments. Along the coast of the North Atlantic, eelgrass, *Zostera marina*, was the exclusive seagrass species found in shallow waters where it often formed vast underwater meadows. Eelgrass covered extensive areas of the Waquoit Bay estuarine complex until recent decades when disease and eutrophication caused rapid declines in abundance and distribution.

Eelgrass Requirements

Eelgrass, *Zostera marina*, is an angiosperm—a seed bearing, flowering plant uniquely adapted to life below water where pollination, flowering and germination occur; in New England, flower production peaks in April and May (Costa 1988). The optimum habitat for eelgrass is shallow water with ample light penetration and a gravel to fine mud substrate. Ambient light level is considered the major factor affecting eelgrass growth (Dennison et al. 1987). In clear waters of Buzzards Bay, eelgrass can be found growing to 6 meters (20 feet) depth, whereas in the more turbid waters of Waquoit Bay, eelgrass (when present) grows no deeper than about 2 meters (6.6 feet) (Costa 1988). Eelgrass is found in sheltered areas with little water motion as well as in high velocity areas where currents may reach 1.5 meters (4.9 feet) per second (Fonseca et al. 1983). It is not normally found in areas of high wave activity or in places where ice-scouring is common, although there are small beds in Vineyard Sound near the Eel Pond barrier beach. Salinities in eelgrass meadows range from 20 to 32 ppt, typical of Waquoit Bay habitats, although eelgrass can grow in salinitites as low as 5 ppt (Thayer et al. 1984).

Eelgrass As Habitat

The presence of eelgrass meadows has significant consequences for the physical environment of the estuary and on its inhabitants. Eelgrass roots and rhizomes form a dense interwoven system that stabilizes and binds sediments. The eelgrass blades or leaves (Fig. 3.3) impede current flow, which in turn promotes sediment deposition, adding to the organic content of the sediments and thus to the food resources of the habitat (Thayer et al. 1975; Short and Short 1984; Costa 1988). The complex vertical and horizontal structure of the eelgrass meadow provides a

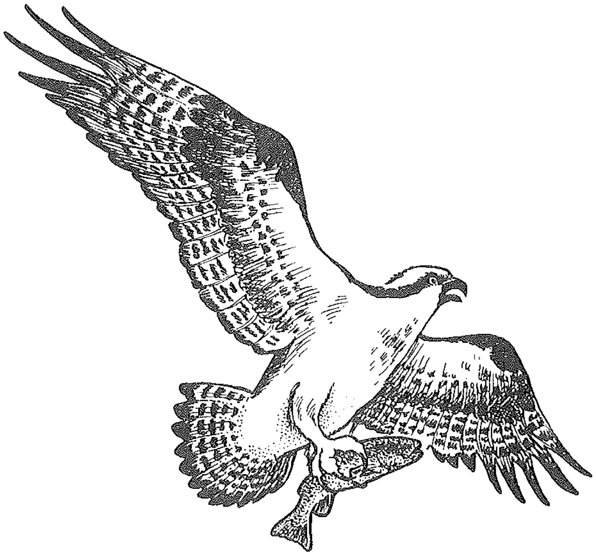


FIG. 3.2

Osprey Pandion haliaretus *bringing food to its young. Drawing by Bob Golder.*

Table 3.2 Estuarine invertebrates identified in the Waquoit Bay Complex.

PHYLUM	LOCATION*	PHYLUM	LOCATION	PHYLUM	LOCATION
Annelids		**Arthropods, cont.**		**Mollusks, cont.**	
Autolytus sp.	C	*Libinia dubia (marginata)*	X, WI	*Eupleura candata*	W-E
Capitella spp.	EMAP	*Emerita talpoida*	X, WI	*Urosalpinx cinerea*	W-E
Cirratulus grandis	Q	*Callinectes sapidus*	X, WI	*Nassarius obsoletus*	W-E
Eteone lactea	Q	*Carcinus maenas*	X, WI	*Anomia simplex*	W-E, WI
Hypaniola grayi	C	*Ovalipes ocellatus*	X	*Argopecten irradians*	W-E, WI
Mediomastus ambiseta	EMAP	*Uca pugilatro*	X	*Crassostrea virginica*	W-E
Neanthes arenaceodentata	EMAP	*Uca pugnax*	X, WI	*Ensis directus*	W-E, WI
Nereis grayi	C	*Cyathura polita*	C, Q	*Gemma gemma*	C. Q
Nereis virens	C	*Edotea triloba*	C. Q	*Geukensia demissa*	W-E, WI
Parahesione luteola	EMAP	*Idotea baltica*	S	*Laevicardium mortoni*	W-E
Podarke obscura	C, Q, S, EMAP	*Erichsoniella filiformis*	C, Q, S	*Mercenaria mercenaria*	W-E, WI
Polydora cornuta	EMAP	*Balanus improvisus*	X, WI	*Mya arenaria*	W-E, WI
Polydora ligni	C	*Balanus eburneus*	X	*Mytilus edulis*	W-E
Prionospio heterobranchis	EMAP	*Limulus polyphemus*	X, WI	*Petricola pholadiformis*	W-E
Prionospio spp.	EMAP	*Callipallene brevirostris*	EMAP	*Spisula polynyma*	W-E, Q
Sabella micropthalma	C,S	**Echinoderms**		*Spisula solidissima*	W-E, WI
Scolecolepides viridis	C	*Cucumaria pulcherrima*	Q, S	*Petricola pholadiformis*	SC
Scoloplos fragilis	C, Q, S	*Leptosynapta* sp.	C, Q, S	*Loligo paelci*	X
Stauronereis ruldolphi	C	*Sclerodactyla briarias*	C,Q ,S	**Nemerteans**	
Tharyx sp.	EMAP	*Ophioderma brevispina*	X	*Lineus ruber*	Q, S
Arthropods		**Mollusks**		*Zygeupolia rubens*	C, Q
Ampelisca vandorum	C, Q, EMAP	*Anachis* sp.	Q S	**Platyhelminthes**	
Ampelisca agassizi	C	*Bittium alternatum*	C	*Euplana polynyma*	Q
Ampithoe longimana	S	*Andara osalis*	WI	**Porifera**	
Corophium insidiosum	EMAP	*Crepidula fornicata*	C, W-E, WI	*Haliclona loosanofii*	X
Cymadusa compta	C, Q, S, EMAP	*Crepidula plana*	WI	*Hypolytus perogrinus*	X
Gammarus mucronatus	Q	*Elysia chlorotica*	Q	*Obelia*	X
Lysianopsis alba	EMAP	*Haminoea solitaria*	EMAP	*Cryptosula pallasiana*	X
Microdeutopus sp.	EMAP	*Hydrobia tonenii*	C, Q	*Diadumine leucolena*	X
Microdeutopus gryllotalpa	C, S	*Ilyanassa obsoletus*	Q	*Haloclava producta*	X
Neopanope texane	C, S	*Littorina littorea*	W-E, WI	**Urochordate**	
Leucon americanus	EMAP	*Polynices duplicatius*	W-E	*Molgula manhattensis*	C,Q,S
Hippolyte zostericola	C, S	*Lunatia heros*	W-E, WI	*Botryllus schlosseri*	X
Palaemonetes vulgaris	C, Q, S	*Mitrella lunata*	W-E	*Amaroucium stellatum*	SC
Crangon septemspinosa	X	*Buscyon canaliculatum*	W-E, WI	*Lysianopsis alba*	Q
Pagurus longicarpus	X, WI	*Busycon carica*	W-E	*Cylichna occulata*	Q

*W-E	species sampled during 1967 survey of Waquoit Bay and Eel Pond, Curley et al., 1971.
SC	species observed off Dead Neck at South Cape Beach State Park, Davis, 1980.
WI	species observed September 1981 off the eastem and western shores of Washburn Island
X	species sampled by WBNERR staff, sites unknown, unpublished data
EMAP	species sampled in benthic grab in Waquoit Bay, during EMAP.
C,Q,S	species sampled in Childs River, Quashnet River, or Sage Lot Pond during 1992 by J. McClelland, WBLMER, unpublished data

refuge, shelter and food source for many invertebrates that attach themselves to eelgrass blades or inhabit the sediments at the base of the plants.

Bay scallops, *Argopecten irradians,* were an important shellfishery in Waquoit Bay in years past. Juvenile bay scallops attach to eelgrass shoots using abyssal threads. That the vertical structure of eelgrass beds promotes scallop survival was shown in studies of eelgrass beds off Long Island, New York, where juvenile scallop survival increased with the height of attachment on the eelgrass blade (Pohle et al. 1991).

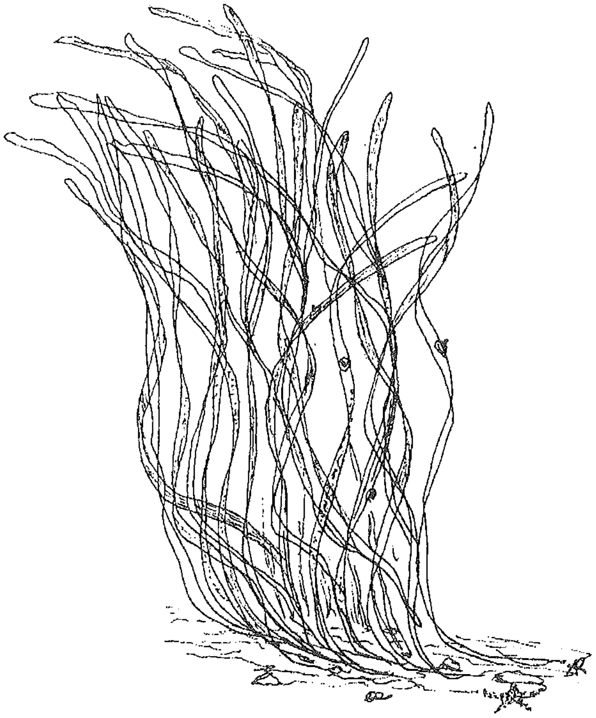


FIG. 3.3

Eelgrass, a flowering plant that lives entirely submerged, provides habitat, shelter, nursery and feeding grounds for numerous estuarine inhabitants and visitors. Drawing by Alison Robb.

The Wasting Disease

In the 1930s the "wasting disease," caused by a slime mold, *Labyrinthula zosterae,* eradicated about 90% of the eelgrass worldwide (Thayer et al. 1984; Muehlstein et al. 1988; Short et al. 1989). As the eelgrass died, populations of many invertebrate and vertebrate species that inhabited or fed on eelgrass beds also declined, including the bay scallop and the Atlantic brant, *Branta bernicala hrota* (Short et al. 1989). Stouffer (1937) reported that about one-third of the 140 species Allee (1923) had listed as characteristic of eelgrass beds was absent or rarely seen following the wasting disease outbreak.

In Waquoit Bay, the decline in eelgrass due to the wasting disease is documented in sediment cores containing eelgrass seeds (Costa 1988). The cores also document the resurgence of eelgrass following the 1930s epidemic. Although the wasting disease has reappeared in some areas of North America, from Nova Scotia to North Carolina, only low levels of infection are reported in Waquoit Bay and its tributaries at the present time (Short et al. 1992).

Eelgrass Decline From Eutrophication

The sediment cores and aerial photographs also reveal a more recent eelgrass decline, not attributed to the wasting disease (Costa 1988). Eelgrass in the deeper parts of Waquoit Bay began to disappear after 1965 and by the mid-1970s eelgrass was no longer found in shallow areas of Waquoit Bay. Figure 3.4 shows the declines in eelgrass distribution in the Bay from 1951 to 1987 (Costa 1988). Surveys from 1987 through 1992 (Fig. 3.5) reveal further decreases in the central Bay but also in Great and Little rivers, as well as in Eel, Hamblin and Jehu ponds (Short et al 1992; Short and Burdick 1996). Today, eelgrass has disappeared from the lower Bay; it is found only at the tidal inlet near the mouth of the Eel Pond adjacent to Washburn Island, in the small salt pond and salt marshes of Washburn Island, and in patches in Jehu and Hamblin ponds. All of these areas are fairly undisturbed sites that are either well flushed, too shallow for boat traffic, or protected in other ways.

The recent pattern of eelgrass decline is attributed to increasing development that has increased the supply of nutrients to Waquoit Bay. Increased nutrients have promoted the growth of macroalgae, phytoplankton and epiphytes which shade the benthos and effectively outcompete eelgrass. Short et al. (1992) attributes eelgrass decline in different parts of the Waquoit Bay system to shading caused by the presence of different algal species: epiphytes in Eel Pond, macroalgal blooms in Hamblin Pond and phytoplankton blooms in Great River and Jehu Pond. Sediment resuspension from boating activities in the central Bay, and from wind in the eastern Bay, may contribute to reduced light (F. Short, University of New Hampshire, Durham, pers. comm.).

Of interest today, in light of the disappearance of eelgrass from most of the Reserve waters, is the comment by Curley et al. in 1971 who noted that, "while eelgrass in moderate density is beneficial, an overabundance may be a problem. Excessive growth in Waquoit Bay is hampering the harvesting of shellfish, swimming and boat navigation." As is discussed briefly below and in Chapter V, the loss of eelgrass in Waquoit Bay has had profound effects on the structure and functioning of the estuarine community.

BENTHIC MACROALGAE

In1967, nineteen species of macroalgae were reported in Waquoit Bay (Curley et al. 1971). In addition to those species, Sears and Wilce (1975) found dense meadows of the red seaweed, *Grinnelia americana*, on shelly substrates in deeper parts of Waquoit Bay and red and brown crustose macroalgae in shallow waters of the Bay. Table 3.3 lists macroalgal species observed in the Waquoit Bay estuarine complex.

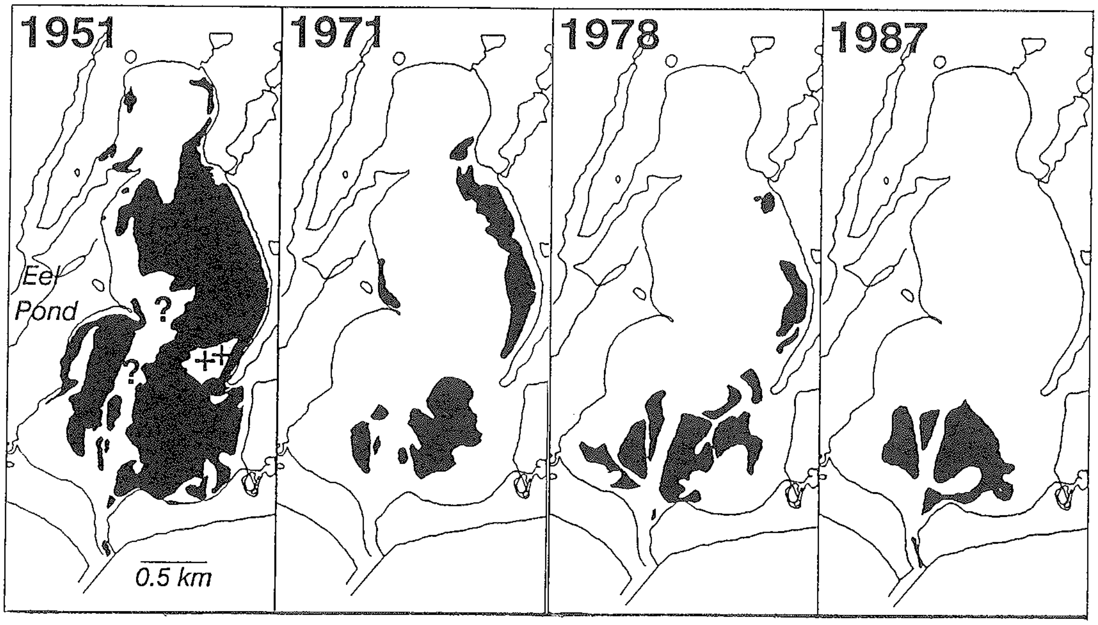


FIG. 3.4

Eelgrass decline in Waquoit Bay (Costa et al, 1991). The shaded area shows the extent of eelgrass. Reprinted with permission of Elsevier Science Ltd.

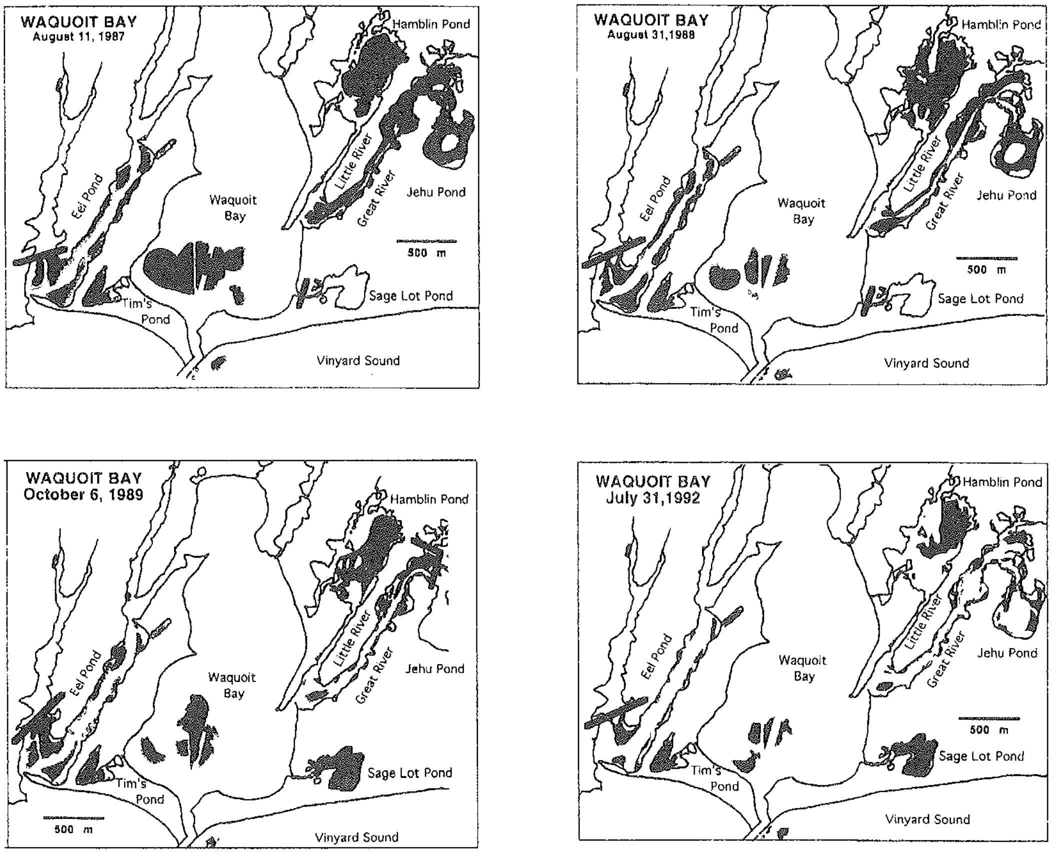


FIG. 3.5

Eelgrass decline in Waquoit Bay and adjacent ponds from 1987–1992. Reprinted with permission of the authors (Short and Burdick 1996).

Among the species noted by Curley et al. (1971) were some that are indicative of eutrophic conditions. *Codium fragile*, an exotic European species, was first identified in Long Island Sound in 1957 and has since successfully colonized shallow marine and estuarine waters along the eastern coast of the United States. This green alga, also known as staghorn or dead man's fingers, attaches to shells with its holdfast. If attached to a shellfish that isn't heavy enough to anchor the buoyant *Codium*, both seaweed and shellfish can float onshore resulting in death to both. *Codium* is found in increasing abundance along the southern end of Waquoit Bay, South Cape Beach and along Washburn Island's beaches in eelgrass beds where the sand and gravel substrate contains many shell fragments, particularly of slipper shells (*Crepidula* spp.). Although it is now one of the more common species found along the Atlantic coastline, the lack of significant amounts of hard substrate in Waquoit Bay suggest that it will not become a dominant species here (J. Sears, University of Massachusetts/Dartmouth, pers. comm.). Also associated with eutrophic waters and seen in Waquoit Bay are sea lettuce, *Ulva,* and species of the genus *Enteromorpha*, which attach to large grains of sand or shell fragments.

Macroalgal Mats

Another seaweed that was identified many years ago as a nuisance is the green macroalga, *Cladophora* spp. During the summers of 1967 and 1968, *Cladophora* formed dense mats in Waquoit Bay and "nearly eliminated" the soft

Table 3.3 Macroalgal species identified in Waquoit Bay Estuarine Complex waters.

GENUS SPECIES	CLASS	LOCATION
Cladophora sp.	green (Chlorophyceae)	W-E
Codium fragile		W-E
Enteromorpha intestinalis		W-E
Enteromorpha plumosa		W-E
Ulva lactuca		W-E
Fucus vesiculosus	brown (Phaeophyceae)	W-E
Fucus spiralis		W-E
Sargassum filipendula		W-E
Laminaria agardhii		W-E
Agardhiella tenera	red (Rhodophyceae)	W-E
Chondrus crispus		W-E
Polysiphonia urceolata		W-E
Grinnelia americana		W
Gracilaria tikvahiae		A
Petroderma maculiforme	brown or red crustose algae	W
Pseudolithoderma paradoxum		W
Pseudolithoderma spp.		. W
Ralfsia spp.		W
Sorapion kjellmani		W
Sorapion simulans		W
Cruoriopsis gracilis		W
Cruoriopsis sp.		W
Gloiosiphonia capillaris		W
Hildenbrandia prototypus		W
Petrocelis sp.		W
Peyssonnelia dubyi		W
Phymatolithon laevigaatum		W
Platoma bairdii		W
Chaetomorpha		HP

W-E:	species sampled during 1967 survey of Waquoit Bay and Eel Pond, Curley et al., 1971
A:	species sampled in all areas by various researchers; *Gracilaria* not observed in 1967
W:	crustose species sampled in Waquoit Bay in 1975 in 1 meter depth; *Grinnellia* sampled in deeper waters of Waquoit Bay, Sears and Wilce, 1975
HP:	species sampled in Hamblin Pond by Deegan et al., 1991.

shell clam flat at the mouth of the Moonakis River (Curley et al. 1971). Today, the dominant macroalgal species in Waquoit Bay are *C. vagabunda* and *Gracilaria tikvahiae.* The latter species was not reported in the Bay by Curley et al. (1971) and appears to be be a relative newcomer. Increased nitrogen loading from the watershed may be responsible for the overgrowth of these two opportunistic macroalgae species (Valiela et al. 1992; Peckol et al. 1994; Rivers and Peckol 1995).

Cladophora vagabunda is a filamentous green macroalga that is found in marine and freshwater habitats. *G. tikvahiae* is a widely distributed, filamentous red macroalga. In Waquoit Bay, these species do not attach to the bottom substrate via holdfasts as is usually seen in seaweeds. Instead these species occur as drift algae, floating in large mats more than 0.5 meters (2 feet) deep over the bottom of the Bay (Hersh 1996).

Because of their significant physical presence and their effects on the water chemistry of the Bay, macroalgal mats are considered a new habitat type in the Waquoit Bay system. Studies of dissolved oxgyen concentration in Childs River reveal high afternoon and low early morning dissolved oxygen concentrations in bottom waters (Valiela et al. 1992; D'Avanzo and Kremer 1994). Macroalgal respiration at night depletes local oxygen supplies in the bottom waters; oxygen levels increase in the morning when macroalgae photosynthesize, or a strong wind mixes the water column sufficiently to resupply these waters with oxygen from surface waters. Chronic bottom water hypoxia is common in summer in areas such as the Childs River that have high macroalgal biomass coupled with salinity stratification (see Chapters II and V) (Valiela et al. 1992; D'Avanzo and Kremer 1994).

The replacement of eelgrass meadows with macroalgal mats has affected the abundance of numerous organisms. Deegan et al. (1991) reported greater finfish abundance and lower predation rates in Hamblin Pond sites where macroalgae were removed from eelgrass beds than in control sites. As discussed earlier, scallops cycle through high and low population levels naturally but recent declines in Waquoit Bay are correlated with a decline in eelgrass coverage. A 1989 search for scallop seed yielded little evidence of successful settlement of that year's larval cohort (Valiela et al. 1992). Had there been numerous scallop larvae, their chances of locating the scarce eelgrass habitat would have been slim (Valiela et al. 1992). In addition to loss of suitable refuge habitat, the bottom of the macroalgal mat is often a hypoxic environment where finfish and invertebrates cannot long survive (D'Avanzo and Kremer 1994). On the other hand, some species, such as the quahog, *Mercenaria mercenaria,* and the soft-shelled clam, *Mya arenaria* (Chalfoun et al. 1994), exhibited increased growth rates in subestuaries dominated by macroalgae. See Chapter V for a discussion of the ecological effects of nutrient-loading on the structure and function of the estuarine system.

INTERTIDAL ZONE

TIDAL FLATS

The Massachusetts Wetlands Protection Act defines tidal flats as "those nearly level portions of coastal beaches extending from mean low water landward to the more steeply sloping face of the beach." They are protean habitats, changing their size and shape as the tide ebbs and flows, uncovering and then covering the sand or mud tidal flat surface. With its relatively small tidal range of 0.5 meter (1.6 feet), Waquoit Bay does not have extensive tidal flat areas, however, there are regularly exposed tidal flats on the eastern shore of the head of the Bay, as well as on the sandy spits at the outlet of the Moonakis River and on the eastern shore of Washburn Island.

Many of the gastropods, polychaetes, amphipods and bivalves found on muddy and sandy bottoms of subtidal areas and salt marsh pools also inhabit the tidal flat environment (Whitlach 1982). At Waquoit Bay, the most easily recognized by the casual observer are the common bivalves—quahogs or hard-shelled clams *(Mercenaria mercenaria)* soft shelled clams or steamers *(Mya arenaria)* and the razor clam *(Ensis directus)*. The quahogs bury themselves in sand or muddy sand sediments, whereas soft-shelled clams prefer a muddier substrate. Easily overlooked because of its small size (3 millimeters or 0.125 inch) but often abundant on Waquoit Bay's tidal flats and in subtidal areas is the tiny bivalve, *Gemma gemma*. These species are suspension feeders which extend their siphons out of the substrate and into the water column to filter and ingest food particles.

During low tide, gulls join shellfishermen on the flats where they excavate infauna or feast on the shellfishermen's leavings. Humans and birds are not the only predators on bivalves in the Bay. The blue crab *(Callinectes sapidus*), green crab *(Carcinus maenus)*, and horseshoe crab *(Limulus polyphemus)* all prey on bivalves in Waquoit Bay. Other predators are some species of gastropods such as moon snails *(Polinices duplicatus* and *Lunatia heros)*, channelled whelk *(Busycon canalicalatum*) and knobbed whelk *(B. carica)*.

Mud flats are often anoxic below one centimeter depth (Whitlach 1982). Infaunal species have adapted to these low oxygen conditions. In Waquoit Bay, these species include spionid polychaete worms that inhabit burrows and extend their tentacles in search of food, and the capitellid polychaete *(Heteromastus filiformis)* and clam worm *(Nereis virens)*—two animals that bury themselves deeper in mud flats. Amphipods *(Corophium)* are also found living in shallow U-shaped tubes.

SALT MARSHES

This section describes the present-day physical and biological characteristics of salt marshes. See Chapter II for a discussion of the historical development of salt marshes and their response to rising sea level. Approximately 120 hectares (300 acres) of salt marsh are located within the Waquoit Bay National Estuarine Research Reserve, mainly around Hamblin, Jehu, and Sage Lot ponds, at the head of Great River, along the shores of Washburn Island, at the head of Waquoit Bay and Eel Pond, and at the mouth of the Childs and Moonakis rivers.

Near Waquoit Bay much of the salt marsh area is on private property; however, wetland protection laws prohibit property owners from disturbing any wetland areas. The Sage Lot Pond marshes of South Cape Beach and the Tim's Pond marshes on Washburn Island comprise over 48.6 hectares (120 acres) and are owned by the Commonwealth of Massachusetts.

