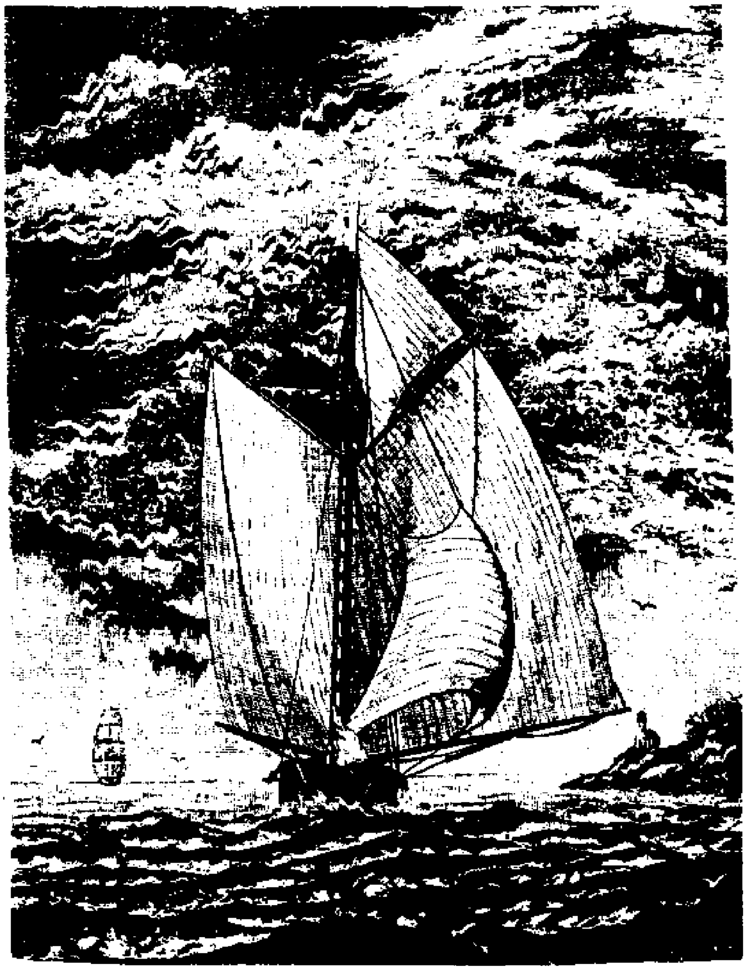
Historical Trends

Water Quality and Fisheries
Narragansett Bay



Alan Desbonnet and Virginia Lee

CRC COASTAL RESOURCES CENTER

RHODE ISLAND SEA GRANT

This publication is sponsored by NOAA Office of Sea Grant, U.S. Department of Commerce, under Grant #NA89AA-D-SG-082. The U.S. Government is authorized to produce and distribute reprints for governmental purposes notwithstanding any copyright notation that may appear heron.

Additional copies of this publication are available from : Rhode Island Sea Grant Publications, University of Rhode Island Bay Campus, Narragansett, RI 02882-1197. Order P1258.

National Sea Grant Depository Publication #RIU-T-91-001. Loan copies available from the National Sea Grant Depository, Pell Library Building, University of Rhode Island Bay Campus, Narragansett, RI 02882-1197.

Rhode Island Sea Grant. December 1991.

Cover Photo: From G.B. Goode. 1887. The fisheries and fishery industry of the United States. U.S. Dept. Interior, Washington, DC.

Sea Grant is a national program dedicated to promoting the wise use and development of marine resources for the public benefit.

Historical Trends

Water Quality and Fisheries
Narragansett Bay

A Report to

National Ocean Pollution Program Office
National Sea Grant College Program
National Oceanic and Atmospheric Administration
U.S. Department of Commerce
Washington, D.C. 20235

Alan Desbonnet and Virginia Lee

Coastal Resources Center
Graduate School of Oceanography
University of Rhode Island
Narragansett, RI 02882

Mapping: Neil K. Christerson
URI Department of Marine Affairs

Published by
Rhode Island Sea Grant
December 1991

Printed on Recycled Paper

Table of Contents

This document should be referenced as:

Desbonnet, A. and V. Lee. 1991. Historical Trends: Water Quality and Fisheries, Narragansett Bay. The University of Rhode Island Coastal Resources Center Contribution No. 100 and National Sea Grant Publication #RIU-T-91-001. Graduate School of Oceanography, Narragansett, RI. 101 pp.

Acknowledgments

Any review such as this, is based on the published work of numerous researchers. To list all of them would require an additional volume. A special thanks for assistance is given to: Caroline Karp and the staff members of the Narragansett Bay Project for the wealth of information they have provided for this project; Environmental Protection Agency Region I staff members for information and data on pollutant discharges into Narragansett Bay; Rhode Island Department of Environmental Management staff members for information concerning bay fisheries and pollution loadings; Scott Nixon at the University of Rhode Island Graduate School of Oceanography for access to a wealth of data, much of which is at present unpublished; Save The Bay staff for several manuscripts and information on Mount Hope Bay; the University of Rhode Island Geology Department for providing GIS data used to produce the maps used in this document; and the University of Rhode Island Pell Library staff for tracking down and providing a number of difficult-to-obtain manuscripts.

We are indebted to Andrew Milliken and Suzanne Bricker-Urso, graduate students who spent countless hours transcribing data into computer files, manipulating and transforming the data, and Neil Christerson, who produced the maps for the document. We are also indebted to Annette Burgess, who provided the nimble fingers and the many hours required to transcribe, lay out, and produce the finished document, and to the numerous referees who reviewed all or portions of this manuscript. We are grateful to Eleanor Ely for her excellent editing.

Funding for this project and publication was provided by the National Ocean Pollution Program Office and the Office of Sea Grant, National Oceanic and Atmospheric Administration, U.S. Department of Commerce.

Alan Desbonnet
Virginia Lee

December 1991

Chapter 1

A Profile of Narragansett Bay

> *But the great feature of the Narragansett Basin was and is Narragansett Bay, the great sunken river at the ocean.*
>
> *T.W. Bicknell, 1920*
> *"The History of the State of Rhode Island and the Providence Plantations"*

The Physical Environment

Narragansett Bay covers an area of approximately 379 km^2 (including Mount Hope Bay and the Sakonnet River) and comprises three drowned river valleys shaped during the Wisconsin glaciation event of 12,000 years ago (McMaster, 1960). These drowned river valleys are referred to as the West Passage, East Passage, and Sakonnet River (see Figure 1.1). They are separated by the major islands of Conanicut and Aquidneck. The estuary is 64.5 km long from Slater's Mill dam on the Blackstone River at the head of tide of the estuary to Whale Rock at the mouth, and averages 8.6 km wide (range 2.1–12.9 km)(Pilson, 1985). For its moderate size, the bay is relatively deep. Average depth is 8.31 m overall, 7.5 m in the West Passage, and 15.2 m in the East Passage (NOAA, 1985). Dredged channels 11 to 13 meters deep extend up the East Passage to the ports of Providence, Rhode Island and Fall River, Massachusetts. The bay contains a total volume of 2.6 x 10^9 m^3 (Chinman and Nixon, 1985) of relatively high-salinity water (25–32 ppt). Although the upper reaches of the bay have been named the Providence and Seekonk rivers, they are not rivers in the usual sense. They are tidal and are part of the estuary, with an average salinity of 18–28 ppt. Table 1.1 is a summary of descriptive physical characteristics of Narragansett Bay.

Table 1.1 Physical characteristics of Narragansett Bay.

Area of Bay[a]	379.1 km^2
Average Depth[c]	8.3 m
Estimated Volume	3.15 x 10^9 m^3
Area of Watershed[d]	4.3 x 10^6 km^2
Average Salinity[b]	29 ppt
Mouth of Bay	32 ppt
Head of Bay	18 ppt
Total Freshwater Input[d]	107.5 m^3/s
Input Range	51-185.0 m^3/s
River Input[d]	88.9 m^3/s
Taunton R.	29.7 m^3/s
Blackstone R.	24.4 m^3/s
Pawtuxet R.	11.7 m^3/s
Woonasquatucket R.	2.8 m^3/s
Moshassuck R.	1.2 m^3/s
All Others	19.1 m^3/s
Rainfall Onto Bay Surface[d]	13.6 m^3/s
Sewage Treatment Plant Input[e]	5.0 m^3/s
Average Tidal Range[c]	
Mouth of Bay	1.1 m
Head of Bay	1.4 m
Average Flushing Time[b,c]	26 days
Range	10–40 days

[a] Including Mount Hope Bay and Sakonnet River
[b] Pilson, 1985
[c] Spaulding, 1987
[d] Ries, 1990
[e] Pilson, 1989

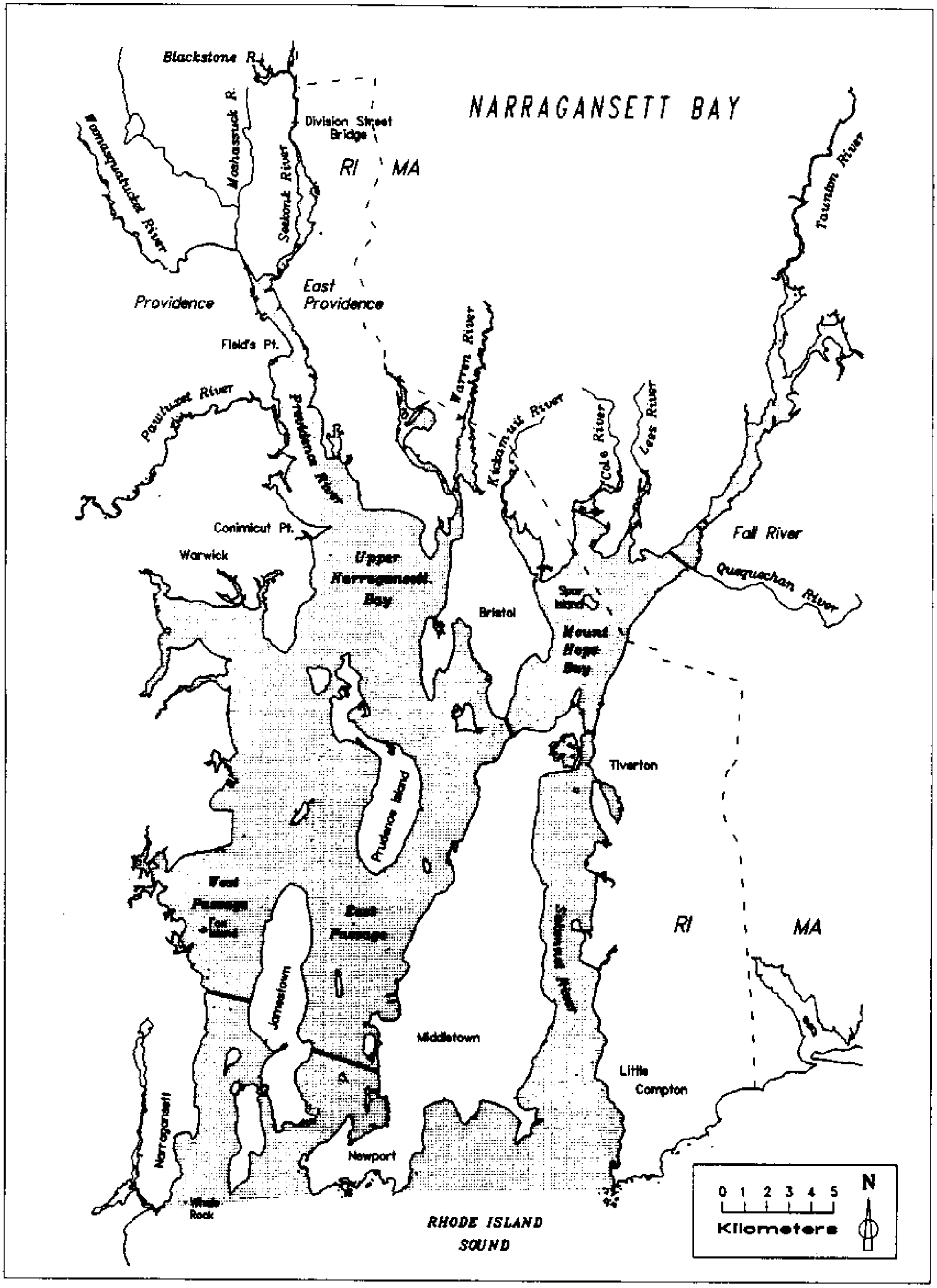


Figure 1.1 Narragansett Bay. Data provided by RIGIS (1990).

Geological Overview

The bay bottom is composed of glacially derived sediments covered with up to 15 m of silt and sand eroded from land over the past 8,000–12,000 years. In general, the sediments tend to be sand toward the mouth of the bay, grading to mud and silt in the upper reaches which receive most of the riverine and wastewater loadings (McMaster, 1960). Because the watershed was scoured during the most recent glaciation event, sediment loads arriving to the bay from rivers are generally small, and the quantity of total suspended matter in the bay is minor. Suspended sediment concentrations average 4 mg/l, but values as high as 100 mg/l have been recorded occasionally in the Providence River and may be attributed to sewage treatment plant inputs. Santschi et al. (1984) determined that, on average, Narragansett Bay presently accumulates sediment at a rate of 0.3 mm per year.

The bay's shoreline is indented and generally steeply sloping, affording sweeping views of the bay. Because of the many islands and small coves, the shoreline is quite long relative to the size of the bay. The shoreline is varied, ranging from rocky headlands at the southernmost wave-washed tips of the mainland and islands, to quiet coves fringed with salt marsh scattered around the bay, to bulkheads in the urban environments of the many small ports around the bay and the city waterfront at its head.

There are a few sandy beaches along the bay in places where longshore currents have built small barrier spits across shallow embayments or formed cuspate beaches such as Conimicut Point. The most common shoreline along the bay is a narrow beach of gravel, cobble, and boulders backed by a scarp or bluff of unconsolidated glacial sediments. The scarp is often unvegetated and steeply sloping. The most erosion resistant shorelines are bedrock. In sheltered waters where sediments accumulate, salt marshes flourish and overlie the rock, sand, or silt; however, salt marshes make up only approximately 3% of the total open-water area of the bay (Halvorsen and Gardiner, 1976). Compared to estuaries like Chesapeake Bay and Indian River Lagoon, Narragansett Bay supports relatively little vegetation. Eelgrass beds are limited to patches. A 1978 shoreline survey by Boothroyd and Al-Saud (1978) revealed that one-fourth of the natural shoreline had been replaced by man-made structures such as piers, bulkheads, wharves, and pilings. Boothroyd is currently conducting a similar study to update these results.

Climate

Narragansett Bay is situated in a temperate climate zone which imparts a marked seasonality to air and water temperatures. Annual air temperature averages 10°C, ranging from temperatures of 1.7°C for January–February (the coldest months) to 22.0°C for July (the hottest) (Figure 1.2). Freezing temperatures typically occur 120 days per year, between November and March. Interestingly, annual air temperature has increased slightly since the early 1960s (Figure 1.2). Surface water temperatures also exhibit a warming trend from 1967 to 1985 (Figure 1.2). Surface water temperature varies seasonally, from an average of -0.5°C in December to 24°C in August (Figure 1.2). Annual water temperature averages 9.9–11.6°C (Figure 1.2). Ice cover during winter months is generally limited to surface waters in the upper parts of the bay and adjacent shallow coves.

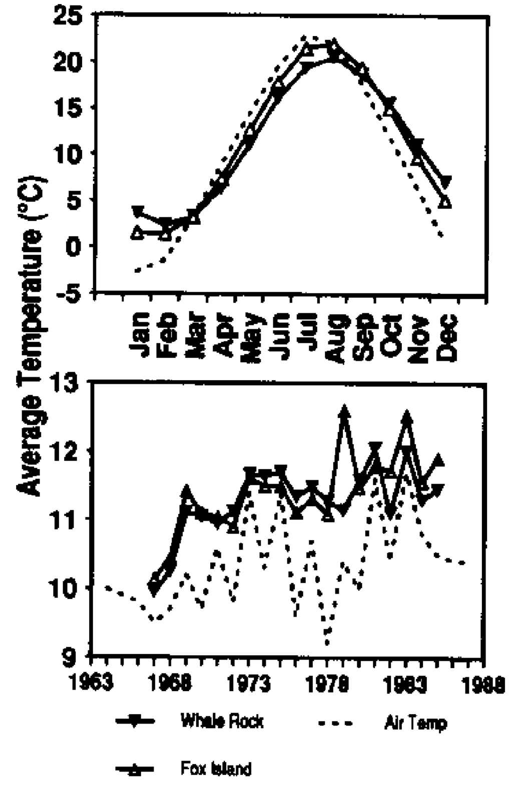


Figure 1.2 Time weighted monthly and average annual sea surface (Jeffries et al., 1988) and air temperature (Pilson, 1989) along Narragansett Bay, showing increases in air and water temperature since at least the mid-1900s. Air temperatures collected south of Providence, RI at T.F. Green State airport. See Figure 1.1 for locations of sea surface sampling sites.

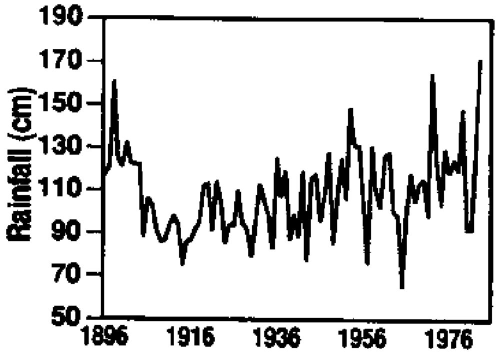
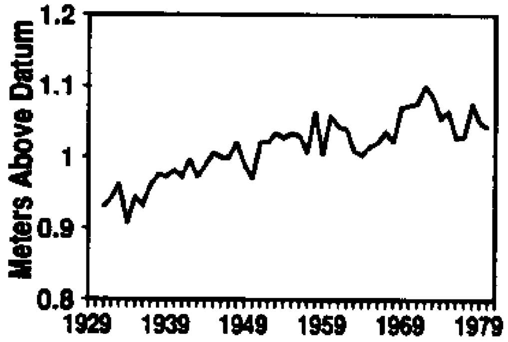


Figure 1.3 Long-term time weighted average annual precipitation in the Providence, RI region, showing a gradual increase since 1915. Data taken from Pilson (1989).

Rainfall averages 106 cm per year, with little seasonal change exhibited in precipitation patterns. In general, July is the driest month with an average rainfall of 2.49 mm per day and December is the wettest month with 3.94 mm of precipitation per day (Pilson, 1989). Measurable precipitation occurs about one day out of three throughout the year. Although average annual snowfall is 101 cm, it is rare for snow to remain on the ground for any length of time. As shown in Figure 1.3, a slightly upward trend in average annual rainfall has been noted for the bay region since the early 1900s. The time-averaged annual precipitation for this period is 115.3 cm. Some seasonality in cloud cover is evident, with November–December being the most cloudy period and July the least.

Figure 1.4 shows an average annual rise in relative sea level at Newport since the early 1930s. This apparent sea level rise is due to a combination of local coastal subsidence and eustatic sea level rise due to global warming trends. Hicks et al. (1983) determined from 50 years of data that Narragansett Bay experiences a relative rise in sea level of approximately 1.8–2.6 cm per decade.

Figure 1.4 Long-term changes in relative sea level height at Newport, RI showing an average increase of 22 mm/decade. Datum refers to a fixed benchmark (1959) from which measurements of sea level are taken, and ensures consistency between years of measure. Data taken from Hicks et al. (1983).



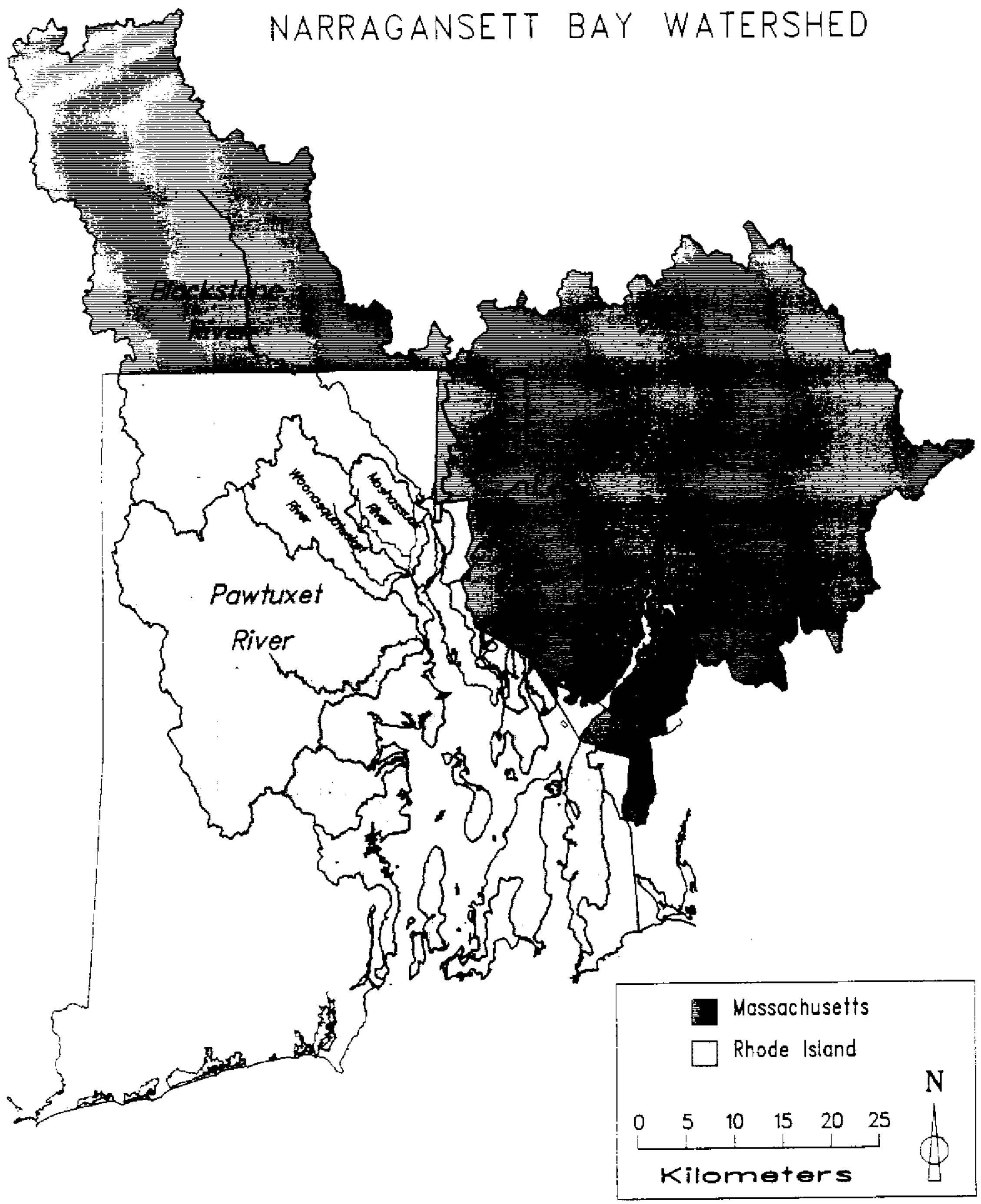


Figure 1.5 The Narragansett Bay drainage basin. The watersheds of the major tributaries to the bay are labeled, as are those portions in the state of Massachusetts. Map data provided by RIGIS (1990).

Freshwater Inputs

Five rivers provide 78% of the surface freshwater input to Narragansett Bay. These rivers drain a watershed of 4.3 x 10^6 km^2, much of which is contained within the state of Massachusetts (Figure 1.5). Total average annual input of fresh water into Narragansett Bay is estimated by Ries (1990) to be 107.5 m^3/sec (adapted from Ries, 1990). Rivers and runoff account for 83% of total fresh water input to the bay, 4% is provided by sewage treatment discharges, and 13% from rain falling directly onto the bay's surface (Table 1.1).

United States Geological Survey (USGS) gauging stations have monitored river flow on the bay's two major tributaries, the Blackstone and the Taunton, since 1929, and on other tributaries more recently (see Table 1.2). The total gauged river flow to the bay is distinctly seasonal, with a maximum in March and a minimum in August (Figure 1.6). The August minimum is a result of a rapid rate of evapotranspiration rather than a seasonal reflection of the amount of rainfall (Pilson, 1989; Figure 1.6). Although river flow to Narragansett Bay is highly variable, a slightly increasing long-term trend is evident (Figure 1.7), possibly correlated to long-term increases in annual precipitation.

It appears that over at least the past thirty years, Narragansett Bay is getting warmer, receives increasing amounts of freshwater from precipitation and river flow, and experiences coastal subsidence due to sea level rise.

***Figure 1.6** Time weighted monthly averages for gauged river flow and precipitation to the bay, showing the lack of correlation between the two, and the lack of seasonality in precipitation to the bay area. Data taken from Pilson (1989).*

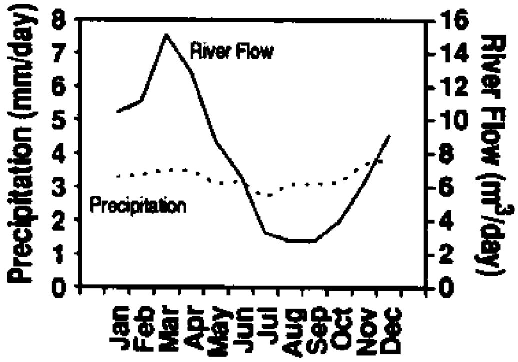


***Figure 1.7** Long-term time weighted average annual river flow to Narragansett Bay, suggesting a slightly increasing trend over time. Data taken from USGS river gauging records for the state of Rhode Island as reported by Pilson (1989).*

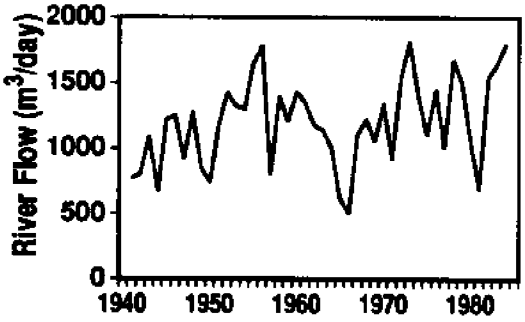


***Table 1.2** USGS river gauging stations used to estimate river flow into Narragansett Bay. Drainage area refers to the area of drainage basin above the gauge, often much less than that of the entire river.*[1]

USGS Gauging Station	Drainage Area (km^2)	Years of Service
Taunton River at State Farm	668.2	1929-1976 1985-1987
Wading River near Norton	112.4	1953-1966
Ten Mile River at N. Dighton	218.3	1967-present
Segreganset River near Dighton	27.5	1966-present
Blackstone River at Woonsocket	1077.4	1929-present
Moshassuck River at Providence	60.4	1963-present
Woonasquatucket River	98.9	1941-present
Pawtuxet River at Cranston	520.6	1939-present
Hunt (Potowomut) River	59.3	1940-present
Annaquatucket River	16.9	1961-1964

[1] From Pilson, 1989

Circulation

Narragansett Bay is a well-mixed or vertically homogenous estuary (NOAA, 1985). Since the bay receives relatively small amounts of freshwater input compared to the volume of tidal flushing, it does not exhibit a strong vertical salinity gradient and stratified conditions do not exist in the bay proper. However, strong vertical density gradients are common where tributaries enter the bay (that is, in areas such as Mount Hope Bay or the Providence and Seekonk Rivers).

Circulation throughout the bay is a function of winds, tides, and riverine input. Semidiurnal tides move the water within the bay every 12.5 hours, producing a tidal range from 1.0 m at Newport to 1.4 m at the head of the Providence River (Wang and Spaulding, 1985). The tidal range produces a mean tidal prism of 347.5 million m^3, or 13% of the bay's total volume (Kremer and Nixon, 1978). The tides are the major as well as the most consistent force that transports materials into, out of, and around the bay.

The residence time of water in the bay averages 26 days (Pilson, 1985) but varies according to freshwater input. Residence time may be as long as 40 days during periods of relatively low river flow, or as short as 10 days during periods of high river discharge (Pilson, 1985). Residence time of water in Narragansett Bay is therefore a function of freshwater input and will vary seasonally (Figure 1.8). Above a mean flow rate of 300 m^3/sec, flushing time stabilizes and little further increase in flushing time occurs with increased freshwater input (Wang and Spaulding, 1985).

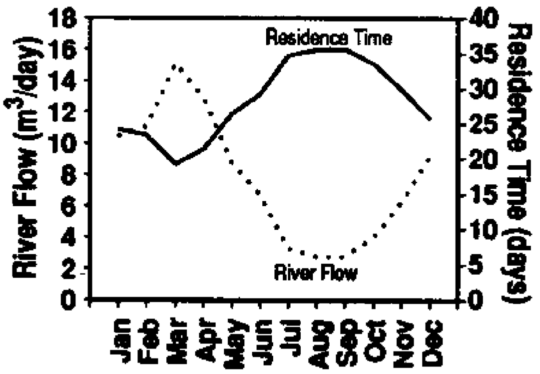


***Figure 1.8** Seasonal pattern of residence time of water in Narragansett Bay compared to seasonal river flow, showing the dependency of flushing time on freshwater input to the bay system. Data taken from Pilson (1989).*

The effect of changes in riverine input is greatest in the Providence–Seekonk River area, where flushing time averages 3–5 days but can be less than 24 hours during storm events (Malcolm Spaulding, pers. comm.). The effect of increased freshwater input is noticed throughout the bay by a decrease in flushing time, but the magnitude of the effect decreases along a downbay transect.

Winds may have some short-term influence on water movement, but their overall long-term effect on circulation patterns is minimal (Malcolm Spaulding, pers. comm.). When blowing from the south, winds have the potential to force water into the Providence River and trap it there; but long-term isolation of water in the Providence River is rare, due to the periodicity of weather fronts which move over the Narragansett Bay region every 3–5 days. Predominant wind direction is from the northwest in winter. It shifts to southwest in summer, contributing to the moderate maritime climate by blowing cool offshore breezes up the bay on hot summer days.

Narragansett Bay is a highly saline estuary with a mean salinity of 28 ppt. Although the salinity of the water varies both spatially and temporally, the salinity gradient observed in Narragansett Bay is weak, having a mean value of 32 ppt at the bay's mouth

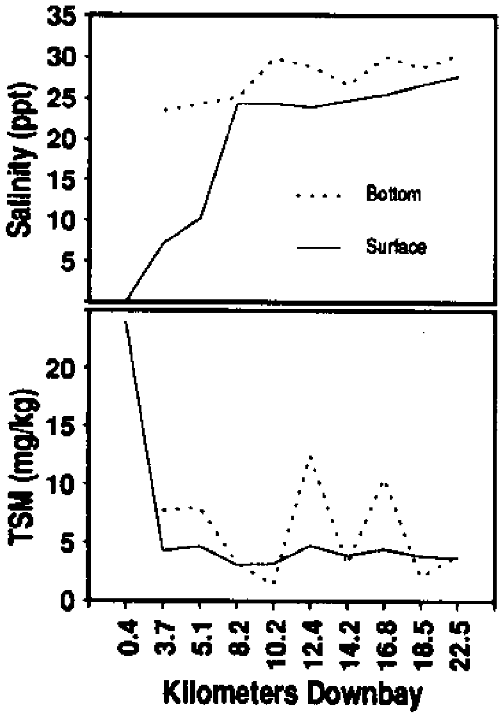


Figure 1.9 Downbay profiles of salinity and total suspended material in bottom and surface waters of Narragansett Bay during August 1987. Note the rapid decrease in TSM at the head of the bay where salinity change is most rapid. Data taken from Doering et al. (1988).

(where it meets Block Island Sound) and 18 ppt at its headwaters in the Seekonk River (Figure 1.9). The transition zone is very short—only a couple of kilometers. Fresh water flows from the Blackstone River over the falls into estuarine water at the head of the Seekonk, where summer salinity reaches 10–23 ppt. As a consequence, the turbidity maximum saltation effect occurs in the Seekonk River, well before the bay proper (Figure 1.9). Since Narragansett Bay is very well mixed, the formation of thermoclines or haloclines is restricted and not characteristic of the bay as a whole.

Major Uses

The following section outlines the major uses of Narragansett Bay. In these discussions, the described uses pertain to the state of Rhode Island, which borders nearly all estuarine portions of the bay. Major uses are not discussed for that portion of Massachusetts which borders Mount Hope Bay.

Shoreline Development

English immigrants first arrived and settled in the Narragansett Bay region in 1636, most gaining their livelihood from farming, whaling, or shipping. Land settlement occurred rapidly in Rhode Island: by 1850, 80% of the state was cleared as cropland or pasture, and by 1880, 26,000 farms existed statewide (Olsen et al., 1980). Subsequently, agricultural land use declined as more productive farm and pasture lands were discovered in the newly opened western territories and prairie states, and farmers began an exodus out of the state. As of 1970 only 600 farms remained in the state, and by the beginning of the 1980s only 9% of the state's total acreage was classified as agricultural (NOAA, 1987a).