Salt marshes form in quiet depositional areas behind barrier beaches or around salt ponds and estuaries and act as a buffer zone between land and sea. Their abundant above-ground biomass is matched or superseded by their extensive root and rhizome system (Teal 1986) that stabilizes the shore and impedes erosion. In addition, marsh sediments are compact and relatively impermeable, restricting the flow of groundwater seaward, thus maintaining the level of the water table landward of the salt marsh. Marsh soils are composed of inorganic matter and peat, the decayed organic remains of salt marsh vegetation. The blades of marsh grasses slow water flow and accelerate deposition of organic and inorganic suspended sediments (Fig. 3. 6). The marsh sediments are a reducing environment where anaerobic sulfur bacteria use the abundant supply of sulfate in seawater together with organic compounds to fuel their metabolic needs, producing sulfides in the process (Teal 1986).

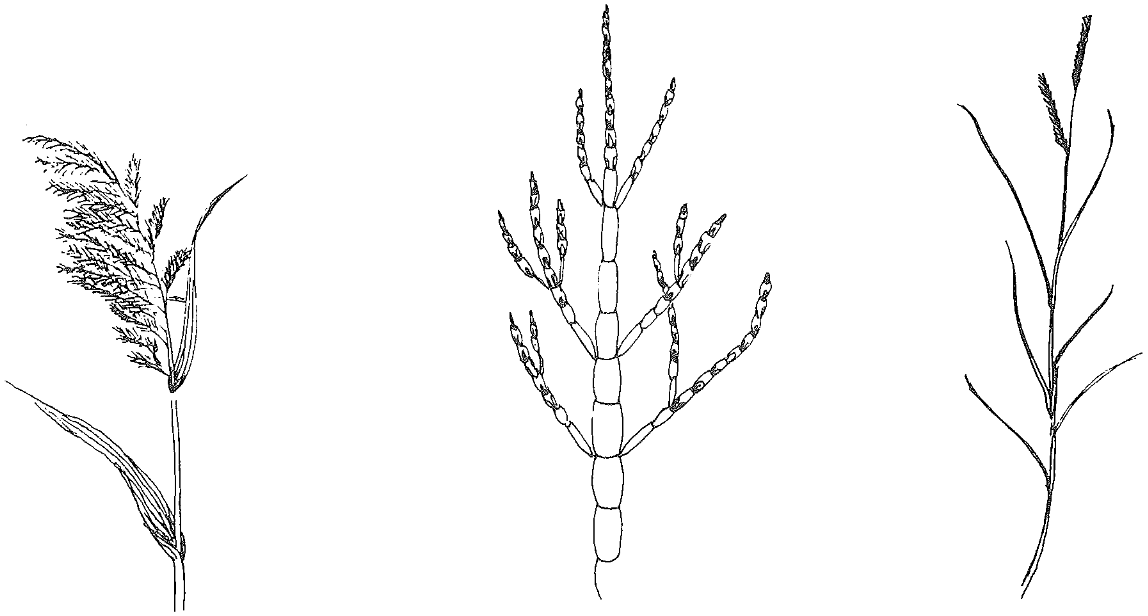
FIG. 3.6

A stand of Spartina alterniflora, *the common cordgrass. Drawing by Alison Robb.*

Salt marshes extend vertically from the low tide mark to the highest high tide mark and are distinguished by a suite of halophytic plants that changes in composition from the low to the high marsh area. The low marsh experiences regular flooding during each tidal cycle, while the high marsh floods only at extreme high tides. The common cordgrass, *Spartina alterniflora*, is the dominant species in the low marsh areas of New England salt marshes where it assumes two growth forms: a "tall" morphotype grows both in areas of active marsh accretion and along tidal creeks where water flow supplies abundant nutrients, while a "short" form is found in other areas. Gradations between these two extreme forms are common (Valiela et al. 1978). *S. alterniflora* spreads by the lateral growth of rhizomes and by colonization of bare areas by seedlings (Redfield 1972).

Although the low marsh often looks like a sea of monotypic grass, glassworts *(Salicornia* spp.) and sea lavender *(Limonium nashii)* are sometimes mixed in with the dominant *Spartina alterniflora*. The high marsh area has two dominant species, salt marsh hay *(Spartina patens*) and spike grass *(Distichlis spicata)*. Glassworts and sea lavendar are also present as are black rush *(Juncus gerardi*), marsh elder *(Iva frutescens*) and switch grass *(Panicum virgatum*). Cattails of the genus *Typha* and the reed of the genus *Phragmites* are found where there is freshwater input (Nixon 1982; Teal 1986). Some typical salt marsh species found in the Waquoit Bay estuarine complex are depicted in Figure 3.7.

Based on plant species transition zones, porewater salinities and periodicity of tidal inundation, Howes and Teal (1990) identified three broad types of salt marsh wetlands within the Reserve system (Fig. 3.8 and Table 3.4). Surrounding the Bay proper, where there is little protection from wind and waves, the wetlands form narrow bands, and plant zonations within the band are likewise narrow; only a few species are found. Greater diversity and a wider bank of marshland are seen along the rivers and some pockets of wetlands on Washburn Island. Finally, the marshes of Hamblin and Jehu ponds are extensive with numerous species and broad transition zones. Refer to Chapter II for an analysis of the differential development of these diverse salt marsh systems.



REED
Phragmites communis

GLASSWORT
Salicornia spp.

SALT MARSH HAY
Spartina patens

CORDGRASS
Spartina alterniflora

MARSH ELDER
Iva frutescens

BLACK GRASS
Juncus gerardi

Fig. 3.7
Representative plants in Waquoit Bay salt marshes. Drawings by Alison Robb.

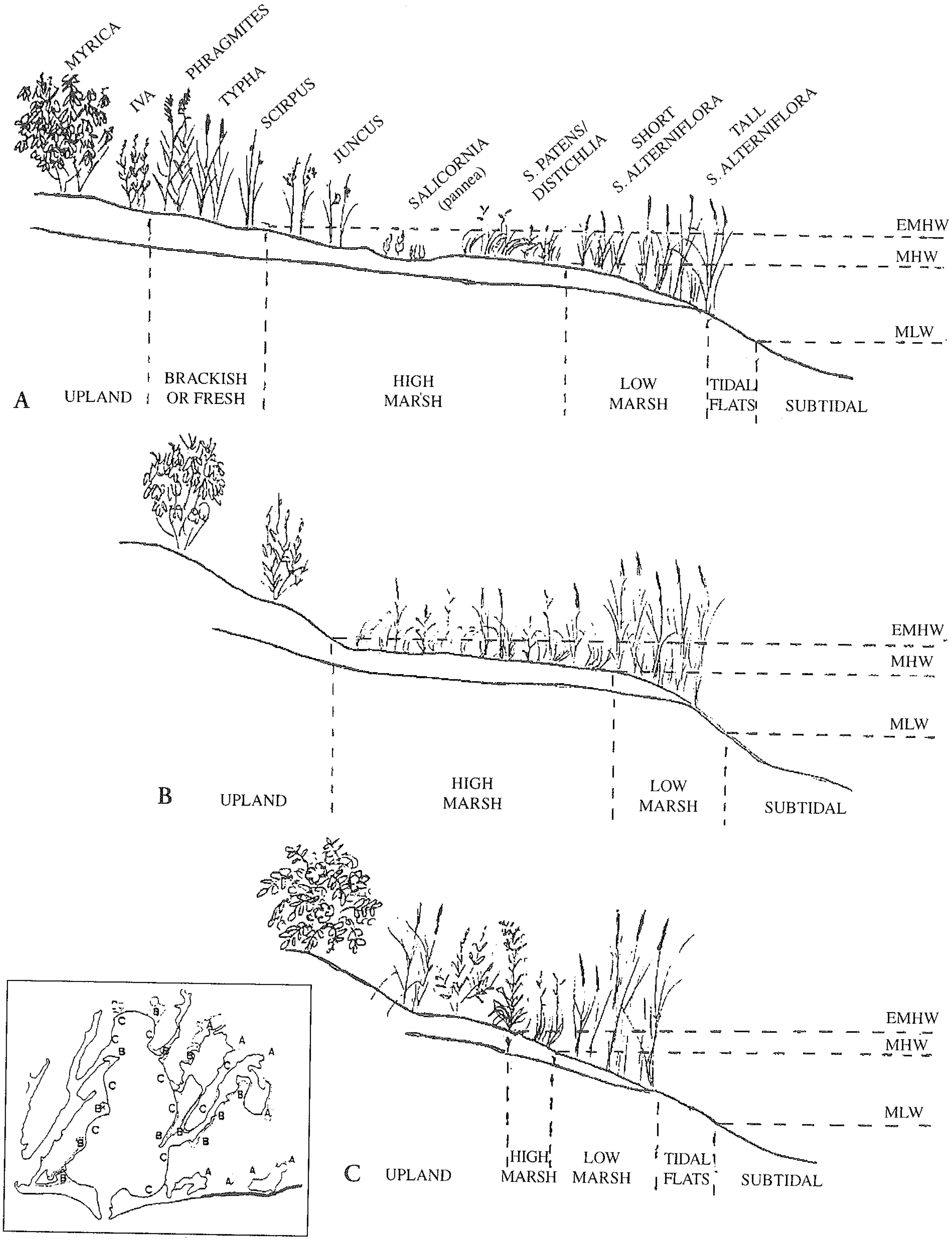
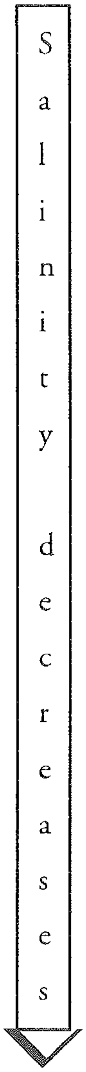


FIG. 3.8

Types of salt marsh wetlands in the Waquoit Bay Reserve. Inset shows locations of different types. (Howes and Teal 1990). Drawing adapted by Alison Robb.

Table 3.4 Salt marsh species found in the Waquoit Bay Estuarine Complex. Species listed in order of emergence (after Howes and Teal, 1990).



SCIENTIFIC NAME	COMMON NAME
Spartina alterniflora	salt marsh cordgrass
Spartina cynusuroides	salt reed grass
Spartina patens	salt marsh hay
Distichlis spicata	spike grass
Juncus gerardi	black rush
Salicornia europa	glasswort
Salicornia bigelovii	glasswort
Salicornia virginica	woody glasswort
Limonium carolinianum	sea lavender
Scirpus americanus	chair-maker's rush
Scirpus maritimus	salt marsh bulrush
Scirpus robustus	robust bullrush
Solidago sempervirens	seaside goldenrod
Iva frutescens	marsh elder
Atriplex patulah	halberd-leaved orach
Phragmites communis	reed grass
Ammophila breviligularta	beach grass
Artemisia stelleriana	dusty miller
Typha angustifolia	narrow leaved cattail
Pluchea purpurascens	salt marsh fleabane
Rhus radicans	poison ivy
Ammophila breviligulata	beach grass
Lathhyrus japonicus	beach pea
Aster tenufolius	salt marsh aster
Myrica pennsylvanica	bayberry
Rosa rugosa	salt spray rose

Salt marshes help preserve and protect the physical character of the Bay, and also the plant and animal communities of the estuary. Some fish species spend all or most of their lives in salt marsh waters, while others utilize salt marshes as nurseries for young fish (Table 3.5). Results from Ayvazian (1992) showed that Waquoit Bay marsh habitat supported higher numbers of species and greater biomass than sandy beach habitat and open water habitat. As might be expected in a transition zone between land and sea, both terrestrial and marine animals inhabit or visit marshes. Animals of the low marsh and high marsh have been reviewed by Teal (1986) and Nixon (1982), respectively.

ESTUARINE CHANNELS AND TIDAL CREEKS

Although estuarine channel and tidal creek habitats cover only a small area of the Waquoit Bay complex, they link the open Bay environment to the smaller, more tidally restricted salt ponds with their associated salt marshes. Hamblin and Jehu ponds, which have the largest areal extent of salt marsh within the Reserve, are connected to the Bay by two tidal creeks, Little and Great rivers respectively. Both rivers have seen considerable residential development and private docks line their banks. Smaller tidal channels within the Reserve include the tidal creek feeding Sage Lot Pond, the constructed channel that links Sage Lot Pond to Flat Pond at South Cape Beach, the tidal creeks connecting small areas of salt marsh at the southern (Tim's Pond) and northern ends of Washburn Island, as well as those connecting Bay waters to Caleb and Bog Ponds (Chapter I, Fig. 1.2).

Table 3.5 Fish species that utlilize salt marshes.

Fish that spend most of their lives in salt marsh waters	
Menidia menidia	Atlantic silverside
Fundulus heteroclitus	mummichog
Fundulus majalis	striped killifish
Cyprinodon variegatus	sheepshead minnow
Apeltes quadracus	fourspine stickleback
Gasterosteus aculeatus	threespine stickleback
Anguilla rostrata	American eel
Fish that use marshes as nursery	
Pleuronectes americanus	winter flounder
Tautoga onitis	tautog
Centropristes strata	sea bass
Alosa pseudoharengus	alewife
Brevoortia tyrannus	menhaden
Pomatus saltatrix	bluefish
Mugil cephalus	mullet
Ammodytes americanus	sand lance
Morone saxatilis	striped bass

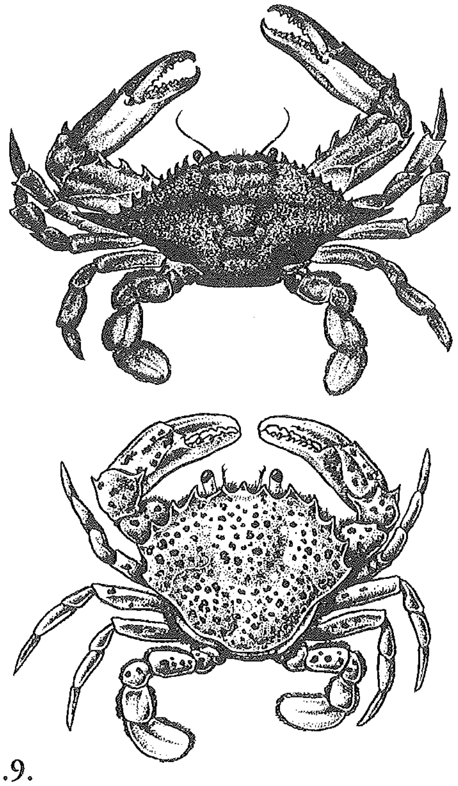


FIG. 3.9.
The blue crab, Callinectes sapidus (above), *and the lady crab,* Ovalipes ocellatus (below). *Drawings by Bob Golder.*

Some of the estuarine channels and tidal creeks of Waquoit Bay have small patches of eelgrass (Saucerman and Deegan 1991), but most are primarily sandy mud with a layer of macroalgae growing over the bottom. Ribbed mussels *(Geukensia demissa)* attach to creek banks while blue crabs *(Callinectes sapidus)* and lady crabs *(Ovalipes ocellatus)* live in the muddy banks of these channels (Fig. 3.9). In more sheltered tidal creeks, the seaweeds, *Codium* and *Fucus,* can be found rooted to the bottom.

BARRIER BEACHES AND SAND DUNES

The combined action of water, wind, and waves along with biological factors make barrier beaches and dunes dynamic habitats. Along the beaches, waves and currents constantly redistribute sands and pebbles while higher up on the shore, winds are the predominant shaper of dunes. Storm events can dramatically alter the appearance of these low lying coastal zones. The beach and sand dunes along the southern shore of Washburn Island and South Cape Beach extend more than 40.5 hectares (100 acres) and protect the Bay and adjacent uplands from coastal erosion and ocean storms. While part of the barrier beach at South Cape Beach State Park is used as for public recreation, most of it is undeveloped and supports a diverse community of species. On the limited-access Washburn Island, beach plants grow in profusion.

DUNE COLONIZATION

Dune creation requires sand and vegetation. Mounds of sand alone cannot withstand the forces of wind and wave, but if plants take hold in the sandy mounds, the sands are stabilized and dune building begins. The first colonizers are often grasses which root in the strand line, where detritus is washed ashore. As more sand is trapped by the plants, the dune grows and in so doing creates additional habitat for plant growth. After the initial stabilization, many species may colonize the dune.

The most conspicuous plant on the coastal beach is beach grass, *Ammophila breviligulata,* which typically grows above mean high water in areas that receive salt spray and where sand accumulates. Beach grass, which grows primarily by rhizomes, is an important and vigorous dune stabilizer, as it can survive a sand burial rate of up to one meter (3.3 feet) per year (Ranwell 1972).

Other colonizers of primary dune in the Waquoit Bay area are dusty miller *(Artemisia stelleriana),* seaside goldenrod *(Solidago sempervirens),* beach pea *(Lathyrus japonicus* var. *glaber),* and beach heather *(Hudsonia tomentos) (*Cullinan and Botelho 1990). Poison ivy *(Rhus radicans),* salt spray rose *(Rosa rugosa),* bayberry

(Myrica pennsylvanica), and beach plum *(Prunus maritima)* are common inhabitants of the back dune environment at South Cape Beach (Fig. 3.10). Of note is the fact that some of these dune inhabitants are exotic species—dusty miller was imported from eastern Asia and salt spray rose was introduced from Japan in 1872 and has successfully colonized the areas behind dune ridges throughout the northeastern United States (Petry and Norman 1968).

Avian Residents and Visitors

The Waquoit Bay estuarine system lies near the Atlantic coast flyway, an important migratory corridor for many birds. Numerous shorebirds use the barrier beach and coastal salt marsh system as an important stopover on their spring journeys to tundra breeding grounds in Canada and on their fall journeys to tropical wintering grounds. Shorebirds appearing in abundance in the spring and fall on Waquoit Bay's barrier beaches include the black bellied plover *(Pluvialis squatarola)*, semipalmated plover *(Charadrius semipalmatus)*, sanderlings *(Caladris alba)*, dunlin *(Caladris alpina)*, semipalmated sandpiper *(Caldris pusilla)*, least sandpiper *(Caladris minutilla),* ruddy turnstones *(Arenaria interpres)*, willets *(Catotrophorus semipalmatus)*, lesser yellowlegs *(Tringa flavipes*), greater yellowlegs *(T. melanoleuca)*, short-billed dowitchers *(Limnodromus griseus)* and an occasional whimbrel *(Numenius phaeopus).*

Many gulls and terns rest on South Cape Beach and Washburn Island's barrier beaches and sand dunes, foraging in the estuarine and coastal waters. These include ring-billed *(Larus delawarensis),* herring *(L. argentatus)*, laughing *(L. atricilla)*, bonaparte's *(L. philadelphia)*, and the greater black-backed gull *(L. marinus).* Among the terns are arctic *(Sterna paradisaea),* common *(S. hirundo),* roseate *(S. dougallii)*, and least terns *(S. antillarum).* As recently as the last century, terns numbered in the hundreds of thousands in Massachusetts, but human activites have reduced the tern populations in Massachusetts.

The roseate tern, *Sterna dougallii,* which was declared a Federally Endangered species in 1987, forages from Waquoit Bay's beaches. Bird Island, in nearby Buzzards Bay, hosts the largest roseate tern colony in North America. Bird Island terns disperse early in the morning to forage for their nestlings. They have been spotted near the inlets to both Waquoit Bay and Eel Pond, where abundant populations of fish are available during the summer breeding season (Heinemann 1991). When predatory bluefish or striped bass drive sand lance or herring schools to the surface, flocks of roseate terns arrive for the feast. To the east of Waquoit Bay on Succonnessett Shoal, roseate terns take advantage of the shallow sand bar where strong tidal currents sweep small prey fish to the surface (Heinemann 1991). As low breeding success has been linked to low prey density in a New York tern population, the ability of nearby estuaries, such as Waquoit Bay, to provide ample numbers of small fish is important to the long-term success of this endangered bird (Heinemann 1991).

Piping plovers, *Charadrius melodus,* rely on barrier beaches for their nesting territories. These birds are listed as Threatened by both the state of Massachusetts and the United States. Piping plovers lay their eggs directly on the sand in the middle of the beach, where the well-camouflaged eggs and chicks are vulnerable to human traffic as well as predators (Fig. 1.6). In the Waquoit Bay Reserve, fencing is used to protect nests from predators, and off-road vehicles are not permitted on the beach during the breeding season.

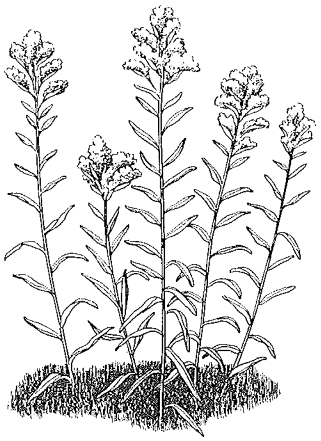
These barrier beach habitats also are critical to the breeding success of the least tern, *Sterna antillarum* (Fig. 1.2),

BEACH PEA
Lathyrus

POISON IVY
Rhus radicans

BEACH GRASS
Ammophila breviliqulata

BEACH PLUM
Prunus maritima



SEASIDE GOLDENROD
Solidago sempervirens

SALT SPRAY ROSE
Rosa rugosa

FIG. 3.10
Representative barrier beach and dune species at Waquoit Bay. Drawings by Alison Robb, except rose and goldenrod by Bob Golder.

which is listed as of Special Concern in Massachusetts. Least tern colonies nest on the high beach between the normal high tide line and the dunes. A large colony can be found at Dead Neck at the western end of South Cape Beach. With a wing span of 50 centimeters (20 inches), the least tern is the smallest of the North American terns; its nest is a simple depression in the sand, which may include bits of stone, shell, and seaweed. Both adult and young terns only eat live prey, mainly small fish caught in shallow water. As they are more visible and aggressively defend their nests, least terns are less vulnerable to disturbance than are piping plovers.

UPLAND HABITATS

FRESHWATER WETLANDS

Important freshwater wetlands in the Waquoit Bay watershed include the Ashumet Pond and Johns Pond shorelines, the nearby Flashy, Grassy and Martha's Ponds, Snake Pond to the north, abandoned cranberry bogs east of Johns Pond, marshes along the shores of the Quashnet and Childs rivers and Red Brook, pockets of marsh and cedar swamps in the northern portion of South Cape Beach State Park, and freshwater kettle hole ponds just to the north of the Bay, including Bourne Pond and Fresh Pond (see Fig. 1.1, Chapter I).

The freshwater wetlands of the Waquoit Bay watershed are rich in plant and animal species. At South Cape Beach, freshwater marsh species include the common cattail *(Typha latifolia)* and reed grass *(Phragmites australis),* as well as twig rush *(Cladium marascoides)* and water lily *(Nymphaea odorata).* Patches of bogs have such species as sheep laurel *(Kalmia angustifolia)*, sweet gale *(Myrica gale),* and *Sphagnum* sp. Many waterfowl are solely dependent upon wetlands for their breeding, feeding and migratory needs. Ospreys forage for fish in freshwater areas. Many upland wildlife species, including game and song birds, opposum, raccoons and white-tailed deer, are seasonally dependent on wetlands.

RIPARIAN HABITATS

Coastal plain streams provide important sources of water for upland species and are prime habitat for fish, turtles, ducks and geese. Forests of scrub oak *(Quercus illicifolia),* and pitch pine *(Pinus rigida)* prosper in the surrounding soils, which are made up of consolidated sand dunes. The Quashnet River is an alewife *(Alosa pseudoharengus),* and blueback herring *(A. aestivalis)* run (Fig. 3.11). American eel *(Anguilla rostrata)*, striped bass *(Morone saxatilis*), white perch *(M. americana)*, eastern brook trout *(Salvelinus fontinalis)*, and white sucker *(Catostomus commersoni)* also are commonly found in this stream.

During the nineteenth century, the Quashnet River was a prized trout stream, with large populations of anadromous, or "sea run" brook trout or "salters." In 1843 an article published in "The Spirit of the Times" reported:

> "The 27th of the month brought our last week to a close and, ever anxious to explore untrodden ground, we a took a look at a river said to be full of brook trout, known as Quoshnet (sic) River...Most of the entire lengths may be forded, but the track is through a tangled thicket and difficult to make headway...at every sandy place we could see hundreds of trout, some, apparently of large size darting back and forth and appearing to be as plentiful as herrings. We fished for an hour or two and caught upwards of a hundred of them, just for the sport, and then departed."

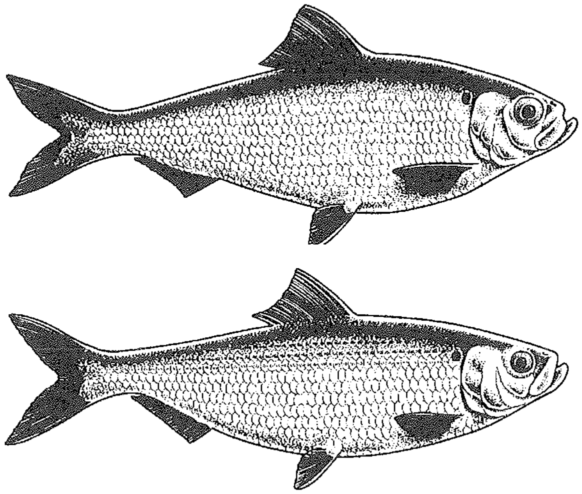


FIG.3. 11

Alewife, Alosa pseudoharangus, *(above) and blueback herring,* A. aestivalis, (below) *are very similar species that spawn in fresh waters of the Waquoit Bay watershed. Drawings by Bob Golder.*

However, industrial and then agricultural demands destroyed the pristine habitat. First dammed to provide water power for mills from 1860 to 1890, the Quashnet River was later altered for the construction of cranberry bogs. The result was a broad, slow-moving, channelized river devoid of its original streamside vegetation. The bottom became silted with sand from the bog operations and the high temperatures further reduced the stream's efficacy as prime trout habitat (anon 1979; Golder 1985).

After World War II, most of the cranberry bogs bordering the river were abandoned. New vegetation grew up around the river banks and the water temperature dropped. In 1956 the Massachusetts Division of Fisheries and Game (the present Massachusetts Division of Fisheries and Wildlife) purchased land along both sides of the river and stocked it with brown trout, *Salmo trutta,* a hardy, aggressive species that grows larger than brook trout and outcompetes them (Golder 1985). The brown trout travelled to the salt waters of Waquoit Bay and fed upon baitfish there. In the early 1970's brown trout weighing 2.3–2.7 kilograms (5–6 pounds) were not uncommon (Pero 1976).

However, vegetation continued to grow up around the banks of the Quashnet and some species like speckled alder *(Alnus rugosa)* and willows *(Salix* sp.*)* expanded into the River, reducing its flow. Shrubs and decaying cranberry bog structures increasingly blocked the river, slowed the current and widened the stream bed, changing its composition from sand and gravel to mud (McLarney 1988b). The composition of the aquatic insect community also changed, as mayfly and caddisfly numbers declined and mosquitoes increased in abundance in the still-water environment (Wright 1987). The habitat favored suckers rather than trout. Although the brown trout survived, the sea-run brook trout all but disappeared.

In 1976, the Cape Cod Chapter of Trout Unlimited spearheaded a major restoration effort with the aid of the Massachusetts Division of Fisheries and Wildlife. The restoration effort continues today, a 20-year project to bring back one of the finest trout streams in the Northeast. The Trout Unlimited volunteers have cut brush, redirected stream flow, planted trees, constructed overhead cover for trout, and in the process of what began as an effort to restore a trout stream, have found themselves major advocates of open space and conservation values (McLarney 1988a; McLarney 1988b). The volunteer effort has successfully restored part of the Quashnet as a viable trout stream, with a self-sustaining brook trout population. Brown trout are no longer stocked in the Quashnet River.

UPLAND PITCH PINE/OAK FORESTS

The European settlers who came to Cape Cod cut down the mature climax forest to clear the land for agriculture and to obtain wood for houses, shipbuilding and local industry. Stripped of cover, the soils were swiftly eroded by ocean winds and the Cape became one of the first areas in North America to undergo a reforestation effort. The climax forest was replaced by secondary growth of pitch pine *(Pinus rigida)* and scrub oak trees *(Quercus ilicifolia)* which grew quickly in the sandy soils. This complex is still the most commonly occurring vegetation community on Cape Cod (Gallagher 1983) and is the principal forest community in the Waquoit Bay watershed.