During the early 1800s, as farming reached its peak in the state, industrialization began along the coastal regions. Industrialization increased at a rapid rate, especially along river courses where the flow of water could be exploited both for moving water wheels to work industrial machinery and as a convenient disposal site for waste products. Development along the rivers in the Providence area progressed rapidly and soon turned Providence into one of the shipping and industrial capitals of the nation.

By World War II, Rhode Island had become a national leader in terms of foreign trade, large automated factories, adaptation of steam power for industrial purposes, and the rapid growth of its industrialized cities.

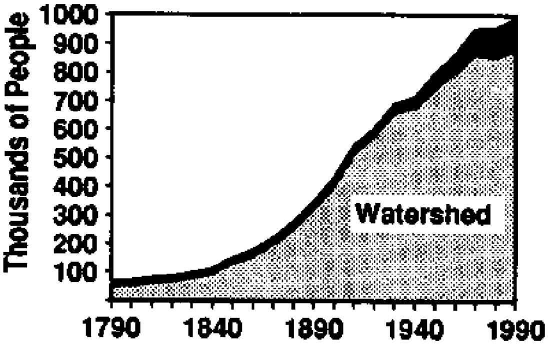


***Figure 1.10** Long-term changes and trends in population growth in the State of Rhode Island (black) and the part of the state draining to Narragansett Bay. The majority of the state's populace resides within the bay watershed. Data from Rhode Island Bureau of the Census and Population Statistics.*

During the middle part of this century, however, the bottom fell out of the New England textile industry and the Providence metropolitan area experienced a loss of population as people moved to more suburban areas.

In the 1970s and 1980s, development along Narragansett Bay's shoreline increased to accommodate the influx of suburbanites. Farm and pasture lands were rapidly converted into housing developments, a trend that continues today. The majority of the Rhode Island population chose to live within the watershed of the bay, intensifying development pressures on coastal resources (Figure 1.10).

As coastal development proceeded at a rapid pace, the shoreline of the bay was significantly altered. By 1960, the U. S. Fish and Wildlife Service Wetlands Inventory estimated that 50% of Rhode Island salt marshes 40 acres or more in size had been lost to development.

Recreation

Recreation has long been a primary use of Narragansett Bay. By 1865 Newport had already become a world-famous resort for the wealthy, and the upper bay's many coves and beaches had become vacation areas for the working-class population. The America's Cup yacht races began in the late 1800s in the waters off Newport and continued to be held there until 1987 when the Cup was lost to an Australian racing team. Well-established ferry services during the early 1900s linked Boston and New York to Newport and other ports in Rhode Island, and steamboat excursions expanded throughout the bay to carry visitors to shore-dinner houses and amusement parks all along the shore. By World War II, the resort businesses of the bay area had reached their zenith. The advent and rapid rise in popularity of trolleys and automobiles however, pushed the ferry services into a decline as people were able to make easy day trips to the ocean beaches along the south shore.

The final blow to both the resorts and the excursion boats was the 1938 hurricane, which leveled many of the resorts and extensively damaged the piers where the boats took on passengers. Today Newport still carries the flavor of a luxurious era, and is home to the Newport Jazz Festival, the La Forge Casino Tennis Hall of Fame, and myriad quaint shops and restaurants. No longer summer cottages for millionaires, the mansions are now major tourist attractions.

One of the major recreational uses of Narragansett Bay is for pleasure boating. Recreational boating exceeds other uses of the bay (commercial fishing and shellfishing, and shipping) in terms of both number of people involved and economic impact (Robadue and Parker, 1986). About one-third of the state's population goes boating on the bay one or more times a year. Between 1960 and 1988, the number of personally owned small craft nearly tripled, increasing from 11,126 registered boats in 1960 to 29,101 boats in 1988 (Willis, 1988). The rise of recreational boating on the bay is also reflected by the fourfold increase in the number of dockage slips: from 2,054 in 1960 to 7,344 in 1979, and to 9,772 in 1988 (Collins and Sedgwick, 1979; Robadue and Parker, 1986; Willis, 1988). Demand for boat slips is such that there is a serious shortage of marina space. As a consequence, the number of recreational boat moorings has increased 250% in the past decade, from 1,621 in 1978 to 5,659 in 1988 (Collins and Sedgwick, 1979; Willis, 1988).

Fishing

Commercial and recreational fishing are important uses of Narragansett Bay. Large recreational fisheries for bluefish, scup, tautog, winter flounder, summer flounder, and striped bass exist within the bay during different times of the year. Recreational fisheries tend to be seasonal, beginning during the winter flounder runs in the early spring and continuing until the striped bass and bluefish schools leave the bay region in the late fall to early winter. Very little recreational fishing takes place during the months of December, January, and February. According to NOAA (1987b), in 1987, 1.7 million saltwater recreational fishing trips were made on the bay by 417,000 people, half of whom were Rhode Island residents.

Winter flounder and hard clams are the most important commercial fisheries in the bay, and Narragansett Bay hard clams are known nationwide for their high quality. The hard-clam (quahog) fishery is currently growing in national importance as a major supplier of clam meat, especially as commercial landings from New York and Florida decline (Haynes, 1989). Limited fisheries exist for lobster, surf clams, and conch, the most important of which—at least in terms of the value of the landed catch—is the lobster fishery.

Shipping

During the colonial period, maritime commerce was the driving force behind Rhode Island's economy. The bay offered excellent harbors and was well situated to support both international shipping and commercial fishing. Newport was a major colonial city and port until it was blockaded by the British during the Revolutionary War.

By 1790 Providence had established itself as the major shipping port for the state of Rhode Island; but the city lost nearly all of its international trade by 1830 due to wars in Europe and pirate activity offshore. Shortly after the downfall of the Providence shipping trade, a boom in the textile industry bolstered the city's population and economic status. Since the fall of the luxurious steamship-ferry industry (see previous section), the major shipping commodity in Narragansett Bay has been petroleum products.

Shipping in Narragansett Bay increased substantially after World War II, reaching a peak in 1973 when more than 5,000 vessels entered the bay. The bulk of the increase can be attributed to the rising demand for imported petroleum products. In 1977, 12.5 million tons of cargo came into the Port of Providence, which handled two-thirds of the total inbound and outbound cargo through the bay, and of this nearly 90% consisted of petroleum products (Robadue, 1986). Along the Providence River at the port facilities, 635 acres were used for import and export of waterborne commodities, and 85% of this acreage was devoted to petroleum handling and storage (Robadue, 1986). Recently the

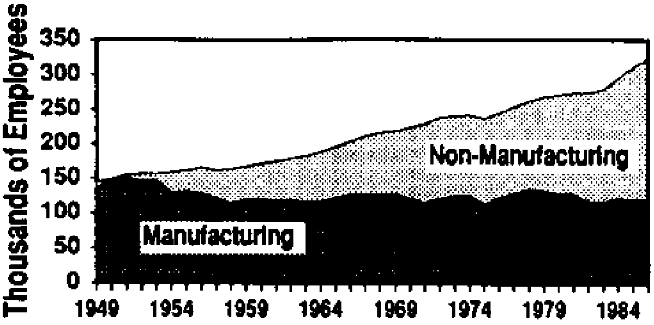


Figure 1.11 Changes in the manufacturing base in Rhode Island since 1950 showing a steady growth of non-manufacturing and service sector employment within the state over time. Data taken from Rhode Island Statewide Planning and Employment Statistics.

port has experienced declining shipping activity due to a trend to consolidate shipping in big ports such as New York and Boston.

Industry

The American industrial revolution started 200 years ago with the mechanization of Slater's Mill at the falls where the Blackstone River empties into the Seekonk River. By 1860 Rhode Island was the most industrialized state in the union (McLoughlin, 1978), and by the turn of the century Providence boasted the world's largest tool factory (Browne and Sharpe), file factory (Nicholson File), engine factory (Corliss Steam Engine Company), and silverware factory (Gorham). In addition, the city ranked number one nationally in the production of woolen and worsted goods and in the manufacture of jewelry (Conley and Campbell, 1982).

Until the mid-1900s, the largest single employment sector in the state was manufacturing (Figure 1.11). Throughout the 1970s and 1980s, employment in manufacturing has been slowly replaced by employment in wholesale/retail, health care, business services, and finance and real estate.

Textile manufacturing was the single largest employer of the work force in Rhode Island for much of the late 1800s and early 1900s. As late as 1950, textile manufacturing still employed 45% of the total manufacturing work force, but by 1980 this proportion had fallen to 8%. The decline of the textile industry has been attributed to foreign competition, with its lure of cheaper labor and overhead, and to the fact that southern states are comparatively nearer to raw products.

Jewelry manufacture boomed in Rhode Island from 1940 to 1970, peaked in 1978, and then declined slightly so that by 1982 it made up 24% of Rhode Island's total manufacturing employment (Figure 1.12). The decline of the jewelry manufacture business is attributed to foreign competition and changes in fashion over the years. The third most important industry in Rhode Island is the metals and machine-tool industry, which recently has also seen some decline. At present tourism is the fastest-growing sector of the economy, ranking third behind jewelry and health care (New England Econometrics, 1988).

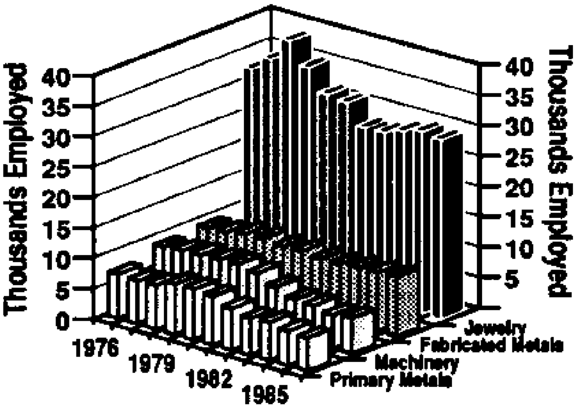


Figure 1.12 Recent changes and trends in the manufacturing employment sector within Rhode Island. Data taken from New England Econometrics (1988).

Chapter 2

Bay Issues and Management: An Overview

Perhaps most importantly, increasing population growth and development throughout the watershed in the last decade, ... threatens to offset the recent improvements we have seen in the upper Bay and Providence River.

Each and every one of us who lives in or visits the Bay and the surrounding region benefits from our proximity to Narragansett Bay waters. And each and every one of us can act to ensure a healthy, prosperous future for the Bay.

The Narragansett Bay Project, 1990
"Planning for a Better Bay"

During the past several decades, concern over the environmental health and well-being of Narragansett Bay has increased dramatically. Newspaper reports, magazine articles, television shows, environmental advocacy and other user groups, governmental and regulatory agencies, and the scientific community are more carefully scrutinizing and reporting upon the conditions and events occurring in Narragansett Bay and adjacent coastal waters. The scrutiny and reporting have been intense since the establishment, in 1985, of the Narragansett Bay Project, funded by the U.S. Environmental Protection Agency and the Rhode Island Department of Environmental Management.

As part of its five-year management and planning agenda for Narragansett Bay, the Narragansett Bay Project undertook an assessment of the public perception of problems occurring in the bay. Representatives of fishing interests, development interests, marina and boating interests, environmental groups, industry, and specialized groups (such as scuba divers) were interviewed, and the results were compiled in a report entitled *Narragansett Bay Issue Assessment: Public Perceptions* (Brown et al., 1987). The following summary is based, in part, on that report.

Issues

Comprehensive Management

The users interviewed for the Narragansett Bay Project assessment perceived current management policies as inadequate to resolve conflicts over uses. Many felt that the bay is being overdeveloped, with environmental concerns given insufficient weight when balanced against coastal development, and that management of coastal areas by state regulatory agencies is short-sighted and pro-development.

Bay users saw a need for a stronger, more unified, more environmentally directed management strategy and authority. However, although most users expressed a desire for management aimed at promoting multiple uses of the bay as a resource, each user group felt that its own interests represented the most beneficial use of the bay. The only two points of consensus across user groups were that quahogging should be given precedence over boating and marinas when conflicts between these uses arise and that a new state authority should be created to manage the bay for multiple use as an integrated entity. At present, towns direct coastal development, using state regulatory guidelines as well as their own set of zoning ordinances. This style of coastal development often results in differing patterns of use of the shoreline in towns along the bay. User groups felt that a state authority should oversee coastal development within the bay to ensure equitable use between user groups, as well as to ensure that development is not environmentally degrading.

Pollution

All user groups except industry, development firms, and marinas viewed pollution of the bay as the most significant problem. Definitions of pollution in the bay included visible trash, sewage-treatment odors, siltation, toxic chemicals, and industrial discharges. Respondents feared that pollution could lead to environmental degradation, habitat destruction, diminished health of the ecosystem, and restricted use of the water for swimming and shellfishing. Many expressed concern about the long-term effects of toxic pollutants, most of which come from industrial discharges. However, sewage treatment discharges were viewed as the pollution that most severely degrades the use and aesthetic quality of the bay, as well as producing human health risks associated with swimming, boating, and shellfish consumption.

Cleanliness of the bay was viewed as a priority, especially because the bay attracts tourists and business, both vital to the financial health of the state. The most common opinion was that the bay should not be used as a waste receptacle. Many respondents recommended that "clean" industry and use of the bay should be promoted in management strategies. Reducing sewage input discharges was seen as essential to cleaning up the bay.

Risk from Contaminated Fish and Shellfish

The health risk from consuming contaminated fish and shellfish was the second major concern expressed by users of Narragansett Bay. In particular, respondents were worried about contaminated shellfish illegally harvested from polluted waters. Seafood consumers suggested increased enforcement policies to reduce the potential for harvesting seafood from polluted waters. Fishermen, on the other hand, defended the quality of their products and believed that poor care and handling of the product after it is brought to market are responsible for seafood-related illnesses. Fishermen suggested that a better sampling protocol be developed to more accurately evaluate human health risks associated with harvested shellfish.

Shoreline Development

Many bay users perceived shoreline development to be out of control in Rhode Island and cited this as an example of the inadequacy of comprehensive bay management. The potential for limiting public access to the bay by overdevelopment of its shore was the most frequently mentioned concern, followed by the fear that the bay's aesthetic appeal would decline. Bay fishermen are particularly concerned about the loss of coastline to development as it pertains to loss of dock space for fishing vessels. All user groups, marinas included, felt that poorly planned coastal development, such as that presently perceived to be occurring in Rhode Island, leads to increased pollution and decreased public access and fish stocks. All users noted a need for better management of coastal development along Narragansett Bay.

Enforcement Issues

All user groups believed that enforcement of regulations for boating safety, fishing limitations on shellfish size, and industrial pollutant pretreatment technology is inadequate. They perceived inefficient enforcement of minimum-size fishing regulations as potentially damaging to future shellfish stocks, and fishing in polluted waters as a threat both to human health and to the reputation of Narragansett Bay shellfish products.

As use of the bay for recreational boating increases, the potential for accidents increases. User groups were of the opinion that the majority of boaters using the bay "know absolutely nothing about boating" and stressed public education as a way to increase boating safety awareness, etiquette, and observance of the "rules of the road."

Dredging

The disposal of dredge spoils from the dredging of channels, harbors, marinas, and commercial docks was perceived to be a problem for Narragansett Bay. Since Rhode Island presently does not have access to a dredge spoil disposal site either on land or at sea, no dredging in the bay has occurred in a number of years and many areas are losing water depth due to siltation. User groups saw a great need to study the potential effects of dredge spoil disposal in the bay and to identify a suitable disposal area before the need for dredging becomes critical.

Permitting Process

A general perception existed among user groups that the permitting process (for building, upgrading facilities, dredging, etc.) is inefficient. A too-broad overlap in regulatory agency responsibilities results in a permitting process that takes too long and is too complex, due to the number of agencies involved. Streamlining the permitting process was viewed as a prerequisite to improving management within the estuary.

Bay Managers

Figure 2.1 shows the major governmental institutions in Rhode Island that are presently involved with water quality control in Narragansett Bay. Although the figure does not provide detailed information for the state of Massachusetts, Rhode Island and Massachusetts are currently organizing joint planning committees in an effort to cooperate to improve water quality in Narragansett and Mount Hope bays. Once the differences between the two states' management systems are worked out, significant progress in attaining improved water quality should be possible.

Historical aspects of Governance and water quality are reviewed in Needham and Robadue (1990) and Hennessey and Robadue (1986). The Rhode Island Department of Environmental Management is primarily responsible for pollution abatement. It oversees the permitting for direct discharges of wastewater or cooling water to the bay and administers the construction grants program for new sewage treatment plant facilities in the state.

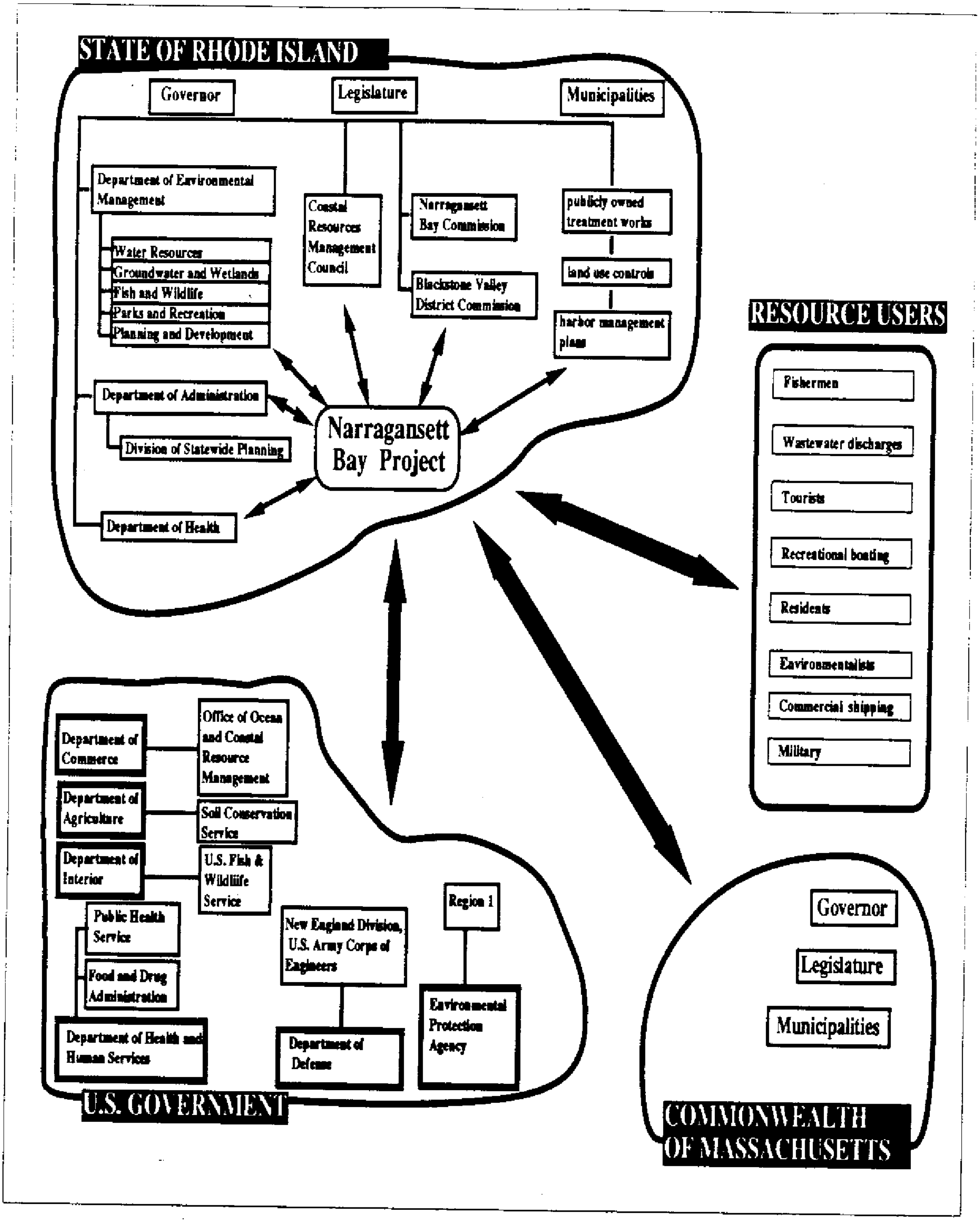


Figure 2.1 Major Rhode Island governmental institutions involved in water pollution control in Narragansett Bay. Taken from Needham and Robadue (1990).

The Narragansett Bay Project– A Major Research Initiative

The Narragansett Bay Project was created in 1985, under amendments to the Clean Water Act, as a $1-million-per-year, 5-year study to determine the condition of Narragansett Bay and to make recommendations for its management. The project defines its overall purpose as "preserve and promote the environmental quality of Narragansett Bay, including its biological, chemical, physical and socio-economic aspects; preserve a healthy Narragansett Bay for posterity so our children may enjoy some of the same benefits we have derived from the Bay." (Narragansett Bay Project, 1987).

The intensive study phase of the project began in 1985 and has proceeded for the past five years. The studies performed by the Narragansett Bay Project have been both numerous and diverse, covering biology and ecology of bay flora and fauna, use of bay resources, and use and management of land bordering the bay. As of this writing, the Bay Project has begun to formulate a management plan for the bay, with expected completion of a plan for the estuary by December of 1991. After this time, the Bay Project is funded for another four-year period to implement and oversee the newly designed management plan. Beginning in 1995, the Bay Project will be dissolved and the state of Rhode Island will be responsible for maintenance of the management plan.

Save The Bay– A Potent Environmental Advocacy Group

Save The Bay, a privately funded, nonprofit organization, was founded in 1970 to answer the need for a grass-roots statewide organization dedicated to protecting and maximizing the assets of Rhode Island's greatest natural resource—Narragansett Bay. At present the organization boasts a membership of approximately 12,000 people, making it the largest local environmental activist group in the nation.

Save The Bay defines its purpose as "to ensure that the water quality of the bay is restored and that the ecosystem of the bay, the tributaries and the wetlands throughout the bay's drainage basin, are protected from the harmful effects of human activity. Recognizing that the quality of life in and around the bay is not to be jeopardized by increasing demands that may be placed upon its resources, we seek carefully planned utilization of the bay within the system's natural capacity to function normally and healthfully both now and in the future." (Save The Bay, 1988).

Save The Bay functions both as a watchdog for activities and programs of government and citizenry that in any way degrade the environmental quality of the bay, basin, or watershed, and as a public awareness group dedicated to education concerning the ecology, value, and pollution problems of Narragansett Bay. Save The Bay has undertaken legal challenges of both industrial and municipal polluters of the bay, and also produces technical reports that investigate pollution sources, such as for combined sewer outflows and municipal sewage treatment discharges.

Chapter 3

The Providence and Seekonk Rivers: Growth and Pollution

> *Nature, in all her goodness, had bestowed upon it (Narragansett Bay) the advantages and resources necessary in an abode for active, hardy, and vigorous men. In the hills, valleys, streams and waterfalls were the exhaustless forces that would create and sustain manufactures of many varieties; in the climate and soils the rewarding fruits of intelligent tillage; in the open-harbor tidal waters, uniting in one great artery to the ocean, the streams of agricultural and manufacturing industries, the opportunities and wealth of commercial enterprises.*
>
> *J.W. Haley, 1939*
> *"The Old Stone Bank History of Rhode Island"*

Colonial Narragansett Bay

The Providence Plantations, originally founded by Roger Williams as a haven for persecuted religious dissenters, were colonized in 1636. The region was rapidly populated as it provided good harbors and waterways for trade and commerce and fertile soils for agriculture. The original industry of the region was shipbuilding, which began in the late 1600s (Hale, 1980). By 1769 Narragansett Bay merchants owned 200 vessels engaged in foreign trade and 300-400 engaged in coastal trade, and employed 2,200 seamen (Hale, 1980). When the first continental navy was formed, Rhode Island played a major role in its development because of the state's large force of skilled artisans. Although colonial times heralded rapid population growth and increased use of Narragansett Bay both as a source of food and for travel, relatively few pollution problems resulted; industries were low-impact and small-scale, and water quality remained near pristine into the late 1700s.

Newport, near the mouth of the bay, was Rhode Island's premier city for trade and commerce. Major commodities were rum, molasses, and slaves, which formed the infamous "triangular trade route" where slaves were purchased in Africa and traded in the Caribbean for molasses, which was then distilled into rum in the states (Hale, 1980). Newport maintained its standing as the state's most prosperous commercial center until the British occupation of the port during the Revolutionary War, when the center of commercial activities shifted up the bay to Providence (Conley and Campbell, 1982).

Commercial and agricultural activities prospered around the bay to such an extent that by the late 1700s and the Revolutionary War, Rhode Island was the most heavily populated colony, with a density of 45 people per square mile (McLoughlin, 1978). Privateering became one of the most popular occupations of the time, with 65 Rhode Island ships engaged in this activity (Hale, 1980). Shipping remained the leading commercial activity in the state until the mid-1800s.

The Industrial Revolution

The cornerstone for industrialization of Providence and the upper bay was laid on December 20, 1790, when Slater Mill at the Pawtucket Falls on the Blackstone River went into operation, using water to provide the power to produce woven cotton cloth (Conley and Campbell, 1982). This event marked the beginning of the factory textile system in America and led to the rise of manufacturing throughout the Narragansett Bay region. Between 1790 and 1830, industrialization in the Providence area began to replace commerce and trade as the state's leading economic activity as businessmen shifted their interests to the developing mill industries at the head of the bay (Conley and Campbell, 1982; Hale, 1980).

The Narragansett Bay region possesses certain distinctive topographical and geological features that helped industrialization progress rapidly. Early industry relied heavily upon the abundantly flowing fresh water at the head of the bay to power machinery and to dispose of solvents, dyes, and other waste products. Unlike many estuaries along the piedmont plain of the Atlantic seaboard, Narragansett Bay has at its head a watershed that is characterized by relatively steep topography. Therefore, the rivers drop steeply as they flow toward the bay, with water velocities sufficient to turn the water wheels that powered industrial machinery. Moreover, since the rivers flowed through glaciated watersheds carrying little suspended sediment load, they provided clear water for washing and rinsing textiles. Convenient access to navigable water and the relatively short distance (approximately 37 km) from the head of the estuary to the open waters of the Atlantic Ocean provided for a cheap alternative to expensive land transportation. The bay is sufficiently deep all along the route from its mouth to its head to allow easy navigation for even the deepest-draft sailing vessels of the day, further increasing the attractiveness of Providence as an industrial site.

With water-powered industry came large-scale damming of all the tributaries leading into the head of the estuary, which created barriers to migrating anadromous fishes. Industrialization not only led to changes in the landscape, as mill towns grew around the upper bay, but also started large-scale pollution of the waterways leading into the bay.

Industrialization of the region initiated the rapid urbanization of land around the Providence and Seekonk rivers by creating a large demand for a labor force. To provide cheap labor for their growing factories, leading industrialists had the port of Providence declared a port of immigration. During the early 1800s, a great influx of immigrants began to arrive at the port of Providence, finding employment as unskilled laborers in the prospering factories of the region. Members of the immigrant labor force were typically given the most hazardous duties and the lowest pay of the mill workers (Conley and Campbell, 1982). As immigrants moved into the city, the more affluent Rhode Islanders began an exodus into suburban areas, converting farm and pasture lands to residential use.

From the time of first settlement until the late 1700s, the development and use of the Narragansett Bay area had a relatively low environmental impact. But this changed dramatically with the advent of the industrial revolution and the bolstering of the region's population to meet the needs of industrialization. However, little thought was given to the environmental impact of industrialization upon Narragansett Bay and its tributaries until the latter part of the 19th century.

As the population in the city of Providence grew from 7,614 in 1800 to 16,832 in 1830, residents disposed of garbage and other refuse, including raw sewage, on city streets and on the banks of rivers in the upper bay near the city. These unsanitary conditions led to a severe epidemic of cholera that ravaged the city of Providence in 1854 (Olsen et al., 1980). Snow's 1855 description of the Moshassuck Canal, which flows into the Providence River, as "foul smelling with hogs, dogs and cats [floating] in the water and large quantities of gas arising from decaying substances" aptly depicts the general environmental conditions present at the head of the estuary.

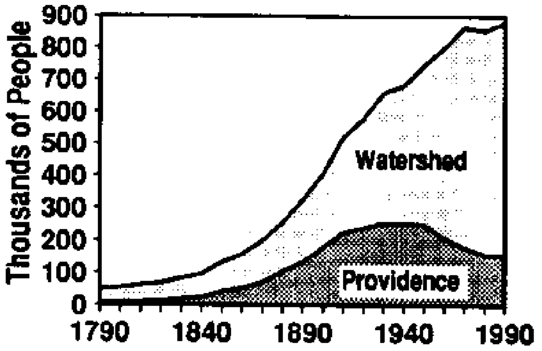
Epidemics of cholera and typhoid became so common and widespread that the city fathers created the post of Superintendent of Health for the City of Providence in 1856. E.M. Snow, a public-health leader of national stature, was the first appointee to this post. His initial job was to enforce the collection and disposal of kitchen refuse and garbage for the city's population, which had swelled to 47,785—more than a sixfold increase in a span of 50 years (Conley and Campbell, 1982). This marked the beginning of actions taken to improve public health in the heavily industrialized Providence region.

The outbreak of the Civil War caused a boom in textile production, as woven material was needed to supply the Union troops with uniforms (Conley, 1986). Even though cotton supplies from southern states were curtailed during the war, textile manufacturing was able to increase production by shifting from cotton to wool. The war, with its demand for guns, cannon, bayonets, swords, ammunition, and other articles of war also bolstered the region's metalworking industry (Conley, 1986). The end of the Civil War heralded the Gilded Age of Rhode Island—a period of rapid industrialization and growth, especially in the city of Providence, accompanied by a dramatic rise in untreated waste loadings to upper Narragansett Bay and its tributaries.

At the time, diseases were believed to be communicated through the air, as is evidenced in a statement by Snow (1865) that "the causes of cholera are, first, the mysterious atmospheric condition...and local conditions of filth and impure air." Worries about cholera, typhoid fever, and other diseases supposedly spread by sewer gases sparked employers' concern over the potential loss of labor due to illness, forcing public officials to act in order to remedy the conditions described by Snow (1865) in the City of Providence: "In many of the sultry days of July and August, this filth of the streets, moistened by the street sprinklers, and fermenting in the vertical sun, filled many portions of our city with a most nauseating and depressing atmosphere." In 1869, in response to this concern, the cities of Providence and Newport were empowered by law to lay public drains and sewers. The first sewers in the city were simple conduits that removed animal and human wastes from city streets and piped it to the bay at the nearest location. City streets were hosed down daily to move manure and refuse from the street to the bay. This phase of sewage treatment cleaned up the filth that had previously accumulated on city streets, and the populace was pleased with the apparent cleanliness of their city.

City population growth accelerated at an even more rapid rate than ever before: In the 44-year span from 1855 to 1899, population tripled, growing from 47,785 to

Figure 3.1 Population growth trends in the city of Providence and the bay watershed contained in the state of Rhode Island. Data from US Bureau of the Census. 1990 census taken from preliminary data.



175,597 (Figure 3.1). Manufacturing was also increasing rapidly, from two mills with 60 workers in 1850 to 17 mills with 8,249 workers in 1895 (Conley and Campbell, 1982). This resulted in increasingly large accumulations of sewage and manufacturing wastes along the banks of the increasingly urban upper estuary. Banks of stinking sewage lined the Seekonk River, and the water turned vivid hues depending on the dye colors discharged each day from the textile mills.

By the late 1800s, the Rhode Island Board of Health considered the Seekonk and Providence rivers a threat to public health. Water quality had deteriorated to the point where it was commonly reported that people fainted from noxious fumes of hydrogen sulfide while crossing over the Providence River. Numerous reports in local turn-of-the-century newspapers told of fetid odors, scum on the water, fish kills, red tides, and persistent anoxic conditions—all testimony to the filthy conditions caused by the disposal of untreated industrial and human wastes into the urban estuary, and the inadequacy of the sewer system.

Such conditions in the portion of the bay that flowed through the heart of the capital city—especially a city entering a gilded age of growth and prominence—had to be corrected, and studies were commissioned to determine ways of alleviating this ever-growing threat. In 1879 the Providence Board of Health sent questionnaires to medical doctors in an attempt to map and locate disease sources and then target problem areas. In 1882, 431 cases of typhoid fever were reported in Providence in four consecutive weeks (Rhode Island Board of Health, 1894). In 1888 Dr. C.V. Chapin, the second Superintendent of Health, traced an outbreak of typhoid in Providence to a tenement on the banks of the Pawtuxet River. The Pawtuxet River had provided the public drinking water supply for the city of Providence since the Pettaconsett water works pumping station opened in 1876 (Providence City Engineer, 1893).

In 1892, European studies demonstrated that many diseases were carried in drinking water supplies that were fouled with sewage, and in 1894 the Rhode Island Board of Health suggested that either the Providence water supply should be moved upstream of major pollutants and filtered prior to distribution in Providence, or else intercepting sewers should be constructed to carry wastes to the mouth of the Pawtuxet River, downstream of the water-supply intakes (Rhode Island Board of Health, 1894). A filtration plant was installed in 1895 to filter the Providence water supply prior to its being pumped to the metropolitan area (Rhode Island Board of Health, 1905). In order to better track potential public health threats, the Rhode Island Board of Health initiated monthly monitoring for contamination of all public water supplies (except the Providence water supply, which was monitored twice monthly) (Rhode Island Board of Health, 1912). It was not until 1925, though, that the Pawtuxet was deemed unfit for use as a domestic water supply and the Scituate

Reservoir was constructed to provide clean drinking water for the Providence metropolitan area.