PINE BARRENS

A particular kind of pine/oak complex is the pitch pine/ scrub oak *(Pinus rigida/Quercus ilicifolia)* barrens that occurs on dry, acidic, nutrient poor, well drained soils in the Waquoit Bay watershed and other coastal outwash plains. An example of a pitch pine/scrub oak barrens can be found west of the Quashnet River and north of the Reserve. Typically a dense understory of scrub oaks and huckleberry *(Gaylussacia baccata)* grows beneath the pitch pines and excludes other plants. Often patches of lowbush blueberry *(Vaccinium angustifolium)*, bearberry *(Arctostaphylos uva-ursi)*, sweetfern *(Comptonia peregrina)*, or lichen grow in the opening spaces between oaks (Fig. 3.12).

This pine barrens community has adapted to occasional fires for its maintenance as nutrients, generally scarce in the poor soils, become more available in the ashes of a fire. The thick bark of the pitch pine resists fire damage while both huckleberries and scrub oaks can sprout new growth from their root crowns following a fire. Species diversity is greatest in the years immediatley after a fire. In fact, these habitats and communitites are threatened by the absence of periodic fire (and by developers who favor the flat easily buildable setting).

COASTAL PLAIN POND SHORES

In Massachusetts, ponds surrounded by state-listed rare species habitats are known as coastal plain ponds. The Massachusetts Natural Heritage Program considers coastal plain ponds to be a particularly vulnerable habitat in need of protection. Globally rare, these groundwater-fed ponds occupy low areas in glacial outwash soils. Near the Reserve Headquarters are two coastal plain ponds, Caleb Pond, and an unnamed pond south of the Waquoit Cemetery. There are also coastal plain ponds on Washburn Island and in the vicinity of Flat Pond at South Cape Beach. Further north in the watershed, Ashumet Pond and parts of Johns Pond shores are also considered coastal plain ponds.

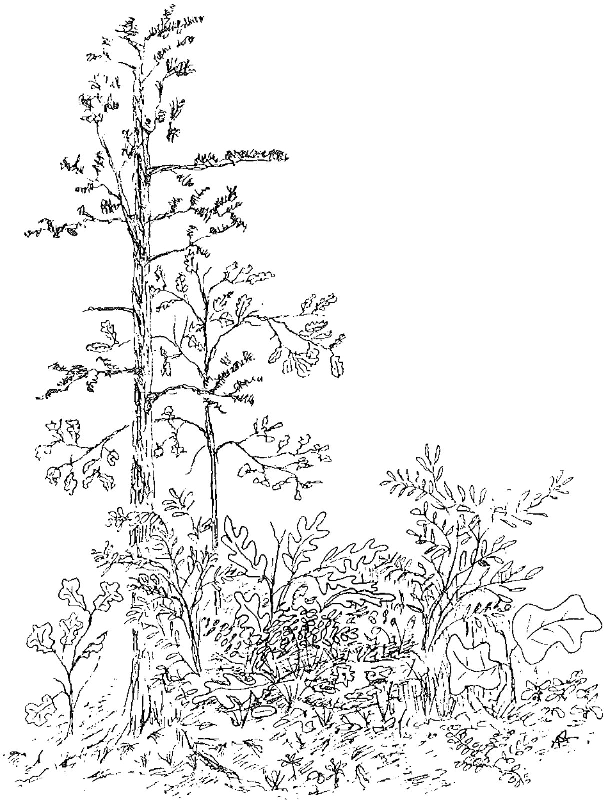


FIG. 3.12

Close-up of vegetation in pine barrens landscape. Drawing by Alison Robb.

VERNAL POOLS

Vernal pools are transitory, small freshwater ponds that typically appear in spring in low-lying depressions that are filled by melting snow and rain and groundwater. In the Waquoit Bay watershed they are most commonly found in kettlehole depressions left by past glacial activity. These kettleholes are found in many places, including wooded uplands, meadows, river floodplains, or even on sandflats. These ponds are crucial to the breeding success of several amphibians which spawn in the temporary ponds. Their offspring depend on the pond during their early life history stages. One of these, the yellow spotted salamander, is found in many of the freshwater wetlands and vernal pools in Waquoit Bay's watershed. Vernal pools also support invertebrate fauna, including fairy shrimp which is found only in vernal pools. The green frog *(Rana clamatans),* the American toad *(Bufo americanus)*, and red-spotted newt *(Notophthalmus v. viridescens)* also may breed in vernal pools, although they are not restricted to these pools for reproductive success.

SANDPLAIN GRASSLANDS

Sandplain grasslands are what their name implies—open, treeless grasslands on dry, sandy, soils. These grasslands are found in areas of glacial deposits in southeastern Massachusetts, including Cape Cod and the Islands, and a few places in Connecticut. Prairie grasses (little blue-stem, *Schizachyrium scoparium*, and Indian grass) are the dominant species of these grasslands. Bird's foot violet *(Viola pedata)*, which grows extensively on the Sargent Estate within the Waquoit Bay Reserve, is an indicator of good sandplain grasslands. A large population of New England blazing star *(Liatris scariosa* var. *novae-angliae)* inhabits Washburn Island. This species is listed as a Species of Special Concern in Massachusetts.

The federally endangered sandplain gerardia *(Agalinis acuta)* is a globally rare sandplain grassland species which is found within the Waquoit Bay watershed and at fewer than 10 other sites in the eastern United States. Researchers from the Massachusetts Natural Heritage Program, the Massachusetts Audubon Society, the New England Wild Flower Society and the Nature Conservancy are examining management techniques that can be used to restore sandplain gerardia to its historical range. The Waquoit Bay Reserve is a site for the restoration project where researchers are experimenting with different methods (burning, scarifying, fertilizing) to increase germination and growth. Over 1,100 plants were produced the first season and treatment plots were pink with sandplain gerardia flowers in late September of 1995 (Paul Somers, Massachusetts Natural Heritage Program, pers. comm.).

Sandplain grasslands are successional communities which were historically maintained by fire and grazing. Presently, fire suppression, housing, and industrial development have depleted much of the habitat necessary for the development of this community. Prescribed burning, mowing and controlled grazing are being examined for efficacy in maintaining remaining grasslands.

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CHAPTER IV

LIFE HISTORIES OF COMMERCIALLY IMPORTANT SPECIES

FOUND IN WAQUOIT BAY

Zooplankton abound in the waters of Waquoit Bay. Photograph by Richard E. Crawford.

INTRODUCTION

Detailed synopses of the life histories of several species common in Waquoit Bay illustrate the complexity of the interactions between human uses of the Bay and the fish and invertebrate fauna. The details of the biology and the natural history, such as the importance of delicate physical structures like cilia and the specific requirements of fragile larvae, respectively, show what these species require.

Four species common in Waquoit Bay, the bay scallop, the hardshell clam (known locally as "quahog"), the American eel, and the winter flounder, are described here in detail.

BAY SCALLOP

The bay scallop, *Argopectin irradians* Lamark, (Fig. 4.1) has been present in Waquoit Bay and other southern New England coastal lagoons for thousands of years. For example, bay scallop shells in sediment cores from a Rhode Island coastal pond similar to Waquoit Bay were determined to be more than 2,500 years old (Boothroyd et al. 1981). Bay scallop shells in Waquoit Bay native American middens reveal that these sweet shellfish were being harvested there long before Europeans arrived. (For the remainder of this account, the term "scallop" will refer to the bay scallop, unless otherwise noted.)

The scallop is one of the most popular shellfish species in the Bay, perhaps because prized abundances of this delicacy are so ephemeral. Although Waquoit Bay has never been a "hot spot" in the Cape Cod scallop fishery (M. Hickey, Massachusetts Division of Marine Fisheries, pers. comm.), local residents flock to the Bay during scallop season in the hope of catching a bushel or two.

Scallop populations throughout New England historically have been highly variable. The cause(s) for the common sudden increase or decline in scallop abundance has so far eluded researchers. Postulated causes include changes in water quality, declines in eelgrass abundance and increases in pesticide residues. The relative effects of these factors in controlling scallop abundance are not known. But because bay scallops usually live for only 20 to 26 months, their short life cycle contributes to instability. The failure of a single year class can wipe out an entire population, something which does not readily occur in longer lived species.

Although catches have reportedly been declining in the recent past, data do not reveal a precipitous decrease in Waquoit Bay landings. Data do suggest

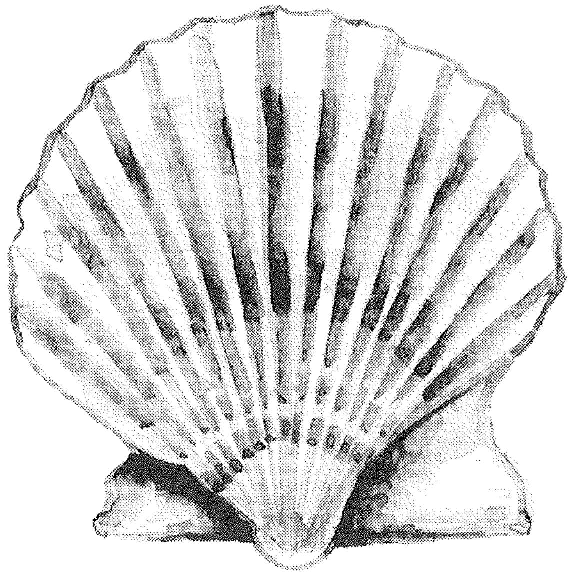

FIGURE 4.1
Shell of the bay scallop, Argopectin irradians. *Drawing by Caroline Goldstein.*

that landings have been in general decline in Eel Pond since the early 1970s (see Chapter V for additional information). Shellfish landing data do not necessarily reflect shellfish abundance; instead higher harvests often reflect poor economic conditions which lead to increased fishing effort (G. Costa, Falmouth Shellfish Commissioner, pers. comm.).

When scallop abundance in the Bay is low, a potential source of replenishment is the offspring from the scallops that can reside in eelgrass beds outside the barrier beach in coastal Vineyard Sound. These eelgrass beds have remained relatively unchanged during the last few decades when eelgrass has been disappearing in the Bay (G. Costa, pers. comm.). Scallops in that habitat would be positioned to provide a supply of young "seed" scallops for repopulating the Bay waters when conditions "are right."

The scallop is epibenthic in habit; it lives on the surface of the bottom rather than in the sediments like many other bivalves (e.g. quahogs and softshell clams). The scallop lies on its side, left side up. Because of this orientation, its shells (or valves) are commonly referred to according to their appearance, as dorsal (actually left side) and ventral (right).

The scallop attaches itself to eelgrass or the sea bed with byssal threads. These threads originate in the byssal gland, located in the scallop's foot. The gland secretes when the foot is extended to the substrate. Travelling along a groove in the foot, the secretions harden into a thread upon exposure to seawater. When the foot is withdrawn the threads form the byssus which is anchored to the substrate at one end and to the byssus opening of the foot at the other (Barnes 1974). Usually several threads are secreted but a scallop is never too firmly anchored to the bottom. If the animal is threatened by a predator, which it may detect chemically (see below), the scallop can release its byssal threads at its foot and swim away.

A scallop swims by "clapping" the valves. This causes a rapid ejection of water from the mantle cavity. The swimming action is evoked by the centrally located posterior adductor muscle (the "meat" harvested by a fishery). The muscle is divided into smooth and striated sections. The rapid contraction of the striated ("quick") fibers powers the swimming activity. The muscular lobe of the mantle margin, when closed against the lobe of the opposite mantle surface, controls the direction of the exiting water jet. A scallop can direct the water jet to either side of the hinge line or from the center of the valves, opposite the hinge line. The direction of movement of the scallop is opposite to the direction of water flow. Thus, a scallop can go either "forward" or "in reverse."

The water jet can also be used to modify the scallop's environment. If a scallop settles onto a sand flat affected by currents or turbulence, maintaining attachment to the fine-grained substrate with the byssus is problematic. In this instance, the water jets can be directed downward to blow out a small depression in the sand. By settling into this depression, the scallop is less likely to be disturbed by a strong current.

The mantle sensory lobes at the margins of the valves are highly developed (Barnes 1974). They bear numerous photoreceptive blue eyes (Fig. 4.2) and many small sensory tentacles, which are both tactile and chemoreceptive. The eyes are most sensitive to the blue spectrum, the wavelength that penetrates most deeply into the sea. This suite of sensory organs enables the scallop to detect predators, from which it will attempt to flee by swimming away. Swimming ability may be impaired by an abundance of 'Aufwuchs' (a collective term for the various organisms—e.g. attached seaweed—that accumulate on the shell surfaces, particularly the dorsal one). If a scallop under attack does not (or cannot) swim away, the smooth "catch" fibers of the adductor muscle will contract to keep the valves tightly closed.

FEEDING MECHANISM

The scallop breathes with an organ known as a sheet gill. This type of gill is composed of rows of filaments that arise from the mantle walls. The filaments are arranged in delicate sheets and are covered with fine cilia, which beat continuously. While this beating serves to ventilate the gills for respiration, the cilia also filter food (phytoplankton and particles of detritus) from the water. The food is trapped in a fine sheet of mucus coating the gills. Specialized cilia transport the mucus sheet—containing the food—to the mouth (Barnes 1974). The sheet gills of a scallop can filter very small particles; large particles are rejected. This size selection allows the scallop to filter only desired food and avoid ingesting "unwanted" items.

The gill structure with its dual function of respiration and feeding apparatus is a delicate mechanism that is susceptible to physical injury. Cilia are vulnerable to physical damage and to harsh chemicals, such as those in pesticides or cleaning agents. The gills may also be clogged by oil or when phytoplankton or detritus particles become too concentrated for effective ciliary clearing of the feeding surfaces. Under such circumstances, feeding and respiration are interfered with and starvation or suffocation is a possibility. At the other extreme, too few food particles in the near-bottom water layer may also result in starvation. Whatever the case, local micro-environmental differences can produce very different habitats for scallops living in Waquoit Bay (e.g., Rhoads and Young 1970).

GROWTH AND REPRODUCTION

Scallop growth varies seasonally due to energy partitioning, a phenomenon that is revealed to a fishery as differences in meat yield (adductor muscle weight) by season or by location. Most body tissue growth occurs during the summer and early fall (Cooper and Marshall 1963). Sexual maturity is reached at the end of the first year. During the spring of the second year, growth is directed to shell and gonad development. Scallops spawn in the summer when water temperatures in the Bay are rising (Taylor and Capuzzo 1983). After spawning, growth energy is redirected to the somatic tissues and the animals increase in size dramatically. This conspicuous period of growth in September and October has been recognized by fishermen for many years (Belding 1909). For example, the 1923 meat yield from Narragansett Bay increased 37.5 percent per bushel between September 1—October 15 (1924 Annual Report of the Rhode Island Commissioners of Shellfisheries). (It is interesting to note that these scallops yielded 16 pints of meat per bushel. Contemporary yields from Waquoit Bay and other southern New England areas are typically about half of that.)

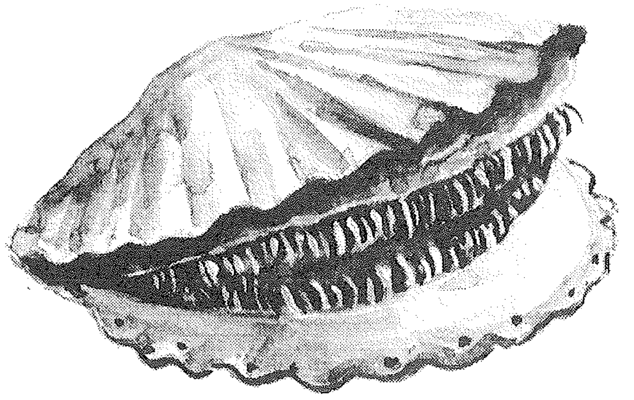

FIGURE 4.2

The eyes of the scallop are visible as a row of blue dots along the lower (right) shell or valve. Drawing by Caroline Goldstein.

Scallops that have lived through a winter can be easily identified by the "winter check," a ring of ridges on the valve surface. During warmer months, the inner surface of the outer fold of the mantle generates new periostracum tissue while the outer surface deposits a calcareous-layer material — both of which are components of the shell. When these activities decrease in winter, shell deposition slows and shell growth is minimal. Shell deposition does not cease, however. The slow continuation serves to thicken the shell slightly during this time. At the resumption of growth in the spring, thin new shell material is deposited at the margin. As a result, a ridge has been formed by the winter's growth cycle (Barnes 1974). Only a small portion of the scallop population lives long enough to have two such ridges.

EARLY LIFE HISTORY

As in other bivalves, scallop fecundity is very high. Fertilization occurs in the water, after gametes have been broadcast into the surrounding waters by several clappings of the valves.

The embryo first develops into a free-swimming trochophore, a primitive type of larva. The trochophore passes into a more highly developed form called a veliger, in which the foot, shell and other structures make their appearance. In both larval forms, locomotion is accomplished by the synchronous movement of cilia. This action allows the larvae to change their location in the water column (i.e. shallower/deeper). They drift in the plankton, getting swept along by the tidal currents that flow in and out of the Bay. It is likely that most larvae that get swept into Vineyard Sound are removed from the Waquoit Bay system. It is also possible that under "normal" conditions, larvae that leave the Bay are less likely to survive.

The planktonic period lasts several weeks, until the weight of the developing valves overwhelms the swimming capabilities of the veliger and the young scallop settles to the bottom. The juvenile scallop retains mobility after settling, except swimming is then accomplished with the valves. The scallop seeks out suitable substrate and habitat, to which it temporarily anchors itself with its byssus.

Eelgrass meadows are prime habitat for the scallop. By attaching to blades of seagrass, juvenile scallops avoid the fine sediments that are common in Waquoit Bay, sediments which can foul the scallop's feeding and breathing apparatus. It is assumed that the habitat presented by drift algae now common in the Bay is inferior to that of eelgrass. Loss of eelgrass, with the concomitant proliferation of seaweeds, are therefore implicated in the subsequent decline in scallop landings from Waquoit Bay waters.

Perhaps more than the other species of mollusks exploited in Waquoit Bay, scallops are also susceptible to low dissolved oxygen (DO). The microhabitat under the seaweed mat is routinely depleted of DO (Valiela et al. 1992) because of light shading and poor water circulation. If the algal mat drifts over a scallop bed, the bivalves would likely be stressed. Accordingly, the bay scallop is vulnerable to environmental perturbations that commonly occur in Waquoit Bay during the summer.

THE QUAHOG

The following synopsis of the life history of the hard clam or quahog, *Mercenaria mercenaria*, has been extracted from Barnes (1974), Fiske (1981), Loosanoff et al. (1951), and Shuster (1971) unless otherwise noted. This summary is relevant to environmental conditions prevalent in Waquoit Bay and adjacent waters. This detailed account provides an insight to the delicate nature of the quahog that is not casually obvious.

"Quahog" (or quahaug) is a native American name for the hard clam (Fig. 4.3), but in popular use it refers to only the largest size class. Generally, "cherry stone" identifies the mid-range size class and "littleneck," the smallest (legally harvestable) size class. There are exceptions to this nomenclature, however. For example, in Connecticut, cherry stone and littleneck are reversed (i.e., cherry stone is the smallest). (Throughout this account the term quahog will be used as the name for this animal, without any implication to age or size.)

SPAWNING AND EMBRYONIC DEVELOPMENT

Most quahogs spawn in early summer, but some may continue into the fall (Diamond 1981). They release millions of eggs and sperm from their exhalant siphons into the water column where fertilization occurs quickly. A free-swimming trochophore larva develops within about 12 hours, and by the time it is about 24 hours old, the trochophore has become a veliger larva. The rate of this development depends on salinity, temperature and type of food available (Davis and Calabreese 1964). The larva drifts in the tides with the plankton, and is swept around (and may be out of) the Bay depending on circumstances.

The veliger is a suspension feeder, and its characteristic organ, the velum, consists of two semicircular lobes bearing long cilia. Cilia are extremely delicate structures susceptible to various agents of water pollution. Because of their important functions and susceptibility to environmental insult, a detailed discussion of the roles cilia play in various phases of the quahog's life cycle follows.

The long cilia of the velum beat rhythmically and produce water currents. This action filters food from the water by bringing phytoplankton into contact with a mucus sheet. This sheet is passed on by shorter cilia to the mouth where the food enters for the processes of digestion and assimilation.

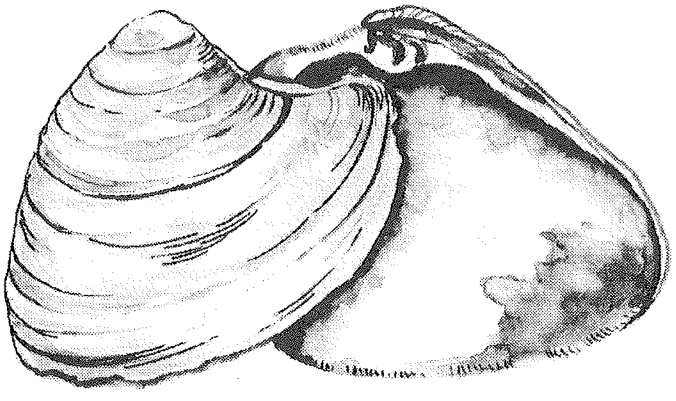

FIGURE 4.3
Shells of the quahog, Mercenaria mercenaria. *Drawing by Caroline Goldstein.*

Although the veliger is truly planktonic, the beating cilia of the velum also function in locomotion. By altering the rhythm of beating cilia, the veliger can adjust its depth in the water column as it searches for the appropriate temperature, salinity, light level, etc. It may remain in the water column for two weeks and experience different microenvironments of varying salinity and quality. During this time it may drift considerable distances from the place it was spawned.

METAMORPHOSIS

During the planktonic phase, growing mantle tissue forms a shroud around the veliger in the form of bivalve shells. Further growth increases the weight of the veliger until it can no longer maintain its position in the water column. It settles to the bottom, alternately swimming and then creeping along on the substrate.

Eventually, metamorphosis is completed by the shedding of the velum. The young quahog then propels itself along the bottom with its strong, recently developed protractile foot. At this stage it is about 200 microns (0.008 inch) in length and it can still get swept along by tides. With the loss of the velum, feeding is now accomplished by cilia on the surface of sheet gills in the newly formed mantle cavity. Cilia move water from the incurrent siphon to the gills, possibly at a rate proportional to the quahog's requirement for oxygen (Hamwi and Haskin 1969; Van Winkle 1975). At the gills a complex arrangement of cilia filter out waterborne food particles. These are subsequently entangled in a mucus layer and passed to a food groove leading to the labial palps surrounding the mouth. Particles too large or heavy are sorted by various ciliated mechanisms and are not passed on to the food groove. They are eventually ejected from the mantle cavity.

The outer surface of the mantle has now become covered by a smooth calcareous shell which thickens and protects the young quahog. Glandular secretions of byssal threads temporarily anchor the young quahog to the substrate. It alternates crawling for short distances with periods of byssal attachment to sand grains or other surfaces. This period of benthic excursions is brief. After mantle tissue has fused into functional siphons, the quahog ceases to produce byssal threads and begins to burrow into the sediments by periodically extending and expanding its muscular foot. Whereas it once maintained its position on the surface by its byssus, it now has developed ridges on its newly formed shell and these enhance its ability to remain lodged in the sediment. It is now about 9 mm (0.35 inch) long.

ENVIRONMENTAL REQUIREMENTS

The quahog is dioecious (separate sexes) and reaches sexual maturity in about three years. It is capable of adapting to broad ranges of DO (Walsh 1974)and salinity (Wells 1961). It can be found in virtually all parts of Waquoit Bay in all types of bottom including gravel, sand, and mud. Thus, quahog habitat may be difficult to define (Saila et al. 1967). But because fine sediments interfere with ciliary mechanisms, the quahog does not thrive in bottoms dominated by finer particles (Pratt 1953; Stickney and Stringer 1957).

GROWTH

Growth rates vary in different bottom types (Pratt 1953)and also in similar bottom types in different locations (R. Crawford, unpub. data). It has been reported that water movement, which influences a benthic organism's food supply, is a potent factor affecting shellfish growth (Ryther 1969). As noted above, growth is also affected by fine suspended sediments that interfere with ciliary selection of food particles (Rhoads and Young 1970).

Quahogs live 30 years or more (Hall 1979) and 20-year old quahogs are not uncommon even in heavily fished areas. Shuster (1971) reported a maximum size of 15.6 cm (6.125 inch long) at 1.1 kg (2.5 pounds) live weight and Bricelj (1979) found no evidence to suggest that egg production declines with increasing age. However, Bricelj (1979) did allow that smaller size classes probably contribute the larger proportion to total population fecundity because they are dominant in numbers.

BURROWING BEHAVIOR

Quahogs burrow in the sediments both vertically and horizontally (Ansell 1962). They can sometimes be found within a centimeter of the surface; occasionally they are partially or completely exposed. Most often, they are buried deeper. They have been recorded at depths to 9.2 cm (3.6 inches) (Ansell 1962), and it is commonly believed by local fishermen that quahogs burrow deeper in the winter than in the summer. Very dense beds of quahogs which have burrowed to various depths appear to be arranged in layers, one on top of the other (R. Crawford, pers. obs.). Quahogs also move along the surface of sediments, most frequently during their early development but occasionally later.

MORTALITY AND PREDATION

Perhaps only one out of 29 million eggs survives to become a legal size clam (Bricelj 1979). While predation can be considered to be responsible for only a portion of that loss, oyster drills, *Eupleura caudata*, *Urosalpinx cinerea*, and *Neopanope texana*, can be very destructive of young quahogs (Stickney and Stringer 1957). Other important predators include the horseshoe crab, *Limulus polyphemus*; blue crab, *Callinectes sapidus*; calico or lady crab, *Ovalipes ocellatus*; spider crab, *Libinia emarginata*; lobed moon shell, *Polynices duplicata*; channelled whelk, *Busycon canaliculatum*; "black-fingered" mud crabs, such as *Neopanopeus sayi*; the knobbed whelk, *B. carica*; and the common sea star, *Asterias forbesi*; all of which are common in Waquoit Bay.

Fish also prey on young quahogs. Winter flounder, *Pleuronectes americanus*, (Medcof and MacPhail 1952; Frame 1972), summer flounder, *Paralichthys dentatus*, and tautog, *Tautoga onitis* (MacKenzie 1977) are all known to include quahogs in their diet, and they too are common in Waquoit Bay. Other fishes such as the cunner, *Tautogolabrus adspersus*, are not as well studied but may also compete with people for a meal of this delicately flavored shellfish. Alteration of quahog predation may represent an area of significant potential in increasing natural production, (MacKenzie 1979a; 1979b; Carter et al. 1984). However, it is not known if it is practically and economically possible to alter the impact of predators by mechanical means.

Another avenue of unresolved research is the elucidation of a methodology for identifying the location of brood stocks within coastal waters. In some areas, a portion of the quahog population is protected from harvesting because of restrictions due to public health hazards (e.g. shellfish bed closures due to high fecal coliform counts). Conrad (1981) has suggested that these protected populations may contribute seed to heavily fished beds in clean waters and may constitute the major reason why many beds sustain a high level of exploitation without becoming more severely depleted.

Similarly, quahog fisheries may be sustained by beds occurring in gravel bars along the shore where the coarse substrate is difficult to dig. Gravel also protects quahogs from predators such as sea stars, crabs, and predatory snails. The same can be said of beds of large (i.e. commercially less desirable) quahogs in the open basins covered with seagrass or seaweed. These beds are less accessible because the water is deeper and the plants quickly foul a shellfisherman's rake, making fishing difficult. (Unfortunately, some fishermen uproot eelgrass to gain access to shellfish, a damaging and short-sighted practice.) The contribution of the quahog resources in these places to the overall health of a fishery is unknown but may be significant.

A practical methodology for identifying natural sources of quahog spat would be a powerful management tool for sustaining valuable quahog fisheries. Research in this area has valuable implications in issues of coastal zone management (e.g., shoreline alterations and boating impacts).

THE AMERICAN EEL

The American eel, *Anguilla rostrata,* is a remarkable fish (Fig. 4.4). Its complex life history remains incompletely understood despite nearly a century of investigation. Its life cycle is intricately linked between coastal waters, such as Waquoit Bay, inland ponds and streams, and offshore areas. Examining this relationship provides a good example of the significance of the connection between these realms.