The system of sewers that drained the city and emptied directly into the bay (two outfalls along India Point and five outfalls along the Dorrance Street docks) created major water-quality problems in the harbor. The city dredged routinely to maintain a 6 meter-deep channel along the Providence and Seekonk rivers into the inner city harbor. In 1891, 4,337 m^3 of sewage deposits had to be dredged from around wharves and docks in Providence (Providence City Engineer, 1891). In response to the fetid conditions occurring in the harbor near the capital city, an interceptor sewer system was proposed. In 1892 the city sewer system was upgraded, and sewer pipes were installed along the west side of the river to intercept the direct discharge of vast amounts of untreated wastes all along the upper bay and transport them to Field's Point at the southern edge of the city. This improved conditions in the Providence River to a limited extent, but created a new set of problems outside the city limits.

The concentrated discharge of large volumes of untreated wastewater directly into the upper bay at Field's Point took its toll on populations of shellfish, particularly the commercially valuable American oyster. In the 1891 Annual Report by the Rhode Island Commissioners of Shell Fisheries it was noted that: "Great Bed [near Field's Point] was considered the best planting ground in the State, but now only a very small part of that ground is used for planting oysters. Oysters planted upon the Great Bed, before being put upon the market, are taken up and planted further down the bay, in order to perfect them for sale. The reason of this failure is difficult for us to explain. Some experienced oystermen attribute it to one cause and some to another. The general opinion is that the ground is too near the city; that the increased amount of sewage pouring into the bay from the city destroys the health of the oyster...".

In 1898 a massive red tide and fish kill occurred in the upper bay region. Nixon (1989) gives an excellent account of the probable reasons for this event. Evidently the concentrated discharge of massive amounts of untreated sewage at Field's Point produced conditions that made the Providence River susceptible to nuisance algal blooms. The algal blooms led to severely reduced dissolved oxygen conditions in the water column, which in turn produced widespread fish kills. The stench and public-health hazard posed by the decaying fish carcasses caused widespread concern over the health of the water in the upper bay, and once again focused attention on the problem of sewage disposal.

From 1900 to World War II

At the turn of the century, cases of waterborne diseases such as typhoid and cholera were decreasing, and it was believed that water quality in the upper bay was improving even though both population and industrial manufacturers—along with the resultant pollutant discharges—were increasing. Public-health concerns shifted to concentrate on bacterial contamination of shellfish and swimming areas. In addition, industrial pollutants, especially petroleum derivatives, emerged as a major concern and focused public attention on water quality to a greater degree than ever before. The oyster industry had grown rapidly to become a prominent economic entity in the state and an important and vocal political lobby for water-quality improvement.

By 1900, 40% of the state's entire population resided in Providence, which ranked 20th in size nationwide with 175,597 people (Conley, 1986), and the number of people living within the watershed had reached 837,170—half the 1980 level (see Figure 3.1). The Seekonk and Providence rivers were still being used as convenient sites for the mass disposal of both human and industrial wastes, with an estimated 6 million gallons of manufacturing refuse and 50,000 pounds of grease being dumped into the river each day (Olsen et al., 1980).

In response to the degradation caused by the untreated sewage discharged at Field's Point, the City Engineer was sent to Europe to study state-of-the-art sewage treatment and design a treatment facility for the city. By 1910 a new chemical-precipitation sewage treatment plant was operating at Field's Point. At the time it was the largest treatment facility of its kind in the country and was considered a model for other cities. With the addition of lime, the 30-million-gallon-per-day (MGD) plant chemically precipitated out solids and discharged the treated wastewater on ebb tide. At first the solids were used as fill around the facility, and later they were pressed into cakes and transported to the Public Dumping Ground, just south of Prudence Island in the East Passage, for disposal (Figure 3.2).

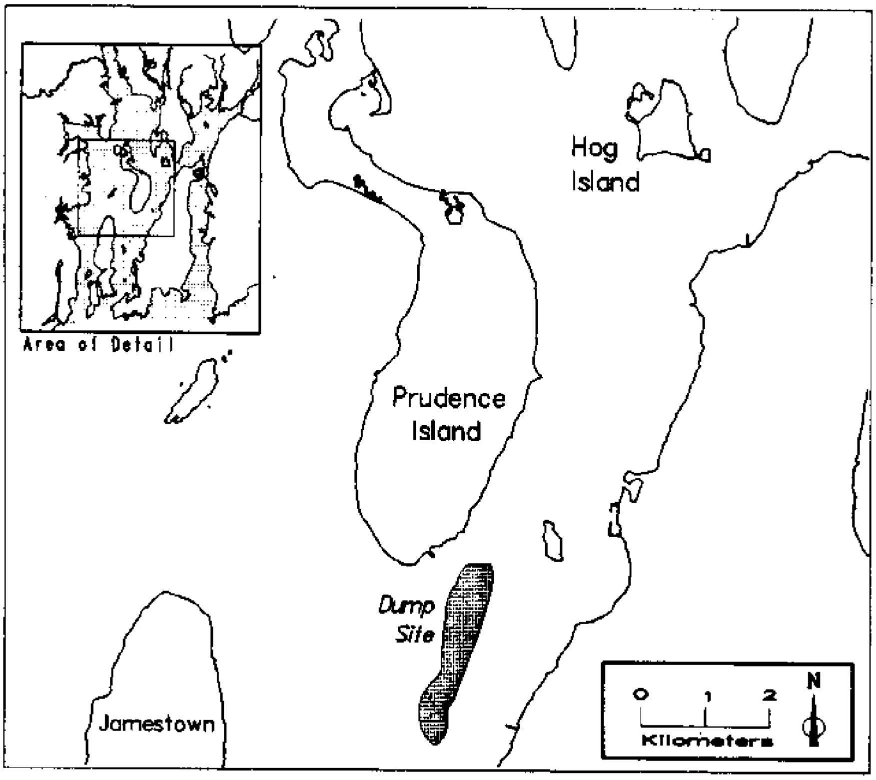


Figure 3.2 Location and extent of the sewage sludge disposal site in Narragansett Bay. RIGIS (1990).

Although by the early 1900s water quality degradation had begun to seriously affect the upper bay, industrial barons were now shifting their concerns away from employee health and toward the need for pure water to produce steam for the steam engines which had nearly replaced water-powered machinery. Coal had now become an important fuel source, and coal gasification residues and oil began to work their way into the upper bay from direct discharges and tank leaks.

Petroleum derivatives had now entered the list of Narragansett Bay pollutants, becoming so widespread that the 1905 Report of the Commissioners of Shell Fisheries reported a large number of oystermen complaining of oysters tainted with gas, a serious threat to the marketability of their product. The Board of Health Annual Report of the same year (1905) confirmed that the esteemed purity of the Narragansett Bay oyster was in jeopardy: "What was once a reliable and safe food is now an absolute source of danger. If perchance they [oysters] have been taken from the beds in the upper river, they are less liable to produce gastric disturbances, for the odor of gas permeates the mass which should be redolent with the salty odors of the ocean, and they are pushed aside in disgust." It was also feared that the oily film on the waters of the Providence River was reducing aeration of the water column and potentially reducing populations of diatoms and other foods for shellfish. A 1906 report by G.W. Field to the Shell Fisheries Commission stated: "We find that this water contains in solution and suspension at least 660 parts per million of the tarry and oily matters which we have found to be directly and indirectly injurious to shellfish in the manner detailed below. It is certain that the above described substances are at present entering the bay in sufficient quantities to seriously injure the growth of shellfish through the destruction of their food supply, and at times even to kill the oysters" Formal suit was filed by the oystermen against the Providence Gas Corporation, which did not contend the case, paid fines on two separate charges, and reportedly rectified the problem by locating wastes where they would not leach into the estuary.

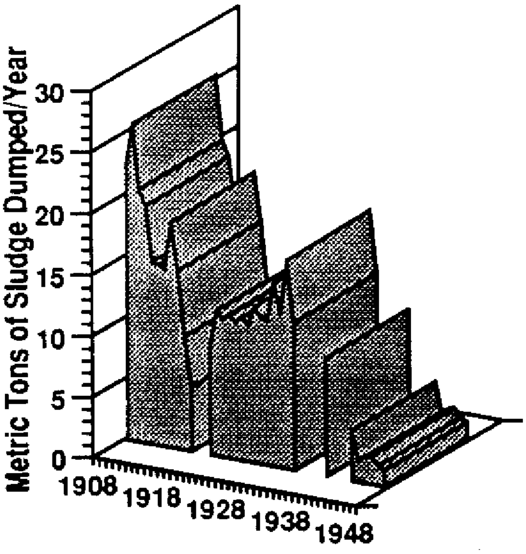
Bacterial contamination of bay waters and shellfish beds also emerged as a water-quality issue. In 1905 it was found that *B. coli (Bacterium coli;* old name for *Escherichia coli*), a bacterial indicator of sewage pollution, could be found in oysters three-quarters of a mile south of the treatment facility at Field's Point (and a surface pollution slick was evident a full six miles south of the plant site). Pollution in the upper bay was perceived as a serious threat to the future of the oyster industry, which had grown to the point of becoming the largest and most important fishery in the bay in terms of both pounds landed and dollars generated.

In 1910 the Oyster Growers Association of Rhode Island filed suit against the state of Rhode Island for pollution of public waters with "sewage and dredgings [sludge cake] and other substances," and noted, "There is a continuance of the prosperity of this industry, although many things have arisen which might be injurious to the same, particularly the pollution of the tide waters of the State" (Rhode Island Commissioner of Shell Fisheries, 1911).

In response to the suit, the Commissioners of Shell Fisheries took two actions. First, they requested that the treatment facility at Field's Point begin chlorination of sewage with bleaching powder to disinfect the effluent (Rhode Island Board of Health, 1910). Although bleaching reduced *E. coli* in the plant effluent by 97%, it apparently had little effect on total bacterial content of the waters of the Providence River because of other pollutant sources. Shellfish-bed closures were common in the Providence and Seekonk rivers during summer months, but the beds were usually reopened in winter when bacteria levels decreased.

Second, the Commissioners of Shell Fisheries requested a study of the effect of tidal currents on the transportation of sewage and other pollutants in Narragansett Bay. Sarle (1911) conducted the first impact assessment for the bay. Based upon these studies, he concluded that the dumping ground for sewage sludge should be moved outside of the bay, and that sludge should be dumped on the ebb tide to ensure that it would not travel back into the bay and affect the oyster-growing grounds. His recommendations were not immediately heeded, and sewage sludge cake continued to be dumped at the site until

Figure 3.3 *Metric tons of sewage sludge dumped in Narragansett Bay south of Prudence Island. Years with missing data indicate that sewage sludge was discharged directly to the bay during that time (World Wars I & II; The Great Depression). Data taken from Providence City Engineer Annual Reports.*



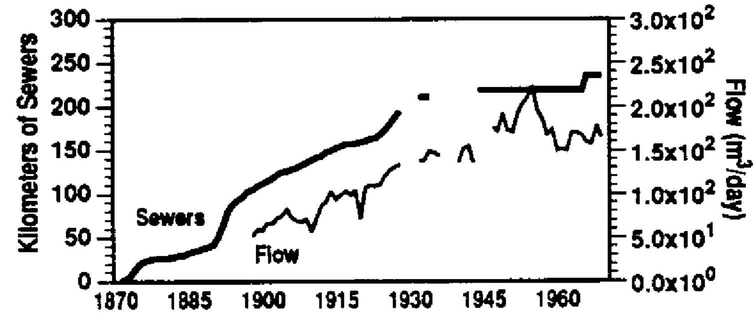
1949 (Figure 3.3), although dumping of sludge on the ebb tide did begin a few years after his report.

In 1912 the state ruled on the oystermen's suit. Despite the large revenue produced for the state by the leasing of oyster-growing acreage ($135,000 in 1912), and the political clout carried by the Oyster Growers' Association, the state ruled that, although pollution from treatment plants and the dumping of sewage sludge was indeed occurring, it was not at harmful levels. It also ruled that in such cases the burden of gathering proof—a duty that had previously been performed by the state itself—was to be placed upon the plaintiff.

The Providence region continued to prosper and grow at a rapid pace, and by 1919, 252 miles of sewer drains were in operation on the east side of Providence, carrying wastes that were once directly discharged along the Seekonk and Providence rivers to the facility at Field's Point for treatment (Figure 3.4). During World War I a shortage of lime disrupted the use of chemical precipitation at the facility. From 1918 to 1921 effluent was discharged with no treatment other than chlorine, which was also in short supply as a result of demands in support of the war effort. As Figure 3.3 shows, the production of sludge stopped during the period of World War I.

In response to the constant water-quality crisis in the upper bay after World War I, an act was passed that prohibited any pollution of the waters of the state of Rhode Island. It also created the Board of Purification of Waters, which was mandated to regulate pollution entering the bay and its tributaries (Rhode Island Board of Purification of Waters, 1921). When the war was over and the treatment facility went back into full operation, there were reports that dissolved oxygen levels in the Providence River were improving and that fish that had not been noted in the area for 10 years had returned to

Figure 3.4 *Increase in the extent of sewer lines in the city of Providence and discharge flow from the STP at Field's Point since 1870. Data from Nixon (1990) and NPDES permit records.*



the upper bay and Providence River (Rhode Island Commissioner of Shell Fisheries, 1922). It was also noted that the ever-present Providence River oil slick was growing smaller and less prominent, and that in general water quality was improving in the Providence River and upper bay. Although the exact causes for this improvement in water quality conditions were not noted by the Commissioners of Shell Fisheries, the work of the Board of Purification of Waters was credited.

In other areas, however, water quality was deteriorating. In 1922, the Board of Purification of Waters reported that the Seekonk River was anoxic on the bottom, particularly in regions near sewage discharge sites, and that the Moshassuck was completely devoid of oxygen at its mouth. Providence River bottom waters were generally less than 10% saturated. At the time it was considered that oxygen saturation of less than 50% indicated undesirable conditions.

A series of remedies to quickly improve conditions were proposed. In 1925 the Board of Purification of Waters declared the treatment plant at Field's Point obsolete, and in 1926 plans were made to convert the plant to an activated sludge process, but it was not until 1929 that a $1-million loan was approved by the state to begin the actual upgrade work. In 1933 the Metropolitan Sewer District proposed running a pipeline from Providence to Prudence Island, where the discharge point for all sewage effluent would be located, thus cleaning up the Providence and Seekonk rivers. The Board of Purification of Waters opposed the matter, as did fishermen, because of the costs involved and the potential adverse impact this would have upon the fisheries located in the lower bay (Rhode Island Department of Health, 1934).

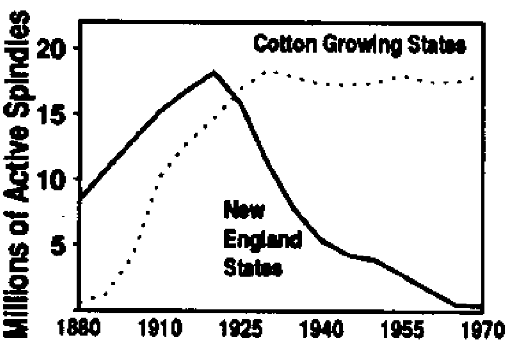


***Figure 3.5** The rise and fall of the New England textile industry using numbers of active spindles as a proxy to changes in the industry. Data from Dunwell (1978).*

By 1930 textile manufacturing in New England was experiencing a major slump, down two-thirds from 1923 levels and employing only 12,000 workers (Figure 3.5). With the decrease in textile production came an increase in other manufacturing industries such as metals processing, jewelry production, and petroleum processing. But this industrial growth did not pick up the slack from the textiles decline. During the Great Depression (1930–1940), the area's population grew by only 2.4% and employment in the textile industry fell to its lowest point. To add insult to injury, the 1938 hurricane wreaked havoc in the Providence area, destroying many homes and businesses and further depressing an already ailing economy. Rhode Island experienced an economic slowdown that persisted until the Second World War.

World War II ended the dismal prospects of the Great Depression, bolstering the regional economy by providing large numbers of jobs in support of the war effort. During the war years, manufacturing and metal-processing industries boomed in the Providence region as manufacturing rallied to supply the military with the goods and weapons needed to maintain Allied troops. Concern for water quality in the Seekonk and Providence rivers was minor compared to

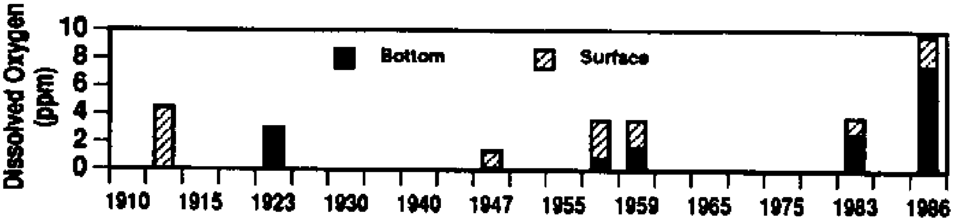


Figure 3.6 Summer dissolved oxygen concentrations in the Seekonk River as measured by various researchers at various times throughout the 1900s, suggesting anoxia/hypoxia were most prevalent during the 1930s and 1940s. Data from Sweet (1915); RI Dept. of Health (1923, 1947, 1956); US Army Corp. Engineers (1959); Nixon (unpublished data); Doering et al (1988).

worries over the war, and water-quality degradation was widespread. Despite its upgrade in 1936 to 50-MGD capacity and activated sludge processing, the treatment facility at Field's Point reverted to discharging untreated sewage into the Providence River when workers and materials were diverted to the war effort (see Figure 3.3). All the rivers flowing into the urban estuary at the head of the bay were considered fouled and polluted. During the summer months, nearly all bay tributaries were referred to as offensive to both sight and smell, and oil slicks and solids were once again a common sight on the water surface. Further cleanup of the upper bay was ignored in the face of war.

From the Postwar Era to 1970

The postwar era, with its increase in leisure time for the working class, brought increased use of the bay as a playground along with greater environmental scrutiny and awareness. This new environmental awareness led to calls for better pollution abatement to protect and enhance the purity of the waters that were a common resource.

Construction of an interstate highway system reduced travel time to major cities and population density increased markedly in suburban regions at the head of the bay. Population density in Providence rose to 21 persons per acre by 1940.

In 1946, when the entire upper bay was closed to shellfishing because of bacterial contamination, the plight of Narragansett Bay became a priority for all Rhode Island residents. This event jolted Rhode Islanders into an unrelenting battle against pollution in Narragansett Bay, which had always been viewed as producing the nation's finest oysters and hard clams.

In the summer of 1947, bottom waters were anoxic and surface waters hypoxic the entire length of the Seekonk River (Figure 3.6). As public scrutiny of water quality in the bay increased, and industry was slow to respond, the voice of the public became increasingly clear to elected officials and improvements in wastewater discharges were begun in earnest.

The 1950s marked a decade of construction of municipal primary sewage treatment facilities. In 1947 the Blackstone Valley District Commission (BVDC), the state's first regional sewer authority, was formed, and bond issues were passed to begin construction of a treatment plant at Bucklin Point on the Seekonk River. The East Providence sewage treatment facility began operation in 1950, and the BVDC facility at Bucklin Point went on line in 1952. In 1956 the Moshassuck Valley was tied in to the BVDC treatment plant and in 1957 Central Falls, Valley Falls, and Lonsdale were also added (Rhode Island Department of Health, 1956 and 1957). In the mid-1950s it was determined by the Rhode Island Department of Health and the City Engineer that the facility at Field's Point was working at only 43% efficiency in removal of biochemical oxygen demand (BOD) (85–95% removal was considered normal), and it was recommended that the plant be upgraded to a secondary treatment phase. This work was completed in the late 1950s.

In the early 1960s, as federal money became available for pollution control, many Rhode Island cities with older sewage treatment plants took advantage of the funding to construct or upgrade wastewater treatment facilities. At this time cities were responsible for their own wastewater treatment and discharges; there was no regional governing body. Pollution control was therefore somewhat scattered, as each city did as it saw fit, when it saw fit. Yet, despite the helter-skelter nature of regulation and planning, water quality continued to improve, due in part to declining textile manufacturing and in part to federal funding for wastewater treatment. Construction of a large number of new sewage treatment facilities, upgrading of many existing ones, and a continuing decline in bay-based manufacturing vastly improved water quality in the upper bay during the 1960s. Fish were reported in good numbers in the Providence River, and dissolved oxygen in the Seekonk River exceeded levels observed in the early 1900s (Figure 3.6).

From 1970 to the Present

As bay conditions improved, the political atmosphere became more charged as cities quibbled over who was responsible for what pollution and who should be responsible for its cleanup. Public awareness of and concern for the quality of water in the bay continued to grow, with local groups forming to combat potentially degrading construction and changes in land use. Ironically, it was as early as 1922 that the Annual Report of the Commissioners of Shell Fisheries noted the problem of one state attempting to clean up its waters while neighboring states do not, and stated that federal control would be "absolutely necessary" to attain water quality improvements in bodies of water shared by more than one state. However, it was not until 50 years later, when the federal government became involved in water quality through the enactment of the Clean Water Act of 1972, that a focused and better-planned approach to water-quality control came into place. The period from 1970 to the present has brought a greater impetus for comprehensive planning, policy, research, and cooperation on local, regional, state, and federal levels as the value of the bay as a public recreational resource has grown.

During the 1970s population densities in urban areas around the bay began either to stabilize or to decrease slightly (see Figure 3.1). This change was mainly a result of the deactivation of Navy installations that had been established during World War II in Newport, Middletown, and North Kingstown. During deactivation, an estimated 20,000 Navy personnel left the state of Rhode Island (Conley, 1986). Despite the trend of decreasing population density in urban areas, the number of new housing units in the coastal region expanded dramatically. Between 1970 and 1980, the overall state population decreased 5%, while housing units grew 12.4%, from 217,706 to 244,721, with two-thirds of those units being located in coastal census tracts. As new population centers arose along many of the smaller coves and inlets throughout the bay, local water quality was affected by runoff, sewage inputs, and poor land-use planning.

1972 brought the enactment of the Federal Clean Water Act, which mandated that discharge concentrations comply with levels set by the federal government. With the passage of this act, wastewater treatment became, in essence, the responsibility of the federal government, in terms both of funding and of enforcing compliance. The single, centralized authority required to bring about true control over pollution discharges and cleanup was now in place.

In 1974 the EPA estimated that $1.4 billion would be needed to clean up Narragansett Bay to meet the goals of the 1972 Clean Water Act (Lee, 1986b). The Blackstone River, originating in Massachusetts and a major tributary to the Providence River estuary, was degraded to the point that its waters were deemed unfit for any recreational or industrial use other than power generation (Mass. Dept. Env. Qual. Eng., 1975). The Blackstone River therefore would require major work and funding to meet EPA standards.

Pollution control continued in 1973 and 1974 with the tie-in of East Cumberland, East Smithfield, and West Lincoln to the BVDC treatment plant. The facility was upgraded to secondary treatment in 1972, with a resultant 60% increase in removal of BOD from its effluent. In 1976 the East Providence municipal treatment facility was upgraded to secondary treatment and 70–75% of total BOD was removed from discharge waters.

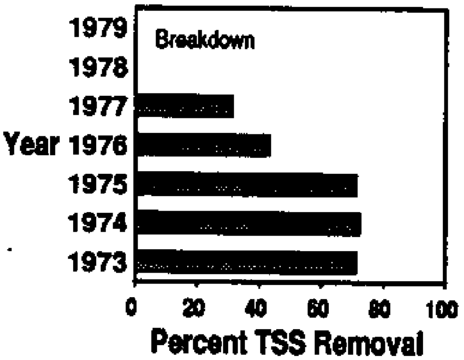


Figure 3.7 Efficiency of the removal of solids for the STP at Field's Point prior to breakdown in 1978. The rapid loss of plant efficiency could have warned of the impending breakdown. Data from plant operations records.

The efficiency of the treatment process at the Field's Point facility declined rapidly after 1975 (Figure 3.7). In 1977 the EPA filed suit against the city of Providence for poor functioning of the treatment plant at Field's Point and EPA ordered that required repairs be made to the plant. In 1978, before the EPA- mandated repairs were made, the plant at Field's Point broke down completely, and was pumping sewage, untreated except for chlorination, into the Providence River for nearly two years. Improvements that had been made in water quality of the upper bay prior to the breakdown were lost during this period of discharge. It has taken a number of years to regain the level of water quality that existed before the breakdown of the treatment plant. In 1980 the BOD loadings produced by the plant at Field's Point were back to the level of 20,500 kg/day that had been achieved in the 1970s prior to the breakdown (Lee, 1986a). The Narragansett Bay Commission (NBC) took over the operation of the treatment plant at Field's Point from the city of Providence in 1980 and has since worked diligently to improve the quality of the discharges from the plant. One major accomplishment was to implement pretreatment of industrial wastes entering the facility, resulting in significantly reduced metal loadings into the bay since 1983 (Hoffman, 1988).

By 1980 progress had been made in cleaning up the Blackstone River, but many areas still did not meet their assigned

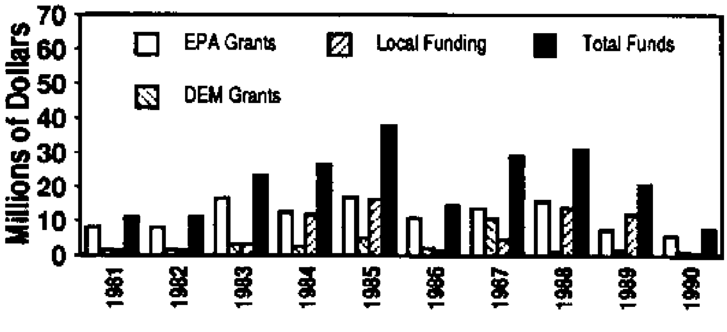


Figure 3.8 Trends in funding sources for the construction and improvement of wastewater treatment facilities in the state of Rhode Island, indicating the loss of funding over time. Data from RI Dept. Environ. Management; 1990 funding is estimated.

classification due to the large number of municipal and industrial treatment plants discharging into the river (Mass. Dept. Env. Qual. Eng., 1980). During dry weather (low flow) periods, treatment facility discharges often exceed freshwater flow, seriously degrading water quality (Mass. Dept. Env. Qual. Eng., 1984). McGinn (1981) found that sediments in the river were severely contaminated with heavy metals, to the point of affecting the fisheries of these waters.

As sewage treatment plants are continually upgraded, and industrial sources monitored and policed, water quality in the Providence River has continually showed improvement. In 1986 it was estimated that 94% of Rhode Island's tidal waters were of fishable/swimmable quality (RIDEM, 1986). Recent studies funded by the Narragansett Bay Project show that water quality in the bay continues to improve, but problem areas still exist that need to be addressed and worked on (see Chapter 2). For example, the Blackstone River continues to be a major source of pollutants entering the Seekonk River; most of these pollutants originate in Massachusetts (Quinn, 1988).

Some of the permanently closed shellfish beds in the upper bay are now opened on a conditional basis (conditional areas are closed only following periods of heavy rainfall, which means that on average they are closed 200 days per year) (RIDEM, 1986). This indicates that water quality, at least in regard to bacterial contamination, is improving in the upper bay. Recent studies of clam tissues show evidence of contamination with heavy metals, but no concentrations exceeding the U.S. Food and Drug Administration's danger alert levels were found (*Narragansett Times*, 1988). Despite tremendous improvements in overall water quality in Narragansett Bay in the past 25 years, concern about future improvements to water quality grows as federal funding dries up (Figure 3.8). New treatment-plant construction and improved treatment of industrial and municipal wastewater discharges to the Blackstone River will be slow to come about without the assistance of federal funding. Without continued federal funding, it is questionable whether states will be able to maintain present water quality standards, much less improve upon them.

Chapter 4

Trends in Water Quality in Upper Narragansett Bay: Providence and Seekonk Rivers

> *Atwell, who presided as bakemaster at the shore dinner hall* (at Field's Point) *from 1887 to 1910, raised this traditional New England meal to the status of a feast. For fifty cents the colonel provided chowder, clam cakes, baked fish, oysters picked just offshore, steamers, watermelon, and other side dishes. For an extra quarter he threw in a "good sized" lobster.*
>
> *Conley and Campbell, 1982*
> *From "Providence: A Pictoral History"*

The Providence and Seekonk rivers constitute the region of Narragansett Bay that has historically been subjected to the worst water quality problems. This region at the head of the estuary is narrow and restricted, and major discharges of the nature and quantity received during early industrialization were simply more than could be assimilated by or effectively flushed from these bodies of water. The consequences of these loadings varied from aesthetically nauseating conditions—such as windrows of raw sewage lining river banks, noxious fumes arising from the water, extensive anoxia, fish kills, algal blooms, water coloration from textile-dyeing operations, and oil slicks on the water surface—to more serious threats such as waterborne diseases, contaminated drinking water, and poisoning of shellfish stocks inhabiting the upper bay.

Early water quality problems arose from massive amounts of untreated industrial and municipal wastes discharged directly into the estuary. After World War II, as publicly owned wastewater treatment facilities were constructed and manufacturing declined, it appears that water quality began to improve in the head of the estuary.

It is difficult to document water quality trends in the upper bay because there has been virtually no continuous monitoring program near the urban portion of the estuary. Neither the state nor the various research institutions in the bay have regularly monitored either discharges or receiving-water quality in the Providence and Seekonk rivers for parameters other than bacteria. During the early 1900s, monitoring was conducted by both the state and the city and included surveys of bacteria by the State of Rhode Island Department of Health and daily tidal records (which have been lost) kept by the Providence City Engineer. Since the 1950s, the Department of Environmental Management has continually monitored bacteria at a number of stations in the conditionally opened shellfish area between Prudence Island and Cominicut Point.

Fortunately, over time there have been enough studies of various problems by different researchers to make it possible to piece together evidence of trends in water quality in the upper bay. This data base includes such disparate but valuable works as a baywide survey of dissolved oxygen by the U.S. Army Corps of Engineers in the late

1950s (to assess potential impacts of constructing hurricane barriers across the mouth of the bay), an environmental impact statement for a proposed nuclear power plant (which provided one of the most complete larval fish surveys of the bay), and a series of more recent surveys of water quality and major sources of contaminants to Narragansett Bay. The National Pollution Discharge Elimination System (NPDES) permit program mandated by the 1972 Clean Water Act provides what is often the only record of pollutant loadings from wastewater discharges after 1972, and the USGS river-monitoring program provides documentation of other major pollutant sources.

Due to the many independent studies that have been conducted in the bay, measurements of dissolved oxygen, salinity, nutrients, BOD, and total suspended solids (TSS) are adequate to reconstruct a historical account of loadings. Accounts from public documents and newspapers also help piece together the effect that wastewater discharges have had upon Narragansett Bay.

The sediments provide one of the best available records of long-term trends in water quality parameters, especially for the less bioactive compounds. Narragansett Bay is one of the few estuaries in the country for which sediment cores have been dated, providing an accurate estimate of sedimentation rate. The sediment cores have been analyzed for levels of a variety of metals, as well as petroleum hydrocarbons, at various depths.

There are four principal sources of pollutants to the upper bay: rivers, sewage treatment plants, industry, and combined sewer overflows. The locations of many of these sources are mapped in Figure 4.1.

Organic Carbon and Dissolved Oxygen

Sources of BOD

A budget of present sources of BOD loads to the upper bay indicates that rivers are the predominant source (Table 4.1). Four rivers provide the bulk of the BOD load: the Blackstone, Moshassuck, Woonasquatucket, and Pawtuxet. Of these four rivers, the Blackstone is by far the largest contributor. Sewage treatment facilities and industry are in turn major sources of pollutants to two of these rivers, the Blackstone and the Pawtuxet.

Sewage treatment facilities provide another major source of organic loading to Narragansett Bay. Historically, treatment plant inputs have ranged from raw-sewage discharges to relatively clean present-day effluents. Three major publicly owned

Table 4.1 Sources and loadings of BOD to upper Narragansett Bay.