The American eel is catadromous. This means that it reproduces in salt water but lives the preponderance of its life in fresh or brackish waters. Adult eels in Waquoit Bay waters are in the phase of growth known as the "yellow eel stage." Most are males. Females move inland up streams and creeks, seeking out freshwater ponds. Eels are very hardy and persistent. Female eels are known to travel through damp riverlets, where the water is barely sufficient to wet the leaves, in their struggle to gain the freshwater habitats.

In Waquoit Bay, eels forage among beds of algae and eelgrass to feed on small fish, mollusks, crustaceans, and worms. In the winter, these fish are inactive and bury themselves in muddy sediments, often in groups or "balls" near freshwater springs where the water is warmer.

As sexual maturity approaches, perhaps more than ten years after they arrived at the coast, eels enter a phase of life known as the silver eel stage. In addition to altering their color, they undergo several physical changes in preparation for a long swim back to the spawning grounds in the Atlantic Ocean. Their seaward journey apparently follows a path deep in the sea because their eyes develop characteristics typical of deep water fish.

The spawning ground of the American eel, and that of the closely related European eel, *Anguilla anguilla,* is between Puerto Rico and Bermuda, although no one knows precisely where. Spawning takes place perhaps 500 feet beneath the sea. It is assumed that silver eels die after spawning, although this aspect of their life cycle remains unclear (Bigelow and Schroeder 1953; Tesch 1977).

The eggs hatch in the spring. Eel larvae are fantastic, transparent, leaf-like creatures called leptocephali. These delicate shapes are easily carried northward by powerful currents of the Gulf Stream. Those that reach Waquoit Bay waters have been larvae for as long as two years. (European eel larvae develop more slowly; their journey may take six years as the Gulf Stream carries them on to Europe.)

Near the Continental Shelf, eel larvae metamorphose into transparent, eel-like forms called glass eels. As these swim toward shore, they develop into young eels or elvers. They enter estuaries and rivers such as those of Waquoit Bay and grow into adults (the yellow eel stage).

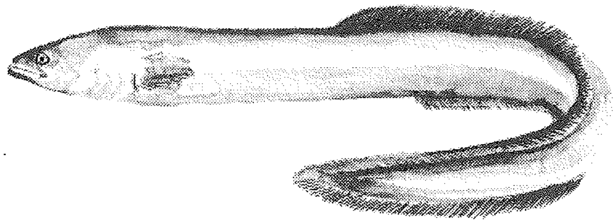

FIGURE 4.4
The American eel, Anguilla rostrata. *Drawing by Caroline Goldstein.*

COMMERCIAL FISHERY

The traditional method of capture is by eel pot, a conical or rectangular wire mesh trap that an eel enters through a funnel. The preferred bait in these waters is a large piece of freshly killed horseshoe crab. In some areas, a fisherman may have more than 200 pots, although most have 50 to 100. Each pot is on a separate buoy and is usually hauled and re-baited every one or two days (Crawford 1988).

Another method of harvest is by eel spear. During the winter, when eels are "balled up" in the mud, fishermen will repeatedly thrust a multi-tined spear into the bottom from a slowly moving boat or through holes in the ice, searching for concentrations of eels. This method has been practiced for centuries by native Americans, a tradition continued in Waquoit Bay.

Another device used for harvesting eels is the eel comb, a type of spear operated from a moving boat when eels are in the mud. The comb is mounted at the end of a pole and its dozen barbless teeth project from the side. To use the comb the operator holds the pole vertically from the aft section of a moving boat. The comb's teeth are maintained in the soft bottom, facing the direction of travel. A tether from the bow of the boat to the comb prevents it from being swept backwards out of the mud as the boat moves slowly along. When the device passes through a ball of eels, a number of them become impaled on or caught between the teeth. The fisherman then retrieves the comb and shakes the eels off. Eels are very hardy and although often wounded by this procedure, mortalities are uncommon (Crawford 1988).

Captured eels are often held in a submerged box or so-called "car" until an eel buyer arrives with a special tank truck for transporting them to a holding facility. Many eels from the bay have been shipped by air to Europe, where live eels command a premium price.

Only a few eels are taken by rod and reel in the recreational fishery and most of these are a by-catch of other fin fisheries. However, eels can be taken by spear at night. The usual practice is to tie a burlap sack containing a wounded horseshoe crab to the side of a boat slowly drifting over eelgrass beds. In darkness, the fisherman stands ready with a spear and an unlighted flashlight or lantern. As he periodically turns the light on the sack, he may see an eel investigating the scent of the crab. If he is quick and accurate with his spear he can soon land enough eels for a delightfully delicious meal or two (Crawford 1988).

PROSPECTS FOR THE FISHERY

The eel fishery in southern New England waters began to decline in the early 1980s. The principal cause for the decline lay within the market rather than the resource. The export value of eels declined while fishing expenses increased. Profits were small. Many fishermen dropped out of the fishery and it collapsed. Throughout there has continued to be sustained, albeit small, demand for eels on the domestic market generated primarily by local ethnic groups. Sport fishermen have also continued to buy eels as bait for other fishes. But today's fishery is much smaller than it was only a few years ago.

Should the economic situation change and market conditions become favorable again, there is apparently sufficient resource in the Bay and other local waters to sustain another successful fishery. The fishery of the 1970s had little apparent adverse impact on the resource. The European market demands an eel larger than 100 grams (about 1/4 lb) and local waters consistently produced a steady supply of suitably large eels for export (John Steiger, personal communication). Resources in other areas, such as Florida, were overfished and larger eels were less common. Although this didn't happen in southern New England, future eel landings should be carefully monitored to avoid over exploitation of the resource (Crawford 1988).

WINTER FLOUNDER

This description of the life habits of winter flounder inhabiting southern New England waters, such as Waquoit Bay, is condensed from Bigelow and Schroeder (1953), Klein-MacPhee (1978) and Crawford (Crawford 1990).

The winter flounder, *Pleuronectes americanus* (also known locally as blackback or simply "flounder"), is a distinctive species (Fig. 4.5). It is particularly adapted to cold water and has a special ability to withstand near-freezing temperatures. During winter months these fish produce an organic antifreeze compound similar to the glycoproteins found in certain species of Antarctic fish (Duman and deVries 1974). This antifreeze lowers the freezing point of the winter flounder's body fluids and allows it to live where it would not survive without this protection. (Throughout the remainder of this account, "flounder" will be used to refer to this fish.)

PREPARATION FOR SPAWNING SEASON

During September, as water temperatures cool, adult flounder return to the Bay from Vineyard Sound (and elsewhere) where they have spent the summer. Often the first arrivals are males, with females arriving in October. Flounder have an extremely flexible diet and the abundance and diversity of food organisms in the Bay puts large amounts of energy for growth readily at hand. During this period of active feeding, flounder are susceptible to fishermen's baited hooks. Many fish are taken by fishermen who cast off the rocks of the jetties at the connection of the Bay to the sea. More are taken within the Bay by fishermen in boats.

In December's cold waters, the fish cease feeding and spend an increasing amount of time inactive on soft sediments. They are no longer easy to catch and fishing activity ceases. During this period, life processes of the fish are sustained by energy reserves stored in their tissues. Although the fish are not feeding, winter is the breeding season for this cold water species. Their gonads continue to develop in preparation for this event.

Beneath the frozen surface of the Bay, approximately one-half million eggs in each large sexually mature female winter flounder develop into tiny spheres about 0.6 mm (0.02 inch) in diameter. During the same time the bellies of males become distended from the swelling of a maturing milt sac. By mid-February, gonads in both sexes are fully developed.

SPAWNING AND EARLY LIFE HISTORY

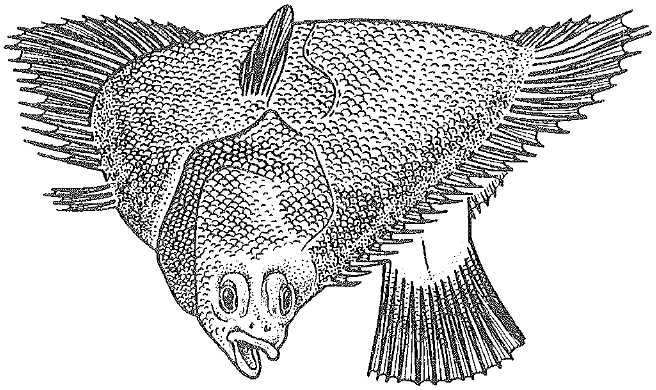

FIGURE 4.5

Winter flounder, Pleuronectes americanus. *Drawing by Robert Golder.*

Spawning occurs in specific areas within the Bay. Perhaps the most important criterion is the rate of tidal flushing in the area. The quiet water of "Tims Pond" on Washburn Island is one such spawning area. Spawning usually takes place in late February and in March, over hard substrate (gravel or sand) or eelgrass. Spawning is thought to occur at night. Unlike those of most other flatfishes, winter flounder eggs sink to the bottom rather than float near the surface. The sticky eggs clump together on whatever surface they may land. Eggs that fall into soft, fine sediments or into an algal mat are probably less likely to develop due to poor water circulation which results in a lack of oxygen for the embryo.

The eggs hatch in about two or three weeks, when water temperatures are typically 3-5°C (37-41°)F. Newly hatched larvae are only about 3.2 mm (0.13 inch) long. They drift in the plankton for about a month (Fig. 4.6). At first they are upright with an eye on either side of the body as in other fishes. About four weeks after hatching, when they are about 6 mm (0.23 inch) long, there is loss of pigment on the left side of the body and differential growth of tissues results in the left eye migrating to the right side of the head. The fish now become horizontally oriented as a flatfish and they assume bottom dwelling habits. By the end of their second month, they resemble the adult form.

During this time the post-spawning adults resume feeding. The warming water stimulates the growth of food organisms and the fish rapidly restore their body tissues on the abundance of readily available energy. Winter flounder adults are not tolerant of warmer waters. Summer water temperatures in shallower areas of Waquoit Bay can be lethal to these fish. By May and June, many of these fattened fish leave the Bay and return to the cool summer waters of Vineyard and Nantucket sounds where they continue to grow. There they are once again vulnerable to commercial fishering and many are captured in the nets of draggers.

Because juvenile winter flounder are more tolerant of higher temperatures, they may remain in the Bay throughout their first year or two. However, during the summer they can survive only in the cooler, well flushed waters of the deeper channels. The young flounder leave Tims Pond for the cooler waters of the Bay.

Although young winter flounder can tolerate moderately high temperatures, they have less flexible requirements for dissolved oxygen concentrations. Occasionally, the dissolved oxygen dips to levels below the minimum requirements of these fish. When the percent of saturation in the Bay waters is insufficient for their needs, the young fish will aggregate near the shoreline where atmospheric mixing within breaking wavelets creates a microenvironment of slightly elevated oxygen concentrations. If conditions worsen, the fish can be seen with their heads "bobbing" as they gulp water from the air/water interface (i.e., the water's surface). Again they are seeking slightly higher oxygen levels in the microenvironment of this region. Unfortunately,

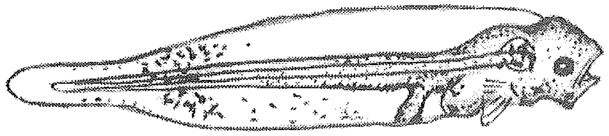

FIGURE 4.6
Larval winter flounder Pleuronectes americanus *at 13 days. Drawing by Caroline Goldstein.*

when conditions get this bad, fish will often die (suffocate). During major events, strand lines of numerous dead fish will form along the shore. In this way, the subtle effects of eutrophication will seriously degrade the quality of an area as nursery habitat for juvenile fishes. Such is the case for conditions in Waquoit Bay in the 1990s.

By September, young flounder that survive the summer are a few inches long. They continue their rapid growth until cold waters diminish their activity for the winter. Also in September, the first adults return from their offshore summer grounds, their gonads already developing in preparation for the upcoming breeding season. With very few exceptions, these fish return to the same water body in which they spawned in previous years (Perlmutter 1947; Saila 1962; Crawford 1984). These fish also appear to return to specific feeding areas within the water body. It is probable that subpopulations of flounder aggregate in a feeding area prior to utilizing a specific spawning area (Crawford 1984).

Saucerman and Deegan (1991) found that juvenile winter flounder also remained in small, discrete areas within Waquoit Bay. Similar results have been observed for juveniles and adult fish elsewhere (Grove 1982; Worobec 1982; Crawford 1984). Although apparent temporary fall emigrations from a coastal pond into the ocean remain unexplained (Worobec 1982), the body of evidence indicates that winter flounder remain within specific areas within a bay to feed and breed.

Eutrophication in Waquoit Bay is also altering spawning habitat for the winter flounder. This too is a subtle but important change, with serious implications for the sustainability of the resource. For many years it was generally assumed that flounder spawn in "the shallows," over seagrass beds or over firm bottom (Bigelow and Schroeder 1953). More recent information discloses that there are additional criteria for defining a suitable winter flounder spawning area.

An examination of larval distribution in salt ponds (Crawford and Carey 1985) revealed that winter flounder larvae that hatched in poorly flushed areas (i.e. those hydrodynamically "distant" from a breachway) would be less likely to be flushed out to sea during their one-month period of planktonic larval development. Young flounder in these backwaters were retained within an area where there is an abundance of food and habitat for their development. Larvae hatched from eggs deposited in tidally flushed areas would be swept out to sea where their survival is thought to be greatly diminished. By spawning in areas of Waquoit Bay that are minimally flushed by tides (e.g., Tims Pond), the hydrodynamics of the system are exploited to help ensure that fish larvae are retained long enough for adequate growth and development.

Unfortunately, the low flushing characteristics that make an area good spawning habitat may serve to facilitate changes deleterious to egg survival. As noted above, the eelgrass habitat in Waquoit Bay waters (including Tims Pond) is disappearing and seaweeds are becoming more abundant. Because drifting mats of seaweed decrease dissolved oxygen in the near-bottom environment (Valiela et al. 1992), increasing seaweed abundance is likely to be deleterious to winter flounder eggs.

WINTER FLOUNDER FISHERIES

Prior to the existence of permanent breachways and channels into Waquoit Bay, winter flounder could enter only when the barrier beach had been breached, whether through natural events or by plow and shovel. These early unstabilized channels were sometimes broad and deep. But more frequently they were shallow enough for flounder to be easily speared by native Americans and later by European settlers. Today, flounder are taken by hook and line in a very popular recreational fishery.

Flounder landings have been in general decline throughout the northwest Atlantic and new regulations are directed at this popular fishery. In 1994, Massachusetts recreational winter flounder fishery regulations imposed a minimum length of 12 inches, a 10 fish daily catch limit, and a fishing season from May 1 – February 28. These regulations are intended to help the resource recover from previous overexploitation by both the commercial and recreational sectors.

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CHAPTER V

ESTUARINE ECOSYSTEM FUNCTIONING

IN RESPONSE TO URBAN DEVELOPMENT

Urbanization of the Waquoit Bay watershed. WBNERR archives, photographer unknown.

INTRODUCTION

In recent years, the ecology of Waquoit Bay and its surroundings has changed. Although ecosystems change in response to environmental conditions, many of the more dramatic changes observed in recent decades are the result of human activities in Waquoit Bay's watershed.

Historically, humans have settled near waterways to facilitate travel and commerce and have used coastal waters as a source of food. As leisure time has increased and commuting has become more widespread, more and more people have moved to coastal areas. Between the years 1960 and 2010, the population of coastal counties in the United States is projected to grow from 80 to 127 million people (Culliton et al. 1990). Coastal counties in Massachusetts reflect this national trend. Indeed, Barnstable County, where Waquoit Bay is located, is one of the fastest growing counties in the northeast (Table 5. 1) (Culliton et al. 1990).

The growth of populations along the coast brings about an increase in the delivery of nitrogen (from atmospheric deposition, fertilizers, and septic systems) to nearshore waters. Nitrogen is generally considered the limiting nutrient in most coastal ecosystems (Ryther and Dunstan 1971),so increasing the supply of nitrogen fuels the growth of primary producers. Increased nutrient-loading from coastal watersheds has rendered coastal ecosystems among the most fertilized in the world, often superseding agricultural systems in their nutrient loads (Nixon et al. 1986).

Along with residential development comes an increase in the recreational use of coastal waters. The numbers of boats, marinas and boat docks have increased dramatically in recent decades. Potential impacts of boating are only beginning to be understood and are a topic of concern at the Waquoit Bay Reserve.

Like many shallow coastal embayments, the Waquoit Bay estuarine complex shows many common signs of an increased supply of nitrogen—decreased water clarity, overgrowth of phytoplankton and seaweeds at the expense of seagrasses, decreased dissolved oxygen in bottom waters, increasing incidence of fish kills and changes in benthic community composition (Valiela et al. 1992). Where eelgrass meadows once flourished, covering the bottom of the Bay and its tributaries and adjacent ponds, there is now bare sediment or mats of opportunistic macroalgae (Costa 1988; Short and Burdick 1996). As eelgrass has declined, the distribution and abundance of other estuarine organisms have changed. These changes in the estuary are related to the changes in land use in the adjacent watershed of Waquoit Bay.

Table 5.1 Leading Counties in Population Change in Northeastern United States (after Culliton 1990.)

County	**Population Change, 1988-2010** (1,000 Persons)	County	**Percent Population Change,** 1988-2010	County	**Population per Square Mile (1,000 Persons)**
Suffolk, NY	225	Spotsylvania, VA	49	NewYork, NY	71
Fairfax, VA	210	**Barnstable, MA**	**48**	Kings, NY	33
Middlesex, MA	144	Charles, MD	43	Bronx, NY	27
Ocean, NJ	124	Dukes, MA	43	Queens, NY	19
Queens, NY	118	Calvert, MD	42	Suffolk, MA	12
Plymouth, MA	114	Falls Church, VA	40	Philadelphia, PA	12
Virginia Beach, VA	105	Rockingham, NH	39	Hudson, NJ	12
Anne Arundel, MD	93	Fredericksburg, VA	34	District of Columbia	11
Rockingham, NH	92	Nantucket, MA	33	Baltimore City, MD	9
Fairfield, CT	91	Gloucester, VA	33	Richmond, NY	8
New Haven, CT	89	Prince William, VA	33	Alexandria, VA	8
Bristol, MA	88	Stafford, VA	33	Essex, NJ	7
Barnstable, MA	**86**	King George, VA	31	Falls Church, VA	7
Bucks, PA	85	Ocean, NJ	30	Arlington, VA	7
Essex, MA	82	Chesterfield, VA	30	Norfolk, VA	6

Land Use Changes in the Waquoit Bay Watershed

The distribution of houses in the Waquoit Bay watershed reflects the national preference for living near the coast, with higher housing density closer to the shore (Fig. 5.1). Like most of Cape Cod, the Waquoit Bay watershed now is suburban to rural; its population has increased fifteen-fold in the past half century (Sham et al. 1995). The watershed covers more than 5,300 hectares (13,000 acres) and there are now more than 8,000 residents and more than 4,000 housing units within the watershed (Sham et al. 1995).

The Waquoit Bay Land Margin Ecosystem Research Project

Waquoit Bay and its watershed have been the study site for a Land Margin Ecosystem Research (LMER) project, a multi-disciplinary, multi-institutional research program that examines the effects of land use in coastal watersheds on the ecology of the adjacent estuarine waters (Valiela et al. 1990; Valiela et al. 1992). The LMER project in Waquoit Bay takes advantage of the fact that there are subwatersheds within the Waquoit Bay drainage basin (Cambareri et al. 1992; Brawley and Sham in prep.) (Fig. 2.11) that have experienced different rates of development and have different housing densities. For example, the Childs River subwatershed has 1.7 houses ha^{-1}, the Quashnet River (including the Moonakis River Reach) subwatershed has 0.3 houses ha^{-1}, and the Sage Lot Pond subwatershed has 0.09 houses ha^{-1} (Valiela et al. 1992). The differential development of the subwatersheds results in different rates of nitrogen-loading to the Bay (Valiela et al. 1992).

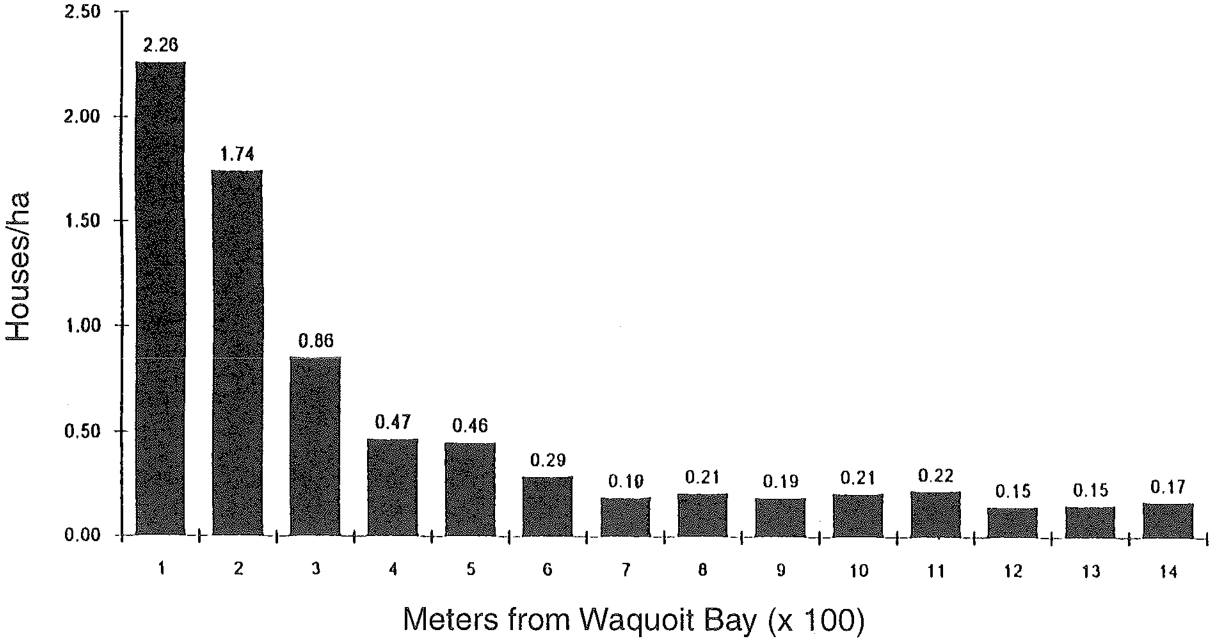

FIGURE 5.1

Houses in the Waquoit Bay watershed reflect the national trend of greater density close to the shore (WBLMER, unpublished data).

NITROGEN CONCENTRATIONS IN GROUNDWATER

Because Cape Cod is underlain by sandy, porous soils, groundwater is a major conduit of nitrogen from anthropogenic sources to shallow embayments (Giblin and Gaines 1990; Valiela et al. 1990; Valiela et al. 1992) and we expect to see the increased supply of nutrients from urbanization reflected in groundwater concentrations of nitrogen. In fact, groundwater concentrations of nitrate-nitrogen in private wells on Cape Cod are higher in areas with greater building densities (Fig 5.2) (Persky 1986). This relationship is seen also in the Waquoit Bay watershed where groundwater nitrogen concentrations are higher beneath the densely developed Childs River subwatershed than in groundwater beneath the Quashnet River and Sage Lot Pond watersheds (Fig. 5.3) (Valiela et al. 1992) .

MODELING NITROGEN-LOADING TO COASTAL WATERS

Using information about the size of the watershed, land use patterns within it, and nitrogen-loading coefficients associated with particular land uses, modelers can sum all inputs of nitrogen and water to a watershed and subtract the losses of nitrogen, which yields an estimate for the concentration of nitrogen or a mass load of nitrogen that enters a water body. This estimate, in combination with measurements of nitrogen in groundwater, and with studies of ecosystem metabolism and the physical attributes of an embayment—such as flushing rate—can be used to estimate how much nitrogen an embayment can assimilate without accelerating the rate of eutrophication. That knowledge can be used by coastal zone managers to set nutrient-loading limits for embayments.

There has been a lot of interest in nutrient-loading models on Cape Cod and several have been developed within

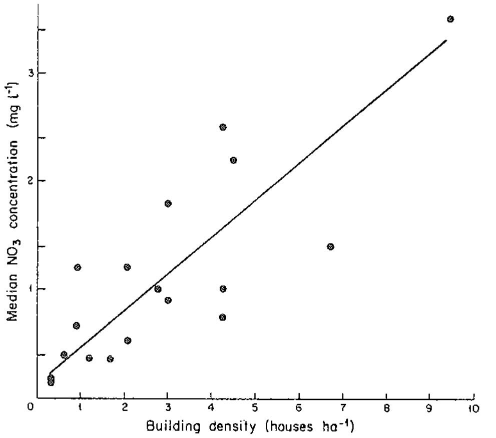

FIGURE 5.2
Median nitrate (NO_3^-) concentrations in groundwater beneath areas of Cape Cod with different building densities (Persky 1986).

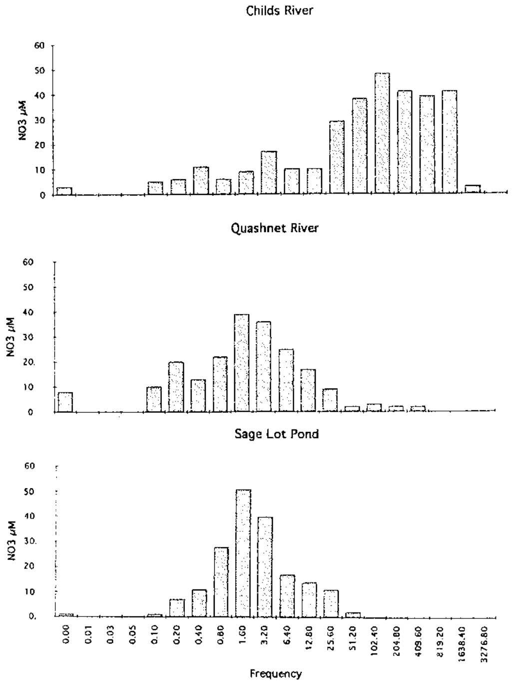

FIGURE 5.3
Groundwater measurements of nitrate are directly related to degree of development in Childs River, Quashnet River and Sage Lot subwatersheds (WBLMER unpublished data).

the past decade (Frimpter et al. 1988; Valiela and Costa 1988; Weiskel and Howes 1991; Costa et al. 1992; Eichner and Cambareri 1992; Valiela et al. in press) and some have become part of regional plans (Costa et al. 1992; Eichner and Cambareri 1992). Nitrogen-loading models under evaluation or use on Cape Cod differ in assumptions and parameters, particularly with regard to the inclusion of atmospheric deposition (wet and dry deposition, including contributions from dissolved organic nitrogen); the importance of losses of nitrogen in septic system plumes and the aquifer; and the effects of travel time of groundwater. The WBLMER project has been reevaluating assumptions underlying nitrogen-loading models and has proposed modifications to existing models (Sham et al. 1995; Valiela et al. in press; Collins et al. submitted b).

SOURCES AND TRANSPORT OF NITROGEN IN THE WAQUOIT BAY DRAINAGE BASIN

To estimate the amount of nitrogen reaching Waquoit Bay, the WBLMER project has used information from studies in the watershed and the literature to evaluate nitrogen inputs to the watershed from atmospheric deposition, fertilizer use and on-site wastewater treatment systems, and to estimate nitrogen losses during travel in soils, subsoils, wastewater plumes and the aquifer (Valiela et al. in press).

Atmospheric Deposition

Studies from the Waquoit Bay watershed and nearby Great Sippewissett Marsh suggest that atmospheric deposition delivers about 15 kg of total dissolved nitrogen (TDN) hectare^{-1} (13 lbs acre^{-1}), about half of which is dissolved organic nitrogen (DON), to the upper Cape Cod area (Lajtha et al. 1995; Valiela et al. in press). In forests of the Waquoit Bay watershed, approximately 65% of the TDN is retained by the forest vegetation and soils (Lajtha et al. 1995), in contrast to inland forests (Bormann et al. 1977; Aber et al. 1993) where there is 80–90% retention of atmospheric nitrogen. The lower retention in Cape Cod forests may be a function of the porous soils that promote rapid percolation of precipitation into the soil carrying along with it nitrogen from wet and dry deposition.