Source	BOD Loading (metric tons/year)
Municipal Treatment Facilities[1]	**3199**
BVDC POTW	1928
NBC POTW	1194
E. Providence POTW	77
Industry[2]	**771**
Rivers[3]	**13142**
Blackstone	**7654**
Pawtuxet	**4265**
Moshassuck	**373**
Woonasquatucket	**850**
CSO Input[4]	**635**
TOTAL BOD LOADING	**17,747**

[1] From RIPDES records, 1989

[2] From RIPDES records, 1989, for only those industries discharging directly to the bay

[3] BOD load determined from TOC estimates (Nixon in prep.), assuming 40% consumption of carbon in rivers and a C:0 ratio of 106:138

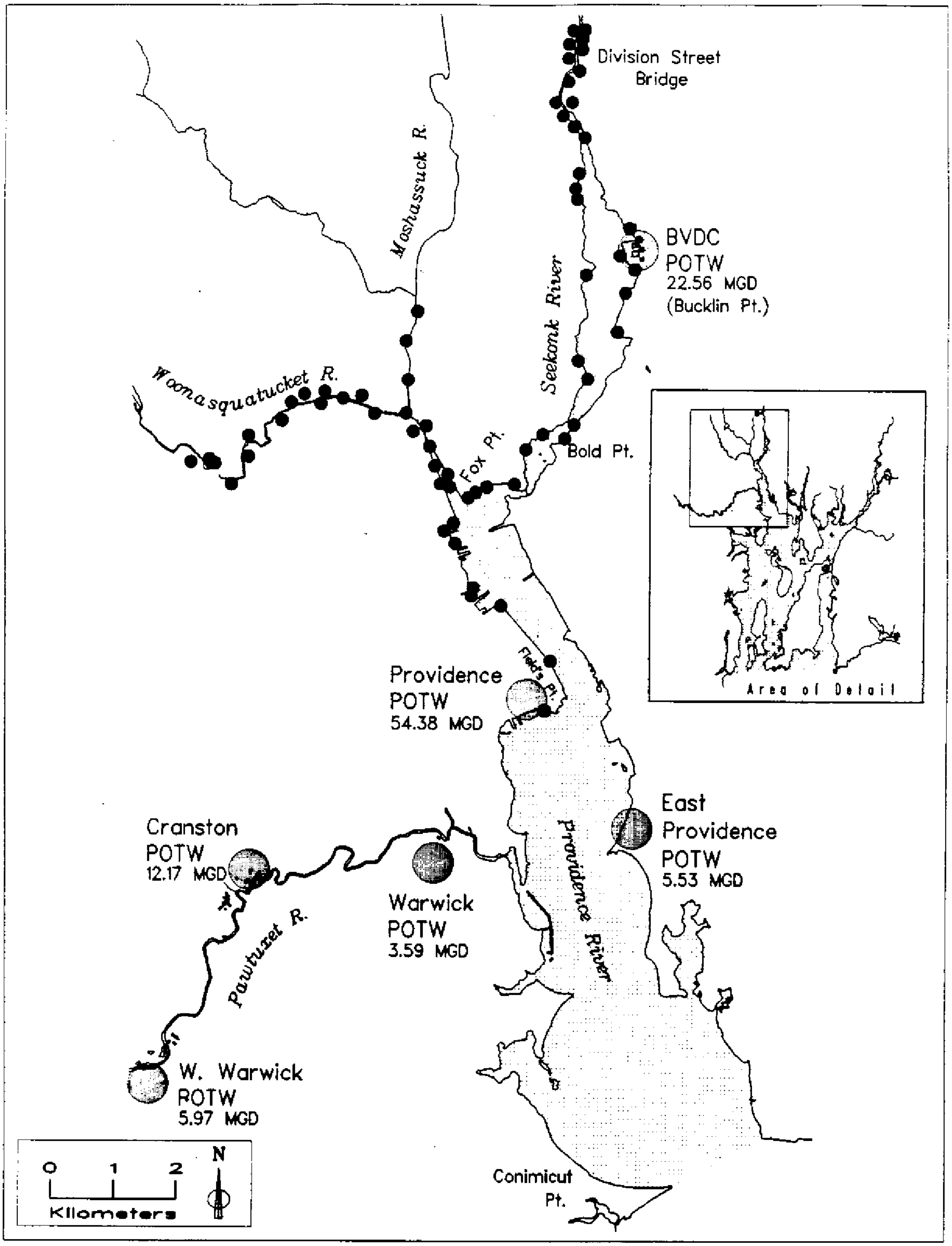


Figure 4.1 *Locations of municipal wastewater discharge sources and combined sewer overflows in the Providence and Seekonk Rivers. Size of source indicators does not correlate to discharge volumes, which are listed on the map for each facility. Data from RIGIS (1990).*

treatment work (POTW) facilities presently discharge effluent containing a BOD load into the Providence and Seekonk rivers. The Narragansett Bay Commission (NBC) facility at Field's Point contributes 37% of the total POTW-associated BOD load (average discharge 52.5 MGD); the Blackstone Valley District Commission (BVDC) facility contributes 60% due to higher concentrations in the discharge effluent, (16.5 MGD); and the East Providence facility contributes 3% (6.4 MGD). The total present BOD loading from these three facilities averages 3,199 metric tons/year, or 18% of the total BOD load to the bay.

Combined sewer overflows (CSOs) have been presumed to contribute significant amounts of BOD to the Providence and Seekonk rivers. During periods of heavy rainfall, stormwater input to the sewage treatment facilities could exceed functional capacity, but the excess stormwater is removed via CSOs discharging directly into the estuary. The contribution of untreated wastes by the CSOs in Providence has been determined to be 635 metric tons/year (Metcalf and Eddy, 1990), rivaling that contributed by industry, but only contributing 4% of the total BOD load to the bay (Table 4.1). Wastewater studies currently under way will be used to calibrate computer models in order to set priorities for treatment of CSOs discharging to the Providence River.

Another source of BOD to the upper bay is industrial discharge. The majority of industries discharge their wastes into municipal wastewater treatment systems, and many of these wastes have undergone pretreatment prior to entering the sewer system. This portion of the industrial BOD load is incorporated into the estimated BOD for sewage treatment facilities. Some industrial plants continue to discharge directly into the Providence and Seekonk rivers, and these loadings are summed from NPDES permits and entered as "industry" in Table 4.1. Overall, industry's BOD contribution to the upper bay is relatively minor when compared to riverine and municipal sources.

BOD Loading

Given the steady increase with time of the population within the bay drainage basin, it would be reasonable to assume that BOD loadings would also be increasing. However, analysis of monthly measurements of flow and BOD concentration recorded at each of the municipal treatment plants directly on the Providence and Seekonk Rivers since monitoring began in the 1950s, indicates that BOD has decreased dramatically (Figure 4.2). Moreover, there is strong evidence that the policies of the 1972 Clean Water Act and consequent conversion of the BVDC facility to secondary treatment effectively reduced

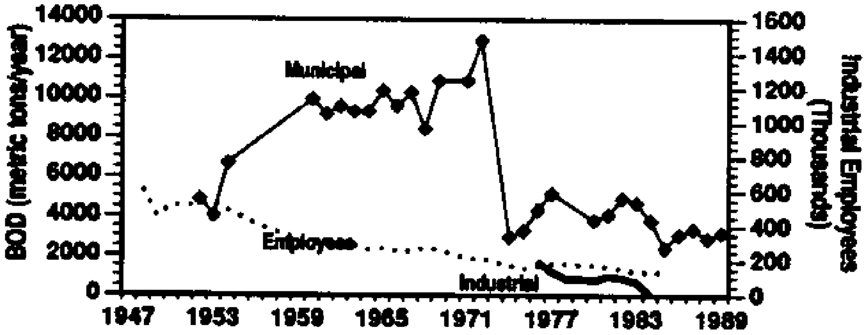


Figure 4.2 Trends in BOD loading to upper Narragansett Bay from municipal and industrial sources. Numbers of persons employed at industry which discharges a BOD load may indicate trends in industrial BOD discharges prior to monitoring records begun in 1976. Data from NPDES records and US Census data.

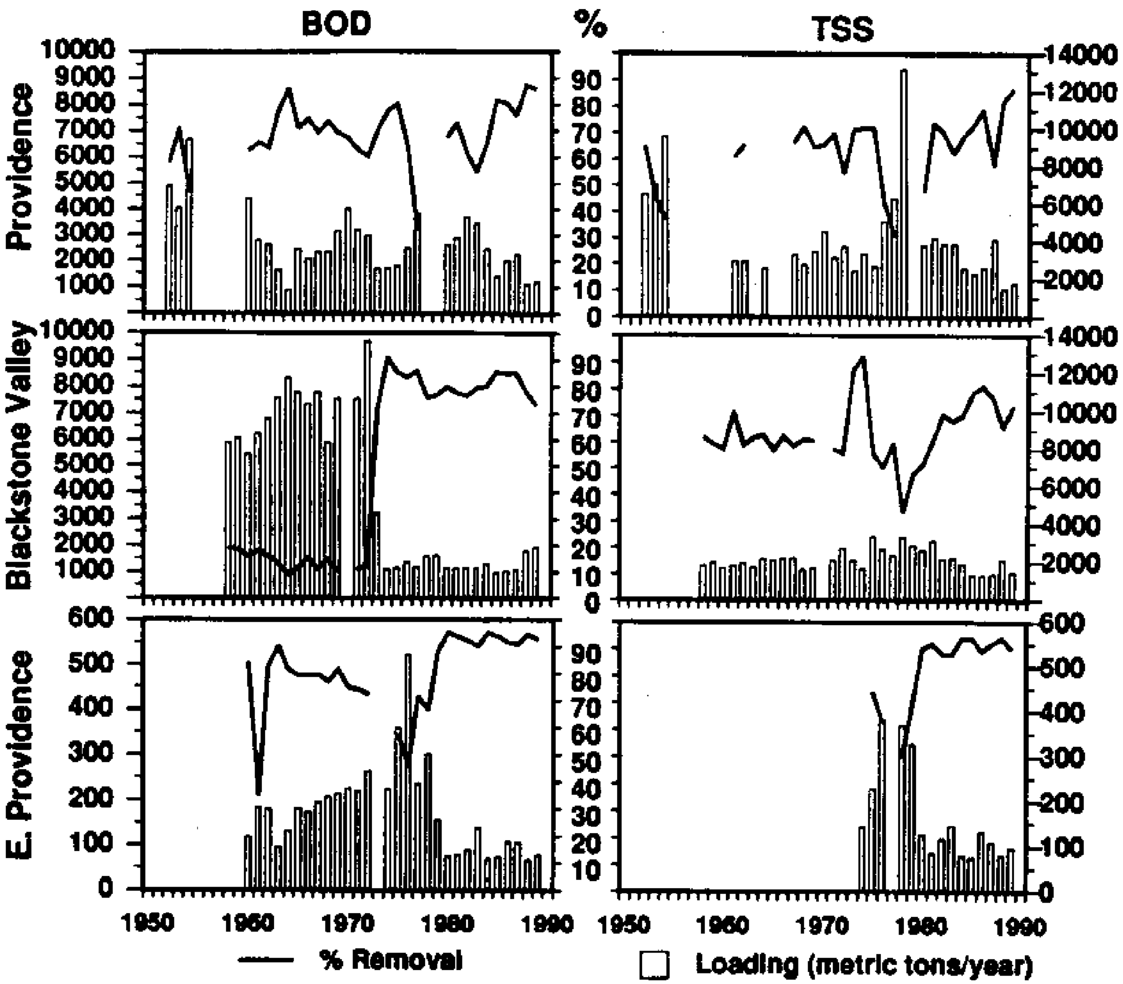


Figure 4.3 Trends in BOD and TSS loading and efficiency of removal for the 3 major municipal point sources in upper Narragansett Bay. Gaps in the data indicates no data available or missing data. Data from NPDES records.

the sewage-derived BOD loading to the upper bay, which has decreased by a factor of 3 (Figure 4.2). With the exception of the total breakdown of the facility at Field's Point in the late 1970s, each of the sewage plants has achieved 80-90% efficiency of removal of BOD in recent years (Figure 4.3). The BVDC facility has however shown a steady decline in efficiency over the past 2-3 years. Efficiency of removal of total suspended solids at the Providence facility has been high, which could be attributed to takeover of facility operations by the Narragansett Bay Commission in 1980.

An equivalent time series is not available for establishing trends in total riverine BOD loadings, but it is assumed that loadings from this source have also decreased over time, reflecting downward trends in industrial discharges and the conversion of municipal sewage treatment plants to secondary treatment.

Data are available to assess the BOD load contributed by those industries that are required to have approved NPDES permit levels for their discharges. Figure 4.2 shows the total BOD load contributed by permitted industries between 1976 and 1984. The magnitude of BOD loading from industry is small compared to that from POTWs, and has decreased steadily since 1976. There are several plausible causes for this trend: (1) The manufacturing base around the upper bay has been declining steadily as industries move out of the region; (2) A greater number of industries have tied in to the municipal treatment system and are no longer included in the direct-discharge category; (3) A greater number of industries are actively pretreating their wastewater. Since there are no long-term records of industrial discharges available, U.S. Census statistics on manufacturing employment are used here as an indicator of industrial activity and the patterns of BOD discharge by industry. The number of employees in manufacturing processes associated with high BOD loads is shown in Figure 4.2, and reflects a steady decline for the past 40 years.

No time-series data are available from which to assess long-term trends in nonpoint discharges or CSOs to Narragansett Bay.

Table 4.2 Studies conducted in the Providence and Seekonk rivers that have measured dissolved oxygen concentrations.

Year	Author	Sites
1913	Sweet	Seekonk R.
1918	RI Comm. Shellf.	Providence R.
1923	RIDOH	Seekonk & Providence R.
1933	RIDOH	Providence R.
1947	RIDOH	Seekonk R.
1955	RIDOH	Providence R.
1956	RIDOH	Seekonk R.
1959	USACE	Seekonk & Providence R.
1971	RIDOH	Seekonk & Providence R.
1980	MERL	Providence R.
1982/83	Nixon	Seekonk & Providence R.
1987	Doering et al.	Seekonk & Providence R.

Dissolved Oxygen Concentrations

Dissolved oxygen concentrations are a generally accepted indicator of the overall health of a body of water, at least in regard to its ability to sustain aquatic life. Observed dissolved oxygen concentrations can therefore provide a relative estimate of the BOD load experienced by a water body over long spans of time. Fortunately, the Winkler method for measuring dissolved oxygen has been the standard since the late 1800s, and consequently measurements of dissolved oxygen provide some of the most reliable and long-term records of trends in estuarine water quality. Table 4.2 lists the major studies in the upper bay that have recorded dissolved oxygen concentrations, and are used here to develop trends in dissolved oxygen concentrations over time in the upper bay.

Descriptions in the late 1800s of fish kills, offensive miasmas rising from the sludge deposits on the banks of the Seekonk, and many pipes discharging refuse directly from the river banks would indicate that hypoxia (low dissolved oxygen) was a problem before the turn of the century. Interestingly, surface dissolved oxygen concentrations in the Providence and Seekonk rivers remained above critical values (3.0 ppm) for much of the early part of the 20th century. Dissolved oxygen content of surface waters declined from concentrations near 7 ppm in 1913 (Sweet, 1915) to hypoxic levels for nearly the

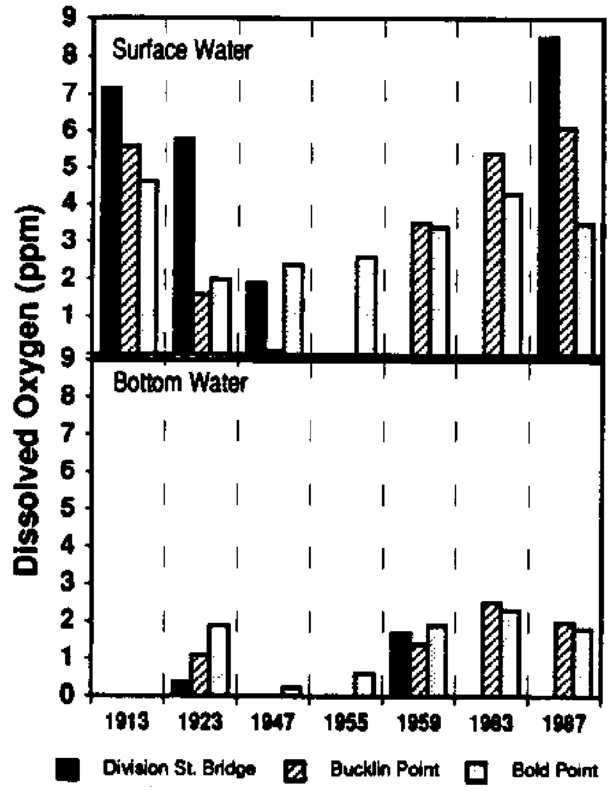


***Figure 4.4** Trends in summer time dissolved oxygen concentrations in the Seekonk River between 1913 and 1987 in both surface and bottom waters. The graphs indicate that improvements have occurred since the mid 1950s, especially in surface waters, while bottom waters show no improvement since 1983. Data from RIDOH 1923, 1947, 1956; Sweet 1915; US ACE 1959; Doering et al. 1988.*

entire length of the water body in 1947 (Figure 4.4). Unfortunately, Sweet did not measure bottom waters, but by 1947, and for a decade thereafter, bottom waters were nearly anoxic all along the Seekonk and for a distance 7 km downbay (Figures 4.4 and 4.5). The drastic decline in surface dissolved oxygen concentrations after 1923 can be attributed to increased industrialization as a result of wartime production demands and growth of surrounding urban population during the 1940s. No sewage treatment plants were in operation on the Seekonk until 1952, when a regional sewage treatment facility was put into operation at Bucklin Point (BVDC). By 1956 summer surface dissolved oxygen concentrations had improved, and by 1959 even bottom-water dissolved oxygen had improved from anoxic to hypoxic (Figures 4.4 and 4.5).

Summertime dissolved oxygen concentrations have increased with time in the Providence River (Figure 4.5). Although the available data suggest that worst case

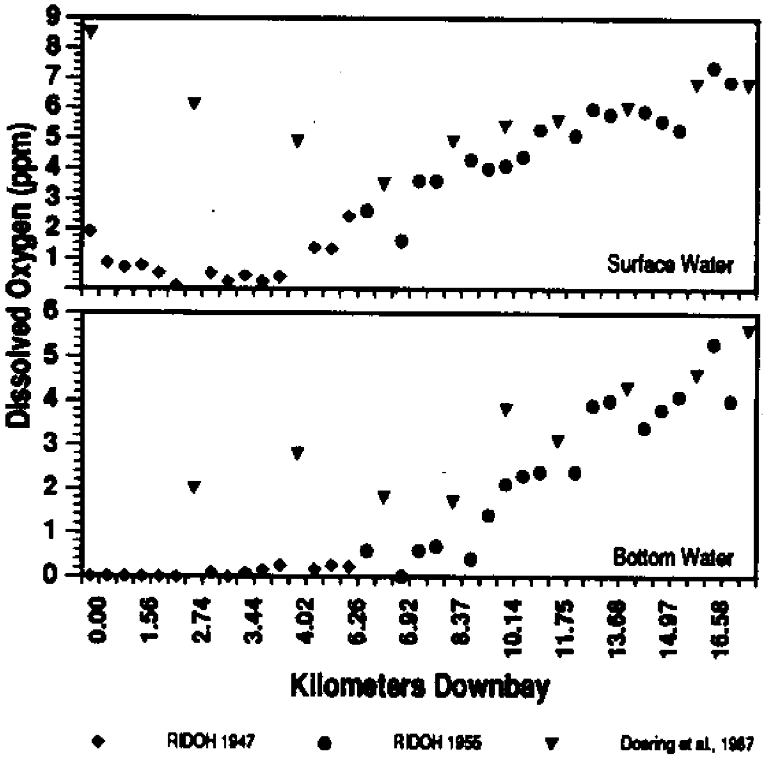


***Figure 4.5** Downbay trends for summertime (worst case) dissolved oxygen concentrations in the Seekonk and Providence Rivers during 3 sampling events since 1947, showing improvements in concentrations with distance from the head of the Seekonk River, and improvements over time. Data from RIDOH 1947, 1955; Doering et al. 1988.*

conditions in the Providence River were better than in the Seekonk River, dissolved oxygen in bottom water was below 3.0 ppm from India Point to near Conimicut Point in 1987. Summertime dissolved oxygen distributions in the Providence River show a distinct gradient of increasing concentration with distance down the estuary toward the more open waters of the upper bay.

Reduction of BOD loading occurred after 1970 as new treatment plants were constructed and improvements were made in plant efficiency, to the point where by 1983 dissolved oxygen concentrations were equal to those observed in 1913 (Figure 4.4). This increase in dissolved oxygen concentrations can be attributed to a loss of industry in the Providence area following World War II, additional sewage treatment facilities being put into operation, and a leveling off of population growth in the city of Providence after 1950. Of particular importance in the Seekonk River was the completion of the BVDC facility and its subsequent upgrade in the 1970s to secondary treatment. The drastic reduction in BOD load brought about by the BVDC treatment plant greatly improved conditions at the head of the estuary, and is clearly seen in Figure 4.2 with the decrease in BOD loading between 1972 and 1973.

Table 4.3 Present-day sources and loadings for nutrients in upper Narragansett Bay (Providence and Seekonk rivers).

	Nutrient Loading (mmol/m³)		
Source	DIN	DIP	Silicate[1]
POTWs[2]			
NBC	2613	72	?
BVDC	871	91	?
E. Providence	442	27	?
Total	**3926**	**190**	**256**
Rivers[2]			
Blackstone	4004	113	?
Pawtuxet	1963	186	?
Moshassuck	140	3	?
Woonasquatucket	273	7	?
Total	**6380**	**309**	**860**
Atmosphere[3]	**1.80**	**.20**	**?**
TOTAL LOAD	**10,307.85**	**499.2**	**1,116**

[1] From Olsen and Lee, 1979

[2] From Nixon, in prep.

[3] From Nixon and Pilson, 1984. Note: prorated for a surface area of 24 km².

Nutrients

Sources of Nutrients

Sources of nutrients to the Providence and Seekonk rivers are municipal wastewater treatment facilities, rivers, precipitation, and influx from offshore waters. A present-day tally for inputs of dissolved inorganic nitrogen, phosphate, and silicate is given in Table 4.3. These are the nutrients available for uptake by phytoplankton, and therefore they are of importance to those concerned about eutrophication of the bay.

Earlier studies suggested that the major proportion of total phosphorus loading to the bay came from sewage plant discharges (20% more than from riverine sources), while rivers were the major source for nitrogen and silica (Olsen and Lee, 1979; Nixon and Pilson, 1984). However, more recent data collected by Nixon (in prep.) indicate that rivers are the major source for all nutrients arriving at the head of the estuary. The upper bay consequently provides the greatest storehouse of nutrients, mainly due to riverine inputs.

Nutrient Loading

No long-term monitoring of either nutrient loadings or nutrient concentrations in receiving water has been conducted. Thus long-term trends in nutrient loading to the head of the estuary can only be inferred from descriptive accounts and the limited data collected by scattered research studies of conditions in Narragansett Bay and its tributaries.

Data collected by MERL in 1979–80 show an increase in measured nitrogen and phosphorus compared to levels of these nutrients measured by Kremer and Nixon at the same sample stations in 1972–73 (see Oviatt, 1981 for data). The MERL study coincides with the time period when the Providence POTW had broken down and was discharging chlorinated-only sewage. That this same increase is not noted for silicate, which is not a major constituent of sewage-treatment effluent, further suggests that additional nutrient inputs resulted from the Providence POTW breakdown during 1979. However, no recent reports of eutrophic conditions in Narragansett Bay are to be found in the literature.

Around the turn of the century however, a six-year period of red tides occurred in Narragansett Bay. The worst of these events took place in 1898, when an extraordinary red tide caused the most extensive mortality of marine animals ever recorded in the bay (Mead, 1898; Nixon, 1989). It appears that this period of red tides and accompanying fish kills corresponded to a stage in the development of Providence's sewage treatment system when sewage collected from around the city was discharged untreated to the bay at a single discharge site at Field's Point (Nixon, 1989). Nutrient enrichment, coupled with the proper climatic conditions, apparently caused the massive algal blooms observed in the upper bay during that period. The mass mortality of marine animals seems not to have been directly related to the algal bloom, but rather due to oxygen stress associated with the increased oxygen demand brought on by both the decomposition of the red tide organisms and the single-point-source sewage discharge. The most noticeable part of the bloom and the most dramatic kills of marine life occurred in the Providence and Seekonk rivers, but the bloom was apparent as far south as Quonset Point. Anecdotal information refers to previous red tides in the Providence River, but none so extensive as that reported in 1898, and none having produced widespread fish kills.

Red tide events have followed a trend of decreasing frequency since 1900, as evidenced by a lack of reports of occurrences in both local newspapers and city documents. Fish kills still occur in isolated areas, but red tides have not been noted in the same areas as the fish kills. Recent kills usually occur in the summer when low dissolved oxygen concentrations occur from temporarily degraded local conditions, rather than to widespread eutrophic conditions.

In 1985 a brown tide occurred in the bay, causing great consternation. The brown tide organism, *Aureococcus anophagefferens*, killed most of the bay's mussel stocks and adversely affected nearly all other shellfish stocks as well as some finfish species. However, this episode differed from the red tide described by Mead in 1898 in that oxygen stress apparently was not the direct cause of death for many shellfish species subjected to the brown tide. The brown tide organism is apparently a nutritionally poor food source. As the organism bloomed, it reduced the relative predominance (in proportion to total available biomass) of typical bay phytoplankton species. Filter-feeding shellfish were taking in plenty of plankton-rich water, but were simply unable to utilize the *Aureococcus* organisms to sustain growth and metabolic functions. In essence, shellfish starved to death in an area rich with phytoplankton.

Trends for brown tides cannot be determined at this time due to lack of sufficient long-term data and knowledge concerning their overall biology and ecology. Whether brown tides are a result of local perturbations in the system due to changes in planktonic community structure or whether they are predator-prey mediated is not known. Brown-algae blooms may be becoming more prominent in estuaries experiencing stressed conditions (e.g., Chesapeake Bay, western Long Island Sound) and may be an indicator of degraded water quality conditions. At the present time not enough long-term data concerning the relationship between nutrients and changes in the bays planktonic communities are available to adequately assess whether brown tide events signify a form of degradation. The lack of correlation of recent algae blooms to nutrient concentrations in the bay, with a lack of reported eutrophic symptoms, suggests that present day nutrient concentrations are not producing noticeable eutrophic conditions in the upper bay area.

Toxics

Sources of Metals

Narragansett Bay, because of its early industrialization, has some of the highest metal loadings of any estuary in the United States (Nixon, 1983). Metals arrive in the bay from a variety of sources: terrestrial weathering, wastewater treatment facility discharges, industry point sources, offshore

Table 4.4 Sources and loading of metals in upper Narragansett Bay. Figures for river loading incorporate all sources within the respective watersheds.

Source	Loading (metric tons/year)					
	Cu	Ni	Pb	Zn	Cd	TOTAL
Rivers[1]						
Blackstone	6.92	7.72	2.22	52.9	0.85	70.61
Pawtuxet	3.02	3.77	0.83	21.5	0.28	29.40
Moshassuck	0.33	0.13	0.18	na	0.009	0.649
Woonasquatucket River	0.43	0.46	0.32	na	0.016	1.226
TOTAL RIVERS	**10.7**	**12.08**	**3.55**	**74.4**	**1.155**	**101.885**
Publicly Owned Treatment Works[2]						
NBC	27.01	35.4	4.72	41.7	1.5	110.33
BVDC	2.42	4.33	2.02	6.0	0.38	15.15
E. Providence	0.22	0.54	0.22	0.54	0.03	1.55
TOTAL POTWs	**29.65**	**40.27**	**6.96**	**48.24**	**1.91**	**127.03**
CSOs[3]	**4.8**	**na**	**3.9**	**0**[5]	**na**	**8.7**
Urban Runoff[5]	**6.7**	**na**	**54.3**	**183.2**	**0.14**	**244.34**
Industry[2]	**11.1**	**0.1**	**8.1**	**10**[5]	**na**	**29.3**
Waste Oil[3]	**na**	**na**	**1.0**	**na**	**na**	**1.0**
Atmosphere[4]	**19.0**	**20.0**	**7**[5]	**7**[5]	**na**	**53.0**
TOTAL METALS	**81.95**	**72.45**	**84.81**	**322.84**	**3.205**	**565.255**

[1] From Nixon, in prep.
[2] From RIPDES, 1985-1989
[3] From Hoffman et al., 1984
[4] From Nixon, Hunt and Nowicki, 1986
[5] From Hoffman, 1987

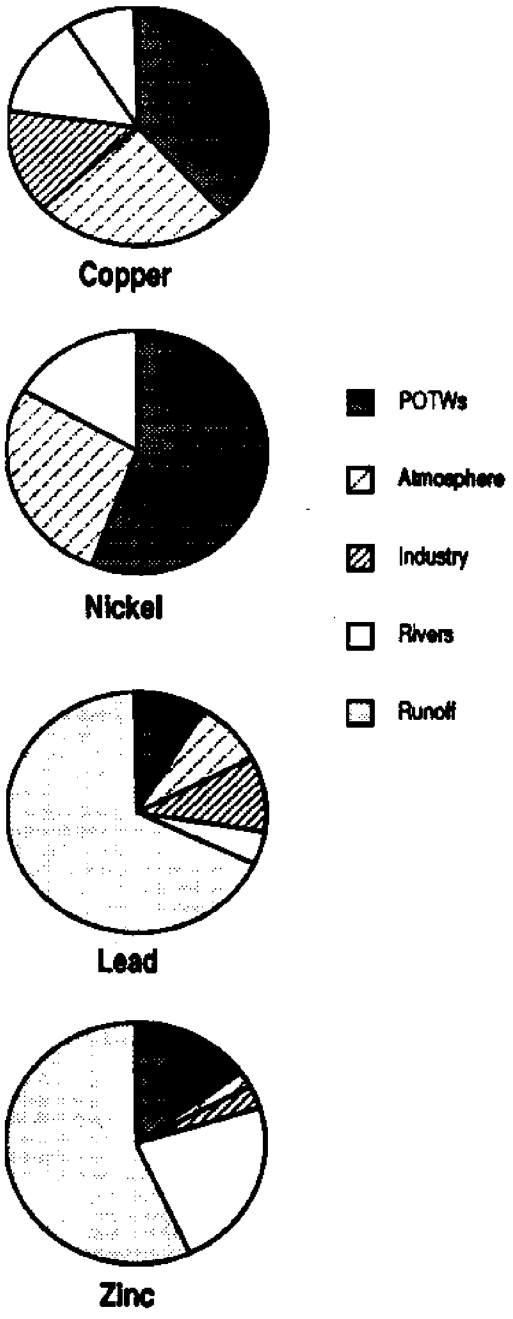


Figure 4.6 Contribution of copper, nickel, lead, and zinc load to the upper bay according to source, and shown as percent of total. Municipal wastewater discharges are the major source of copper and nickel, while urban and stormwater runoff are the major sources of lead and zinc. Data from Table 4.4.

waters, atmospheric deposition, and CSOs. Table 4.4 gives present-day inputs for each source and Figure 4.6 gives a graphic representation of the percent of total input contributed by each source for four common metals measured in the bay.

Major sources are different for the different metals—for example, POTWs are the biggest contributors of copper and nickel, while urban runoff is the major source of lead and zinc (Figure 4.6). By far, sewage treatment plant discharge and urban runoff to the rivers and bay are the major sources of all metals. Hoffman (1987) calculates the relative loadings expected from urban runoff for various metals based upon land use. These data, reproduced in Table 4.5, show that loading increases dramatically as land use becomes less rural in character, and that roadways are significant contributors of metal pollutants to the bay.

Metals Loadings

Due to the bay's long industrial history, metal loadings were much greater prior to the 1950s (Nixon, 1990). By the time metal inputs were being monitored (starting in the 1970s), their input to the estuary had decreased markedly. Long-term loading data for metals are generally unavailable because the methodology for measuring metals in seawater has only recently been developed.

In recent years, since monitoring of metals has become routine, toxic metal discharges from wastewater treatment facilities have decreased (Figure 4.7). The discharge of some metals, such as zinc and lead, has fallen to less than 5 metric tons per year. These decreases are probably not due to a decline in manufacturing associated with metal-containing discharges (Figure 4.7), but rather to improvements in metals removal by recently mandated pretreatment processes.

As shown in Figure 4.7, loadings of nickel, zinc, lead, and copper from the three

Table 4.5 Urban runoff loadings as a function of land use given an annual rainfall of 121 cm/yr.

Pollutant	Loading by Land Use (kg/km²/yr)			
	Residential	Commercial	Industrial	Highway
Iron	135	166	856	915
Manganese	49.6	8.6	65.8	513
Copper	3.0	3.0	35.3	146
Lead	22.4	43.6	166	2250
Cadmium	0.18	0.69	0.85	2.48
Zinc	43.5	—	639	702

Data from Hoffman, 1987

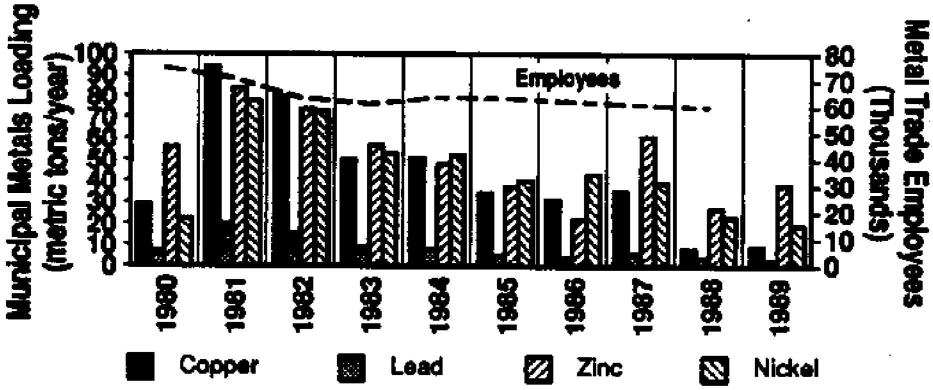
major sewage treatment plants have been reduced significantly in the past decade. The Narragansett Bay Commission, operator of the Providence facility at Field's Point, has instituted a pretreatment program that has reduced metals loading in the influent by 85% since 1981 (NBC, 1989). The only toxin to show an increase in loading is cyanide, which has doubled in its average annual loading (increasing from 3,000 to 6,000 kg/yr) and is typically not removed during wastewater pretreatment (NBC, 1989).