Although the age of a forest can affect the amount of nitrogen stored by a forest system, results in Waquoit

Bay drainage basin forests revealed no significant differences with age of the forest (Lajtha et al. 1995). Of greater importance were seasonal differences in uptake. During the growing season, forests retained nitrogen; in fall and winter, throughput of nitrogen to groundwater equaled inputs of nitrogen from the atmosphere. Large storms can also change the throughput of nitrogen (Lajtha et al. 1995; Valiela et al. 1996).

Fertilizer Inputs To The Waquoit Bay Watershed

In the Waquoit Bay watershed, land use is primarily residential; cranberry bogs and cropland comprise less than 4% of the land use (WBLMER unpublished data). A survey on Cape Cod showed that about 34% of the households use fertilizers (A. Giblin, Marine Biological Laboratory, pers. comm.) Fertilizer application rates on Cape Cod ranged from 49 kg ha $^{-1}$ (about 43 lb acre^{-1}) in an Orleans, Massachusetts, study (Giblin and Gaines 1990) to 147 kg ha^{-1} (about 130 lbs acre^{-1}) for a Buzzards Bay embayment (Nelson et al. 1988). Of nitrogen applied as fertilizer, Petrovic's review of the literature (1990) reported that about 40% is lost to volatilization and denitrification. In the Waquoit Bay watershed, cranberry bogs are the only large-scale agriculture ventures and their contribution to nitrogen-loading to receiving waters is small (about 13 kg ha^{-1} or 14 lbs acre^{-1}) (Teal and Howes 1995).

On-Site Septic Systems As Source Of Nitrogen

There are no centralized sewage treatment facilities in the Waquoit Bay watershed. Instead each house has an on-site septic system, consisting of a holding tank and leaching pit or field, or in the case of some older homes, a cesspool. To estimate the nitrogen load from on-site septic systems, the per capita contribution of nitrogen is needed. Reviews of the literature suggest that on an annual basis each person contributes about 3–5 kilograms (6.6–11 lbs) of nitrogen (Buzzards Bay Project 1991; Valiela et al. in press). The efficiency of individual septic systems installed in sandy soils such as those found on Cape Cod varies from 10–90%, with a mean of 46% (Valiela et al. in press).

Nitrogen Losses in Transport To Coastal Embayments

As nitrogen from atmospheric deposition, fertilizers and septic systems travels through unsaturated soils and the aquifer to the receiving body of water, some of the nitrogen is lost through various processes—volatilization, uptake, adsorption, denitrification— depending on the travel pathway. Nitrogen delivered via atmospheric deposition or as fertilizer seeps through the surface to subsoils and the aquifer. Nitrogen from septic systems is inserted beneath the surface and exits leach fields in distinct wastewater plumes; it then travels in diffuse form in the aquifer. The presence of large ponds that intercept the aquifer can result in additional losses of nitrogen during travel to a receiving embayment (Valiela et al. in press). In the Waquoit Bay watershed, Ashumet and Johns ponds are relatively deep in relation to the depth of the aquifer (Fig 2. 18). Studies from many areas show that freshwater ponds intercept an average of 44% of the entering nitrogen, thus decreasing the amount of nitrogen continuing through the aquifer to the coastal embayment (Valiela et al. in press).

STEADY-STATE MODELS

A steady-state mathematical model developed by the WBLMER project sums nitrogen additions from atmospheric deposition, fertilizers and septic systems and subtracts nitrogen as it travels through vadose zones, wastewater plumes and the aquifer (Table 5.2). The model shows that the relative amount of nitrogen that arrives at the estuary from a particular source is not indicative of the relative amount of nitrogen delivered to

Table 5.2 The nitrogen loading algorithm proposed by the Waquoit Bay Land Margin Ecosystem Research Project (Valiela et al. in press).

N TO AND THROUGH WATERSHED SURFACES (kg N y^{-1}) via

Atmospheric deposition to:

Natural vegetation: [1]: atmospheric deposition (kg N ha^{-2} y^{-1}) x area (ha) of naturally vegetated land x 35% not retained in plants and soil

Turf [2]: atmospheric deposition (kg N ha^{-2} y^{-1}) x area (ha) of turf x 38% not retained in plants and soil

Agricultural land [3]: atmospheric deposition (kg N ha^{-2} y^{-1}) x area (ha) of agricultural land x 38% not retained in plants and soil

Impervious surfaces [4]: { [atmospheric deposition (kg N ha^{-2} y^{-1}) x area of roofs+driveways (ha^{-2})] x 38% not retained in plants and soil} + [atmospheric deposition (kg N ha^{-2} y^{-1}) x area of roads+runways+commercial]

Fertilizer application to:

Turf: [5]: fertilizer application rate[a] (kg N ha^{-2} y^{-1}) x area (ha) of lawns x 34% of houses fertilizing lawns x 61% not lost as gases

Agricultural land [6]: [crop fertilization rate[b] x area (ha) under cultivation x 61% not lost as gases] - nitrogen removed as crop

N TO AND THROUGH VADOSE ZONE AND AQUIFER (kg N y^{-1}) via:

Nitrogen percolating diffusely from watershed surface [7]: [sum of items 1-6] x 39% not lost in vadose zone x 65% not lost in aquifer

Wastewater from septic systems[c] [8] calculated as N released per person y^{-1} x people/house x No. houses x 60% not lost in septic tanks and leaching fields x 66% not lost in plumes x 65% not lost in aquifer

NITROGEN LOADING TO ESTUARY (kg N y^{-1}) sum of items 7 + 8.

[a] 136 kg N ha^{-2} y^{1} for landscapes with low intensity agriculture and with mixed crops. For intensive agriculture, values for specific crops are available (Loher 1974, Stanley 1988, Frimpter et al. 1988, Hayes et al. 1990, Correll et al. 1992).

[b] This term is appropriate where crops are not consumed within the watersheds. In watersheds with intensive export agriculture, harvest loss should be subtracted.

[c] Assuming conventional design. Where wastewater disposal is via cesspools (9% of the houses in the Waquoit Bay watershed, for example) the calculation for loading by cesspools is the same as for septic systems, except that losses in leaching fields are omitted.

the watershed from that source. For example, the WBLMER model estimates that more nitrogen is delivered to the Waquoit Bay watershed from atmospheric deposition (42%) than from on-site septic systems (28%) but relatively more nitrogen from septic systems (47%) reaches the estuary than from atmospheric deposition (29%) (Valiela et al. in press). About 90% of atmospherically-derived nitrogen is intercepted before reaching the estuary, whereas about 67% of septic system nitrogen is intercepted during travel (Table 5.3) (Valiela et al. in press).

Other steady-state models in use on Cape Cod (Frimpter et al. 1988; Nelson et al. 1988; Buzzards Bay Project 1991; Eichner and Cambareri 1992) would result in higher estimates of nitrogen loading if applied to Waquoit Bay because they use different variables and parameters. For example, these models weight

Table 5.3 Estimates of nitrogen loading (kg N y-1) from atmospheric deposition, fertilizer and wastewater to Waquoit Bay and losses during transport through different land covers (Valiela et al. in press).

Source of nitrogen	Nitrogen input to watershed	% of N load to watershed	% of nitrogen input lost within watershed	Total N input to Waquoit Bay	% of N load to estuary
Atmospheric deposition to					
Natural vegetation	47,036	42	91	4,447	20
Turf	9,934	9	90	957	4
Cranberry bogs	1,713	1.5	90	165	0.8
Other agric. land	90	0.08	90	9	0.04
Roofs and driveways	625	0.5	90	60	.3
Roads, runw., comm.	1,685	1.5	75	429	1.9
Ponds[a]	894	0.8	56	394	1.8
Total atm. deposit.	**61,977**	**55**	**90**	**6,460**	**29**
Fertilizer used on					
Lawns	7,019	6	84	1,095	5
Golf courses	5,889	5	84	918	4
Cranberry bogs	3,198	3	54	1,485	6.8
Other agric. land	816	0.7	84	127	0.6
Total fertilizer	**16,922**	**15**	**78**	**3,625**	**16**
Wastewater	**31,323**	**28**	**67**	**10,241**	**47**
Ponds upgradient[b]	**2,574**	**2**	**35**	**1,673**	**7**
Grand total	**112,797**	**100**	**81**	**22,000**	**99**

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[a] This refers to direct atmospheric deposition on ponds.

[b] This is an import from larger ponds or lakes that are deep enough to intercept the flow through the aquifer. Nitrogen additions to the watersheds upgradient of the ponds total 25,261 kg y^{-1} (atmospheric deposition: 15,264 kg y^{-1}; wastewater: 3,621 kg y^{-1}; fertilizers: 6,376 kg y^{-1}). Ninety percent of this nitrogen is lost during travel to and within the ponds. The nitrogen that passes through ponds is then subject to 35% interception in the downgradient aquifer.

nitrogen contributions from impervious surfaces more heavily than those to pervious surfaces, and exclude losses of nitrogen in vadose zones, the aquifer, or in wastewater plumes.

GROUNDWATER TRAVEL-TIME CONSIDERATIONS

As part of the WBLMER project, Sham et al. (1995) developed a travel-time model of nitrogen-loading from septic systems. The model showed that nitrogen loading to Waquoit Bay lags behind the rate of development by almost a decade due to the time of travel of groundwater, about 0.3–1 meter yr^{-1} (1 – 3 feet yr^{-1}) (Sham et al. 1995). As Figure 5. 4 shows, even if residential development had ceased in 1989, the amount of nitrogen arriving at Waquoit Bay would continue to increase for more than 100 years (Sham et al. 1995).

Expanding the travel-time approach, Collins et al. (submitted b) incorporated nitrogen inputs from atmospheric deposition and fertilizers as well as septic systems into a travel-time model of the Childs River and Quashnet River subwatersheds and compared the output to the steady-state WBLMER model. The results showed the steady-state model underestimated the time-dependent predictions by 10–15 % (Collins et al. submitted b). Differences between steady-state and time-dependent models depend on the total length of groundwater travel time in the watershed; the types of land use in the watershed, with their attendent nitrogen-loading coefficients; the rate of change in land use; and the proportion of change occurring far from the estuary (Collins et al. submitted b).

The difference of 10–15 % between the steady-state and time-dependent estimates of nitrogen-loading to the Childs and Quashnet rivers must be analyzed in light of the larger uncertainty associated with estimates of nitrogen loading that stems from the uncertainty in the variables used in the calculations. Using parametric and non-parametric methods to assess the uncertainty in loading rates, Collins et al. (submitted a) found that the standard deviation of the estimate of nitrogen loading to Waquoit Bay was about 38% of the loading rate. As more research is done, some of the disparities among models will likely be reduced, as will some of the uncertainty surrounding the nitrogen-loading variables.

THE USE OF STABLE ISOTOPE SIGNATURES TO IDENTIFY SOURCES OF NITROGEN

The use of stable isotope signatures to identify nitrogen sources may help to decrease the uncertainty associated

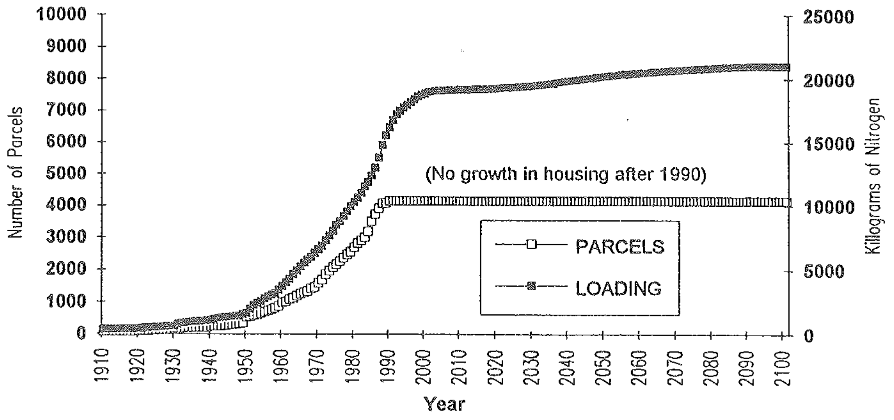

FIGURE 5.4

Growth in residential housing in relation to increased nitrogen loading to the estuary. Nitrogen loading lags development due to the slow travel time of groundwater (Sham et al. 1995).

with coefficients used in nitrogen loading models. Wastewater nitrogen has a higher stable isotope ratio than nitrogen from atmospheric deposition or fertilizer. Results from the WBLMER project that show elevated nitrogen isotope ratios in Childs River compared from Sage Lot Pond presumably reflect the larger amounts of wastewater nitrogen entering the Childs River subestuary from its densely developed subwatershed (McClelland et al. submitted).

ECOLOGICAL EFFECTS OF INCREASED NITROGEN-LOADING

As increasing amounts of nitrogen from human developments have entered coastal waters, the functioning of the estuarine ecosystem has been altered. Discussed in the following sections is research at Waquoit Bay that has linked differences in the development of adjacent lands to ecological effects observed in various parts of the Waquoit Bay estuarine system.

PRIMARY PRODUCTION

Primary producers in the waters of the Waquoit Bay estuarine complex include macroalgae (generally detached seaweeds), phytoplankton, epiphytes and the flowering plant, eelgrass *(Zostera marina)*. Macroalgae and phytoplankton now dominate primary production in much of the system.

Much is known about the physiology and production of a few opportunistic macroalgal species that have flourished, especially in the more enriched parts of the Waquoit Bay ecosystem. Of the phytoplankton, studies of chlorophyll *a* concentration and production have been on-going for a few years; less is known about species composition. Epiphytes have not been studied as to species composition or productivity. Studies of eelgrass distribution, growth rates and biomass in different parts of the Waquoit Bay estuarine complex have been undertaken by Costa (1988) (Fig 3.4), Short et al. (1993), Short and Burdick (Fig 3.5) (1996) and by researchers in the Waquoit Bay Land Margin Ecosystem Research Project (Valiela et al. 1992).

Phytoplankton

Phytoplankton production in Waquoit Bay waters exhibited distinct annual cycles with peak production in August in Childs River, Quashnet River and Sage Lot Pond (Fig. 5.5) (Kenneth Foreman, WBLMER, unpublished data), as opposed to the spring bloom peaks commonly observed in temperate estuarine waters. Phytoplankton production was directly related to the degree of development and thus

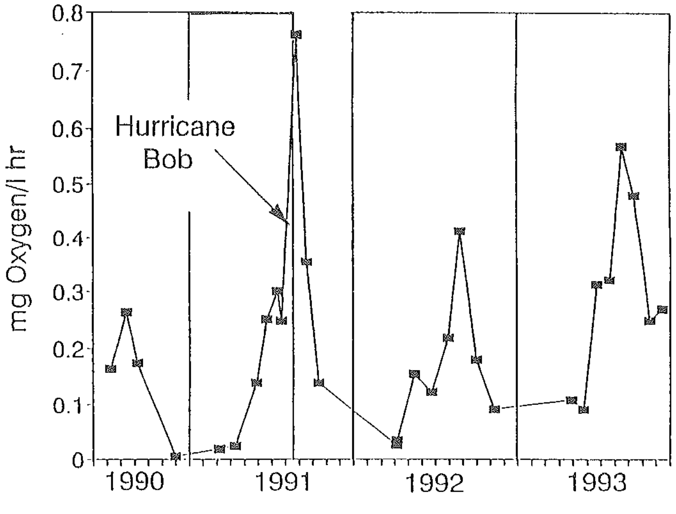

FIGURE 5.5
Phytoplankton production in subwatersheds of Waquoit Bay. Note the spike associated with nutrient resuspension from Hurricane Bob and the increase in phytoplankton production over the years of the study. (Data of Kenneth Foreman, WBLMER and Marine Biological Laboratory.)

Table 5.4 Average net annual phytoplankton production in Waquoit Bay estuaries subject to different nitrogen loadings from their adjacent watersheds. Production is measured as the amount of oxygen evolved from photosynthesis that was not used by consumers. Data of Kenneth Foreman, WBLMER and Marine Biological Laboratory.

Estuary	Degree of Development	grams oxygen meter^{-1} year^{-1}
Childs River	high	820
Quashnet River	medium	249
Sage Lot Pond	low	177

the amount of nutrient-loading from the adjacent subwatershed (Table 5.4). As is evident in the increasing heights of the peaks seen in Figure 5.5, phytoplankton production in Waquoit Bay waters increased from 1990–1993, unlike macroalgal production as will be discussed below.

Storm events that overturn stratified waters and mix nitrogen into the water column affect phytoplankton production. Figure 5.5 shows a spike in phytoplankton production following Hurricane Bob which struck Cape Cod in August of 1991 (Valiela et al. 1996).

The response of primary producers to nutrient enrichment is further modified by the hydrographic patterns in an estuary. The shorter residence time—the average time a parcel of freshwater remains in the estuary—in the Quashnet River (0.5 days) compared to the Childs River (2.5 days) (Geyer in press) means nitrate-laden groundwater is not available for uptake as long in the Quashnet River as it is in the Childs River. In addition, phytoplankton are flushed out of the Quashnet River more quickly than from the Childs River.

Macroalgae

Today, thick layers of macroalgae, mainly *Cladophora vagabunda* (L.) van den Hoek, a green alga, and *Gracilaria tikvahiae* (McLachlan), a red alga, cover the bottom of the more eutrophic parts of the Waquoit Bay estuarine complex. These algae aggregate in large mats up to 75 cm, or a little less than 3 feet (Peckol and DeMeo-Anderson 1992). The mats rest on or float above the bottom, effectively shading the benthic environment. Presumably, *G. tikvahiae* is a relative newcomer to the waters of the Bay; its presence was not noted in a survey in the late 1960s (Curley et al. 1971). Nor was *G. tikvahiae* among the species noted in a 1949 survey of some of Rhode Island's salt ponds (Lee and Olson 1985).

Gracilaria tikvahiae and *Cladophora vagabunda* are opportunistic macroalgal species, whose physiological make-up permits adaptation to changing environmental parameters. Both species have large geographic ranges illustrating their ability to flourish under different temperature and light regimes (Schneider and Searles 1991). They also have been shown to possess mechanisms to take advantage of an increased nutrient supply, including increased nitrogen uptake rates and the ability to store excess nitrogen (Gordon et al. 1981; Ryther et al. 1981; Lapointe and Duke 1984).

A comparison of benthic primary producers between the nutrient-enriched Childs River subestuary and the relatively pristine Sage Lot Pond subestuary revealed differences in biomass and species composition (Hauxwell et al. in prep). In the Childs River, mean summertime biomass of Cladophora *vagabunda* was 5 times higher than that of *Gracilaria tikvahiae*; the eelgrass, *Zostera marina*, was not present at all (Fig. 5. 6 and Table 5.5). By contrast, in Sage Lot Pond, biomass of *C. vagabunda* and *G. tikvahiae* was similar, and *Z. marina* biomass was considerably higher than the combined biomass of the two macroalgae (Fig. 5.6 and Table 5.5). June production of macroalgal biomass in Childs River was about 300 grams dry weight m^{-2} (gdw m^{-2}), similar to the Venice Lagoon in Italy, reportedly one of the most eutrophic estuaries in the world (Valiela et al. 1992). In both subestuaries, biomass of *C. vagabunda* and *G. tikvahiae* peaked in June and declined through August (Fig. 5.6).

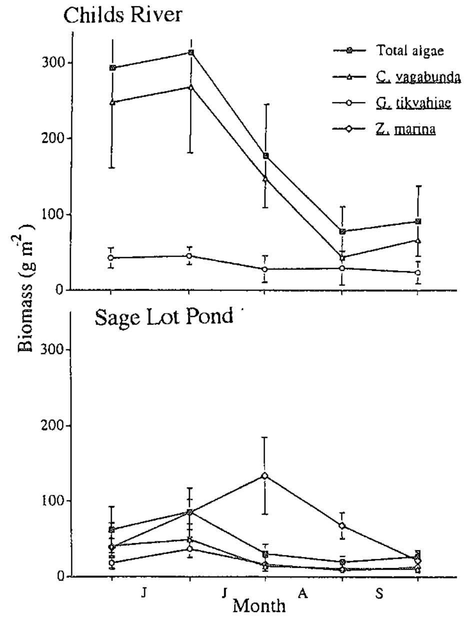

FIGURE 5.6

Biomass (g m^{-2}) of macroalgae, Cladophora vagabunda *and* Gracilaria tikvahiae, *and eelgrass,* Zostera marina, *in subestuaries of Childs River and Sage Lot Pond (From J. Hauxwell in prep.).*

Nitrogen uptake rates by macroalgae increase in Waquoit Bay estuaries subject to larger nitrogen inputs (Peckol et al. 1994). Algal specimens collected from the Childs River and exposed to different concentrations of ammonium (NH_4^+) had higher NH_4^+ uptake rates than did Sage Lot Pond populations even in summer when ambient NH_4^+ concentrations were lower (Fig. 5.7) (Peckol, et al. 1994). *Cladophora vagabunda* exhibited higher summertime rates of photosynthesis in Childs River than in Sage Lot Pond probably due to the higher photosynthetic pigment concentration in populations from Childs River (Peckol et al. 1994). In addition, higher growth rates were seen in populations from the Childs River than in Sage Lot Pond (Peckol et al. 1994).

The macroalgal canopy is not a homogeneous environment. Light and oxygen levels decrease rapidly within the mat while concentrations of NH_4^+can reach 500 µM (Charlene D'Avanzo, Hampshire College and WBLMER, unpublished data). Growth rates of *Cladophora vagabunda* at Childs River and Sage Lot Pond, at the mat surface and within the mat, showed that growth rates were higher above the macroalgal canopy than within it (Fig. 5. 8) (Peckol et al. 1994).

Table 5.5 Comparison of nitrogen-loading rates (kg y^{-1}) to summer biomass of macrophytes expressed as the mean ± SE grams dry weight m^{-2} in two estuaries of Waquoit Bay (data from J. Hauxwell, WBLMER).

	Childs River	**Sage Lot Pond**
Nitrogen-loading rates (kg y^{-1}) (WBLMER unpublished data)	7039	207
Macrophyte biomass		
Cladophora vagabunda	154.9 + 39.8	25.0 + 7.0
Gracilaria tikvahiae	33.8 + 7.1	18.5 + 3.7
Total macroalgae	190.8 + 42.1	44.9 + 8.2
Zostera marina	0.0 + 0.0	69.2 + 13.6

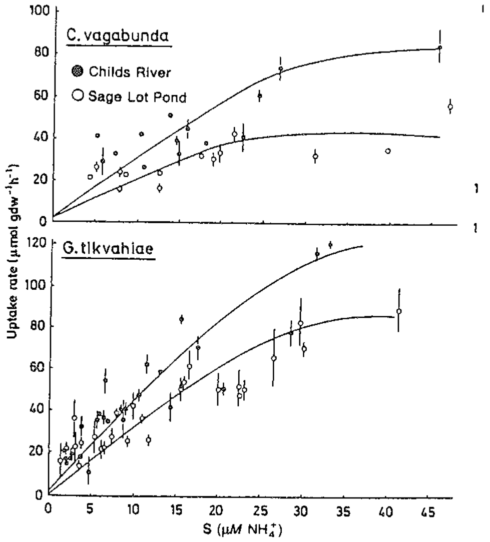

FIGURE 5.7
Ammonium uptake rates of Cladophora vagabunda *and* Gracilaria tikvahiae *are higher in the more nutrient-enriched waters of Childs River than in Sage Lot Pond (Peckol et al. 1994).*

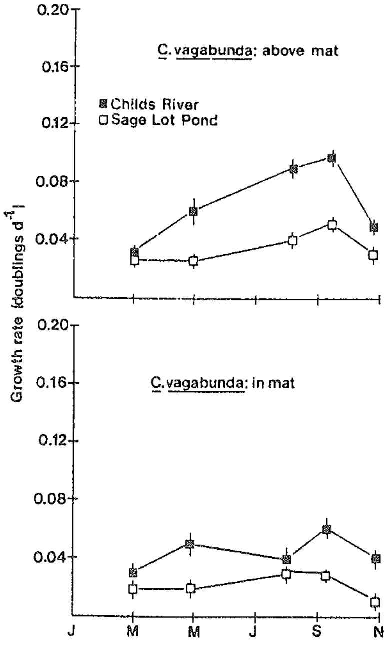

FIGURE 5.8
Growth rates of Cladophora vagabunda *were higher above the macroalgal mat than within it (Peckol et al. 1994).*

Algal species can be acclimated to "sun" or "shade," an indication of their relative ability to grow under high- or low-irradiance conditions. Plots of photosynthesis versus irradiance curves indicate that photosynthesis in *Cladophora vagabunda*, but not in *Gracilaria tikvahiae,* is inhibited at high irradiance levels (Peckol et al. 1994). Acclimation to low irradiance is evident in the distribution of *C. vagabunda* in the Waquoit Bay complex. This species is typically found below a canopy of *G. tikvahiae* or in deeper portions of the Bay where light attenuation is significant (Peckol et al. 1994).

Although nitrogen is considered the limiting nutrient in most coastal waters, experiments on the rate of photosynthesis in *Gracilaria tikvahiae, Cladophora vagabunda*, and *Ulva lactuca* from Waquoit Bay indicate that under nitrogen sufficiency, CO_2 availability may limit *C. vagabunda* photosynthesis in peak summer production times (Rivers and Peckol 1995). These results suggests that *C. vagabunda* does not possess the necessary enzyme to transform HCO_3 (the prevalent form of dissolved inorganic carbon at the typical pH of seawater) to CO_2.

Studies of the net production of macroalgae and phytoplankton suggest competition between these primary producers (WBLMER, unpublished data). Macroalgal growth rates are higher in spring and summer; as the water warms in late summer, the macroalgae appear to senesce. As macroalgal production declines, phytoplankton production increases. High phytoplankton concentrations in late summer, which decrease light penetration, may further contribute to the decreasing production of macroalgae (WBLMER, unpublished data). Hydrographic characteristics may also contribute to phytoplankton production. The large difference in phytoplankton production between the Childs and Quashnet rivers (Table 5.4) may be explained by the longer average residence time of freshwater in the Childs River than in the Quashnet River.

The bottom waters of the Childs River undergo large diel excursions in dissolved oxygen, principally reflecting metabolism of the macroalgal mat in conjunction with physical factors (D'Avanzo and Kremer 1994). Records of diel oxygen (O_2) changes show chronic hypoxic conditions in bottom waters at dawn in summer, due to night time respiration of seaweed and sediment bacteria. By afternoon under sunny conditions, macroalgal photosynthesis may increase dissolved O_2 in bottom waters to 10 – 15 mg/liter (Fig. 5.9). Light was the major factor regulating the concentration of bottom water dissolved oxygen (D'Avanzo and Kremer 1994).

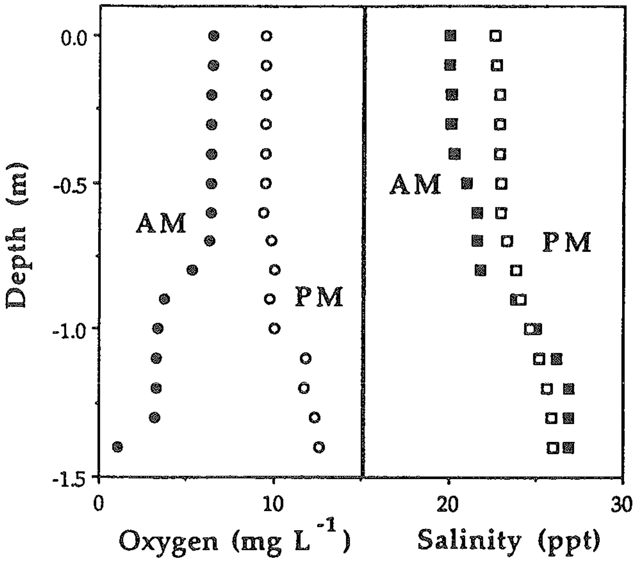

FIGURE 5.9
Dissolved oxygen concentrations in the bottom water of Childs River undergo large diel excursions. Density stratification isolates surface and bottom waters (D'Avanzo and Kremer 1994).