It can be concluded that metal loading to the upper bay has been significant, that it increased in response to industrialization of the region, and that it has generally decreased in recent years in response to improved treatment of municipal and industrial wastewater discharges in the upper bay. As a consequence, 1987 average concentrations of dissolved metals in surface waters of upper Narragansett Bay were below EPA chronic criteria levels for lead and cadmium and at or below these levels for nickel. However, dissolved copper concentrations exceeded EPA chronic criteria in surface waters of both the Providence and Seekonk rivers (Figure 4.8). All metals decline in concentration outside the mouth of the Providence River.

Sources of Organotoxins

The major sources of chlorinated organotoxins (PCBs, DDE, DDT, Aroclor, etc.) discharging into Narragansett Bay are rivers and municipal treatment sites. Overall, rivers contribute the greatest concentrations of PCBs, accounting for 69% of the total annual input (Table 4.6). The load of PCBs contained in rivers arrives from industrial point sources along the rivers and nonpoint

Figure 4.7 Trends in discharge of metals to upper Narragansett Bay by municipal point sources (POTWs) showing over 50% reductions for all metals since 1980. Numbers of persons employed in metal trades is used as a proxy to metal trade activity, indicating that the reductions are not the result of a decrease in the metal working industry. Data from US Census and NPDES permit records.



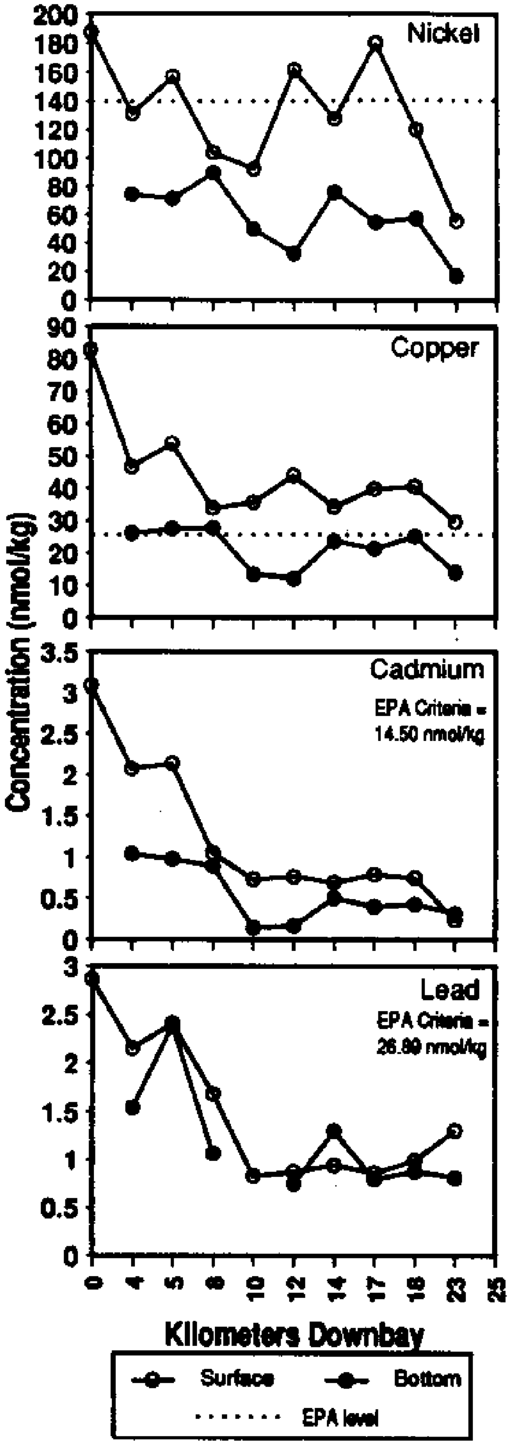


Figure 4.8 Downbay trends in concentrations of dissolved metals in Narragansett Bay waters. Only copper consistently exceeds EPA Chronic criteria levels, and all metal concentrations, except nickel, decrease rapidly once outside the waters of the upper bay. Data from Doering et al. (1988). EPA criteria level is for chronic exposure.

Table 4.6 Present-day PCB loading to Narrgansett Bay by source.[1]

Source	Loading (grams per year)
Rivers	**18,040**
Blackstone	14,654
Pawtuxet	1654
Taunton	768
Woonasquatucket	598
Moshassuck	366
POTWs	**8160**
BVDC	3619
NBC	3082
Others[2]	1341
East Providence	118
Quonset Point[3]	**108**
TOTAL PCBs	**26,308**

[1] From Latimer, 1988.
[2] Bristol, E. Greenwich, Fall River, Newport, Warren, Jamestown
[3] Naval shipyard point source in mid-bay region

sources such as urban runoff, as well as from resuspension of contaminated sediment lining the river bottom. Atmospheric input of PCBs has been measured by Christensen et al. (1979) in the Providence region, but their values were derived during the time when production of PCBs was still ongoing, and therefore concentrations in the atmosphere would presumably have been greater than at present. No recent estimate of atmospheric PCBs in the Providence region has been reported. Table 4.6 gives present-day loading estimates for PCBs into Narragansett Bay.

At present the Blackstone River is the major contributor of PCBs, adding 81% of the total riverine input of PCBs to the upper bay. The Blackstone River exceeds the EPA criteria of 14 ng/l for PCB concentrations along most of its length (Latimer, 1988). The Woonasquatucket River contains the highest concentrations of PCBs of all bay tributaries evaluated to date, but its low flow makes it a relatively insignificant overall contributor to the upper bay (Latimer, 1988; see Table 4.6). The overall PCB loading for sewage treatment facilities is 8 kg/yr, and for rivers, 18 kg/yr. Of the sewage treatment facilities, the BVDC and NBC POTWs are the greatest contributors of PCBs to the Seekonk and Providence rivers (Table 4.6).

Organotoxin Loadings

Since 1979, PCB concentrations have declined dramatically in the Pawtuxet River (from 4.3 μg/l to 5.0 ng/l) and the Blackstone River (from 500 ng/l to 35 ng/l) (Latimer, 1988). The marked decrease in concentrations can be attributed to a halt in production during 1979, as well as restriction of their use. Latimer (1988) determined that reductions in riverine concentrations of PCBs could not be attributed to changes in flow regime, concluding that the reductions were attributable to reduced source inputs.

Trends in PCB concentrations over longer periods of time can be derived from analysis of sediment core samples. Most PCBs and other chlorinated compounds are not easily lost through chemical reactions in seawater; rather, they become trapped and accumulate in the sediments, giving reasonable estimates of past PCB loading. Sediment cores show an increase in PCB concentrations with decreasing depth into the sediment (Figure 4.9). The maximum PCB concentrations are seen to occur around the time of World War II (about 25 cm), the time of greatest use and production of PCBs, and before their period of regulation (Latimer, 1988).

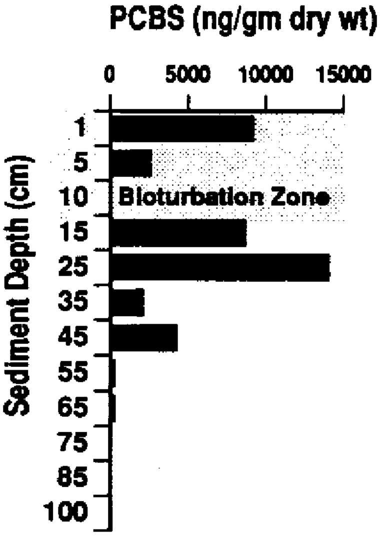


Figure 4.9 *Trends in loadings of PCBs in the Providence River over time, using sediment depth as a proxy to age, showing highest concentrations during the period of World War II. The grayed region indicates the disturbed upper layer of sediment, in which concentrations at a given depth may not correlate well to age. Data from Latimer (1988).*

The tendency of PCBs to concentrate in sediments and not degrade rapidly leads to major problems in disposing of dredged materials, since these are often heavily contaminated with decades worth of accumulated PCBs.

Table 4.7 *Sources and loadings of petroleum hydrocarbons in upper Narragansett Bay.*

Source	Loading (metric tons/yr)
Runoff & Rivers	820
POTWs	630
Waste oil	130
Industry	50
CSOs	50
Spills	30
Atmosphere	16
TOTAL	1726

From Hoffman et al., 1984

Sources of Petroleum Hydrocarbons

Sources of hydrocarbon inputs to Narragansett Bay are river runoff, sewage treatment discharges, waste-oil disposal, industrial discharges, CSOs, oil spills, and atmospheric deposition. Loadings for each of these sources are given in Table 4.7. A total of 1,726 metric tons of hydrocarbons enters the bay each year.

Petroleum hydrocarbons exist in two forms: (1) petroleum hydrocarbons (PHCs) and (2) polycyclic aromatic hydrocarbons (PAHs). In general, PHCs are less soluble in

Table 4.8 *Sources of hydrocarbon types by percent of total loading.*

	Source	% of total loading
PHCs		
	Rivers	40
	Blackstone River	61
	Other rivers	39
	STPs	60
	NBC	30
	BVDC	13
	Others	57
PAHs		
	Rivers	93
	Taunton	55
	Blackstone	18
	Pawtuxet	8
	Woonasquatucket	2
	Moshassuck	1
	Others	16
	STPs	7
	NBC	51
	Others	49

Narragansett Bay Project Progress Rep., 1989.

water than are PAHs, and therefore they tend to settle into the sediments more readily than do PAHs. Table 4.8 shows the various sources of each hydrocarbon form, and the percent of total input contributed by each source. Note that rivers contribute a greater amount of the more soluble PAHs than does sewage treatment effluent, whereas sewage treatment plants input greater amounts of PHCs.

Of the hydrocarbons discharged into the Providence River, Olsen and Lee (1979) estimated that 50% of the total becomes incorporated into the sediments, the other 50% being transported downbay where eventually 34% is transported into Rhode Island Sound. Santschi et al. (1984) estimate that 20–60% of all hydrocarbons entering the bay are retained within the sediments. Once in the sediments, biodegradation is minimal and the hydrocarbons remain trapped unless resuspended into the water column through bioturbation or local events that resuspend the bottom sediments (e.g., dredging, storm events).

Hydrocarbon Loadings

In general, hydrocarbon inputs have decreased in the Providence River, as is evidenced by comparison of studies performed in 1974–75, 1981–82, and 1985–86. PHCs discharged from the POTW at Field's Point were 226 ± 105 metric tons/year in the 1974–75 study, 258 ± 119 metric tons/year in the 1981–82 study, and 95 ± 63 metric tons/year in the 1985–86 study (Quinn, 1988). The decrease in PHCs in the plant effluent was apparently due to repairs and to upgraded treatment processing which took place after the completion of the 1981–82 study.

Core sample analyses show a gradient of hydrocarbon concentrations that decreases with sediment depth in the Providence River. Prior to a sediment depth corresponding roughly to 1925, hydrocarbon concentrations remain stable and at very low levels, reflecting a time when machinery powered by fossil fuels was uncommon (Quinn, 1988) (see Figure 4.10).

Although hydrocarbon input to Narragansett Bay has apparently decreased over recent years, studies suggest that certain benthic organisms, particularly hard clams (*Mercenaria mercenaria*), may be bioaccumulating hydrocarbons in their tissues. Boehn and Quinn (1977) found hydrocarbon concentrations in wet clam tissues to be 15 ppm in 1971; this had increased to 42 ppm in 1977. Hydrocarbons are not rapidly depurated by hard clams, and their physiological effect upon the clams is presently unknown. No guidelines exist for hydrocarbons in clam tissues for human consumption, and more recent estimates are unavailable.

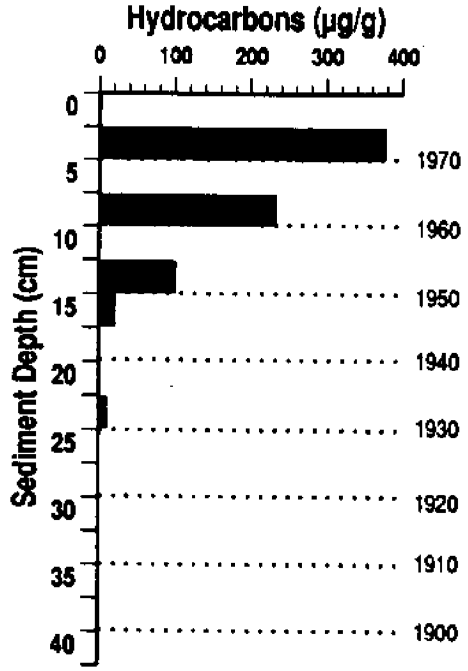


Figure 4.10 Trends in petroleum hydrocarbon loading in the Providence River over time, using sediment depth as a proxy to age, showing a marked increase in concentrations about the time of the popularization of gasoline driven engines to the area (1940). Figure adapted from Nixon, Hunt, and Nowicki (1986).

Pathogens

Sources of Pathogens

Upper bay bacteriological water quality is a function of temperature, tidal phase, sewage treatment plant effluent quality and quantity, and the frequency and amount of rainfall. Because of difficulties involved in isolating pathogenic bacteria and viruses from seawater, it is standard practice to infer water quality from concentrations of coliform bacteria. Fecal coliform bacteria are natural inhabitants of the human intestinal tract and are passed to the environment in the feces. Fecal coliforms are the present standard by which potential water quality contamination from human feces is measured. Water is also sometimes tested for "total coliforms," but this test is considered a less precise indicator of potential human health hazard since it detects bacteria that occur naturally in the intestines of many warm-blooded animals.

At present CSOs are the principal source of coliforms entering the bay, providing 92% of the total input (Table 4.9) Wastewater treatment facilities, on the other hand, normally contribute less than 1% of the total coliforms entering the bay (Roman, 1989). Rivers and urban runoff are also major coliform contributors to the bay. Table 4.9 gives present-day bacterial loading to Narragansett Bay.

Pathogens also enter Narragansett Bay through boating activity, when heads are discharged directly into the bay. Recreational boating activity has continuously increased during recent years, with an estimated 34,000 boats equipped with marine heads currently using the waters of Narragansett Bay each year (Roman, 1989). Roman (1989) estimates that between 51 x 10^{10} and 51 x 10^{13} fecal coliforms per day enter the bay from this source, depending upon the percent of boats in the bay that are occupied at any particular time.

Presently, concerns are shifting to viral pathogen concentrations in the water. Compared to bacteria, viruses are less affected

Table 4.9 Pathogen loading to Narragansett Bay.

Source	Loading (x 10^{13}/year)
Rivers	**280**
Blackstone	263
Pawtuxet	17
POTWs	**4.1**
NBC	1.4
BVDC	2.7
E. Providence	0.01
CSOs	**3347**
TOTAL	**3631.1**

From Roman, 1989

by chlorination processes performed at wastewater treatment plants and also are apparently less affected by cold winter water temperatures. In light of an increased incidence of gastrointestinal disease related to shellfish consumption (82% of reported gasteroenteritis cases from shellfish consumption occurred between 1980 and 1988), concerns currently focus on whether or not fecal or total coliforms are good indicators of virus concentrations in seawater, and whether they are good indicators of consumer risk for eating potentially contaminated shellfish (Roman, 1989).

Pathogen Loadings

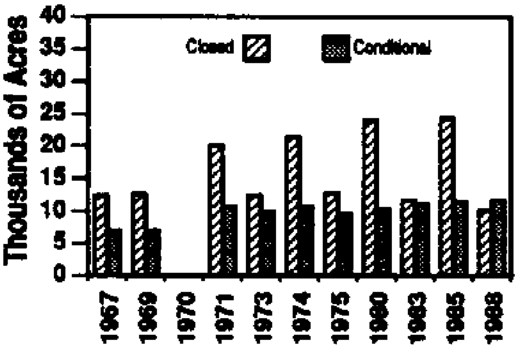
Because of their potential as indicators of bacteriologically contaminated waters, coliforms have been monitored weekly in the upper bay since the 1960s and monthly in waters over shellfish beds since the 1950s, and coliform levels in shellfish meats have been measured since the early 1970s. Coliform levels generally were low in the 1960s, corresponding to years of low rainfall, while the 1970s show increased coliform levels, corresponding to greater-than-average rainfall. Because CSOs cause bacteria levels to increase during rainstorms, state officials close shellfishing areas if rainfall is more than one-half inch in a 24-hour time span. The conditional area was closed continuously during the breakdown of the POTW at Field's Point.

Long-term data on coliform loadings are lacking, but records of shellfish-bed closures give some indication as to whether coliform concentration in the water column has increased or decreased over time in the upper bay region.

Figure 4.11 shows the number of acres of shellfish beds in Narragansett Bay permanently and conditionally closed in various years since 1967. There are presently approximately 41,000 acres of shellfish beds in Narragansett Bay. During the 20-year span from 1947 to 1967, 2,466 acres of shellfish beds were closed on either a permanent or a conditional basis. During the 21-year span from 1967 to 1988, 1,918 acres have been changed from permanently closed status to conditionally closed status. Whether this trend signifies an actual change in pathogen concentrations over time, or whether it is an artifact due to better or more frequent monitoring, is unknown, but suggests improving conditions.

If improvements in water quality in the Seekonk and Providence rivers are to be achieved however, correction of CSO discharges will need to occur. The Narragansett Bay Commission is presently undertaking an assessment of the 65 Providence CSOs and will be drafting a management plan, to be completed within the next 3–4 years, which will address correction of these discharges to the upper bay.

Figure 4.11 Trends in pathogenic contamination of upper Narragansett Bay using permanently and conditionally closed shellfish beds as a proxy to contamination extent. It is not known if the increase in closed acreage is a function of increased pathogenic contamination or due to more frequent and better monitoring efforts. Data from RIDEM shellfish bed monitoring records.



Chapter 5

Trends in Lower Narragansett Bay Water Quality

The public can be assured that there is no question but what oysters grown in Rhode Island are purer this year than they have ever been before, and that they are far better than oysters grown elsewhere, where government and State supervision have not been so strict as here....The sanitary quality of Rhode Island oysters can therefore be thoroughly relied upon.

F.P. Gorham, 1911
Report to the Commissioners of Shell Fisheries

Water quality in the lower bay is generally very good, with the exception of some coves and marinas around the edges; and portions of Mount Hope Bay. Most of the lower bay is classified SA, the highest saltwater classification (Figure 5.1). The urban area at the head of the bay has been, and still remains, the major source of pollutants to Narragansett Bay with its greater abundance of point sources (Figure 5.2). The flushing dynamics of the estuary move pollutants from the upper bay through the lower bay and eventually into Rhode Island Sound. As a result, pollutant concentrations in both water and sediment exhibit a downbay gradient, while point and nonpoint sources that exist along lower reaches of the bay generally cause adverse conditions on a local basis only and have little impact on the bay as a whole.

With a few notable exceptions, long-term databases do not exist from which to piece together changes in pollutant concentrations and related parameters over any great length of time or over any extent of the lower bay. Sporadic measurements exist for various physical factors, such as dissolved oxygen and nutrients. In addition, various surface sediment samples have been taken which provide data on metals and toxins in the lower bay. Within recent years a number of studies have been performed in the lower reaches of the bay, but since water quality is generally good, monitoring of the lower bay on a routine basis is minimal and generally restricted to academic studies rather than true monitoring programs.

Several remarkable long-term data sets do exist for the lower bay which are consistent, using the same sampling and analytical techniques since their inception, and are listed in Table 5.1.

Dissolved Oxygen

Anoxic conditions have never been a problem in the waters of the lower bay, except in very localized sites in constricted or deep basins. The lower bay is generally well mixed, experiences good tidal exchange, and is farther from the primary sources of BOD entering the bay. With recent improvements in sewage treatment plant effluent and decreased BOD loading in the upper bay, it may well be that the lower bay will never experience widespread anoxic conditions. Summertime (worst-case conditions) dissolved oxygen has fallen as low as 7 ppm from Conimicut Point south, well above the

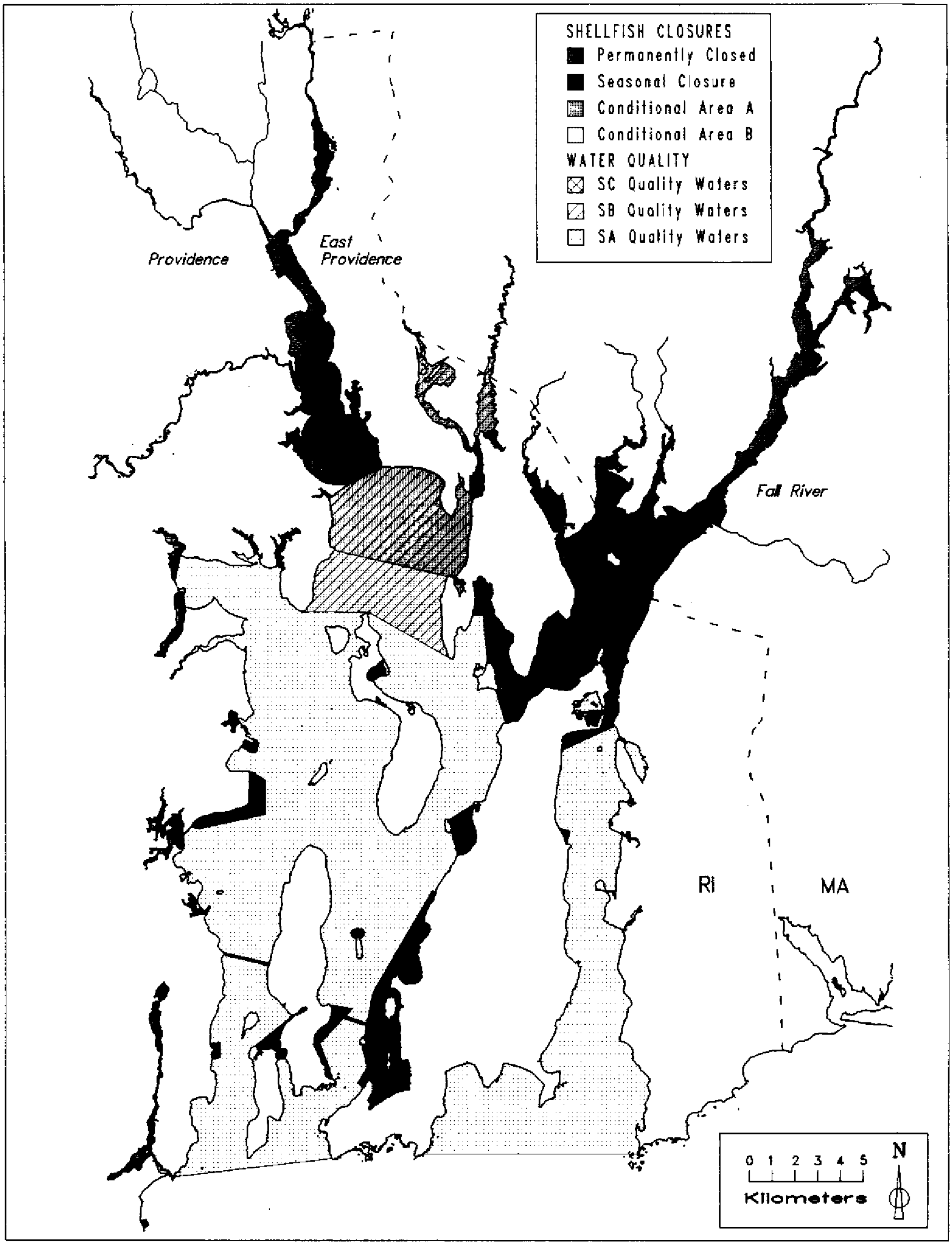


***Figure 5.1** Water quality classification and condition of shellfish beds in Narragansett and Mount Hope Bay, as determined by RI Dept. of Environmental Management for 1990. From RIGIS (1990).*

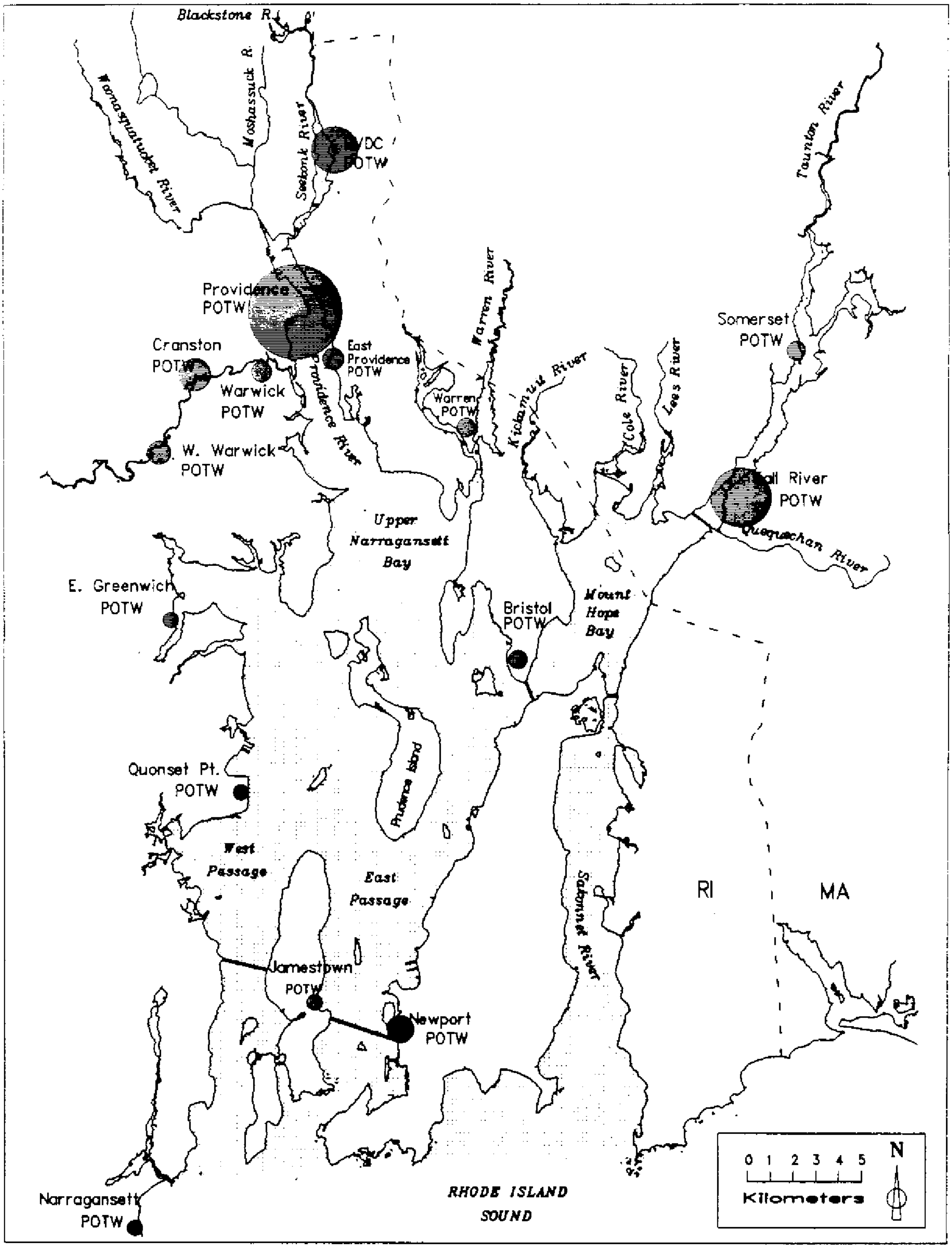


Figure 5.2 Location of municipal wastewater treatment facilities in Narragansett and Mount Hope Bay. Size of the indicator circles indicates the relative size of the volume discharged to receiving waters. From RIGIS (1990).

***Table 5.1** Long-term data sets available for Narragansett Bay.*

Sampling Party	Station Locations	Sampling Frequency	Period of Sampling	Major Parameters Sampled
Jeffries (GSO)	Fox Island, Whale Rock	Weekly	1959–Present	Benthic Fishes
Smayda (GSO)	West Passage	Biweekly	1959–Present	Nutrients Phytoplankton Zooplankton
MERL (GSO)	GSO Dock	Variable	1976–Present	Temperature Salinity Nutrients
Rhode Island Fish & Wildlife	Mid and Lower Bay	Monthly	1969–1977	Benthic Fishes
RIDEM	Upper Bay	Monthly	1947–Present	Coliform Bacteria

EPA recommendation of 6.0 ppm to be considered high quality saltwater. Unpublished reports note that certain local areas do experience anoxic conditions during summer months in the lower bay. The reported sites are generally restricted to deep waters lying at the bottom of the shipping channel and isolated deep holes that experience little mixing during the hottest summer months and therefore have the potential to become oxygen-depleted.

There never has been routine monitoring of dissolved oxygen in the lower bay, and therefore long-term trends cannot be adequately evaluated. Gradients in both surface and bottom water dissolved oxygen concentrations from the upper to lower bay were found during an August–September 1980 MERL study (Figure 5.3). Dissolved oxygen increases by a factor of 1.5 in surface water and by a factor of 6 in bottom water between Fox Point (at the head of the Providence River) and Conimicut Point (which marks the entrance to the upper bay). Although low levels of dissolved oxygen still exist in the Providence and Seekonk rivers during summer months (Figure 5.3; also see Chapter 4 for details), lower bay dissolved oxygen concentrations, even in bottom waters, remain well above the EPA criterion of 6.0 for waters considered able to support a diversity of marine life, and is not to be considered stressful to the aquatic biota.

Nutrients

Excessive levels of nutrients have been reported to cause symptoms of eutrophication in coastal waters. Given the trend of increasing population in the watershed of Narragansett Bay (Figure 3.1), concern over increases in nutrient concentrations in the bay is not inappropriate. However, published data are insufficient to determine whether there are long-term increases in nitrogen concentrations that would be indicative of eutrophication.

Nitrogen

Figure 5.4 shows surface water nitrate nitrogen concentrations as measured by Oviatt (1981) during 1979–80 throughout the bay. A comparison of transects performed

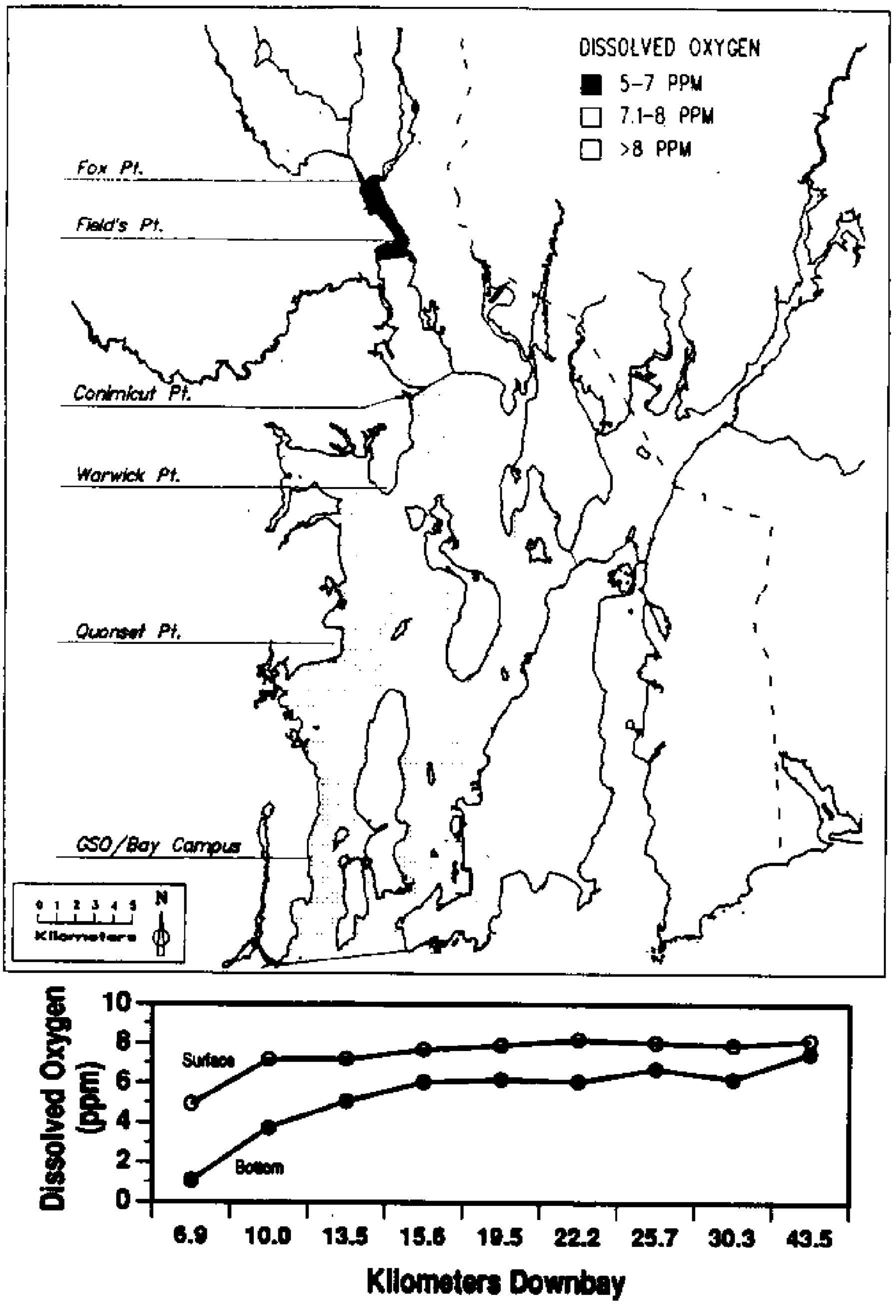


***Figure 5.3** Idealized schematic of surface water dissolved oxygen content in Narragansett Bay, not accounting for localized or small scale variances. Lower figure shows a downbay transect of surface and bottom water dissolved oxygen content during August of 1987. Data from Doering et al. (1988) and RIGIS (1990).*

in 1972–73 and again during 1979–80 shows that although nitrate levels were higher in 1979–80 than the earlier study in the upper bay, in the lower bay the 1979–80 levels were the same as, or lower than, the earlier levels. Increased nitrogen and phosphorus concentrations in the upper bay during the 1979–80 study may have been a result of the enriched effluent from the POTW at Field's Point, which had broken down from 1978 to 1980 and was adding chlorinated-only sewage to the Providence River during that time (see Chapter 4).

Kremer and Nixon (1978) published an account of seasonal and spatial changes in nutrient concentrations in Narragansett Bay which show that nitrogen concentrations decrease with distance down bay. Nitrogen apparently becomes a limiting factor throughout the bay during the spring and summer months, when it becomes depleted relative to available phosphorus by phytoplankton uptake. Concentrations of nitrite and nitrate are not very different over the length of the bay, decreasing only slightly from the head of the estuary to Rhode Island Sound. They did find however, that ammonia levels were elevated in the Providence River relative to downbay

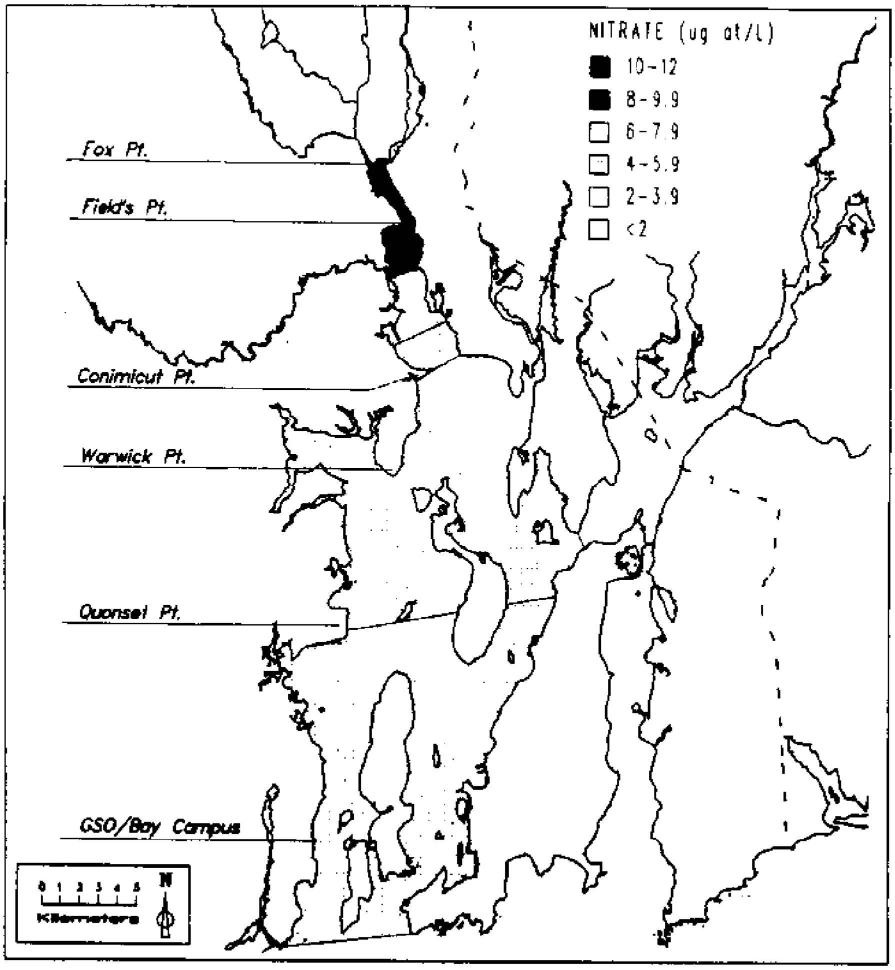


Figure 5.4 Idealized schematic of nitrate nitrogen (NO_3) concentrations in Narragansett Bay, excluding the Seekonk River for which no data were available, and based upon measurements reported in Oviatt (1981) and RIGIS (1990).

concentrations, reaching concentrations near zero at the mouth of the bay, suggesting sewage treatment facility discharges as the major source of ammonia.

Phosphate

Phosphate, like nitrogen, shows a trend of decreasing concentrations downbay (Figure 5.5). During a 1972–73 study, a decrease in phosphate concentrations by a factor of 2.5 from Fox Point to Conimicut Point was observed (Kremer and Nixon, 1978). Comparison of monthly surveys conducted in 1972-73 with 1979-80, indicates that phosphate levels in the lower bay did not change significantly over time (Oviatt, 1981). Since phosphate is a major constituent of POTW discharges, the increased phosphate concentrations found in the upper bay during the 1979–80 study could be a result of the POTW breakdown at Field's Point (see Chapter 4). Other sources of available data also give no indication of increasing phosphate concentrations in the lower bay. Smayda's (1984) biweekly monitoring of Station II (just north of the Jamestown Bridge) did not indicate any increasing trend in phosphorus concentrations between 1973 and 1983, and is in general agreement with that seen by Oviatt (1981).

Kremer and Nixon (1978) found phosphate to be distinctly seasonal throughout the bay. Since it is effectively recycled within the biota during the summer months, it is generally not considered to be limiting in Narragansett Bay.

Silica

Silica is a major component of diatoms, which are an important food source for fish and shellfish. The distribution of

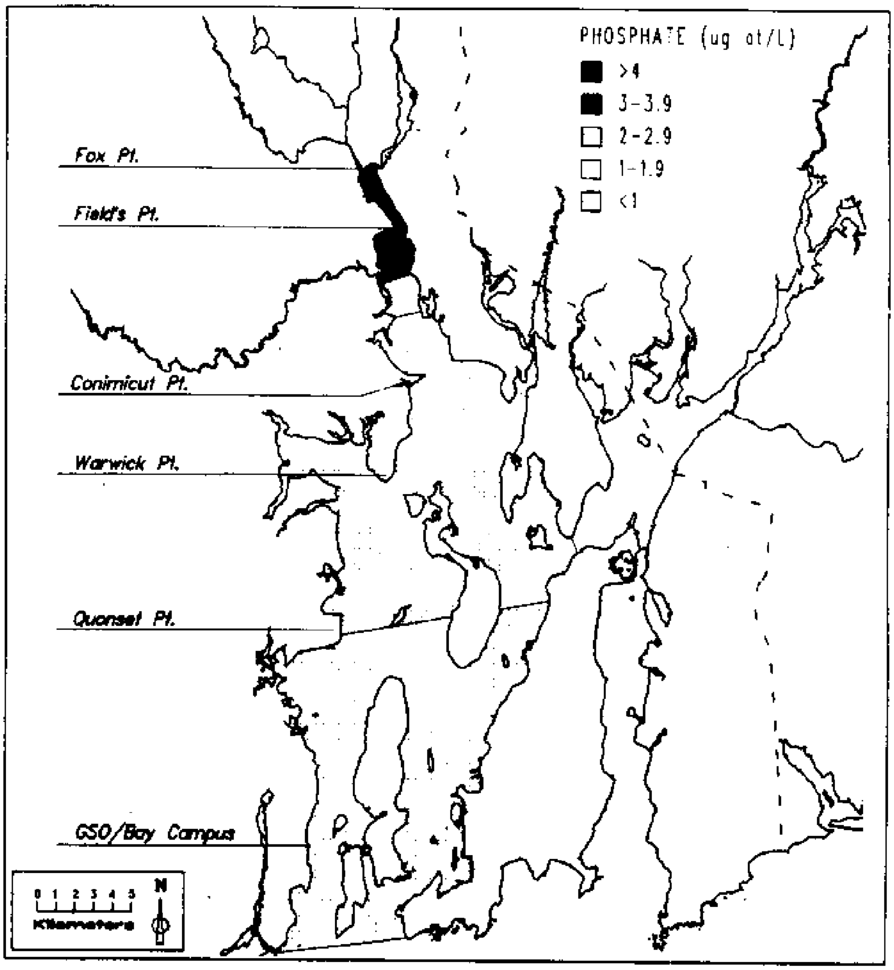


Figure 5.5 Idealized schematic of phosphate (PO_4) concentrations in Narragansett Bay, excluding the Seekonk River for which no data were available, and based upon measurements reported in Oviatt (1981) and RIGIS (1990).

silica has long been linked to the abundance and distribution of diatoms in coastal waters. Silicate was found to be highly seasonal in Narragansett Bay (Kremer and Nixon, 1978). A major depletion of silicate in the water column is observed during the period from March through May, corresponding to the spring diatom bloom (see Figure 5.7).

Silica sources are mainly terrestrial, rivers are the major transport mechanism for this important nutrient. Silicate concentrations show a decreasing trend downbay similar to that observed for other nutrients (Figure 5.6). A decrease by a factor of 1.4 from Fox Point to Conimicut Point is observed for both studies shown in Oviatt (1981). Since silicate is not a major constituent of sewage treatment plant effluent, increased concentrations were not observed during the 1979–80 study relative to those of 1972–73, in spite of the Providence POTW breakdown. Differences in silicate concentrations between the two study periods are minimal but there is a slight increase in wet years (1972–73) compared to dry years (1979–80) (see Figure 1.3), as would be expected since rivers are the major source.

Plankton

A 20-year record of diatom abundances from a station in the West Passage of lower Narragansett Bay shows that little overall change in diatom biomass has occurred since 1958 (Smayda, 1984). Hinga et al. (1988), in their review of all long-term phytoplankton data sets for Narragansett Bay, could find no evidence of an increase in biomass or abundance, except within some of the less dominant phytoplankton species. Flagellates did not appear to be increasing at the expense of diatoms or other phytoplankton

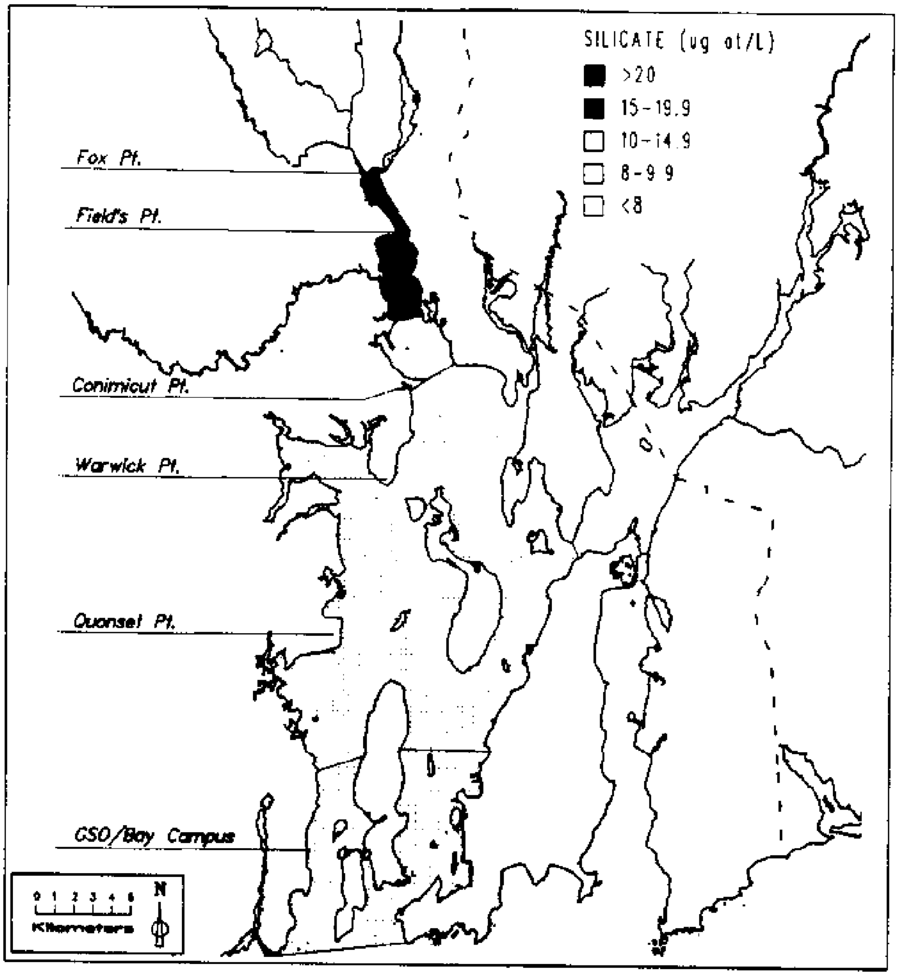


***Figure 5.6** Idealized schematic of silicate (SiO_2) concentrations in Narragansett Bay, excluding the Seekonk River for which no data were available, and based upon measurements reported in Oviatt (1981) and RIGIS (1990).*

species, as might be expected if there were a trend toward eutrophication of the bay.

Kremer and Nixon (1978) present spatial and seasonal variations in chlorophyll *a* concentrations, an estimate of phytoplankton concentration, from the Providence River to the mouth of the bay (Figure 5.7). These data show a slight decrease in chlorophyll *a* concentrations downbay, as would be expected in correspondence with a downbay gradient of reduced nutrient concentrations. As is typical of many estuarine and marine coastal waters, a bimodal seasonal abundance of chlorophyll *a* is noted, with one of the peaks arising in very early spring and the other in late summer/early autumn, corresponding to spring and fall phytoplankton blooms. Zooplankton biomass estimates (Figure 5.8) also show a bimodal seasonal pattern, which typically lags slightly behind the pattern for the phytoplankton (chlorophyll) on which the zooplankton feed (Kremer and Nixon, 1978).

Implications for Eutrophication

Although the data are not complete enough to determine whether eutrophication is occurring in the east and west passages of Narragansett Bay, the evidence that is available suggests that it is not an issue for the lower bay. Although river input is still the greatest source of nutrients to the bay, most of this input is received by the upper bay region. The contribution by oceanic waters exceeds that which enters from sewage treatment facilities (Table 5.2). However, nutrient levels in the lower bay do not seem to have significantly changed for at least the past 35 years, suggesting that oceanic waters have historically been the major source of nutrients to the lower bay, and have provided a relatively stable supply. The overall implications, as well as interactions of ocean derived nutrients are not well known at present, but it can be said that this source supplies a readily available source of nitrogen and phosphorus to Narragansett Bay.

As was shown in Chapter 4, the probability of eutrophication is much greater in the upper bay, since sewage treatment facilities and rivers provide the majority of nutrients to the bay and most of these sources are located in the upper reaches of the bay or localized in coves around the margins of the bay. If any concern is warranted, it is that the current trend of increased development and population growth within the Narragansett Bay watershed will cause increased nutrient loading, particularly to the upper bay area.

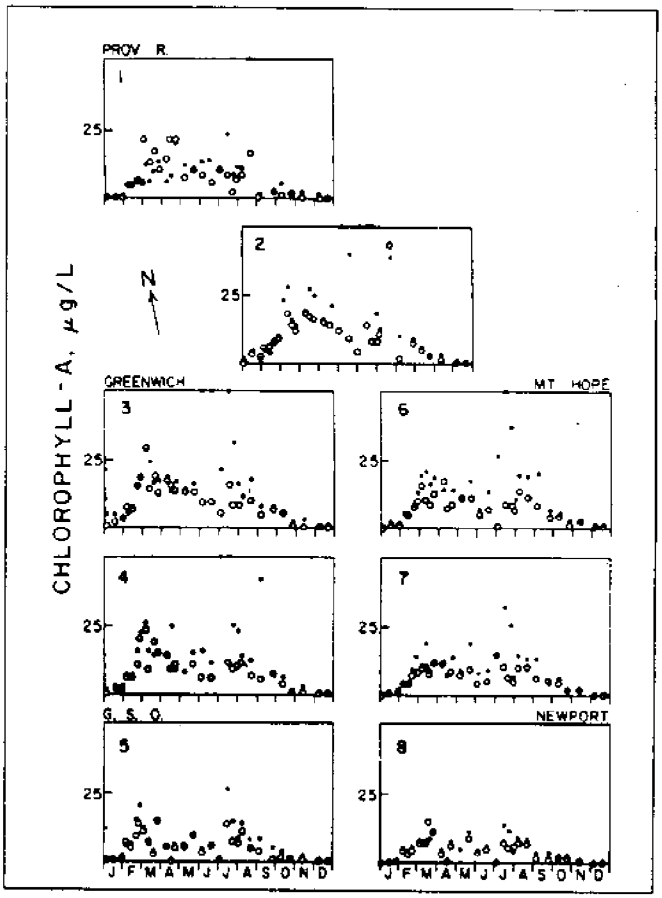


Figure 5.7 Surface (solid) and bottom (hollow) concentrations of chlorophyll-a in Narragansett and Mount Hope Bay from August 1972-August 1973, showing the bimodal seasonality of phytoplankton abundance. Taken from Kremer and Nixon (1978) their Figure 5.

Data presented by several researchers is suggestive of general estuarine stress, particularly in the Providence and Seekonk River areas of the bay. Frithsen (1989) found a shift in the dominant benthic invertebrate species in mid-bay regions over the past 30 years. Community composition changed from being dominated by *Nephtys-Nucula* to being dominated by *Mediomastus-Nucula*. *Mediomastus* increases have been correlated to increased organic enrichment of the benthos, and is hypothesized to be occurring in mid-Narragansett Bay. A similar pattern is observed for Mount Hope Bay (See Chapter 7). Although the existence of a *Mediomastus*-dominated benthic community does not definitively imply eutrophication of the bay, it may imply a stressed environment and organic enrichment of the benthos. Nutrient concentrations and their accumulation in the benthos should be closely monitored in order to assess the potential for trends toward eutrophication, although present conditions

Table 5.2 Nutrient loading to Narragansett Bay (mmol/m²/yr).[1]

Source	DIN	DIP
Atmosphere	29	3.5
Rivers	1102	56
Sewage	429	42
Ocean	459	102
TOTAL	2019	204

[1] Nixon and Pilson (1984)

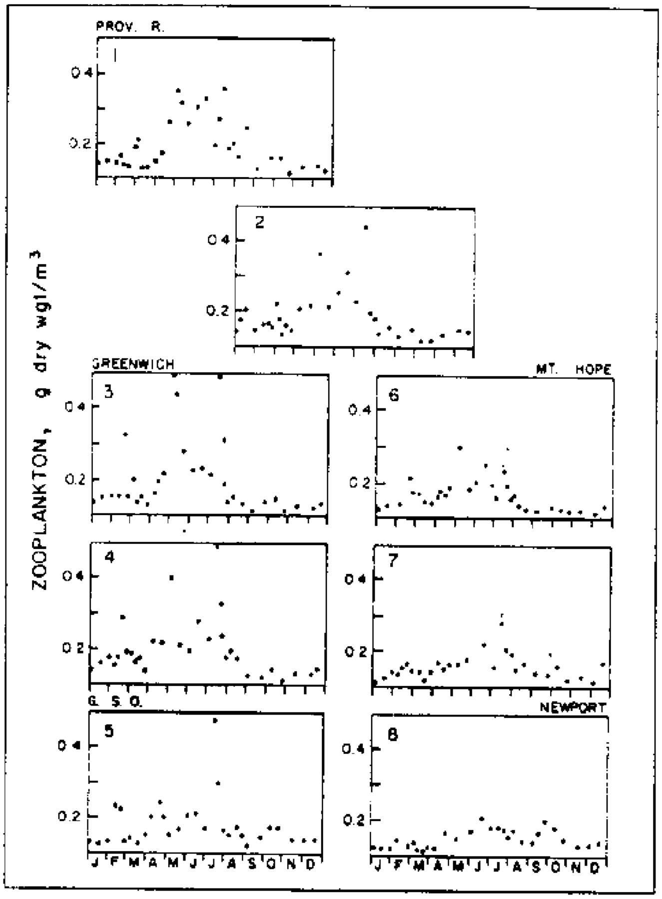


Figure 5.8 Zooplankton biomass estimates in Narragansett and Mount Hope Bay from August 1972-August 1973, showing typical predator-prey response when compared to phytoplankton abundance (Fig. 5.7). Taken from Kremer and Nixon (1978) their Figure 6.

in Narragansett Bay show no apparent adverse effects that are generally associated with eutrophication events.

Toxins

Metals

Metals in the marine environment are of concern because of their potential toxic effects upon marine aquatic flora and fauna. Metals also pose potential health risks associated with human consumption of fish and shellfish contaminated with toxic metals. Although marine plants and animals require very small or trace amounts of most metals as growth factors, problems arise when concentrations of metals in estuarine waters exceed these trace levels.

As metal concentrations increase in the water column, phytoplankton remove metals in excess of the trace amounts required for growth, and these excess metals may be accumulated within body tissues. Bioaccumulation can produce two outcomes: (1) accumulations reach a toxic level within the individual phytoplankton cell and cause its death, or (2) accumulations do not reach a level toxic enough to cause cell death, but are instead passed along the food web and are bioaccumulated at higher concentrations as they progress into higher trophic levels. Bioaccumulation can cause death or other adverse effects (thin egg shells in osprey, for example) if toxics accumulate.

Metals also have an affinity for binding with sediment, where they often undergo chemical changes by reaction with sediment pore water or other metals. Once bound to the sediment, or buried under accumulations of silt and sediment, metals can be very long-lived, leaving a history of past deposition events. Metals in sediments can also be ingested by benthic organisms and bioaccumulate through the aquatic marine food web.

Metal concentrations in the water column all show decreasing downbay gradients from the Providence River to Rhode Island Sound (Figure 5.9). Note the difference between concentrations of various metals: cadmium is at low levels while copper is elevated throughout the estuary.

Since major metal discharges were occurring in Narragansett Bay long before

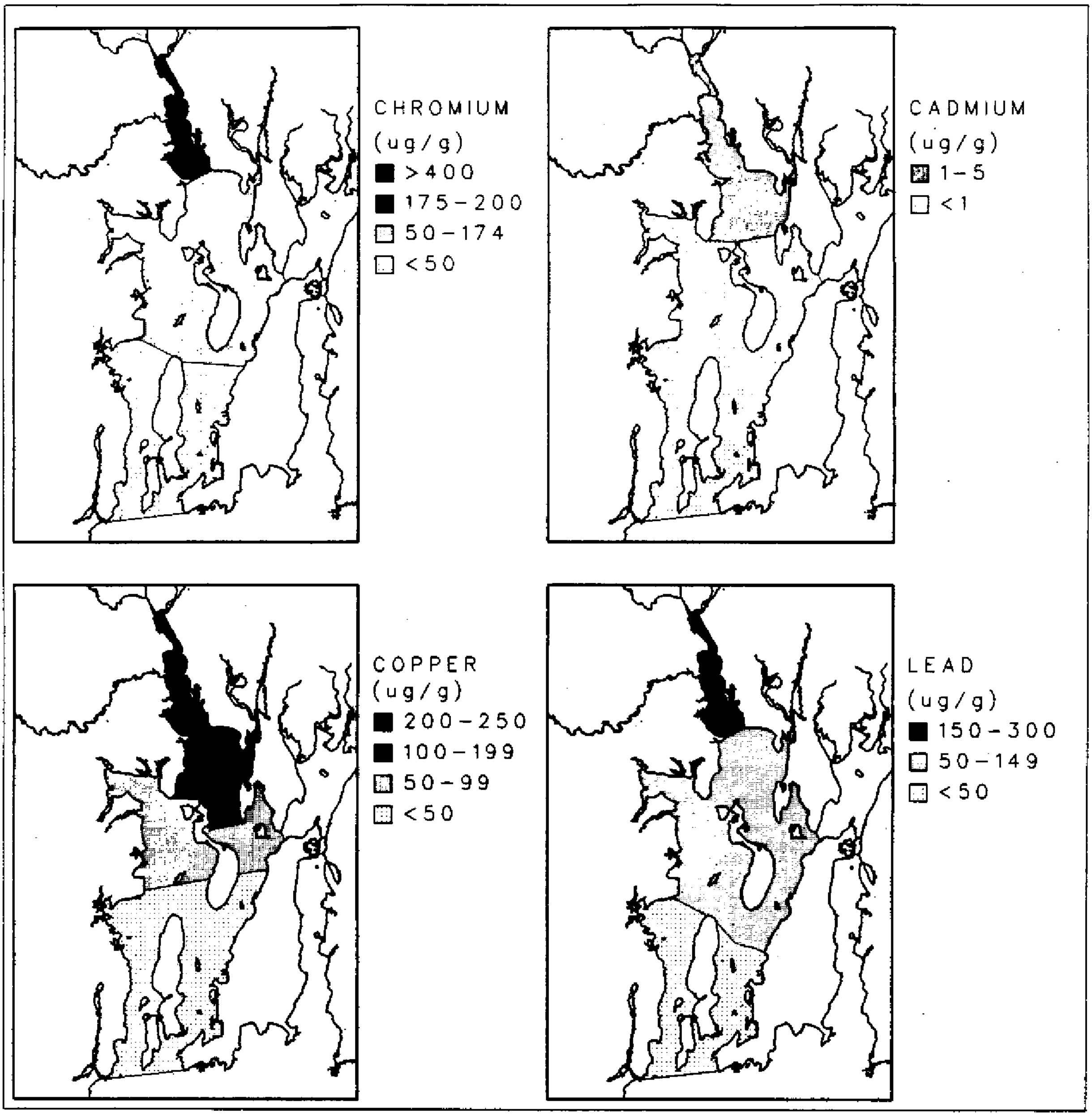


Figure 5.9 Idealized schematic of concentrations of dissolved chromium, cadmium, copper, and lead in Narragansett Bay, not accounting for localized "hot spots". Adapted from data reported in Doering et al. (1988) and RIGIS (1990).

monitoring was adopted, analysis of the record in sediments is one of the best sources for determining long-term trends in metal loadings. Patterns of metal concentrations in bottom sediments have been measured by Goldberg et al. (1977), Hunt (unpubl.), and Santschi et al. (1984), and for salt marshes by Bricker (1990). Unlike bottom sediments, salt marshes have not been disrupted by dredging, trawler dragging, or quahog tonging, and therefore the record reported by Bricker (1990) for salt marsh cores taken on Prudence Island have been used here to depict metals trends in the bay.

Metal concentrations in salt marsh cores taken on Prudence Island in the middle bay are approximately 2-10 times less than they are at Field's Point in the upper bay near Conimicut Point. In the salt marsh on Prudence Island, copper, chromium, and lead

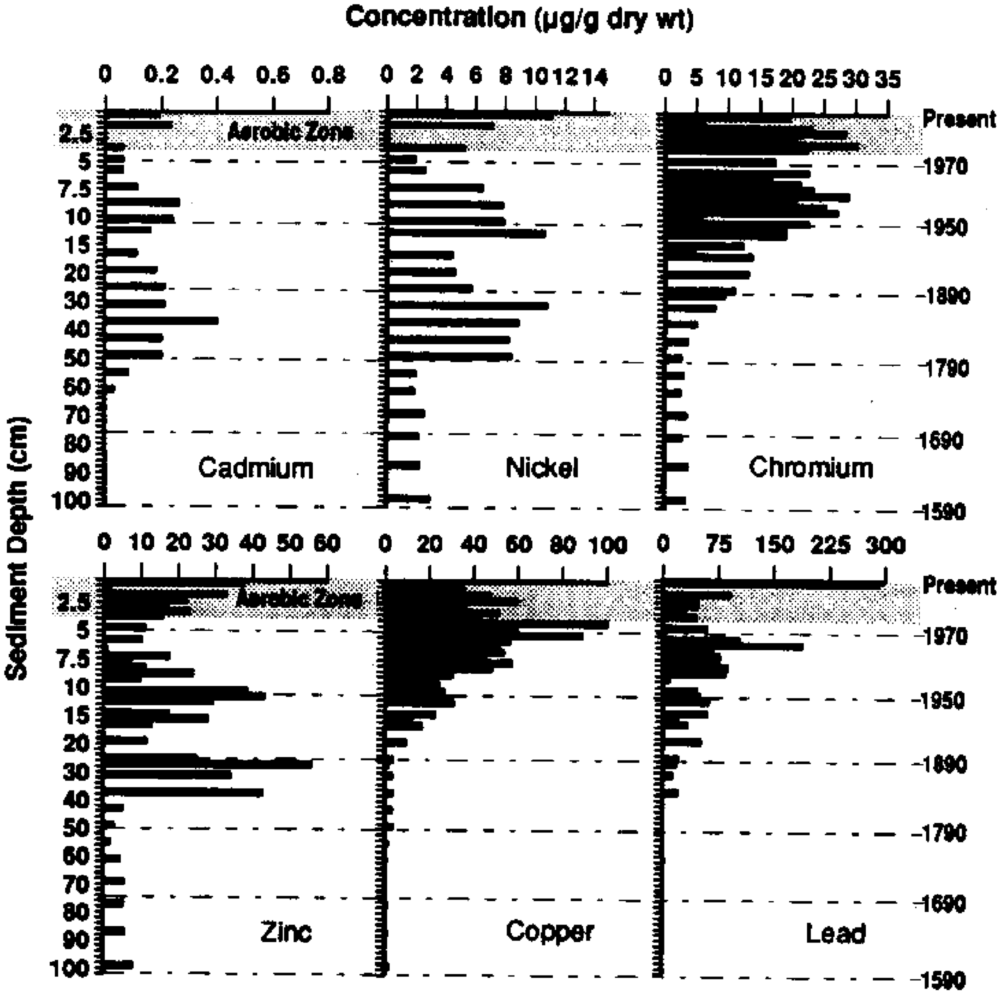


Figure 5.10 *Representation of trends over time for cadmium, nickel, chromium, zinc, copper, and lead in Narragansett Bay. Nickel, zinc, and cadmium show anomalous trends, increasing in sediment concentrations prior to the onset of the industrial revolution. Data taken from Bricker (1990) as reported for salt marsh sediment core samples taken on Prudence Island in the lower bay (see Fig. 1.1).*

all show similar trends, beginning a sharp increase at approximately 50 cm depth, which corresponds nicely with the onset of rapid industrial growth in the Providence region 100 years ago (Figure 5.10). For all three metals, loading leveled off approximately 20–30 years ago, corresponding to a period when many sewage treatment facilities were being constructed and put into operation. Although the facilities were not originally designed for the removal of metals, most metals are highly particle-absorptive and the simple process of solids removal from the effluent apparently was sufficient to stabilize the previously increasing trend for metals discharged into the bay.

Despite overall decreasing downbay trends, "hot spots" of higher sediment concentrations exist in isolated places in Narragansett Bay. The most extensive one is located near Quonset Point, where a former U.S. Naval Air Rework Facility was in operation between 1942 and 1973. Here, several trace metals are found in sediments at levels above EPA standards, and the contamination extends for several kilometers from shore (Eisler et al., 1977). Other isolated hot spots—generally a result of localized industry—are located at Apponaug Cove, Brushneck Cove, Bullock's Cove, Greenwich Cove, Newport Harbor, Pawtuxet Cove, and Wickford Cove, all former or present sites of point sources of specific metals (Bender et al., 1988). As noted previously, the impact of these hot spots is local; they do not generally affect the quality of the water in Narragansett Bay as a whole.

Studies have been performed to measure the concentrations of metals in the tissues of living organisms, particularly the hard clam, *Mercenaria mercenaria*. In general, the tissues of hard clams throughout Narragansett Bay are contaminated with metals, but not above federal alert levels. Metal concentrations in clam meat tissues generally do not correlate very well to concentrations detected in either the sediments or the water column (Bender et al., 1988).