Vertical stratification prevents mixing of surface and bottom waters in the Childs River system. According to Geyer (in press), the vertical stratification is the result of the large volume of freshwater floating above the denser saltwater, the geometry of the Childs River area, and tree coverage that both impedes wind velocity and reduces wind-driven mixing.

The rate of photosynthesis of the benthic macroalgae in summer averages about 6.5 mg O_2/gram dry weight/hour (mg O_2 gdw^{-1} h^{-1}) (D'Avanzo and Kremer 1994). This rate is consistent with a macroalgal biomass of about 80 g m^{-2}, photosynthesizing at a rate that increases the amount of dissolved oxygen in the bottom water 0.5 g m^{-2} h^{-1}. A macroalgal biomass of about 80 g m^{-2} is approximately one quarter of the estimated macroalgal biomass in the Childs River, supporting the position that only the upper portion of the mat that receives adequate light actively photosynthesizes. Vertical profiles of dissolved oxygen that show daytime increases in dissolved oxygen only in the top one-quarter of the mat support this estimate (C. D'Avanzo, unpublished data).

Estimates of typical algal respiration of 1.6 mg O_2 gdw^{-1} h^{-1} (Paulette Peckol, Smith College and WBLMER, unpublished data) explain about 70% of the observed decrease in dissolved oxygen at night. Respiration by other members of the benthos or chemical O_2 demand may account for the remainder of the decrease (D'Avanzo and Kremer 1994).

Eelgrass

Although once a dominant primary producer in shallow embayments of the North Atlantic, the abundance and distribution of eelgrass, *Zostera marina*, have declined in this century, first in the 1930s due to the wasting disease caused by the slime mold—*Labyrinthula zosterae*—and more recently from reduced light due to eutrophication (Short and Short 1984; Short et al. 1988; Short et al. 1989; Short et al. 1991). Eelgrass has disappeared from most parts of the Waquoit Bay system (Costa 1988; Valiela et al. 1992; Short et al. 1993; Short and Burdick 1996). Aerial photographs and sediment cores documented the loss of eelgrass in the main Bay between 1951 and 1987 (Fig. 3.4) (Costa 1988; Costa et al. 1992). Aerial photographs

Table 5.6 Growth rates (above ground) and biomass (above ground and below ground) of eelgrass *Zostera marina* in different areas of the Waquoit Bay estuarine complex (after Short et al. 1993).

SITE	GROWTH CHARACTERISTICS				BIOMASS (g m^{-2})				
Waquoit Bay	Year	Areal g m^{-2} d^{-1}	Shoot cm d^{-1}	Specific Gr. cm cm^{-1} d^{-1}	Density	Shoots	Roots	Rhizomes	Total
Red Nun 6	1987	1.6	1.9	.015	304	149	11	36	196
Red Nun 4	1988	10.0	7.1	.031	469	231	45	48	324
Red Nun 4-6	1988	5.6	4.5	.027	1059	189	67	72	328
Red Nun 2-4	1988	8.8	4.3	.032	-	-	-	-	-
W of Red Nun 4	1989	5.1	6.9	.024	581	343	54	38	435
Great River	1989	3.3	3.5	.043	-	-	-	-	-
Hamblin Pond	1987				320	124	52	199	375
Hamblin Pond	1989	4.3	3.9	.022	397	278	74	133	485
Eel Pond	1989	8.1	6.2	.033	376	196	32	32	260
Washburn Pond (Tims Pond)	1989	2.4	3.2	.030	-	-	-	-	-

from 1987–1992 revealed additional losses in the Bay and in the adjacent rivers and coastal ponds (Short et al. 1993; Short and Burdick 1996).

To provide a baseline over time and to compare eelgrass stocks at different National Estuarine Research Reserves, Short et al. (1993) determined the growth rates, density, biomass, morphology, and nutrient status of eelgrass in some parts of the Waquoit Bay system. Table 5.6 summarizes some of these data. No significant differences in growth rates were seen between Reserve sites.

The effects of additional nitrogen on eelgrass are readily seen in the Waquoit Bay estuarine ecosystem. The absence of eelgrass in the highly nitrogen-enriched Childs and moderately nitrogen-enriched Quashnet rivers and the presence of eelgrass in Sage Lot Pond suggest that nutrient loading from residential development is responsible for the declining abundance and distribution of eelgrass in this system. Using WBLMER estimates of housing units and nitrogen loads, Short and Burdick (1996) found an inverse relationship between percent eelgrass and number of houses (Fig. 5.10) and between percent eelgrass and nitrogen loading estimates in 5 areas of the Waquoit Bay estuarine complex.

Short and Burdick (1996) also studied eelgrass growth in response to nitrogen increases in mesocosm studies and found that nitrogen-loading stimulated growth of phytoplankton, epiphytes or macroalgae, all of which outcompeted eelgrass for light. In field studies at Waquoit Bay they found different algal competitors outcompeting eelgrass at different sites; epiphytes at the mouth of Great River and Eel Pond; macroalgae in parts of Hamblin Pond and central Waquoit Bay, and phytoplankton in Jehu Pond (Short and Burdick 1996).

ECOSYSTEM METABOLISM: RESPONSE TO NUTRIENT LOADING

Anoxic Events

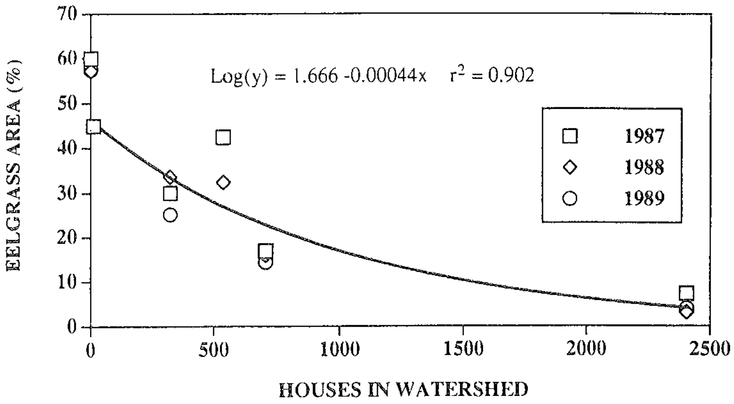

FIGURE 5.10

Decline in percent eelgrass coverage in relation to housing density in sub-basins of Waquoit Bay (Short and Burdick 1996).

As described above, eutrophic subestuaries of Waquoit Bay experience dramatic swings in daily, dissolved oxygen levels in bottom waters in summer. In the past several years, Waquoit Bay has experienced two dramatic anoxic events in which thousands of invertebrates and finfish died. Analyses of biological and physical conditions suggest that a combination of lower light, higher water temperature and low winds trigger these events (D'Avanzo and Kremer 1994). A sequence of cloudy days, where light levels remain low (limiting photosynthesis), is a key factor in predicting an anoxic event as can be seen in Figure 5.11 (D'Avanzo and Kremer 1994).

Major anoxic events in Waquoit Bay are correlated with cloudy weather but also with relatively high (25° C or 77° F) water temperatures. Lower water temperatures decrease the respiration rates of the benthic community. Cooler summertime water temperatures are thought to be responsible for the absence of an anoxic event in August of 1992 when there were 3 cloudy days in a row (Fig 5.12) (D'Avanzo and Kremer 1994). Anoxic events are also more often correlated with windless conditions in which mixing is minimal.

Anoxic events have both short and long term effects. In 1988 and 1990, decomposition following the event caused a short-lived surge in nitrogen concentration in the water column that triggered an increase in phytoplankton production for several days (Fig. 5.5) (Valiela et al. 1992). Winter flounder disappeared in affected areas following the 1988 anoxic event (L. Deegan, Ecosystems Center, Marine Biological Laboratory, Woods Hole, pers. comm. in D'Avanzo and Kremer, 1994). Although macroalgal mats may harbor large numbers of invertebrates of many species, anoxic conditions and the production of toxic sulfides may be responsible for the inverse relation between species richness and abundance and biomass of macroalgal mats (Valiela et al. 1992).

Ecosystem Respiration and Production

In addition to measuring the metabolism of specific components (e.g., phytoplankton, macroalgae) of the Waquoit Bay subestuaries, WBLMER researchers have measured total system metabolism in the subestuaries (D'Avanzo et al. in press). These studies allow them to assess the response to nutrient loading of the estuaries as whole units. Automatic meters recorded surface and bottom water oxygen, temperature and salinity in each subestuary for 1–3 weeks per year. Multi-day measurements are necessary due to variable day-to-day rates (Fig. 5.13) (D'Avanzo et al. in press). Total system metabolism is determined from increases in free water oxygen during the day (production) and decreases at night (respiration). The Waquoit Bay study of estuarine metabolism is the first to use automatic sensors for such extensive measurements.

Figure 5.13 also shows that nightly respiration rates in Childs River are about the same as daily rates of

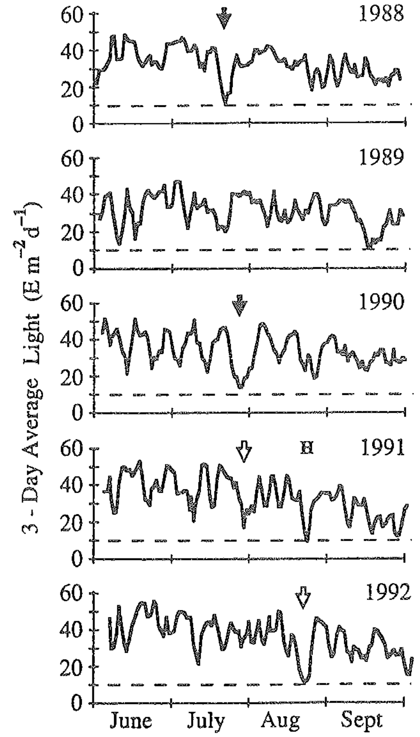

FIGURE 5.11

The record of 3-day average light (E m^{-2} d^{-1}) documents dates of dramatic anoxic events (black arrows) and lesser events, including Hurricane Bob (white arrows) (D'Avanzo and Kremer 1994).

production. During summer, respiration rates are high, nearly 15 g O m^{-2} d^{-1}, demonstrating the vulnerability of this nutrient-enriched subestuary to anoxic events. After a series of cloudy days, production cannot keep up with respiration, and respiration exceeds production for a brief period (Fig. 5.13) (D'Avanzo and Kremer in press).

Annual rates of metabolism were calculated by summing average daily rates from each deployment. Annual ecosystem gross production, the sum of system production and respiration over the year, was highest in the highly nutrient-enriched Childs River and decreased with loading in the other two subestuaries (Fig. 5.14) (D'Avanzo et al. in press). Thus, nutrient enrichment enhances the combined metabolisms of production and respiration. Annual ecosystem net production, calculated as annual production minus respiration is the production that is not respired by all of the organisms (mainly bacteria) in a system. Ecosystems with positive ecosystem net production are autotrophic; those with negative ecosystem net production are heterotrophic.

As expected in this highly enriched subestuary, ecosystem net production in the Childs River is positive with a value of 180 g O_2 m^{-2} y^{-1}. This is a high rate of annual production, equivalent to about a quarter of the average seaweed biomass in this subestuary (D'Avanzo et al. in press). There are two fates for this net production—export or burial in bottom sediments—and so high rates of nutrient loading to shallow embayments result in organic rich sediments and export of organic matter which can be used as food elsewhere. In the Quashnet and Sage Lot Pond, ecosystem net production was small, so these estuaries may not export organic matter to adjoining systems (D'Avanzo et al. in press).

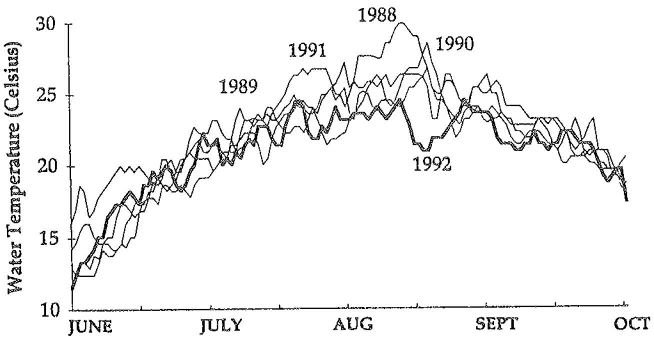

FIGURE 5.12

Cooler water temperatures in 1992 (heavier line) may explain the lack of anoxic event in August during a period of cloudy weather (D'Avanzo and Kremer 1994).

Invertebrate and Vertebrate Production

Shellfish

It is generally assumed that the loss of eelgrass has meant a loss of habitat for numerous species. Among the invertebrates, the bay scallop, (*Argopecten irradians*), populations have declined

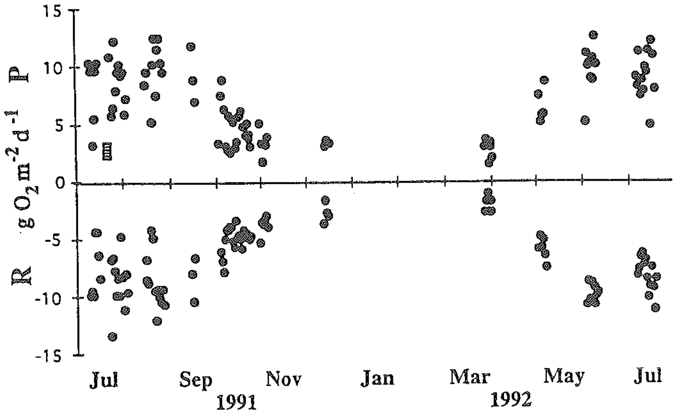

FIGURE 5.13

Day-to-day variation in daily ecosystem production and respiration (g O_2 m^{-2} d^{-1}). Daily production levels and nighttime respiration are about equal in Childs River. The bar is the average standard deviation of 3 measurements along the estuary on 7 day or night cycles in midsummer. (D'Avanzo et al. in press).

over the past decades in Waquoit Bay waters. The decline of scallops has been greater in Eel Pond which receives nitrogen from the two most densely settled subwatersheds (Childs River and Eel Pond) than in Waquoit Bay proper (Fig. 5.15). As scallop populations fluctuate naturally, it cannot be said with certainty that their decline is linked to the changes seen in Waquoit Bay. However, research indicates that juvenile scallops escape predation from whelks, crabs, starfish and oyster drills by moving higher in the eelgrass canopy (Pohle et al. 1991). The loss of habitat coupled with the occurrence of anoxic and hypoxic events in bottom waters suggest that the few scallops that survive are unable to find suitable habitat (Valiela et al. 1992).

Populations of soft-shelled clams (*Mya arenaria*), and hard-shelled clams or quahogs (*Mercenaria mercenaria*), have not declined (Fig 5.15). In fact, a study by Chalfoun et al. (1994), showed that growth rates of *M. arenaria* were positively related to the amount of nutrient loading. Growth rates were highest in Childs River, intermediate in Quashnet River and lowest in Sage Lot Pond (Chalfoun et al. 1994). *Mercenaria mercenaria* also grew faster in the Childs River; however growth of this species was lower in the Quashnet River than in Sage Lot Pond. The authors speculate that the faster flow regime in the Quashnet River might impede feeding of *M. mercenaria,* which depends mainly on phytoplankton, more than *M. arenaria,* which feeds on resuspended detritus as well as phytoplankton (Chalfoun et al. 1994).

Amphipod and Isopod Grazers

Although macroalgal production increases in summer in Waquoit Bay estuarine waters, survey data (Hersh

Table 5.7 Species and relative mid-summer abundances of small crustacean grazers found in the Waquoit Bay estuaries. Rare refers to <1, Common 1-10, and Numerous >10 average individuals per sample from mid-summer surveys (Data of J. Hauxwell, WBLMER).

GRAZER	CHILDS RIVER	SAGE LOT POND
Amphipods		
Ampithoe longimana		Numerous
Cymadusa compta	Common	Rare
Elasmopus levis	Rare	
Gammarus mucronatus	Rare	
Lysianopsis alba	Common	Rare
Microdeutopus gryllotalpa	Numerous	Numerous
Isopods		
Edotea triloba	Rare	Rare
Erichsonella filiformis	Common	Common
Idotea baltica	Rare	

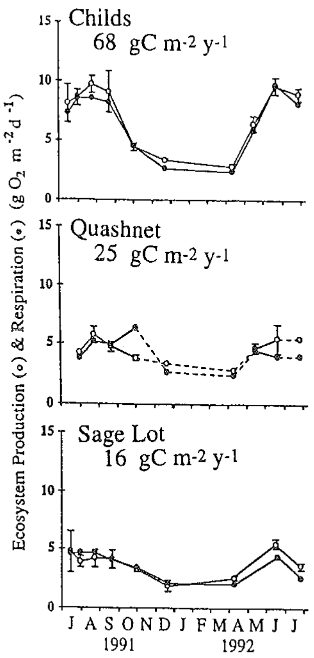

FIGURE 5.14

Ecosystem net production and respiration in the 3 estuaries over a year. Inset numbers indicate the annual net ecosystem production of carbon (D'Avanzo et al in press).

1995) did not reveal increases in macroalgal standing stocks. A recent study has examined how the interplay of nutrient loading ("bottom-up control") and grazing ("top-down control") affect macroalalgal standing stocks (Hauxwell et al. in prep). Nine major taxa of small crustacean grazers were identified in the Childs River and Sage Lot Pond (Table 5.7). The density of grazers was lower in the highly nitrogen-enriched Childs River than in Sage Lot Pond where nitrogen inputs are low. Peaks in grazer abundance differed between estuaries as well. Grazer abundance peaked in July in Childs River and in August in Sage Lot Pond (Fig. 5.16); in both estuaries grazer abundance followed the June peak in macroalgal biomass reported above (Fig 5. 6).

In Childs River, grazers control macroalgal production from late June to late August, whereas in Sage Lot Pond, grazers exert top down control from early July to late September (Fig. 5. 17) (Hauxwell et al. in prep). The combination of higher macroalgal growth rates in Childs River and lower grazer density makes it more difficult for grazers to control macroalgal growth in Childs River over the summer (Fig. 5.17). In low nitrogen-enriched sites where eelgrass is found, such as Sage Lot Pond, the cropping of epiphytes on eelgrass by abundant grazers may contribute to the maintenance of the eelgrass habitat (Hauxwell et al. in prep). The combination of increased nutrient loading and decreased grazing seen in Childs River may have contributed to the shift of the primary producer community from eelgrass-dominated to algae-dominated, whereas in Sage Lot Pond, the lower density of macroalgae and higher density of grazers contribute to the maintenance of the eelgrass habitat (Hauxwell et al. in prep).

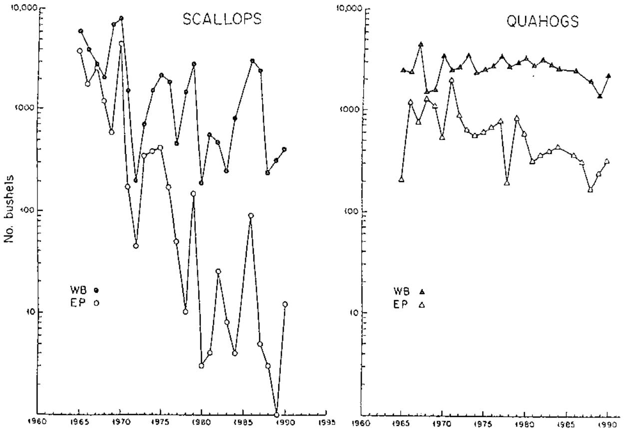

FIGURE 5.15

Reported harvest of scallops, Argopectin irradians, *and quahogs,* Mercenaria mercenaria, *from Waquoit Bay and Eel Pond. (Data from Annual Report of the Town of Falmouth, compiled by the Shellfish Warden, from Valiela et al. 1992.)*

Finfish

Relative abundance of finfish species appears related to eelgrass coverage in Waquoit Bay and its adjoining waters. A comparison of species abundance in 1966 to 1987 showed that only 5 of 17 species increased in abundance (Deegan et al. 1990). Species considered estuarine dependent declined the most, suggesting that the loss of eelgrass habitat was responsible for their decline. Of the species that increased, the most dramatic increase was seen in *Lucania parva,* (the rainwater killifish) a species that prefers filamentous algae as opposed to eelgrass (Deegan et al. 1990). In related research (Deegan et al. 1991) examined the effect of removing macroalgae from eelgrass beds on primary producers, fish, decapods and macrofauna. Their results showed that eelgrass abundance, fish density and invertebrate species diversity increased with macroalgal decrease; the abundance of invertebrates increased with macroalgal density.

In a comparative study of several sites in Waquoit Bay and Buttermilk Bay, Massachusetts, that have been altered by anthropogenic stress, Deegan et al. (in press) found that number of species, dominance, density and biomass of finfish in submerged aquatic vegetation were all lower in severely degraded sites compared to moderately degraded sites. Information on species abundance and distribution, and on water quality have been used to develop an Estuarine Biotic Integrity Index that reflects the differences in fish communities in submerged aquatic vegetation (Deegan et al. in press).

RECREATIONAL BOATING IMPACTS

An important agent of change in the Waquoit Bay ecosystem is recreational boating. During the 1980's, there was a marked increase in the number of recreational boats plying the shallow embayments along the southeast Massachusetts coast. For example, in Waquoit Bay, with an area of 334 hectares (825 acres) and mean depth of 0.82 meters (2.7 feet), the number of boat moorings increased from 285 to 400 from 1987 to 1989 (Anon 1989). The total number of recreational boats using Waquoit Bay and its adjacent waters, which have a combined area of 517 hectares (1278 acres), was

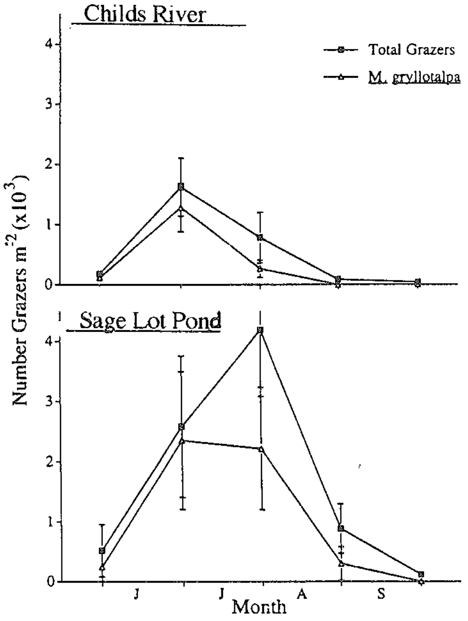

FIGURE 5.16

Total numbers of grazers and numbers of the most abundant grazer, the amphipod Microdeutopus gryllotalpa, *were lower in the highly nutrient-enriched Childs River than in Sage Lot Pond (Hauxwell et al in prep.).*

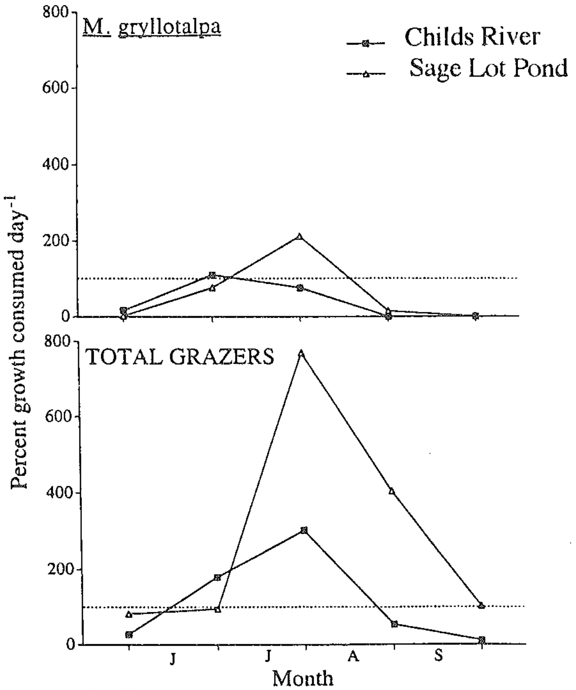

FIGURE 5.17

Percent macroalgal growth consumed in summer in the highly enriched Childs River and the relatively unenriched Sage Lot Pond. Grazers controlled production over the summer season in Sage Lot Pond, where they were more abundant (Hauxwell et al in prep.).

about 1000 in 1992, about twice the number using the Bay in 1970 (Crawford et al. 1994). The total impact of this intensive recreational activity on a fragile coastal area is unknown.

Effects of Anti-Fouling Paints

One consequence of boat storage and operation in the Bay stems from boat bottom antifouling paints that have been used (and misused) on Waquoit Bay boats for many years. Early formulations were based on heavy doses of copper (e.g., cuprous oxide) which readily sloughed off into the environment. Some paints contained polychlorinated biphenyls (PCBs) as well. More effective (i.e., toxic) compounds (e.g., based on mercury or tributyltin (TBT)) were developed more recently. However, research revealed the sensitivity of nonfouling marine organisms (e.g., crustaceans and fish larvae) to these compounds (Weis 1976; Milliken and Lee 1990). New regulations place severe limitations on the use of TBT and other substances. The application of modified formulations of copper-based paints persists. But the long history of unregulated use of these substances undoubtedly has affected shellfish and finfish spawning and nursery habitat in the Bay. For example, in other water bodies sediments and organisms near marinas have elevated concentrations of toxic substances (Nixon et al. 1973; Young et al. 1979). In these instances contaminated sediments from past applications continue to negatively impact lagoon resources in spite of new restrictions (Young et al. 1979). This potential problem has not been examined in Waquoit Bay.

Effects of Boat Operation

Although the detrimental physical effect of boat moorings on seagrass beds in the Bay and elsewhere has been documented (Walker et al. 1989; Short et al. 1993) the effects of prop wash in shallow embayments and lagoons are less understood. Sediment resuspension is known to be a naturally occurring phenomenon with potent ecological effects (Arfi et al. 1993), but the relation between it and boating activity remains little studied and poorly understood (Hilton and Phillips 1982).

The turbulence and water displacement resulting from boat operation in a shallow system will likely generate a cascading series of impacts. Two direct consequences are increased turbidity and mixing. Increased turbidity, caused by the resuspension of sediments, can affect several important environmental variables, such as:

- light intensity, more specifically the photosynthetically active radiation (PAR) level;
- oxygen concentration, by increasing the biological oxygen demand (BOD) or by shading phytoplankton and submerged aquatic vegetation; and
- sedimentation rate (which can lead to smothering epiflora, epifauna, and larval benthic organisms, or which can affect the growth and reproductive potential of benthic organisms, such as shellfish).

Enhanced mixing can affect the physical environment in the water column, such as the temperature, the salinity, and the concentrations and distribution of dissolved oxygen and nutrients (Yousef 1974; Yousef et al. 1980). These changes can have broad consequences within a lagoon ecosystem.

The effects of propeller scour are similar to those for wake turbulence except for the additional impact of direct mechanical disturbance of the bottom. So-called "prop-dredging" will rapidly disturb large amounts of sediments. Thus, the effects associated with turbidity can be augmented. Another result of this alteration is the disruption of the biogeochemical processes that occur in the upper layers of the bottom sediments. In highly productive shallow lagoons with an abundance of submerged aquatic vegetation, bottom sediments are richly organic. Sediment pore waters are usually anoxic. Ammonia is the dominant nitrogenous compound and hydrogen sulfide is also prevalent. The benthic community is dominated by burrowing, deposit feeding invertebrates. When a propeller digs through the upper few centimeters of surface sediments, it is like a plow turning over a field. Sediments are oxygenated, ammonia and sulfides are released and the recycling of nutrients is enhanced. The increased nutrient flux may stimulate eutrophication and the alterations to the local environment are likely to result in changes to the composition of the biological community.

Additional consequences are the lethal and sublethal damage to biota that occurs during the physical disruption of the benthos. The negative effects of this are intuitive. A less obvious but positive result may be the creation of habitat that is exploited by opportunistic species, particularly where species richness is low and dominated by one or two species (e.g., the polychaete *Capitella capitata*, as in Waquoit Bay). The disruption may serve to promote coexistence among opportunistic infauna with similar resource requirements and life histories—a process that results in increased biodiversity (Zajac 1985).

EFFECTS OF DOCKS

Shading

Docks and moored boats cast shadows that can alter the microenvironments beneath them. Wetzel and Penhale (1983) concluded that light was the single most critical factor in the survival and growth of eelgrass in Chesapeake Bay. For example, Backman and Barilotti (1976) found that reducing the light level by 63 percent resulted in eelgrass densities that were only 5 percent of the unshaded controls. Short et al. (1993), working in Waquoit Bay and elsewhere, recommended that the number of boat moorings and docking facilities should be controlled to limit the shading of the bottom. In a study of eelgrass bed quality beneath docks, Burdick and Short (1995) showed that narrow docks, oriented north to south and placed more than 3 meters in height above the bottom had the least impact on eelgrass beds.

Effects of Wood Preservatives Used in Docks

There is similar concern for the past and present use of treated wood for pier and bulkhead construction. To prevent decay and destruction by marine borers, wood used in dock construction is treated with toxic preservatives. Creosote was the preservative of choice for many years. It was effective, long-lasting, and cheap. It was also a noxious pollutant. Although the sheen of a creosote oil slick was a common site at wharf construction sites, the environmental threat went unregarded. Only when creosote was identified as a human carcinogen was its use as a wood preservative restricted.

Chromated copper arsenate (CCA) has replaced creosote as a wood preservative of choice. Although it is safer from the human health perspective, leachate from CCA treated wood has been shown to be toxic to a variety of estuarine organisms (Weis et al. 1991; Weis and Weis 1992a; 1996). All three metals leach from wood, can accumulate in biota and sediments (especially the fine grained fraction, silts and clays), and are known to be toxic (Weis et al. 1991; Weis and Weis 1992b; Weis et al. 1993). Observed environmental impacts resulting from the use of this wood are: uptake of heavy metals by organisms living on treated wood with subsequent toxic results; uptake of heavy metals by benthic organisms living near treated structures;

and food chain transfer of heavy metals from prey to predators (Weis and Weis 1992a; Weis and Weis 1992b). Materials made from recycled plastic offer hope for an alternative and less toxic resistant construction material (Weis et al. 1992c).

EFFECTS OF SEPTIC DISCHARGE

It has long been recognized that septic discharge from boats in lagoons and estuaries pose a human health risk (Faust 1982). Regulations concerning the installation and use of different types of marine sanitation devices are intended to alleviate this problem. However, compliance with the letter of the law has received lukewarm support from the boating industry and the devices may be misused. For example, some boaters add odor controlling media to marine sanitation devices. When the wastes are eventually dumped overboard, the discharge may include several toxic chemicals in addition to the nitrogenous waste (Ross, 1985).

To address this potential problem, Waquoit Bay was designated a "No Discharge Zone" in May, 1994. Since then it has been unlawful to discharge septic wastes from boats into the Bay. This effectively curtails the use of marine sanitation devices (MSD Types I and II) that do not have holding tanks. A pump out facility for boats with holding tanks (MSD Type III) has been installed at Edwards Boat Yard (Childs River, East Falmouth). A mobile unit (pump-out boat) is operated by Little River Boatyard (Little River, Mashpee).

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CHAPTER VI

MANAGEMENT ISSUES

IN THE WAQUOIT BAY RESERVE

Sunset at Waquoit Bay. WBNERR archives, photographer unknown.

INTRODUCTION

For generations residents and visitors have enjoyed Waquoit Bay for swimming, fishing, shellfishing, boating, and birding (Fig. 6.1). Although at first glance the Bay appears clean and productive, those familiar with Waquoit Bay are aware that it has changed: it is hard to find many kinds of fish that used to be plentiful; scallops are only found in quantity on the first day or two of the season; the Bay which used to support several commercial shellfishermen now produces only enough to augment a few people's livelihood; eelgrass which used to cover the Bay is now limited to a few patches near the mouth; and seaweed (also known as macroalgae) floats around the Bay in three-foot mats, covering the beaches after a busy boating weekend. The mission of the Reserve is to conduct research that will help us understand the causes of the changes and develop, implement and encourage management strategies that will reverse the trends and protect the coastal and estuarine resources.

Waquoit Bay was selected for a National Estuarine Research Reserve (NERR) site because it is representative of shallow coastal embayments in the Northern Virginian biogeographical area. The research information and management approaches generated by the Reserve are applicable to similar embayments within this area. As a member of the NERR System, the Waquoit Bay Reserve provides long-term resource protection; conducts and coordinates research and long-term monitoring to foster a better understanding of the estuarine resources and the impacts of humans on them; and translates the information learned to the public and coastal decision-makers to encourage more informed and responsible coastal management.

MANAGEMENT OBJECTIVES

The 1988 Waquoit Bay NERR Management Plan outlined the major goals of the Reserve. The words in parentheses are added for clarification.

- To enhance and facilitate resource protection within the Reserve and those surrounding areas (within the watershed) that affect the Reserve.
- To (engage in) facilitate and encourage opportunities for short and long-term scientific research within the Reserve (and surrounding areas) that serve to increase our knowledge and understanding of estuarine areas (and man's impact on them) to assist in their protection.
- To facilitate and encourage education and interpretation of conditions and resources existing at Waquoit Bay NERR, and educate about general principles characteristic of all estuarine areas.
- To develop information for improved coastal decision-making (based on research and sound science).

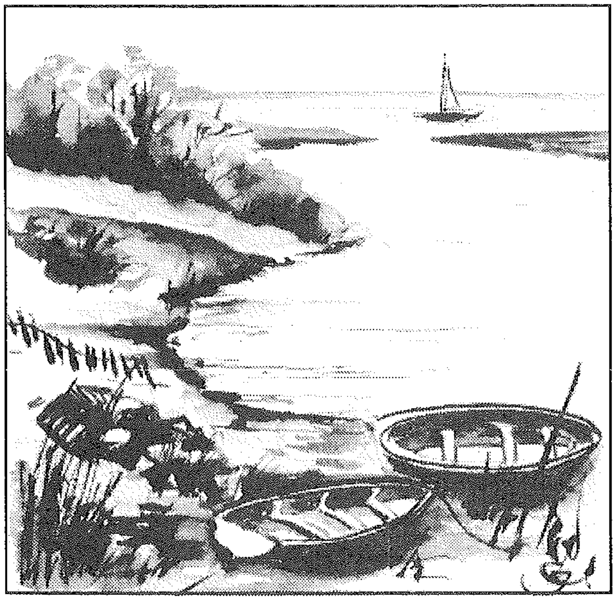

FIGURE 6.1
Shallow embayments are pleasing to the eye and have economic and recreational value. Unfortunately, beneath the waves are many hidden problems caused by human activitites in the adjacent watersheds that have degraded the living and non-living resources. Drawing by Caroline Goldstein.

- To heighten awareness and promote cooperative efforts among local, state and federal levels on issues pertaining to Waquoit Bay NERR.
- To encourage multiple use of Waquoit Bay NERR resources to the degree compatible and consistent with the protection of the (resources of the) Reserve and maintenance of education and research activities.
- To develop a restorative activities plan if, and/or where appropriate.
- To use the site as a model for how other similar systems work and how they can be managed.

The 1988 Management Plan is being revised and will incorporate elements of several planning initiatives that have been made over the past 8 years. Among these are: the WBNERR/McGregor Road Beach Recreation Area Management Plan, the Quashnet River Property Management Plan, the Citizen's Action Committee's Waquoit Bay Watershed Action Plan and the EPA Ecological Risk Assessment.

The Waquoit Bay NERR Management Plan addresses the lands within the Reserve boundaries. Research findings have made it increasingly apparent that managing the land and resources within the boundaries isn't sufficient to protect the resources within the Reserve. Because most of the impacts come from land use in the entire watershed (see discussions in Chapter V), we must examine the management of the entire watershed. However, the land in the rest of the watershed is owned by a variety of public and private entities. To develop a management plan for the watershed (which includes parts of Falmouth, Mashpee and Sandwich) would present the challenge of coordinating many often conflicting interests and getting the landowners to endorse the outcome. This regional coordinating job might be most appropriately conducted by the Cape Cod Commission.

The following discussions highlight some of the most pressing management issues that affect the Reserve. Since the Reserve is representative, these discussions are applicable to many other shallow coastal embayments.

EUTROPHICATION/NITROGEN LOADING

The most pressing management issue for Waquoit Bay is coastal eutrophication caused by nitrogen loading from various human activities in the watershed. Coastal eutrophication resulting from land use changes has become a national issue as evidenced by the recent federal efforts to reduce non-point source pollution through legislation such as the NOAA-administered Section 6217 of the Coastal Zone Management Act.

Research at the Reserve, particularly the Waquoit Bay Land Margin Ecosystem Research Project, (WBLMER) has been based on the premise that land use in coastal watersheds affects the adjacent estuarine ecosystems.

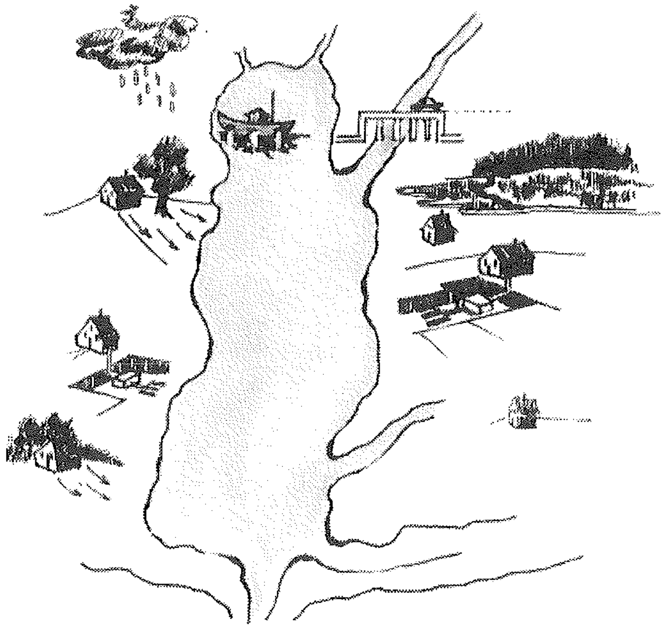

FIGURE 6.2
Sources of non-point-source pollution to coastal embayments. Drawing by Caroline Goldstein.

In Waquoit Bay the increased nutrients from human development have led to increased growth of algae (both macroalgae, seaweed, and microalgae, phytoplankton), decreased concentrations of dissolved oxygen during certain times of the year, habitat degradation and changes in community structure. Thus, nitrogen inputs have a strong influence on many facets of estuarine structure that concern natural resource planners and managers. Elevated nitrogen levels in drinking water also can be a potential human health hazard.

The research at Waquoit Bay, Buzzards Bay and elsewhere has shown that the major non-point sources of nitrogen are on-site septic systems, atmospheric deposition (acid rain and dry deposition), fertilizers, and storm water runoff (Fig. 6.2). Although scientists agree on the general principles of nitrogen loading, there remain questions about the relative contribution of nitrogen from different sources to the watershed, the amount of nitrogen that arrives at the Bay, and how rapidly the estuary responds to various amounts of nitrogen (see Chapter V).

Like other coastal states, Massachusetts is grappling with ways to manage nutrient inputs. Each possible solution has social, economic, and technical considerations. In addition, there is still scientific uncertainty about the amount of nitrogen to remove to restore the ecosystem to some previous state, or if it is possible to restore an earlier set of conditions. The Waquoit Bay Watershed Action Plan developed in 1992 by the Waquoit Citizens Action Committee suggested a reduction in nitrogen to the level that existed between 1951 and 1971 as an appropriate target to achieve desired water quality. These dates were chosen based on the abundance of eelgrass in 1951 which disappeared by 1971 (see Chapters III and V). Targeting a nitrogen loading rate that existed in the past means that an approach must be found to reduce nitrogen loading from existing development, in addition to that from future development. Following is a discussion of some of the options under consideration by the Reserve and/or various groups with which the Reserve works.

TECHNOLOGICAL APPROACHES

Dredging

Dredging the inlets to the Bay would increase water flow and the turnover time of the Bay's water. This could improve the flushing rate and therefore dilute nutrients. Dredging requires scientific data, special equipment, time, funds and a complex permitting process that involves numerous federal, state and local agencies. (The Dredging Handbook produced by the Massachusetts Coastal Zone Management in 1987 outlines the permitting process involved in dredging.)

Dredging can have significant impacts including habitat alteration, sediment resuspension, accumulation of toxics, and removal of organisms. The disposal of dredged materials, especially if they are contaminated, is also a problem. Land disposal requires space and funds for transportation. The possibility of introducing salt to land and to groundwater needs to be considered. On the positive side, clean dredge materials could be used for beach renourishment.

The costs of dredging can be prohibitive because dredging must be repeated frequently. Additionally, since this approach does not address the source of the nutrient loading, it is unlikely that dredging alone would significantly alleviate the problems in Waquoit Bay.

Harvesting Seaweed

Another option is to remove the seaweed that has proliferated throughout the Bay as a result of nutrient-loading. The environmental impacts of harvesting seaweed have not been well studied; however, it is certain that the bottom sediments would be disturbed with possible positive and negative consequences for the biota. Furthermore, without source reduction, the seaweed will return. Like dredging, harvesting seaweed requires equipment and ongoing funding for annual removal.

Alternative On-Site Wastewater Treatment Systems

A possible approach to reducing nitrogen from on-site wastewater treatment systems and cesspools is the use of advanced systems that denitrify the waste stream before it enters the groundwater. The Reserve held a conference in 1992 to explore the use of these systems. Since that time some alternative systems have been installed in demonstration sites in Massachusetts, and Massachusetts now permits some of these systems under its revised sanitation code (called Title V). In 1993 Waquoit Bay was chosen as one of 8 "communities" to participate in the Small Flows Clearing House National On-Site Demonstration Project. With funding through EPA, some of these alternative technologies will be installed and monitored in the Waquoit Bay watershed to determine if they provide enough additional denitrification (over the conventional Title V systems) to warrant their higher costs (Fig. 6.3).

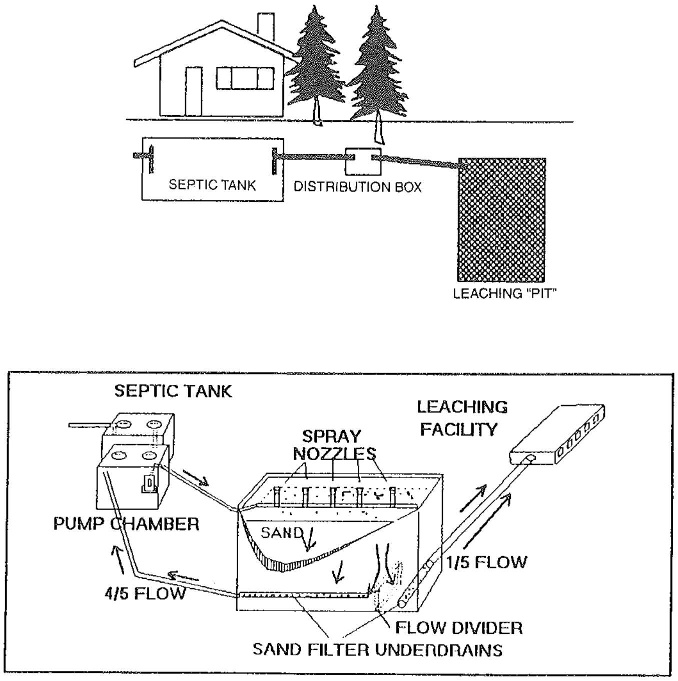

FIGURE 6.3

Schematic of conventional on-site wastewater treatment system (top) and example of advanced on-site denitrifying system (bottom)(reprinted from Barnstable County Board of Health 1994, 1995).

If these systems do remove a significant amount of nitrogen, it is hoped many will be installed in the Waquoit watershed (and elsewhere). An overlay district could require their installation in new buildings, upon additions to existing buildings or upon sale of a property . These systems could be used without an overlay district, but a district provides a means of requiring their use and guaranteeing proper maintenance—one of the DEP's concerns about the use of these more complicated systems. The Reserve received an Environmental Technology Initiative Grant from EPA to hold a conference in December 1995 to explore management districts; decentralized waste water facilities and management planning; and site evaluation, design and engineering. Papers on these subjects plus one on accountability for on-site systems are available at the Reserve. See the section below, Regulatory Approaches, for additional information.

Storm Water Runoff

Storm water runoff carries nutrients as well as pathogens and petrochemicals which can degrade water quality. There are several official drains and many unofficial "waterways" from state and town roads and private property within the Waquoit Bay Reserve. The Town of Falmouth has mapped the official storm drains but not the "waterways" which often route storm water into sensitive areas. The Town of Mashpee has not mapped their storm drains. The Massachusetts Department of Transportation will soon begin major work on Route 28, a state highway bounding part of the Reserve and traversing the watershed. The Department has maps of the official storm drains, but not the "waterways" on Route 28. The Reserve, the Town of Falmouth and WBNERR volunteers are working with the State to include non-point source pollution abatement in the project work area.

An assessment is needed of the contributions of nutrients to Waquoit Bay from storm water compared to that from wastewater, fertilizers and atmospheric deposition. The contribution of petrochemicals and pathogens also must be determined. To address this need, the Reserve, with the help of volunteers, has conducted Phase I of a citizens' shoreline survey in which signs of non-point sources of pollution from private land and public roads were mapped. During Phase II the significant sites will be sampled to determine how much pollution they contribute to the Bay.

Efforts to protect water quality need to include mapping storm water drains, waterways and other non-point source runoff sources. Remediation should involve the use of state-of-the-art approaches.

REGULATORY APPROACHES

Zoning

Horsley and Witten (1991) describe several zoning strategies that result in reduced nitrogen loading: overlay districts, prohibition of various land uses, special permitting, large lot zoning, the transfer of development rights, cluster designs, performance standards and growth clusters. Some of these options are discussed in the following sections.

• *Management Districts*

One approach to limiting nitrogen-loading is the creation—through town by-laws or intermunicipal agreement—of a water protection district that establishes nitrogen loading standards (Fig. 6.4). Bylaws and regulations would be developed that require practices that reduce the nitrogen generated from different land uses. Examples of regulations include: the Sanibel Island, Florida, laws that limit the area of a lot that can be cleared and made into a lawn which limits fertilizer use and maintains vegetative cover; and by-laws that require denitrifying septic systems in resource sensitive areas. The overlay district approach has been used in

Buttermilk Bay and includes the towns of Wareham, Bourne and Plymouth. In this case, the district is meeting the nitrogen loading standards by increasing buildable lot size thus reducing the number of homes, the source of much of the nitrogen (see "Downsizing" below).

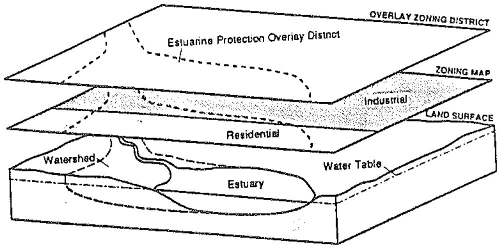

FIGURE 6.4

An overlay district is a zoning technique that communities can adopt via regulations or by-laws to protect water resources (reprinted from Horsley et al. 1991).

Intermunicipal cooperation and coordination would be required to implement a management district in the Waquoit Bay watershed as it includes parts of Falmouth, Mashpee and Sandwich. The main disadvantage is that many if not most of the lots within this watershed would probably be exempt due to the 7 protections under MGL Ch. 40. A section 6 which include "grandfathering" which exempts existing lot owners from new regulations. Only when a lot is sold is it subject to the new regulations.

- *Management District by Legislation*

Yet another option would be the establishment of a management district by legislative act at the state level. Within the district, various regulations or approaches that wouldn't be subject to the "grandfathering" restrictions could be implemented to reduce nitrogen loading, ensuring that everyone does their part.

- *Subdivision Control Act*

The Subdivision Control Act gives the towns the ability to set conditions, such as lawn size limits or septic system requirements (that go beyond normal town-wide bylaws) on specific developments. However, this approach would only limit nitrogen from new developments and would not reduce nitrogen from existing sources.

- *Downzoning*

Downzoning is an approach that requires specific mention. The Buzzards Bay Project (1991), a National Estuary Program, developed a nitrogen loading model to better understand nitrogen impacts from land use within their area. The model results suggested that water quality protection of Buttermilk Bay could be achieved if the three towns within the watershed cooperated to reduce the number of homes contributing nitrogen to Buttermilk Bay. As mentioned above, the towns created an overlay district using "downzoning" to increase minimum lot sizes (Fig. 6.5).

Although downzoning does not address the excess nitrogen from existing development, it may be feasible for reducing additional nitrogen loading. Concern has been expressed that regulations that significantly change land use will be perceived as a threat to property rights. Another frequently expressed concern is that requiring larger lots spreads development over more land. Instead, many people recommend clustering homes, leaving more open space. A comprehensive planning process could identify which areas should be left as open space and which should be buildable.

Nitrogen-Loading Regulations

The Town of Falmouth adopted a zoning by-law in the 1980s to limit nitrogen-loading to sensitive embayments. This regulation is noteworthy as it was one of the first efforts to regulate nitrogen loading to

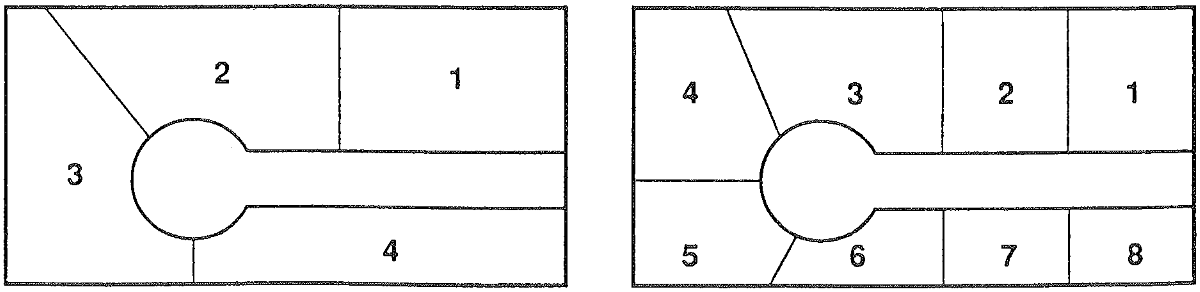

FIGURE 6.5

Large lot zoning reduces the number of buildable lots, thereby limiting the degradation of water resources from nutrient loading (reprinted from Horsley et al. 1991).

coastal embayments. The by-law sets limits for nitrogen levels as measured in the water column. Since water column nitrogen measurements do not reflect the nitrogen loading rate (because macroalgae rapidly take up nitrogen, removing it from the water column, and because nitrogen from some existing buildings has not yet traveled to the receiving waters), a mass loading approach which ties into a comprehensive planning effort may be preferred.

District of Critical Planning Concern

The Cape Cod Commission has the authority to declare an area a District of Critical Planning Concern (DCPC). A town or towns can nominate an area for a DCPC designation based on water resource, aquaculture, agriculture, wildlife, ecology, cultural, historical, economic, hazards, commercial, transportation or affordable housing concerns. The Commission sets the objectives for the DCPC, such as reducing nitrogen-loading, and the towns decide how to meet the objectives though regulations, by-laws or policies. Advantages of this approach include the lack of grandfathering provisions and the ability to create a management entity that transcends town boundaries.

Utility District

In this approach a public or private utility is created to provide wastewater treatment via on-site systems or several community systems. Fees are assessed on all homes and businesses within the district. The utility determines which nitrogen reduction systems would be appropriate, helps select the technology, oversees the design and construction of the systems, and provides the proper inspection and maintenance of existing systems.

Federal Regulations to Control Acid Rain

In Waquoit Bay, as in the Chesapeake and other bays, a significant amount of nitrogen comes from atmospheric deposition. A reduction of nutrients at the source is needed. However, this is a national issue because major sources (coal fired power plants) are often hundreds of miles away in other states and sometimes other countries. Because of the scale of the problem, it will be much harder to reduce nutrients from sources outside the watershed. However, if we are serious about improved coastal management, solutions must be found through legislative, regulatory and grassroots efforts.

Vegetative Management, Choice and Cover

Reducing household and agricultural fertilizer use will contribute to reducing the overall nitrogen load. The reduction can be accomplished through regulations and/or through educational programs that encourage voluntary efforts. Several ongoing outreach efforts seek to inform the public about the possible impacts of the overuse of fertilizers and to teach more responsible application techniques; other efforts encourage the use of native plants because they are believed to require less fertilizer, water, pesticides and herbicides than plants indigenous to other parts of the country.

Another approach would be to limit the amount of disturbance to natural vegetative cover for construction because it is believed that diverse vegetation intercepts nutrients more efficiently than lawns. Vegetative buffers between developments and sensitive areas such as wetlands, rivers, coastal banks and marshes intercept some nutrients and other contaminants that could degrade the ecosystems. There are currently requirements for vegetative buffers in the Massachusetts Wetlands Protection Act which are strengthened in several towns in local wetlands protection regulations.

Other Regulations

The Commonwealth of Massachusetts has recently upgraded its Title V regulations to provide some restrictions on building in sensitive areas, and as discussed above, to permit the use of some advanced denitrifying on-site septic systems. In addition, the Wetlands Regulations administered through the Massachusetts DEP's Division of Wetlands and Waterways and local Conservation Commissions, provide opportunities to regulate potential impacts to the marine resources. Conservation agents have authority to regulate within a prescribed area and can govern vegetative buffers, surface water discharges, erosion and sedimentation and possibly fertilizer and lawn chemical use within that area.

The Cape Cod Commission has developed and implemented a mass balance approach to limit nitrogen-loading from some new developments (Eichner and Cambareri 1992). The Mashpee Conservation Commission recently adopted the Commission's mass balance approach in a regulation that states that no housing unit within the Commission's jurisdiction, which is limited to within several feet of wetlands and coastal banks, can exceed 5 ppm nitrogen in its waste stream. This is a drinking water guideline and is probably not restrictive enough to protect the coastal resources of shallow, poorly flushed embayments.

Board of Health regulations are an extremely effective approach to regulating nitrogen-loading because they do not have a grandfathering requirement and can be passed without a public hearing. However, with some exceptions, such as the Cape Cod towns of Brewster and Chatham, traditionally boards of health have been reluctant to address marine environment nutrient loading issues (as opposed to nutrients in drinking water) since a clear human health connection has not been established. There is a need to clearly define the jurisdiction of the boards of health and to investigate the connection between marine nutrient loading and human health. Presently, there are many human health regulations from health boards that do protect the marine environment. Among those are regulations that control the use of underground storage tanks, on-site waste water treatment systems, privately owned package treatment plants, and boat pump-out facilities.

OPEN SPACE APPROACHES

Preserving land as open space reduces the potential number of houses and businesses and thus nutrients in the watershed. During 1994 and 1995 the Reserve worked closely with the towns of Mashpee and Falmouth, the U.S. Fish and Wildlife Agency, the Massachusetts Division of Fisheries and Wildlife, the Massachusetts Heritage

Program, the Mashpee Wampanoag Tribe, the Falmouth Rod and Gun Club, Trout Unlimited, Orenda Wildlife Trust and others to create a 6,000-acre U.S. Wildlife Refuge, much of it in the Waquoit watershed (Fig. 6.6). These partners all own open space land within the refuge boundaries and will continue to own and manage their lands. Federal funds will be used to purchase the approximately 3000 acres that could still be developed. The Reserve serves on the Mashpee National Wildlife Refuge Management Committee and will continue to seek funds and work to purchase land for open space within the watershed.

IMPACTS OF DOCKS, PIERS AND RECREATIONAL BOATING

Docks and piers are believed to have cumulative effects on coastal resources, especially when combined with the impacts of recreational boating associated with docks. Concerns include: vegetation loss from shading, chemical leachates from treated wood, construction impacts, fragmentation of beach habitats, sediment resuspension from boat propellers, boat paints, petrochemical spills and leaks, marine sanitation chemicals and nutrients, and propeller impacts on eelgrass. Although there have been several studies of commercial-scale piers and vessels, the cumulative impacts of many small private docks have not been adequately researched (See Chapter V).

According to the WBNERR Recreational Boating Survey (Crawford et al. 1994), there were about 1,000 boats moored or docked within contiguous Waquoit Bay waters in the summer of 1992. Many more boats access the Bay through the inlets or boat launching areas. A count made in 1992 by Reserve staff documented about 246 docks in the Falmouth portion and about 128 docks in the Mashpee portion of Waquoit Bay.