Petroleum Hydrocarbons

Since petroleum products are a major commodity shipped through Narragansett Bay, it is to be expected that hydrocarbons would be a common source of pollution in both water and sediment. A rapid increase in the rate of hydrocarbon use from approximately 1947 onward spurred the onset of hydrocarbon pollution in Narragansett Bay (see Figure 4.10). This pollution is a reflection of the use of petroleum products as a major source of fuel in automobiles and other machinery, as well as increased petroleum transport on the bay and in the port of Providence. Concerns over hydrocarbon pollutants are for toxic effects in living tissues of fish and shellfish and potential toxicity to

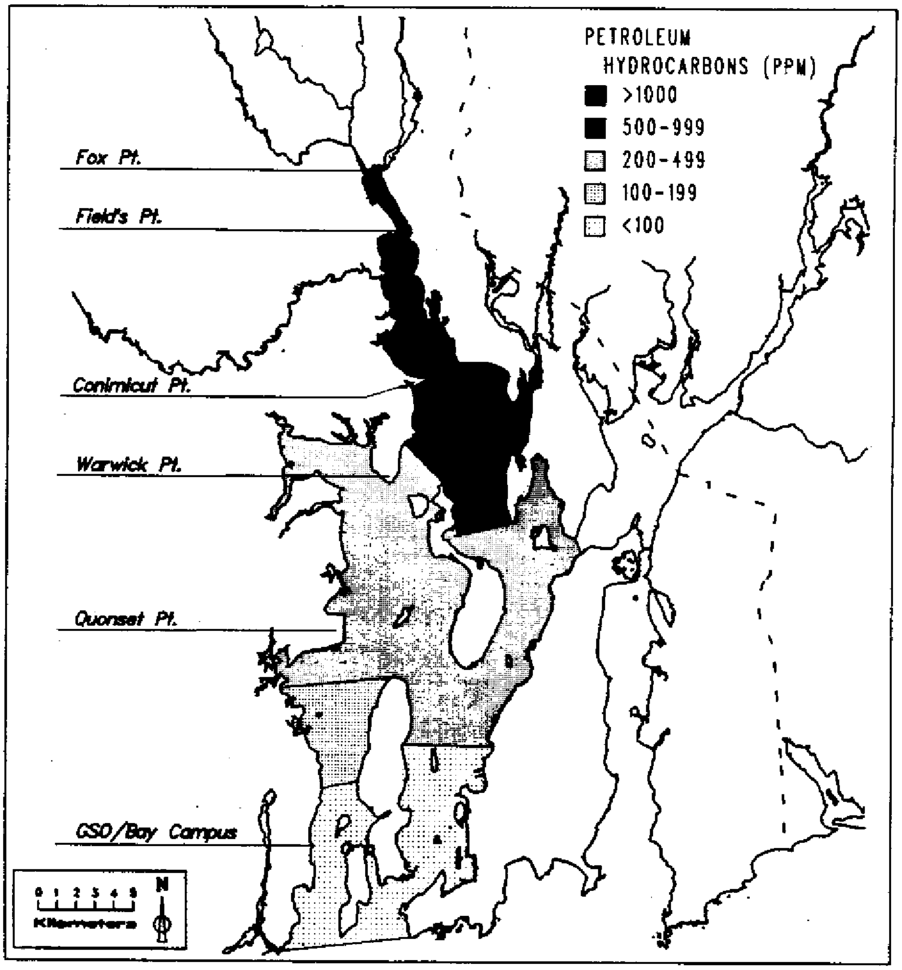


***Figure 5.11** Idealized schematic of petroleum hydrocarbon concentrations in Narragansett Bay surface sediments, not accounting for localized or small scale variances or "hot spots". Adapted from data reported by Quinn (1988) and RIGIS (1990).*

humans when contaminated fish or shellfish are consumed.

Petroleum hydrocarbons have been more carefully studied in Narragansett Bay than in most other estuaries in the country. As with all other pollutants found in Narragansett Bay, a decreasing downbay gradient is observed in hydrocarbon concentrations in surface sediments (Figure 5.11). Note that concentrations in the East Passage, the main shipping artery for tanker traffic into and out of the bay, are typically higher than in the West Passage. Increased petroleum hydrocarbon concentrations are also seen in the lower bay in the region near the naval base in Newport. Petroleum hydrocarbon concentrations are greatest in the Providence and Seekonk rivers, decrease 2-fold by Conimicut Point, and further decrease with proximity to Rhode Island Sound. Although publicity focuses on oil spills from tanker accidents, most hydrocarbon contamination of the bay occurs where petroleum products are transferred to storage facilities, continuous road runoff, disposal of crankcase oil down storm drains all around the developed part of the bay, and occasional small spills.

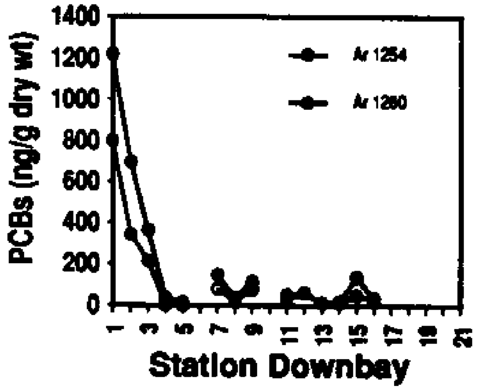


Figure 5.12 Concentrations of PCBs along a downbay transect through the East Passage of Narragansett Bay. Transect begins in the Seekonk River and ends near Whale Rock. From data reported in Latimer (1988).

Hydrocarbon residues have been found in the tissues of hard clams, particularly those in the upper bay–Providence River area. However, no EPA criteria exist by which to evaluate hydrocarbon contamination in the bay or its potential effect for human consumption. Black et al. (1988) found significantly higher levels of PHCs (but not PAHs) in winter flounder eggs at Gaspee Point (in the Providence River) than at Fox Island (in the West Passage, just north of the Jamestown Bridge). This is not surprising considering that hydrocarbon concentrations in sediments can be 10 or more times greater in the Providence River than in the West Passage (Figure 5.11).

Urban runoff may become an increasingly important source to the lower bay as more land within the watershed and along the coast is converted from rural to urban use, thus increasing urban runoff and pollutant loadings, potentially by orders of magnitude (see Table 4.5).

PCBs

Chlorinated hydrocarbons are relative newcomers to the Narragansett Bay ecosystem, since production started in the early 1950s and continuing into the early 1970s. It was not until Rachel Carson's *Silent Spring* was published in 1962 that widespread concern and monitoring of these toxins was begun. Major sources of PCBs have been industry and urban runoff, with rivers providing the major load of PCBs to the bay by collecting and channeling the urban runoff.

As noted in Chapter 4, PCB inputs to the Providence and Seekonk rivers have decreased dramatically since production was halted in 1979. PCBs are still concentrated in the Providence and Seekonk Rivers, and there is a dramatic 42-fold decrease in PCB concentrations from the head of the Seekonk River to Conimicut Point (Figure 5.12). PCB concentrations are relatively low throughout the entire lower bay and do not pose a problem, especially since production and use of these toxins has ceased and concentrations will probably not increase in the future. Slight but measurable PCB concentrations do exist in hard clam tissues, but the risk to human health is difficult to assess since no federal alert levels or guidelines have been established for this class of toxins.

PCB contamination of sediments potentially poses problems other than health hazards for human consumption. Black et al. (1988), in a laboratory experiment, found that smaller-sized winter flounder larvae hatched from eggs containing higher levels of PCBs. However, when these investigators collected larval flounder from Fox Island and Gaspee Point and tested them for a variety of biological responses affected by PCB contamination, they found no significant differences between the two populations. Although PCBs exist in sediments in the bay, their effect on growth and survival of winter flounder in Narragansett Bay is apparently not significant.

Waterborne Pathogens

Water quality degradation due to pathogenic contamination is probably the form of pollution of which the public is most aware. Closures of both swimming areas and shellfish beds result when water is contaminated by high concentrations of fecal coliform bacteria. Because closure of such areas limits use of the bay, and may have adverse effects upon the rapidly growing tourism business, the public often judges the overall health and cleanliness of Narragansett Bay by the extent of fecal coliform contamination.

Water classified as unfit for shellfishing or swimming due to bacterial contamination is mainly found in the upper bay, while only very localized sites in the lower bay fail to meet the highest standards set forth in the Clean Water Act of 1972 (see Figure 5.1). Localized closures of waters are due to coliform pollution that can be attributed to marinas or boating facilities, sewage treatment facilities, and other point sources at various sites around the shores of Narragansett Bay. The lower bay sewage treatment facilities are smaller than at the head of the bay, and the body of receiving water is much larger and better flushed than are the Providence and Seekonk rivers, therefore most of the lower bay is considered safe for fishing and swimming. In the upper bay, extensive areas of shellfish beds have been managed on a conditionally open basis since 1947. After large rainfalls, sewage mixes with stormwater and flows out CSOs at the head of the bay. Conditional areas are closed for at least 7 days when one-half inch of rain falls within a 24-hour period, longer if rainfall is greater or falls over a longer span of time. The majority of problems from coliform-contaminated waters occur in the upper bay and Mount Hope Bay, due to proximity to the source of pathogens (sewage treatment facility outfalls and CSOs) and reduced flushing and mixing properties.

As discussed in Chapters 3 and 4, the main source of coliform contamination is effluent from the 65 CSOs in Providence. Control of these discharges would vastly improve the bacteriological quality of the water in the upper bay region. Perhaps as a result of improved sewage treatment technology, water quality has recently improved to the point where consideration is being given to permanent opening of Conditional Area B (see Figure 5.1).

General Conclusions: Upper and Lower Bay

The preceding pages have told the story of a long history of abuse in upper Narragansett Bay. In contrast to the previous century of industrial and municipal discharges into the bay, recent efforts at pollution abatement are resulting in improved water quality throughout most of the bay. In fact, the biennial review on the State of the State's Waters (1988), reported that 90% of coastal waters meet the fishable-swimmable goals of the Clean Water Act.

Metals (except for copper) and toxics generally do not occur at levels exceeding EPA chronic criteria throughout most of the bay, and recent trends show decreased loading by both industrial and municipal dischargers. Loadings of BOD and TSS are significantly reduced from levels in the mid-1970s and show continued improvement. Nutrient loadings from rivers have decreased in the last decade and concentrations drop to relatively low levels south of Conimicut Point. Tidal mixing of offshore waters is now one of the largest sources of nutrient input to Narragansett Bay.

No apparent trend toward nutrient enrichment and eutrophication of the bay, especially in the lower reaches, is observed in recently compiled historic data sets. The potential for widespread anoxia is small, especially in light of increased dissolved oxygen concentrations in the upper reaches of the bay, a trend that may continue as BOD loading is further decreased.

The overall conditions in the upper bay suggest that it is improving as a viable aquatic habitat. Recent reports of increased species diversity in the Providence River, coupled with improvements in water quality, suggest that the upper bay, once the most heavily polluted section, is undergoing improvement that species are responding to. Certainly problems and concerns still exist, as outlined in Chapter 2, and many will continue to persist, but great improvement has been made in the overall quality of Narragansett Bay waters since the early 1970s. It is only reasonable to assume that as public awareness, public concern, scientific knowledge, and technological capabilities increase, further improvement in the waters of Narragansett Bay will occur.

Chapter 6

Trends in Water Quality in Mount Hope Bay

We know almost nothing about how Mount Hope Bay and Narragansett Bay interact. We know that a good bit of pollution enters from Fall River and upstream into the Taunton River. Our friends in Massachusetts are trying hard to clean up. Nonetheless, a lot of material enters and we have no idea how much of it gets from Mount Hope Bay into Narragansett Bay.

Dr. Scott Nixon, 1987
Introductory remarks at a NOAA Estuary-of-the-Month Seminar

Mount Hope Bay is a large northeasterly section of Narragansett Bay (Figure 6.1). The bay has a surface area of 35.2 km^2, 46 km of shoreline, and an average depth of 5.7 m, giving the bay a total volume of 201.7 x 10^6 m^3 (Chinman and Nixon, 1985). Seventy percent of Mount Hope Bay lies in Rhode Island, and 30% in Massachusetts.

The major tributary of Mount Hope Bay is the Taunton River, which originates in the state of Massachusetts and provides 34% of the freshwater input to Narragansett Bay. The Mount Hope Bay watershed covers 1,476 km^2, and 90% of the fresh water flowing into Mount Hope Bay originates in Massachusetts.

The coastal region of Mount Hope Bay is dominated by the city of Fall River, situated on the bay's northeastern flank (Figure 6.1). The history of the city of Fall River parallels that described in Chapter 3 for the city of Providence, but on a smaller scale. The city developed as a New England mill town, and, as in Providence, the textile industry once dominated the region's economics. Today the city maintains the character of an old New England mill town, with a number of textile mills refurbished into historic sites and retail shops. Fall River is still an active port and receives approximately 50% of the tanker traffic entering Narragansett Bay.

Just as Fall River's historical development paralleled that of Providence, Mount Hope Bay experienced a history of pollution similar to that of upper Narragansett Bay, used as a convenient receptacle for both industrial and human waste products (Brubaker and Hamblett, 1989). The city of Fall River was the major polluter of Mount Hope Bay waters, and, as in Providence, the construction and upgrading of sewage treatment facilities lagged far behind the need. From early industrial times through 1983, the city of Fall River discharged partially treated or raw wastes into the Taunton River and Mount Hope Bay.

Despite its long history of water quality degradation and its connection to Narragansett Bay, Mount Hope Bay has historically been perceived as having little interaction with or impact on Narragansett Bay. Little attention was given Mount Hope Bay, perhaps because most of Mount Hope Bay is in another state's jurisdiction, or perhaps because there was confusion over whether water flowing from Mount Hope Bay affected the rest of Narragansett Bay. Part of Mount

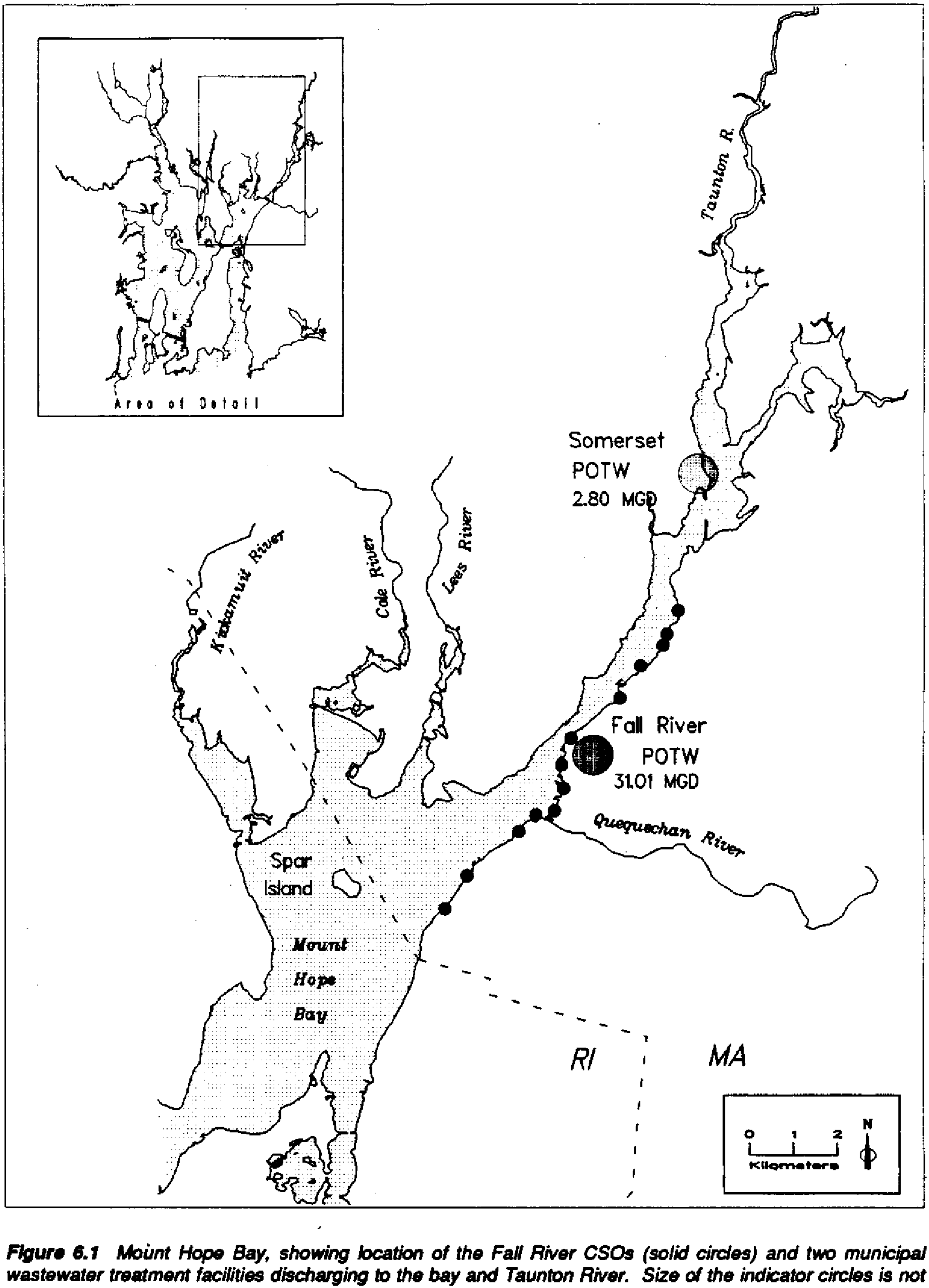


Figure 6.1 Mount Hope Bay, showing location of the Fall River CSOs (solid circles) and two municipal wastewater treatment facilities discharging to the bay and Taunton River. Size of the indicator circles is not representative of discharge volumes, which are provided in the figure legend. From RIGIS (1990).

Hope Bay waters interact with the Sakonnet River, which is fully tidal, connects with Rhode Island Sound, and by definition is not a true "river", and part flows under the Mount Hope Bay Bridge to the East Passage of Narragansett Bay. This confusion led to the exclusion of Mount Hope Bay from most studies and reports pertaining to Narragansett Bay water quality and the overall dynamics of the estuary.

It was not until the 1980s that Mount Hope Bay was increasingly studied. It is now generally recognized that the major interaction of Mount Hope Bay was with Narragansett Bay—not with the Sakonnet River, which in fact has so little interaction with Mount Hope Bay that it is better considered an arm of Rhode Island Sound rather than an integral part of the bay's dynamics. Mount Hope Bay water quality has the potential to influence water quality in Narragansett Bay and vice versa, and Mount Hope Bay should be considered more critically as part of the entire Narragansett Bay system.

Water Quality Concerns

As the largest urban center on Mount Hope Bay, the City of Fall River has therefore been, and continues to be, the focus of most water quality problems. Present day water quality concerns focus on poor water quality conditions due to fecal coliform contamination of swimming/shellfish-bed areas, and concentrations of metals found in sediments and hard clams.

Bacterial Contamination

Fecal coliform pollution is the uppermost concern for water quality in Mount Hope Bay at present. Large tracts of hard clam beds, estimated at a present market value of $5.3 million, remain permanently closed due to high coliform bacteria concentrations in overlying waters. Present major contributors of coliforms are Fall River CSOs and the Taunton, Lee's, Cole, and Quequechan rivers (Figure 6.1).

Problems in the Lee's and Cole rivers apparently result from failed individual septic discharge systems (ISDS), which cause excess nutrients, eutrophication, and numerous fish kills in those rivers (Brubaker and Hamblett, 1989).

A major contributor of coliform bacteria to the Taunton River is the Somerset POTW, which until recently has operated in violation of its permit for a variety of constituents, including coliforms (Brubaker and Hamblett, 1989). The Somerset POTW has recently undergone an upgrade to secondary waste treatment, which will presumably reduce its impact on the Taunton River in the near future.

The contribution of coliforms by the Fall River CSOs accounts for frequent and/or permanent closures of shellfish and swimming areas. Coliforms enter the bay not only during periods of heavy rainfall but also during dry weather conditions, due to a poorly maintained CSO network (Roman, 1989). Clogging of connections within the CSO network causes backup and overflow of wastewater during dry weather conditions (Brubaker and Hamblett, 1989). Because dry weather discharges are concentrated, they exceed wet weather coliform concentrations. Food and Drug Administration (FDA) studies have concluded that 95% of the coliform contamination entering Mount Hope Bay originates from CSOs on the Taunton River, which provide over 1 billion gallons of untreated wastes each year (Rippey and Watkins, 1987).

In recent years, studies have been conducted to determine the extent of the CSO problem and to recommend plans for upgrading the system. In 1986–87, several CSOs were cleaned, repaired, and upgraded by the city of Fall River. This will presumably correct a major portion of the dry weather CSO input to Mount Hope Bay. Plans are currently being made to upgrade the wet weather CSO capacity to store water for later treatment at a municipal treatment facility (Brubaker and Hamblett, 1989). Implementation of these plans would essentially stop CSO input to Mount Hope Bay, resulting in a model system if it works as expected, and would greatly improve the overall water quality of the bay, allowing hard clam beds to be open to shellfishing.

Toxics Contamination

Metal concentrations in sediments of Mount Hope Bay are a potential concern, especially in regard to shellfish consumability. Mercury contamination has been a major concern. Mercury inputs to the Taunton River by ICI America (an industrial manufacturer) as high as 7 pounds per day were recorded into the 1970s. Levels of mercury in sediments are high, on average exceeding 2 µg/g dry weight and reaching a maximum of 7.5 µg/g dry weight. Recent mercury discharges are reduced, but elevated levels in both the water column and the sediments raise concerns for long-term accumulations of this toxin in shellfish. Hard clam tissues measured in 1986 showed mercury concentrations below the FDA guideline (for clam tissue) of 1 ppm (Pratt, 1988). Due to its potential for harmful health effects, mercury will remain a concern in Mount Hope Bay. However, because mercury inputs have been reduced and concentrations in hard clam and water column samples fall below federal alert levels, mercury contamination is not impeding present use of the bay.

Table 6.1 *Concentrations of various metals in seawater and hard clam tissues from Mount Hope Bay. (From Rippey and Watkins, 1987)*

Metal	Seawater Concentration (ppb)	Clam Tissue (µg/g)
Cu	1.4	16.3
Ni	2.1	14.9
Cd	0.1	0.7
Zn	N.D.	178.0
Cr	0.2	3.6
Pb	0.3	3.1
Ag	0.02	N.D.
Hg	16.0 picomolar	0.56

N.D. = no data available

Small amounts of other metals, such as zinc, copper, nickel, and lead, exist in Mount Hope Bay sediments and in the water column, but none has been measured in excess of federal alert levels (Rippey and Watkins, 1987; Table 6.1). Like mercury, these metals continue to be a concern but do not at present impede use of the bay.

PCBs, pesticides, and petroleum hydrocarbons are all present in measurable quantities within Mount Hope Bay sediments, but are not found at or above federal alert levels in hard clam tissues (Pruell and Norwood, 1989).

Trends in Pollutant Loadings

CSOs

During the 1950s, the city of Fall River installed a sewer system that intercepted wastewater discharges to the Taunton River, delivering them to the Fall River POTW for treatment (Brubaker and Hamblett, 1989).

The sewer system was designed to accommodate sanitary flow only; any greater flow was diverted to Mount Hope Bay through CSOs. The CSO problem has therefore been present in Mount Hope Bay for nearly 40 years, and the impact from the CSO network has increased over time. As the CSO network aged, it was not maintained in good working order, and eventually it degraded to the point of diverting sewage and runoff during dry weather periods, further increasing the pollutant load received by Mount Hope Bay. At present, 11% of the total wastewater entering the Fall River collection system is diverted to Mount Hope Bay as wet weather overflow (Maguire Group, 1987).

Rivers

The pattern of pollutant loading for rivers varies. Some rivers, like the Taunton, have shown improvement with time, while others, like the Lee's, Cole, and Quequechan have degraded due to failure of ISDS and CSO systems. The Taunton River, the bay's major tributary, historically carried the largest pollutant burden of all rivers to Mount Hope Bay. Into the early 1950s, the river was used as a receptacle for untreated wastes from both industries and municipalities.

With the initiation of industrial pretreatment and secondary municipal treatment, the load of pollutants carried by the Taunton River decreased, particularly for fecal coliforms. Currently the Taunton River provides less than 4% of the total fecal coliform input to Mount Hope Bay (Roman, 1989).

Other rivers, such as the Lee's, Cole, and Quequechan, have become more important as sources of pollutants to Mount Hope Bay. Individual septic system failures have accounted for recent problems along both the Lee's and Cole rivers, but according to Brubaker and Hamblett (1989), this problem is being studied and will be remedied once studies are completed. The Quequechan River, on the other hand, is severely polluted with fecal coliforms from three CSO outfalls on its banks. A survey completed in 1987 by Rippey and Watkins found coliform levels indicative of raw sewage. Plans to remedy the Quequechan River pollution problem are included in those for the entire Fall River CSO system.

POTWs

The pollutant-loading history for treatment facilities discharging into Mount Hope Bay and its tributaries is similar to that seen for the Providence and Seekonk rivers (see Chapter 4). POTW discharges into Mount Hope Bay generally consisted of partially treated or raw sewage until the1970s, when some new facilities were constructed and other aging facilities were upgraded to secondary treatment. Of 12 municipal treatment plants in operation in the Mount Hope Bay watershed during 1971, only four complied with EPA regulations (Brubaker and Hamblett, 1989). During 1983 the Fall River sewage treatment facility was upgraded to secondary treatment, and water quality improved in adjacent waters. Since its upgrade to secondary treatment, the Fall River POTW has generally operated within compliance of federal discharge levels for all monitored constituents (Brubaker and Hamblett, 1989; Fall River POTW plant records 1983–1989). The Fall River POTW is the largest sewage treatment facility discharging into Mount Hope Bay, and its record of discharge since the initiation of secondary treatment is detailed in the following paragraphs and illustrated in Figure 6.2.

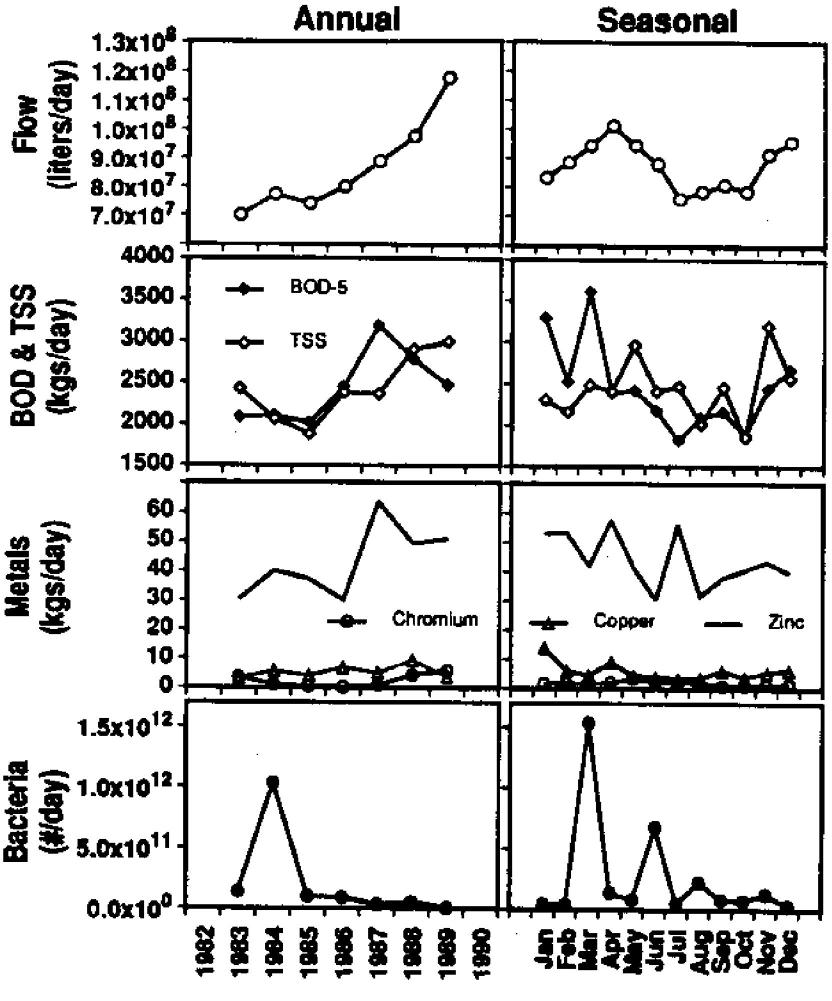


Figure 6.2 Average annual and seasonal trends of various pollutant discharge volumes for the Fall River STP. The facility was converted to secondary sewage treatment during 1982. Data from plant operation records.

The Fall River municipal wastewater treatment facility began secondary treatment in 1983 when upgrading was completed. Its first two years of operation as a secondary treatment facility showed reductions in total suspended solids (TSS) and generally low levels of BOD loading. From 1985 to 1987, a major increase in BOD loading from the facility was observed, followed by a decrease during 1988 and 1989, but not to 1985 levels. Since 1985, TSS in the Fall River treatment facility discharge has nearly doubled. Both BOD and TSS loadings correlate well to increased flow rates from the facility since 1985, although average annual BOD loading has decreased since 1987, indicating increased plant efficiency in the treatment process.

As shown in Figure 6.2, levels of TSS in the facility discharge show some correlation to time of year, with lowest values in summer and highest in winter and spring. BOD levels appear more distinctly seasonal, with peaks occurring from November through March and minimum values reached during summer months. Both TSS and BOD appear to follow a seasonal trend that correlates with effluent discharge flow rates, all presumably correlated to rainfall.

Three effluent metals—copper, chromium, and zinc— are monitored on a continuous basis by the Fall River treatment facility. Average annual loadings of all three have increased since 1983 (Figure 6.2). Chromium shows a steady decrease from 1983 to 1986, but then a rapid increase from 1986 to the present. Zinc loadings are variable, but a doubling in loading has occurred since 1986 and these elevated levels have since been maintained. Copper exhibits a distinct saw-toothed pattern in loading concentrations, but has generally increased since 1983. A sharp drop in 1989 levels has returned values to nearly those of 1983, but the trends observed for other metals, BOD, and TSS suggest that copper loadings may increase again during 1990.

Fecal coliform loading by the Fall River treatment facility has generally been low, despite an elevated value for 1984. Coliform loading is distinctly seasonal, reaching maximum levels early in the year and tapering off during late summer through midwinter, presumably due to wet weather flow to the facility (Figure 6.2).

Physical and Biological Trends

The role that pollution has played in changing the dynamics of biological systems in Mount Hope Bay is unknown. Historical records of water quality, biotic assemblages, and physical characteristics do not exist for Mount Hope Bay to the extent that they do for Narragansett Bay. However, data for a suite of physical and biological factors do exist in the published quarterly reports of the Brayton Point Power Plant (Marine Research, Inc., 1974–1990). These data represent an excellent source of information concerning physical and biological parameters of Mount Hope Bay. Consistently sampled data using standard methods are available for 1974 through the present. Unfortunately, several parameters are no longer collected, but generally the data allow comparison of nutrient and dissolved oxygen concentrations and abundances of biota before and after secondary treatment operations were implemented at the Fall River POTW.

The following data, unless otherwise noted, have been taken from the Brayton Point Power Plant quarterly reports for their sampling station at Spar Island (their Station F; see Figure 6.1). Data from this station were chosen since they are less likely to be influenced by anthropogenic factors more common near shore. The data are presumed to be representative of the entire Mount Hope Bay water body, and provide a starting point for observing the characteristics and potential trends of this portion of the Narragansett Bay estuary.

Physical Trends

Temperature

Average monthly water temperature in Mount Hope Bay ranges from 24°C (August) to 2°C (February). The average annual water temperature is 16.6°C, with an approximately 1°C difference between surface and bottom waters. Average annual water temperatures from 1975 through 1988 show a slightly decreasing trend (Figure 6.3). This decreasing trend, which may be attributed to improvements in the thermal discharge from the Brayton Point Power Plant, contrasts with the trend of increasing temperature in Narragansett Bay (Figure 1.2).

Salinity

Salinity in Mount Hope Bay ranges from 31 ppt to 23 ppt and averages 27 ppt, with an approximately 2 ppt difference between surface and bottom water salinities. Since salinity is inversely related to freshwater input, it is greater during late summer when river flow is reduced and evaporation is enhanced and tends to be lower during the season of spring rain and snowmelt. Average annual salinity from 1975 through 1988 shows a slightly decreasing trend (Figure 6.3), which may be due to slightly wetter weather in recent years.

Dissolved Oxygen

A slightly decreasing long-term trend in dissolved oxygen is apparent in Mount

Hope Bay, although average dissolved oxygen concentrations remain above critical levels of 6.0 ppm (Figure 6.3). Dissolved oxygen values show a rough inverse correlation to average annual BOD loadings by the Fall River treatment facility, although the two parameters are not closely coupled (Figure 6.4).