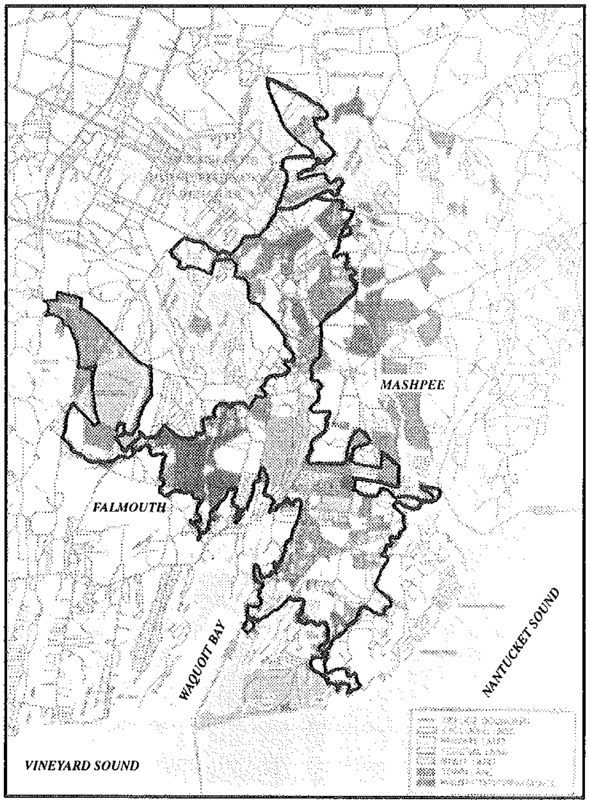

FIGURE 6.6
Boundaries of the Mashpee Wildlife Refuge. The preservation of open space reduces the amount of nutrients reaching coastal waters.

Out of concern for the potential degradation of water quality in the Bay from marine sanitation devices, the Intermunicipal Committee and the Association for the Preservation of Cape Cod (APCC) submitted an application to EPA to designate Waquoit Bay and its tributaries a "No-Discharge Area." The area was so designated in the Spring of 1994. Any discharge of either treated or untreated wastes is prohibited. Pump-out facilities are located at Edward's Boatyard on Childs River and at Little River Boatyard on Little River. The Little River pump-out is mobile and provides regularly scheduled service.

Another management option for regulating impacts from boating and docks is to implement watersheet zoning where certain areas of the waterbody such as resource protection areas (for example, eelgrass beds) are set aside for specific uses and/or protections. This approach has yet to be tried extensively but is seen as a natural extension of land use zoning.

OTHER CONTAMINANTS

Plumes From the Massachusetts Military Base

Contaminants from a variety of sources threaten the health of the Bay and its resources. There have been several toxic waste sites identified on the Massachusetts Military Reservation (MMR), which is now a Superfund Site, with about a dozen plumes traveling from the base in various directions. Part of the MMR is within the Waquoit watershed. At least one or two plumes are believed to be impacting Johns and Ashumet Ponds in the upper part of the watershed. Another plume is believed to be on an intercept course with the Quashnet River. Plans to contain the plumes and clean the groundwater are under development. There is still much to be learned about the plumes before it can be determined how effective a clean up will be and how much impact these plumes will have on the rivers and bays.

Septic System Pathogens

Failing septic systems can cause high fecal coliform counts that result in shellfish bed closures. The revised DEP Clean Water and Title V Regulations instruct towns to require that failing septic systems be replaced at time of property transfer.

Storm Water Runoff

Storm water runoff carries pathogens, petrochemicals, metals, salts, volatile organic compounds, nutrients and sediments that can lead to shellfish bed closures and other problems. The Moonakis River is frequently closed to shellfishing due to high fecal coliform counts. The Meadow Neck road bridge over the River has several gullies on either side where water pours into the river during storms. Storm drains would probably help reduce the shellfish closures and improve water quality. In addition the bridge is quite small, which constricts the river and impacts flow. The engineer for Falmouth's Department of Public Works has scheduled this bridge to be replaced in 1997. Prior to that there will be hearings to determine if the bridge should be lengthened so that the river width under the bridge more closely conforms to the natural width of the River.

Pesticide and Herbicide Applications

Pesticide and herbicide application on cranberry bogs, golf courses and lawns can impact marine organisms. Education and outreach programs could encourage people to voluntarily reduce chemical use.

Sedimentation

Sedimentation from boat propellers and erosion from construction projects and all-terrain vehicles can cause habitat and ecosystem degradation. Trout Unlimited has spent hundreds of hours and dollars stabilizing river banks along the Quashnet River because sediments were eroding into the river bed covering trout spawning habitat.

BARRIER BEACH DYNAMICS

JETTIES AND GROINS

Barrier beaches are inherently dynamic, the sand constantly shifted by wind and water. Attempts to stabilize beaches through groins, jetties and revetments often interfere with the natural processes of sediment transport and beach nourishment (see Chapter II). These attempts may actually increase the rate at which sections of the coastline change.

There are jetties on the eastern end of Washburn Island and on either side of the main Waquoit Bay inlet. Several groins are in place on the west side of the Menauhant inlet. Migration of the Washburn Island spit near Menauhant has resulted in stranding of groins placed many years ago on the western end of Washburn Island (Fig. 2.10). These groins no longer function as originally intended but might still affect the sand movement in the area. The Reserve needs to assess whether it is possible or desirable to remove some or all of these groins. Several federal and state regulations now make it more difficult to place structures that will interfere with coastal dynamics.

BREACH ON WASHBURN ISLAND

During Hurricane Bob in 1991 a new breach opened on the barrier beach of Washburn Island, in an area with a long history of inlet changes. This third inlet to the Bay was considered a threat by property owners behind the island who were now exposed to the Sound. The Reserve's Research Coordinator, Richard Crawford, working with Graham Giese of the Woods Hole Oceanographic Institution and student interns conducted a monitoring program, including aerial photography, to document the changes in the area and to predict the rate of future change (see Chapter II).

DREDGING

The Menauhant Inlet requires maintenance dredging. Before the 1991 breach, the inlet was dredged about every five years by the Falmouth Waterways Committee under a long-term permit through the Massachusetts DEP. Because the new breach has slowed the velocity of water passing through the Menauhant inlet, more frequent dredging is required. Within the constraints of the permit which include prior notification to the Falmouth Conservation Administrator and stipulations about fill placement, the Waterways Committee decides the frequency and extent of dredging. When the Menauhant inlet has been dredged during the past few years, the fill has been placed on the Menauhant side of the inlet. The Reserve has an agreement with the Falmouth Waterways Committee regarding the possible placement of clean dredge materials on Washburn Island. The agreement stipulates that the action must be discussed first with the Reserve Manager; the fill must be tested and determined "clean"; the material can only be disposed of on the beach outside of the piping plover nesting season; and the fill can only be placed on the beach between the vegetation and the high tide mark.

When the Reserve was designated, a few other areas were delineated as maintenance dredging areas. These include the main Waquoit inlet, the main channel in the Bay, and the Little River and Great River channels. To date dredging has not been required in these areas.

WATER WITHDRAWAL AND INTERCEPTION - IMPACTS ON RIVERS

CRANBERRY OPERATIONS

There are cranberry bogs along Red Brook, the Childs River and the Quashnet River. Cranberry growers regularly impound water during phases of their operations. This practice can be a problem for anadromous fish management because migration requires a specific range of water flow and temperature. Coordination would have to be accomplished through the joint efforts of the cranberry growers, the town conservation agents, the town herring wardens, the Massachusetts Department of Fisheries and Wildlife (DFW) and the Massachusetts Division of Marine Fisheries (DMF).

WELLS

Municipal Wells

A few years ago the town of Mashpee requested permission to place a municipal well on DEM and DFW land along the Quashnet River that is managed by the Reserve. The Commonwealth required the town to conduct a study to determine the potential impacts of water withdrawal on the Quashnet River, in particular on the ability of the River to sustain trout and herring fisheries. The town hired the USGS whose report indicates that water withdrawal has the potential to change the height, flow and temperature of the River, although to a very small degree. The Division of Marine Fisheries must decide whether these possible hydrological changes will affect the fisheries. The concern is that the River already has less flow than is considered optimal for a River to support trout. Could the small changes possibly caused by water withdrawal push the River beyond its ability to sustain the fisheries? These factors must be taken into account during reviews of other requests for water withdrawal in the area.

Private Wells

Numerous smaller single home on-site wells also intercept water that would go to the River with unknown cumulative consequences.

Massachusetts Military Reservation

The Massachusetts Military Reservation cleanup plan involves water withdrawal, filtering and reinjection. The clean-up plan released in early 1996 included provisions for pumping 27 million gallons of water a day which would be reinjected through several "galleries" the size of a football field. Because of the possibility of drawing down ponds as much as 4 feet, drying up wetlands, and impacts on groundwater, a technical team has assessed the plan and is recommending changes that would minimize the ecological impacts. There are still many questions about the feasibility of the clean up. Some fear that the solution is worse than the pollution in this case. An option might be to proceed a few at a time.

OBSTRUCTIONS

Along the Quashnet River there are several concrete structures from current and past cranberry operations. The largest structure, located within the 1 1/2 miles that Trout Unlimited has refurbished, now has a fish ladder. At the Johns Pond outlet to the Quashnet River there is a structure designed to regulate pond height. Pond users often remove or add boards to this weir which alters water flow in the Quashnet River. These structures, along with large tree snags and trash, form obstacles to the anadromous fish. The DFW has jurisdiction and responsibilities for managing the sea run trout; the DMF has jurisdiction for herring which they delegate to the local Mashpee herring warden. Despite all of the effort that has gone into restoring the Quashnet River, there are still problems with flow and sedimentation. Much more restoration work and vigilance is needed to insure unobstructed passage and compliance with regulations.

WILDLIFE HABITAT, MARINE RESOURCES AND ENDANGERED SPECIES MANAGEMENT

The habitats of Waquoit Bay and its watershed have been extensively altered over the past 350 years. The wetlands have been diked and channeled for mosquito control and drained for building. Eelgrass habitat has been lost due to a variety of impacts including coastal eutrophication, wasting disease and boat propellers. The decline of eelgrass affects fisheries, shellfish, waterfowl and the overall health of the Bay. River habitat has been channelized for cranberry bogs. Land has been molded, dug out and leveled. Much of the Waquoit Bay watershed has been developed. Where there used to be hundreds of waterfowl, deer, pheasant, quail, and furbearing animals, there are now just a few that are occasionally glimpsed. But these few remnants of larger populations are dependent on the remaining open spaces and wetlands that survive. These areas are often just fragmented pieces of larger ecosystems, not enough to support wildlife populations. It is important to protect these areas and where possible to connect the smaller pieces together and recreate some of the "wilderness." Several options and ongoing management strategies for protecting these valued resources are discussed below.

OPEN SPACE

Land protected from development will reduce nitrogen loading and preserve wildlife values and riparian habitat. The U.S. Wildlife Refuge, discussed in a previous section, is one approach to protecting wildlife habitat. The Refuge would provide almost 6,000 acres of contiguous habitat which includes wetlands, rivers, vernal pools, and hardwood forests. The Refuge would also connect to other open areas such as the Reserve lands at South Cape Beach, the Massachusetts Military Reservation, Crane Wildlife Reservation and the Mashpee Woodlands, creating even more contiguous open space.

ENDANGERED SPECIES

Several species found within the watershed and the Reserve are protected under state and federal regulations. The piping plover *(Charadrius melodus)* is a Federally threatened species that nests on South Cape Beach and Washburn Island. For years predators and human impacts interfered with successful hatching. In 1990 the Reserve started the volunteer Piping Plover Patrol. In cooperation with the DFW and the Massachusetts Audubon Society, the Reserve trains volunteers to patrol the beach for signs of mating and nesting. When eggs are laid, volunteers erect predator exclusion fences according to DFW instructions. In 1995, the first DEM Piping Plover Ranger was hired to coordinate the efforts on Reserve lands. Since the inception of the Piping Plover Patrol, more birds have returned to nest and they have expanded their nesting territory to Washburn Island.

Volunteers also inform beach-goers about the impacts of their activities on the birds: dogs can interfere with successful hatching; kites, which can resemble birds of prey, scare parents off the nests, leaving the eggs to fry in the hot sand; and illegal driving can destroy both nests and chicks.

The Federally Endangered roseate tern *(Sterna dougallii)*, which nests on Bird Island in Buzzards Bay, fishes for sand lance on the shoals off of South Cape Beach. The barrier beach provides an important resting and staging area for their feeding activity.

The least tern *(Sterna antillarum)*, a State species of Special Concern, also nests on South Cape Beach and is protected by the Piping Plover Patrol. The box turtle *(Terrapene carolina)* is another species of State Concern that is found on South Cape Beach, Washburn Island and the Reserve headquarters.

Sandplain gerardia *(Agalinis acuta)* is a Federally Endangered plant species that grows within the watershed near the Reserve boundaries. This extremely rare plant is found in only one other place in Massachusetts and only a few other places in the world. With funding from the U.S. Fish and Wildlife Service, the DFW is studying propagation techniques on Reserve lands. The Reserve's endangered plant management program limits mowing to certain times of the year. This program also protects other listed plants found within the Reserve:

- Bushy rock rose *(Helianthemum dumasum)* is listed in Federal Category 2 which indicates it is in need of further study. It is also a plant of State Concern.
- Two kinds of ladies tresses orchids grow at the Reserve headquarters. *Spiranthes vernalis* is a species of special State Concern. *Spirathes tuberosa* is on the State Watch List.
- Three kinds of sundews are found on South Cape Beach: *Drosera filiformis, D. rotundifolia,* and *D. intermedia. Drosera filiformis* is on the State Watch List.
- Birds-foot violet (*Viola pedata*) is a species of State Interest.
- Blazing star (*Liatris borealis*), found on Washburn Island, is in Federal Category 2 which indicates the need of further study and a possible change in listing to provide further protection.
- Butterfly-weed (*Asclepias tuberosa*), a large population of which is found on Washburn Island, is on the State Watch List.

Both butterfly-weed and blazing star would benefit from a controlled burn on the eastern side of Washburn Island to the south of the camp sites because they appear to be in danger of being choked out by rose, bayberry and other low shrubs. An accidental fire a few years ago resulted in a dramatic population increase. The Massachusetts Audubon worked with the Reserve to develop a management plan for blazing star which would include a controlled burn every few years.

MARINE SPECIES HABITATS AND RESOURCES

Eelgrass

The ability of the existing eelgrass *(Zostera marina)* beds to survive and for the traditional beds to be restored are dependent on improving water quality which involves managing nutrient inputs and boating practices (Fig. 6.7). Once nutrient loading is decreased and the macroalgae mats are reduced, eelgrass restorative practices such as planting could be implemented.

without an overlay district, but a district provides a means of requiring their use and guaranteeing proper maintenance—one of the DEP's concerns about the use of these more complicated systems. The Reserve received an Environmental Technology Initiative Grant from EPA to hold a conference in December 1995 to explore management districts; decentralized waste water facilities and management planning; and site evaluation, design and engineering. Papers on these subjects plus one on accountability for on-site systems are available at the Reserve. See the section below, Regulatory Approaches, for additional information.

Storm Water Runoff

Storm water runoff carries nutrients as well as pathogens and petrochemicals which can degrade water quality. There are several official drains and many unofficial "waterways" from state and town roads and private property within the Waquoit Bay Reserve. The Town of Falmouth has mapped the official storm drains but not the "waterways" which often route storm water into sensitive areas. The Town of Mashpee has not mapped their storm drains. The Massachusetts Department of Transportation will soon begin major work on Route 28, a state highway bounding part of the Reserve and traversing the watershed. The Department has maps of the official storm drains, but not the "waterways" on Route 28. The Reserve, the Town of Falmouth and WBNERR volunteers are working with the State to include non-point source pollution abatement in the project work area.

An assessment is needed of the contributions of nutrients to Waquoit Bay from storm water compared to that from wastewater, fertilizers and atmospheric deposition. The contribution of petrochemicals and pathogens also must be determined. To address this need, the Reserve, with the help of volunteers, has conducted Phase I of a citizens' shoreline survey in which signs of non-point sources of pollution from private land and public roads were mapped. During Phase II the significant sites will be sampled to determine how much pollution they contribute to the Bay.

Efforts to protect water quality need to include mapping storm water drains, waterways and other non-point source runoff sources. Remediation should involve the use of state-of-the-art approaches.

REGULATORY APPROACHES

Zoning

Horsley and Witten (1991) describe several zoning strategies that result in reduced nitrogen loading: overlay districts, prohibition of various land uses, special permitting, large lot zoning, the transfer of development rights, cluster designs, performance standards and growth clusters. Some of these options are discussed in the following sections.

• *Management Districts*

One approach to limiting nitrogen-loading is the creation—through town by-laws or intermunicipal agreement—of a water protection district that establishes nitrogen loading standards (Fig. 6.4). Bylaws and regulations would be developed that require practices that reduce the nitrogen generated from different land uses. Examples of regulations include: the Sanibel Island, Florida, laws that limit the area of a lot that can be cleared and made into a lawn which limits fertilizer use and maintains vegetative cover; and by-laws that require denitrifying septic systems in resource sensitive areas. The overlay district approach has been used in

Buttermilk Bay and includes the towns of Wareham, Bourne and Plymouth. In this case, the district is meeting the nitrogen loading standards by increasing buildable lot size thus reducing the number of homes, the source of much of the nitrogen (see "Downsizing" below).

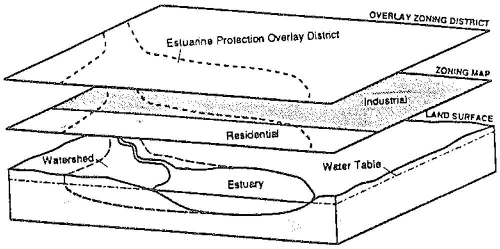

FIGURE 6.4

An overlay district is a zoning technique that communities can adopt via regulations or by-laws to protect water resources (reprinted from Horsley et al. 1991).

Intermunicipal cooperation and coordination would be required to implement a management district in the Waquoit Bay watershed as it includes parts of Falmouth, Mashpee and Sandwich. The main disadvantage is that many if not most of the lots within this watershed would probably be exempt due to the 7 protections under MGL Ch. 40. A section 6 which include "grandfathering" which exempts existing lot owners from new regulations. Only when a lot is sold is it subject to the new regulations.

- *Management District by Legislation*

Yet another option would be the establishment of a management district by legislative act at the state level. Within the district, various regulations or approaches that wouldn't be subject to the "grandfathering" restrictions could be implemented to reduce nitrogen loading, ensuring that everyone does their part.

- *Subdivision Control Act*

The Subdivision Control Act gives the towns the ability to set conditions, such as lawn size limits or septic system requirements (that go beyond normal town-wide bylaws) on specific developments. However, this approach would only limit nitrogen from new developments and would not reduce nitrogen from existing sources.

- *Downzoning*

Downzoning is an approach that requires specific mention. The Buzzards Bay Project (1991), a National Estuary Program, developed a nitrogen loading model to better understand nitrogen impacts from land use within their area. The model results suggested that water quality protection of Buttermilk Bay could be achieved if the three towns within the watershed cooperated to reduce the number of homes contributing nitrogen to Buttermilk Bay. As mentioned above, the towns created an overlay district using "downzoning" to increase minimum lot sizes (Fig. 6.5).

Although downzoning does not address the excess nitrogen from existing development, it may be feasible for reducing additional nitrogen loading. Concern has been expressed that regulations that significantly change land use will be perceived as a threat to property rights. Another frequently expressed concern is that requiring larger lots spreads development over more land. Instead, many people recommend clustering homes, leaving more open space. A comprehensive planning process could identify which areas should be left as open space and which should be buildable.

Nitrogen-Loading Regulations

The Town of Falmouth adopted a zoning by-law in the 1980s to limit nitrogen-loading to sensitive embayments. This regulation is noteworthy as it was one of the first efforts to regulate nitrogen loading to

RECREATIONAL MANAGEMENT

BEACH ACCESS FOR FISHING AND SHELLFISHING

Access to the shore and water for recreation and commercial shellfishing is a controversial issue. While many people are supportive of rightful access for shellfishermen, several people have expressed concern that area wetlands are being degraded through their use as access. An example is the path that has been worn through the wetlands around the small pond at the head of the Bay and to the right as you look out on the Bay. However, legitimate access is limited. In Waquoit Bay, although there are three public boat landings and open access at South Cape Beach, there are popular shellfish beds without any legal access nearby.

The Reserve discourages recreational fishing or shellfishing access through the headquarters since this site is a research and educational site. There is potential for user conflicts since there is only one narrow flight of stairs to the beach which is frequently used by researchers and outreach programs. People are instead encouraged to use the boat landings and South Cape Beach.

The Resource Protection Subcommittee has discussed installing boardwalks to protect the wetlands at the head of the Bay. However, there are additional issues such as parking, permits and financing that would have to be resolved first.

VEHICULAR ACCESS

The Reserve restricts vehicular access to the beach and back dirt roads on South Cape Beach because of adverse impacts on the resources and illegal dumping, and also restrict access to dirt roads on the Quashnet River property by request of the Mashpee Board of Health due to illegal dumping of household and construction trash, including some asbestos. Closing dirt roads is difficult in Massachusetts, especially if they are considered ancient cartways and have historic rights. However, the Reserve is expected to manage and protect the resources of these isolated areas which means either having more staff to provide a presence or eliminating vehicular access.

OFF-ROAD VEHICLES

There is a history of beach driving at South Cape Beach. Although both state and town regulations now prohibit this activity, the desire for easy access to good fishing still lures people through fences, gates and boulders onto the beach. As the vehicles drive over dunes, the vegetation that holds the sand in place is compacted and destroyed. Without the roots and rhizomes of the plants to stabilize the sand, the dunes quickly erode.

Driving on the beach has also destroyed nests and the nesting habitat of the Federally threatened piping plover. To combat the illegal beach driving the Department of Environmental Management and the town of Mashpee have worked to restrict access through the parking lots. A few years ago the town placed boulders across the front of the parking lot which are regularly replaced as the need arises. In the state parking areas there are gates, fences, boulders and signs preventing access. However, some people still get through. Because the Reserve's volunteer Piping Plover Patrol is on the beach every day during the Piping Plover nesting season, we are able to immediately report beach drivers and automobile tracks to the Environmental Police. It is hoped that fining a couple of illegal drivers will provide a deterrent to others.

People have also gained access through Wills Work Road which is a narrow, very rough dirt road. To prevent vehicular access which was resulting in dune erosion, the dumping of household garbage and large parties with accompanying fires and trash, the Department erected a metal gate. When several user groups complained about the limited access to Wills Work Road, the Reserve incorporated them into the South Cape Beach management program. Four user groups took monthly turns opening the gate at Wills Work Road early morning and closing the gate at dusk (since most of the inappropriate behavior takes place at night). They patrolled the area and cleaned up trash. These groups helped spread the word in the community about acceptable behaviors within the Park and provided valuable help in managing the area. Currently, in the summer when there are additional seasonal employees, the gate is closed in the evening and opened in the morning by Reserve staff. One of the neighborhood civic associations has expressed some interest in helping with the gate during the off season months provided they are assured that they will have no liability. DEM is rewriting the volunteer form to clarify the extent of liability and it is hoped that this will resolve this long standing management problem.

Foot Traffic

Foot traffic can also cause environmental degradation. At South Cape Beach people have worn paths around the banks of the salt ponds and through the dune vegetation, making these areas vulnerable to erosion. In the most heavily used section of South Cape, snow fencing has been erected to direct people to use the boardwalk.

Hunting

Hunting has been conducted continuously on South Cape Beach and Washburn Island beginning with the Wampanoags and then the colonists. An agreement between the Town of Mashpee and the Massachusetts Department of Environmental Management which details allowable uses on South Cape Beach such as swimming, fishing, hiking and birding does not specifically mention hunting. Uses not listed are reviewed on an annual basis by the South Cape Beach Advisory Committee, which makes recommendations to the Department of Environmental Management. During the review which includes a report on hunting from the South Cape Beach Supervisor, Committee members have consistently voted to allow hunting, although the number of votes against hunting has slowly increased.

During the past several years more houses have been built near the boundaries of South Cape Beach. The new parking area at South Cape Beach further limits the area available for safe hunting. In addition there is increasing recreational and research use of South Cape which could conflict with hunting. Eventually there could be increased public pressure against hunting in that area.

Many Wampanoags believe they have aboriginal hunting rights that exempt them from federal and state regulations and believe they should be trusted to know and respect nature's laws which would prevent them from hunting under conditions that would hurt the animal populations.

There is little camping and boating use of Washburn Island during the hunting season so there have not been conflicts between campers and hunters. However, WBNERR staff have removed illegal duck blinds from the Island on several occasions.

CAMPING

There are 11 legal wilderness campsites on Washburn Island available by permit through Reserve headquarters. No open fires are allowed and campers have to provide all they will need, including water.

The Island has been used for camping for years, long before the State of Massachusetts owned the property and before the Reserve was designated. As the number of people using the Island increased, the impacts on the resource intensified. For example, people burned trees, cut vegetation, impacted sensitive areas, caused sanitary problems, and left large amounts of trash. In a few instances people lived on the Island for several months with no sanitary facilities.

In 1988 DEM developed a management plan for Washburn Island. Campsites were selected on the basis of a resource survey. Camping was eliminated on the rest of the Island. During the first season rangers patrolled by horseback. Since 1990, island managers have lived on the island during the summer season. They check permits, discuss regulations, give interpretive walks and do light maintenance. First outhouses, then composting toilets, were provided. Gradually compliance with the regulations has increased so that most campers today have permits. However, there are still occasional wild parties with huge bonfires and several instances of illegal camping every year. In 1993 an illegal campfire burned about a third of the Island.

The campsites have been located in the same places for several years. An assessment needs to be done to determine if they should be moved to provide an opportunity for the resources in those areas to recover.

To properly manage the island, island managers should be available from May 15 through October 15, instead of just July and August. Although the Massachusetts Environmental Police are responsible for enforcing state regulations on state-owned land, they cover a large area and are frequently not available to respond. A person with enforcement authority needs to be available on a regular basis, preferably as a staff member.

EDUCATION AND OUTREACH

Education and outreach are important management tools. Most impact on coastal resources in shallow embayments comes from land use in the watershed. Management of the resources therefore involves increasing people's awareness of the impacts of various types of land and water use and encouraging them to make conscious life style decisions that will minimize the impacts (Fig. 6.9).

The Reserve offers an array of activities designed to increase people's awareness of the natural processes at work in an estuary and the impacts of man's activities on those processes. During the summer the Washburn Island Managers, the Interpretive Naturalist, the Education Coordinator and other staff plan and implement guided walks, open houses, special programs, the Evenings on the Bluff Series, canoe programs, a nature camp and request programs. During the year the Reserve holds workshops, conferences, training sessions, meetings and the annual Research Exchange Day that target local, regional and state coastal decision makers. Reserve staff present programs to an assortment of groups upon request throughout the year. The Reserve is also a "museum" partner to the Falmouth School System and conducts teacher training. As people understand the importance of estuarine and coastal habitats, it is hoped that they will take the appropriate actions needed to protect and better manage these valuable resources.

FIGURE 6.9
Education and outreach are tools that foster stewardship of valued coastal resources.

RESEARCH

Meeting the objectives of the Reserve for long term protection of the coastal and estuarine resources requires a continuing research and monitoring program that seeks to describe the natural and anthropogenic processes within the system. The Waquoit Bay Reserve has been an active research site since 1987 funded through a variety of sources, including NOAA's Sanctuaries and Reserves Division, the National Science Foundation and the Environmental Protection Agency. Also several state agencies such as the DEP, DMF and DFW have funded studies in the Bay. Much of the research has been described in Chapters II through V.

The Waquoit Bay watershed provides an interesting research site because there are multiple management issues. A long term database will allow us to assess changes over time. An understanding of the system and the development of management approaches based on the research will contribute to the overall understanding and management of shallow coastal embayments in the region. The successful management solutions applied in the Waquoit Bay watershed can then be shared with other similar watersheds along the Atlantic coast.

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