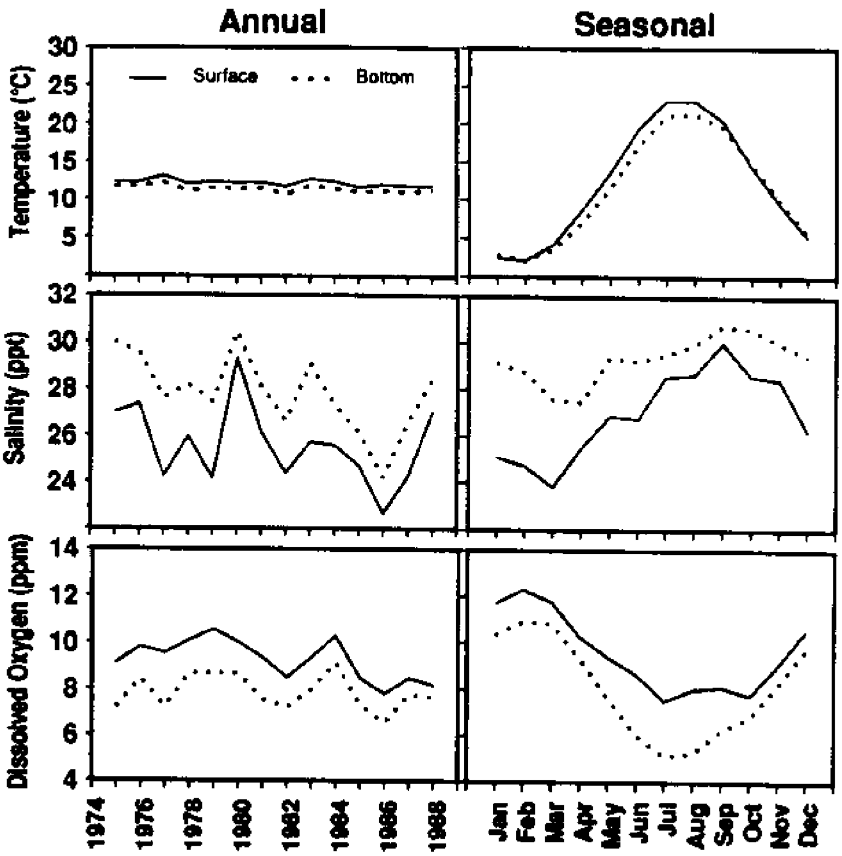


Figure 6.3 Average annual and seasonal trends in surface and bottom water temperature, salinity, and dissolved oxygen concentrations in Mount Hope Bay.

Although average annual dissolved oxygen concentrations pose no potential threat to aquatic biota, bottom waters during summer months exhibit concentrations below the EPA value of 6 ppm (class SA criteria) considered to be required for a healthy and diverse aquatic flora and fauna (Figure 6.3). It is typical of estuarine waters to occasionally become oxygen-depleted in summer, but hypoxic levels (2 ppm) are known to be potentially stressful and/or fatal to aquatic life.

Inorganic Nitrogen

Nitrate is distinctly seasonal in Mount Hope Bay, showing peak concentrations in early winter through early spring (Figure 6.5). This is in agreement with general estuarine patterns, reflecting the fact that nitrate is used by rapidly growing phytoplankton during early spring, is depleted throughout the summer, and then is regenerated during fall and winter. No long-term trend is evidenced for nitrate, although

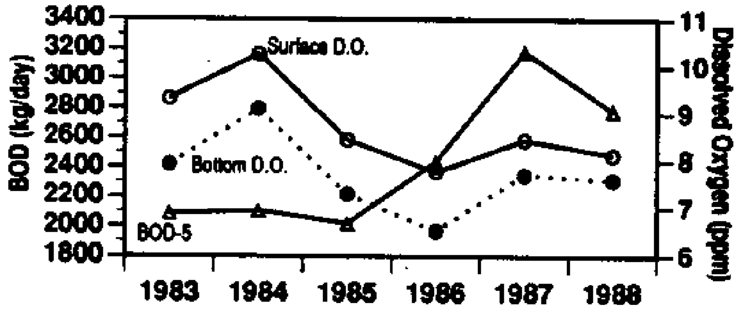


Figure 6.4 Schematic of the relationship between BOD loading to Mount Hope Bay and ambient dissolved oxygen concentrations, showing the imperfect negative correlation between the two parameters.

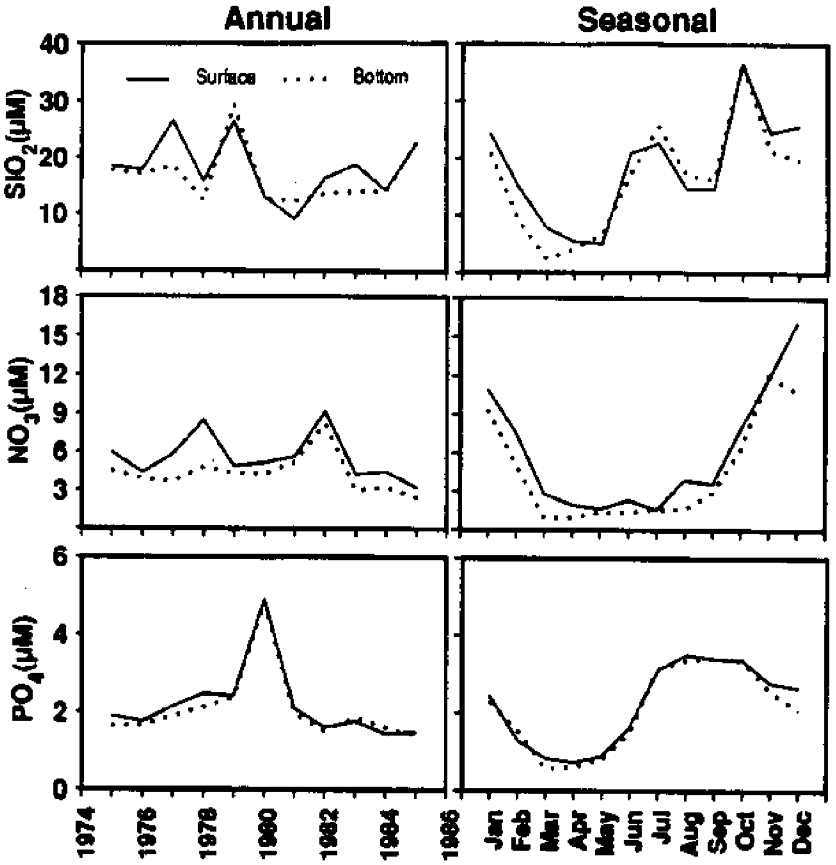


***Figure 6.5** Average annual and seasonal trends in surface and bottom water silicate, nitrate, and phosphate concentrations in Mount Hope Bay. Monitoring of nutrients was discontinued after the 1985 sampling year.*

concentrations seem to have generally decreased since peaking in 1982 (Figure 6.5). A similar pattern is seen for total dissolved inorganic nitrogen (DIN) in Mount Hope Bay (Figure 6.6), with the main difference being a very high DIN value recorded for 1984, when ammonia levels were greatly elevated. The cause for this increase in ammonia, which is reflected in all stations sampled by Marine Research during November of 1984 (Marine Research, Inc., 1985), is not known for certain. Possibly the elevated nitrogen values seen in 1984 were due to a temporary shutdown of the Fall River treatment facility or some other episodic event. After the 1985 sampling season, nutrients were no longer sampled by Marine Research, Inc.

Inorganic Phosphate

Average annual phosphate concentrations in Mount Hope Bay show an overall decreasing trend, despite a large peak during 1980 (Figure 6.5). This anomalous peak is due to high phosphate concentrations observed throughout the spring and summer months of 1980, but not seen during 1979 (Figure 6.7). While 1979 was a year of typical precipitation, 1980 was abnormally wet. Since most sewage treatment facilities account for large inputs of phosphate (Olsen and Lee, 1979), it may be assumed that

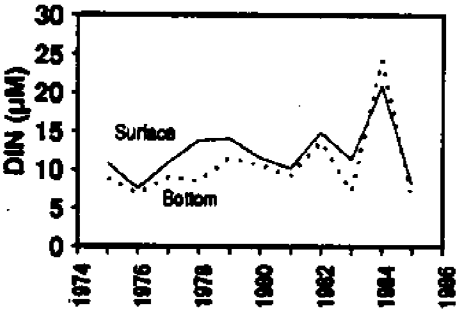


***Figure 6.6** Trends in dissolved inorganic nitrogen in surface and bottom waters in Mount Hope Bay over time. Although quite variable, the long term trend suggests a slight increase.*

Figure 6.7 Seasonal trends in phosphate concentrations for Mount Hope Bay during wet (80) and dry (79) years, showing a dramatic increase in phosphate availability during wet years.

increased flow through the POTW, as well as CSO and river discharges, account for the abnormally elevated 1980 phosphate values.

Like nitrate, phosphate exhibits a high degree of seasonality in Mount Hope Bay, being utilized rapidly by the flora and fauna during early spring, recycled throughout the summer, and regenerated during late fall and winter (Figure 6.5). The seasonality observed in Figure 6.5 may be somewhat exaggerated due to the high phosphate concentrations that occurred during the summer and fall of 1980.

Silicate

Average annual concentrations of silicate show a slight decrease from 1975 through 1980, after which time silicate shows an overall increase (Figure 6.5). Silicate is also seasonal in Mount Hope Bay, showing a peak in July and again in early winter (Figure 6.5). The observed seasonality of silicate is more closely linked to diatom blooms than to POTW discharge or river flow (see following section).

Potential for Eutrophication and Anoxia

Observations of nutrients, dissolved oxygen, temperature, and salinity show that Mount Hope Bay is truly estuarine, and well mixed, throughout its general extent. The bay shows no indication of anoxic potential, even during extreme conditions such as in bottom waters averaged for the month of August, but may occur in localized areas such as shallow bays and coves. Considering that dissolved oxygen concentrations are only loosely correlated with BOD load, it is difficult to determine what effect, if any, the present BOD load to the bay has upon dissolved oxygen concentrations.

Eutrophication does not seem to be a present problem for Mount Hope Bay. Figure 6.8 shows the ratio of DIN to PO$_4$ found in Mount Hope Bay as compared to the Redfield Ratio of 16:1. The majority of the points fall to the right of the Redfield Ratio, indicating that nitrogen is limiting in Mount Hope Bay while phosphate is not, which is in general agreement with Kremer and Nixon's (1978) and Nixon and Pilson's (1984) findings for Narragansett Bay. The pattern of seasonal availability for the two nutrients—i.e., phosphate becomes available rapidly after initial depletion whereas nitrogen remains depleted and limiting throughout the summer

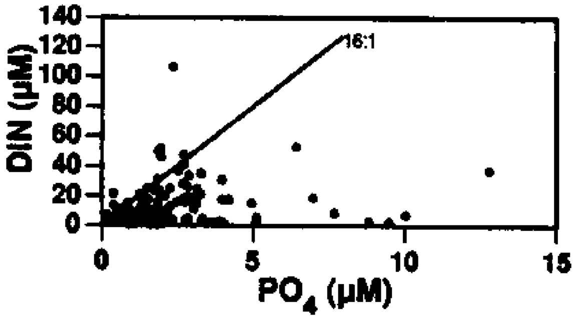


Figure 6.8 Comparison of total nitrogen and phosphate for Mount Hope Bay to that idealized by the Redfield Ratio of 16(N) : 1(P), indicating that nitrogen is limiting in the system as is typical of estuarine and coastal marine waters.

and fall months (Figure 6.5)—also indicates that nitrogen is limiting while phosphate is not. No reports of algae blooms or other conditions considered typical of eutrophication are noted in the literature for Mount Hope Bay.

Biological Trends

Phytoplankton

Diatoms are generally considered to be a major portion of the diet of copepods, which in turn are important in the diet of larval fishes. Diatom abundance shows distinct peaks during a yearly cycle, being greatest in early spring and early fall (see Figure 6.10). This pattern coincides with the pattern of spring and fall diatom blooms that is commonly observed in estuaries throughout temperate latitudes.

Throughout the years 1975 to 1985, little overall change is seen in the average annual abundance of diatoms in Mount Hope Bay. Surprisingly, the diatom abundance generally does not correspond very well to silicate availability in Mount Hope Bay (Figure 6.9). This lack of correlation suggests that silicate is very abundant, and not limiting in the bay.

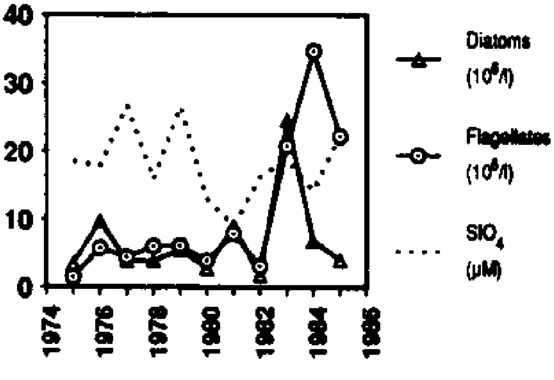


Figure 6.9 Trends in diatom and flagellate abundances in Mount Hope Bay. Note the lack of correlation between silicate concentrations and diatom abundances, suggesting that silicate is not limiting in bay waters.

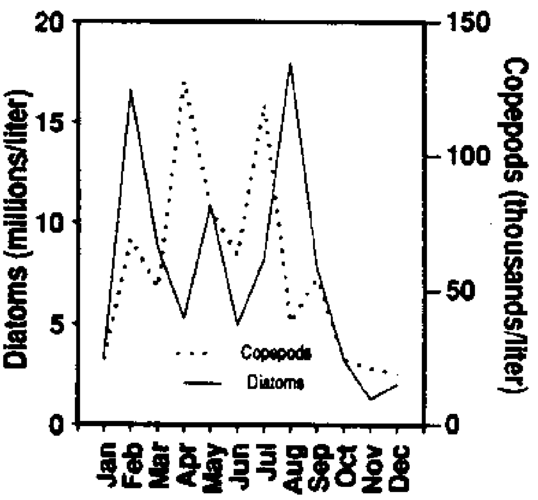


Figure 6.10 Seasonal relationship between diatom and copepod abundances in Mount Hope Bay near Spar Island. Note the close correlation and the classic lag pattern between the predator (copepods) and prey (diatoms).

During the years 1975 to 1982, flagellate abundance in Mount Hope Bay remained relatively constant (Figure 6.9). During 1983 and 1984, however, a nearly 7-fold increase in flagellate abundance occurred, followed by a decrease in 1985. Since Marine Research ceased sampling phytoplankton as of January 1986, it is not known whether or not flagellate abundance has remained high or decreased. The data for 1982-86 show that the increase in flagellates did not occur at the expense of diatom abundance, as might be expected if nitrogen enrichment and eutrophication were occurring and resulting in species composition changes.

Zooplankton

Copepods are an important part of the zooplankton community, especially in plankton-based systems (Kremer and Nixon, 1978). Their abundance is distinctly seasonal and corresponds to diatom abundances in Mount Hope Bay (Figure 6.10). Since 1975, a general decrease in copepod abundance

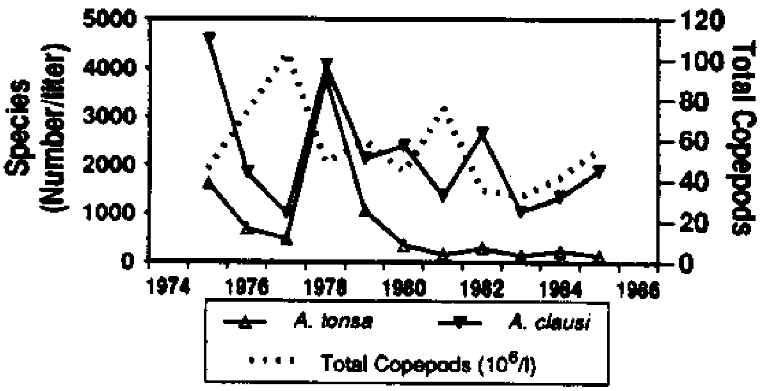


Figure 6.11 Long-term trends in the abundances of the two most dominant species of copepod, and total copepods, sampled at Spar Island. The pattern suggests competition between A. clausi and other copepod species, as well as a long-term decline in total copepod abundance in Mount Hope Bay.

occurred in Mount Hope Bay (Figure 6.11). This trend however does not agree with that observed for diatoms (Figure 6.9). A lack of further samples limits the assessment that can be made concerning shifts in phytoplankton assemblages and resultant changes observed in the zooplankton community.

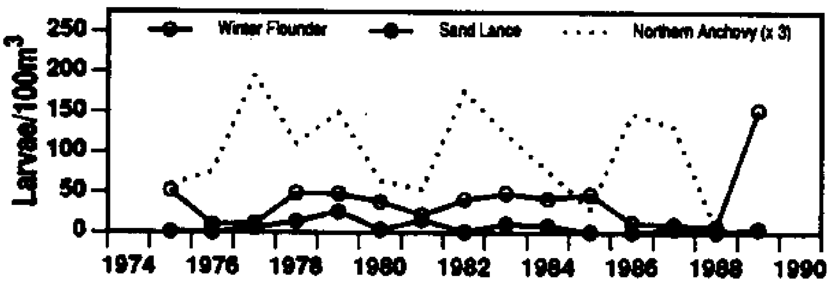
Both of the two most abundant copepod species in Mount Hope Bay show overall declines since 1978 (Figure 6.11). Since diatoms do not show the same trend as the copepods, other reasons for the decline of these zooplankters must be operating. Other factors, such as salinity, temperature, and dissolved oxygen, all show decreasing trends, which may be resulting in changes in the foods available to zooplankters in Mount Hope Bay, or a combination of these effects may be causing the apparent copepod decline. Unfortunately, the sampling of plankton was terminated as of January 1986, leaving a gap in the most recent events of the copepod story. Moreover, the database covers a relatively short period of time, making it difficult to distinguish trends from simple long-term natural cycles in both nutrients and biota.

Ichthyoplankton

Since at least 1975, Mount Hope Bay ichthyoplankton has been dominated by the Northern anchovy, which has exhibited an overall decline since 1976 (Figure 6.12). Other abundant larval fish species are the winter flounder and sand lance. Neither of these species shows a readily apparent pattern of increase or decline since 1975 (Figure 6.12).

Whether or not decreasing patterns in larval fish abundances are related to decreases in copepod abundances and/or increases in flagellates and other plankters is not readily apparent. If copepods are the predominant food and energy source for a species of fish larvae, then decreases in larval abundances may be based upon food web dynamics.

Figure 6.12 Trends in the abundances of the three most dominant larval fishes collected in Mount Hope Bay near Spar Island, showing great variability but little evidence of long term trends. Note that abundance of Northern Anchovy is 3X the Y-axis value.



With a suite of other physical parameters also experiencing change, it is difficult to determine the relationships of the players and how they affect one another based upon a limited time-series database.

Demersal Fishes

Winter flounder, scup, and windowpane flounder are the three most abundant demersal fish species collected in otter trawl collections at the Spar Island sampling station in Mount Hope Bay. Scup are an important recreational fishery species, winter flounder are an important component of both commercial and recreational fisheries, and windowpane flounder have no commercial or recreational value (except possibly as lobster trap bait). All of these species have shown a general decline since 1975 (Figure 6.13). The winter flounder has declined dramatically in abundance since reaching a high in 1979. As was found for Narragansett Bay winter flounder stocks (see Chapter 7), the species showed intermittent good years early on, but has not shown an increase in numbers since 1984. The adult pattern for changes in abundance does not appear to correlate very well to larval abundances, even given some lag time between year classes (compare Figures 6.12 and 6.13).

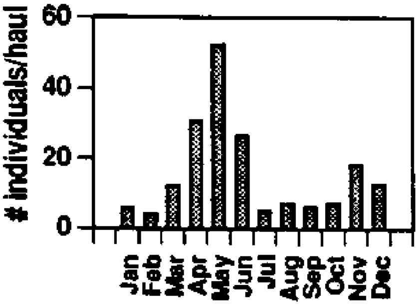


***Figure 6.14** Seasonal abundance of winter flounder in trawl surveys at Spar Island, showing the influx of adults during spring (for spawning purposes) and a migration out of the bay during the late spring as the water warms.*

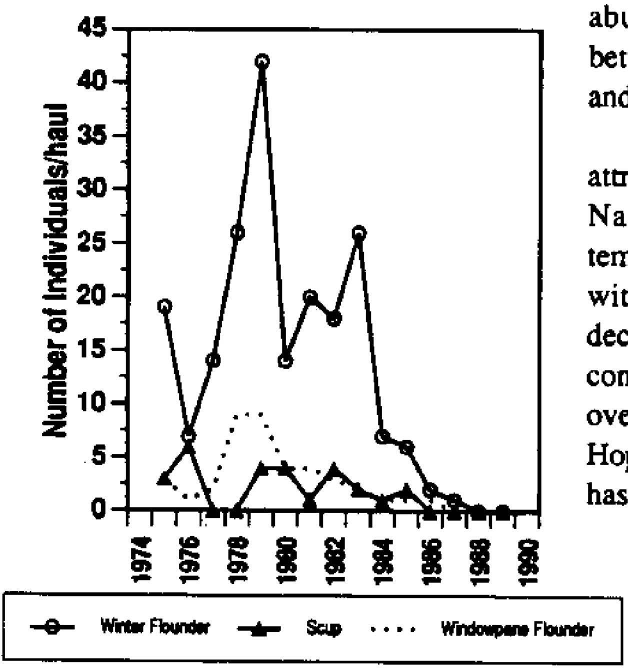


***Figure 6.13** Trends in the abundances of the three most dominant adult fishes collected in Mount Hope Bay near Spar Island. Note that of the three most abundant larvae, only winter flounder remain so as adults (Fig. 6.12), and that the larval and adult patterns of abundance for winter flounder are not very well correlated, even given a lag time from juvenile to adult.*

Jeffries and Terceiro (1985) attributed the decline of winter flounder in Narragansett Bay to increased water temperature and overall warmer conditions within the bay. Other factors, such as decreasing salinity and/or dissolved oxygen concentrations, may be contributing to the overall decline of winter flounder in Mount Hope Bay since average annual temperature has decreased slightly over time. Jeffries and Johnson (1974) noted that winter flounder populations in both Narragansett Bay and Mount Hope Bay were of the same genetic origin, and it would be expected that Mount Hope Bay winter flounder population dynamics would closely mimic those observed in Narragansett Bay.

Jeffries et al. (1988) noted an influx of adult winter flounder into Narragansett Bay during early winter, followed by a departure before the onset of warm summer water temperatures. Figure 6.14 shows that the major influx of winter flounder into Mount Hope Bay occurs from March to May, with most flounder having left the bay by the beginning of July. This trend generally agrees with the pattern noted by Jeffries et al., further supporting the idea that both flounder populations arise from a single stock, but also suggests that winter flounder utilize Mount Hope Bay later in the season, possibly a result of immigration from Narragansett Bay.

Benthic Invertebrates

The five most abundant species of benthic invertebrates collected in Spar Island grab samples are three polychaetes (*Polydora, Exogone, Mediomastus*), one bivalve (*Nucula*), and one amphipod (*Ampelisca*). Both *Mediomastus* and *Ampelisca* are found in the benthos at numbers an order of magnitude higher than any of the other three most abundant species. Of these five species, only *Mediomastus* exhibits any trend over time, and appears to be increasing (Figure 6.15). In the case of *Mediomastus*, great variability between years occurs, but the species has steadily increased in Mount Hope Bay near Spar Island since at least 1975. The abundance of *Ampelisca* is highly variable from year to year in the bay, and is apparently not inversely correlated to *Mediomastus* abundances (Figure 6.15).

Since 1975, the diversity of invertebrate species sampled at the Spar Island station in Mount Hope Bay has decreased, especially during the years 1975 to 1982 (Figure 6.16). During this time the diversity of benthic invertebrates declined nearly 60%, followed by a resurgence of diversity from 1982 through 1986. It is interesting to note that during the time of declining diversity the total abundance of benthic invertebrates increased, nearly quadrupling between 1975 and 1981 (Figure 6.16). It is often typical of stressed estuarine situations for species abundance to increase while species diversity declines.

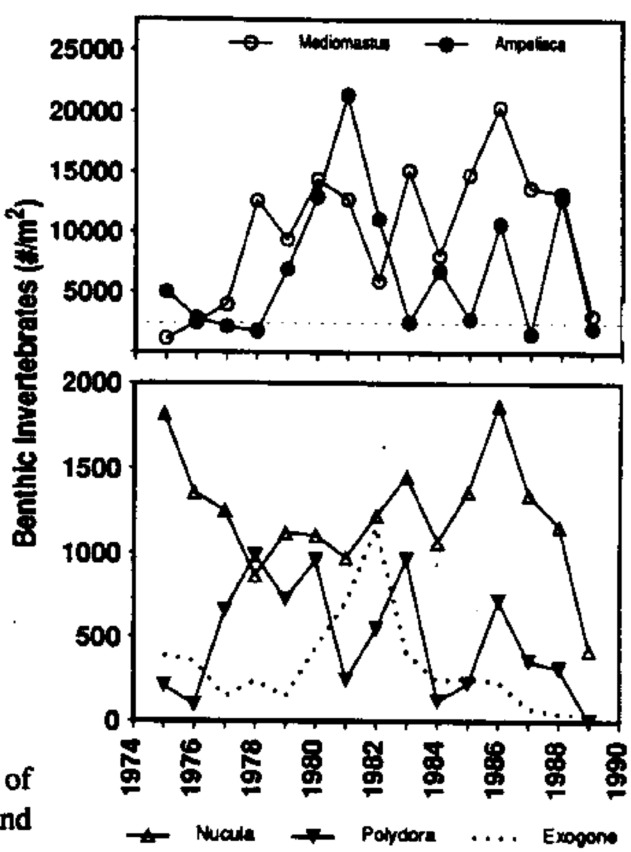


Figure 6.15 Trends in the abundances of the five most dominant benthic invertebrates collected near Spar Island. Note the change in magnitude between the two most abundant invertebrates and other species. The only species showing any apparent trend is Mediomastus, which shows a slightly increasing trend over time.

Interestingly enough, the decline in species diversity occurred during the time period prior to the conversion of the Fall River wastewater treatment facility to secondary operation in 1982. A distinct rise in species diversity is noted after 1982 (Figure

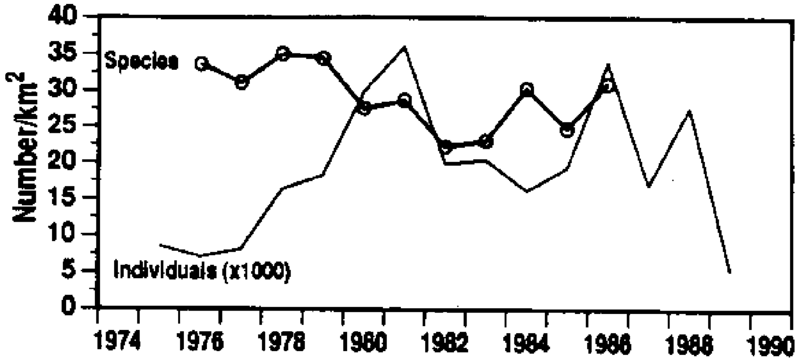


***Figure 6.16** Trends in the number of individuals and species diversity in Mount Hope Bay over time. Species diversity begins to increase after a decline through 1982, which corresponds with the time the Fall River STP began operations as a secondary treatment facility. Note that as species diversity increases, the number of individuals (total biomass) decreases.*

6.16). The total number of invertebrates seems to have remained relatively stable over this time period. This suggests that degraded conditions may have been responsible for the decline in benthic invertebrate diversity, allowing for more opportunistic species to become numerous. Once degraded conditions were eased by secondary treatment at the Fall River facility, less opportunistic species of invertebrates were able to repopulate Mount Hope Bay, increasing species diversity once again. The short-term nature of the database used to arrive at this conclusion however, leaves this speculative since longer term natural cycles of species abundances and diversity are not available for analysis and comparison.

Hard clams are presently quite plentiful in Mount Hope Bay, but investigators have noted a lack of juvenile and small individuals in the bay's high-density populations, raising questions about the recruitment of new individuals into those populations which consist mostly of older individuals (Pratt et al., 1988). The length of time the area has been closed to shellfishing (since 1947) may have reduced recruitment of juveniles to certain areas, assuming that adult clams at high density inhibit spat settlement or juvenile recruitment. Studies are now under consideration to test the validity of this argument, and to better plan the management of this economically valuable resource.

The observed changes in planktonic assemblages may also have some implication for future Mount Hope Bay hard-clam abundances. Pratt and Campbell (1956) found faster growth in hard clams feeding on diatoms than in those feeding upon flagellates. Although it is uncertain whether or not diatoms are decreasing in Mount Hope Bay, flagellates have increased in recent years, which could potentially stress the establishment of an already very limited juvenile population of hard clams in the bay.

General Conclusions

Mount Hope Bay appears to provide reasonably good habitat, at least with regard to nutrients and dissolved oxygen concentrations. Nutrient concentration patterns from 1975 to 1985 show little indication of eutrophication within the bay system. Phytoplankton communities have sporadically altered their composition to increased flagellate abundances and back, although apparently not at the expense of reducing absolute diatom abundance. Whether or not these shifts relate to decreases in benthic invertebrate diversity and decreases in abundances of fish larvae and adult demersal fish populations is unclear given the current database for Mount Hope Bay. It is also unclear how changes in both physical and biological parameters affect the overall dynamics within Mount Hope Bay.

Overall, Mount Hope Bay generally resembles Narragansett Bay, with a major difference being the lack of a highly polluted and restricted region similar to the Providence and Seekonk rivers. As in Narragansett Bay, water quality conditions in Mount Hope Bay have improved in the recent past; and much of this improvement may be attributed to improvement in the Fall River POTW effluent, and may reflect further upon general trends for better wastewater treatment and management in the region. Increased species diversity in recent years suggests an improved aquatic habitat, where pathogen concentrations in the water column and in shellfish are the most common cause of use impairment of the resource. Correction of the Fall River CSOs will alleviate this problem to a great degree, further improving water quality and the use of Mount Hope Bay's resources.

Chapter 7

Trends in Narragansett Bay Fisheries

The streams, bays, harbors, ponds and lakes were stocked with fish, and the mud flats were as yet undisturbed, hoarding unlimited stores of shellfish down through the ages.

J. W. Haley, 1939
"The Old Stone Bank History of Rhode Island"

Narragansett Bay is considered important habitat as spawning and nursery grounds for a variety of finfishes, in particular menhaden and winter flounder. The bay is also the home of one of the major fisheries for hard clams *(Mercenaria mercenaria)* in the United States.

Although hard clams now constitute the major commercial fishery in Narragansett Bay, a variety of species have been of major economic importance in the past. Atlantic salmon, alewife, oysters, and scallops all were once major bay-based fisheries, but all these fisheries have now been abandoned. Menhaden, winter flounder, and lobster continue to be fished commercially in Narragansett Bay, but mostly on a limited or small-scale basis.

The demise of these once-abundant fisheries has been blamed more often than not on degraded water quality in Narragansett Bay. However, studies indicate that water quality has been improving in the bay during the past 20 years. Relative to water quality, records of phytoplankton and zooplankton species composition and abundance show that these parameters have not changed significantly over the past three decades, despite improvements in water quality during this time. This suggests either that water quality in the lower bay has not changed significantly in the past 30 years, or that the changes have been slight enough to not cause any planktonic response. Unfortunately, records do not extend further back in time, so we cannot be sure whether changes in water column biota, which could potentially affect fisheries, occurred prior to the 1970s. Yet filter-feeding species have been prevalent in Narragansett Bay throughout history, with some species, such as the blue mussel, having increased in population throughout the 20th century; implying that filter feeders have generally not been food-limited in Narragansett Bay. It is therefore reasonably safe to assume that there have been no permanent changes in plankton abundance and/or species composition that have been directly responsible for the observed changes in Narragansett Bay fisheries, and that food sources to the bays fisheries are not responsible for the long-term declines in fishery landings.

It is difficult to measure whether natural abundances of fish and shellfish have changed over time in the bay. Although recreational landings are not tallied in the state of Rhode Island, two important commercial fishing centers exist within the state: one in Newport, and a larger port at Point Judith, just outside Narragansett Bay. Commercial landing records date back into the early 1800s for several species of finfish, but observation of trends from commercial landings can be misleading, because the commercial catch does not necessarily reflect the natural abundance of the target species. Market value of a species, changes in fishing technology, and number of boats and persons expending a given amount of effort in pursuit of a given species all affect the commercial landing records. To further confuse the issue, the record of commercial landings does not discriminate between those species caught within the bay and those caught offshore, often as far away as Georges Bank, and then landed in ports in the state of Rhode Island.

Although the commercial landing record is at best a distorted reflection of the true abundance of a target species, it is still useful when combined with more detailed information concerning the abundance and distribution of a species. Fortunately, trawl surveys conducted by various state departments, independent researchers, and power plants provide several 20–25 year abundance records for finfish in Narragansett Bay (see Table 5.1). These data give a more accurate estimate of the distribution and abundance of finfish species in the bay, and are used to detail trends in fisheries during more recent times.

Finfisheries

Anadromous Fisheries

Atlantic salmon once constituted a large portion of the commercial catch in Narragansett Bay. However, this fishery was very short-lived in the bay, completely collapsing by 1869. The collapse can be attributed to the salmon's loss of access to suitable spawning grounds in upper reaches of bay tributaries. All tributaries to the Providence and Seekonk rivers were dammed by the early 1800s to provide water power for the region's burgeoning industrial needs (Goode, 1887). This closing of the tributaries at the head of the estuary would have severely limited, if not completely eliminated, access of salmon to the spawning beds upon which they were reared. Although the fishery was not studied to any great extent before it collapsed, and reference to damming as a cause for fishery collapse is anecdotal, the adverse effect of river dams on salmonids is well documented for both Pacific Coast and Atlantic salmon stocks. With no recruitment occurring in Narragansett Bay for Atlantic salmon populations, local extinction of the species from the area was rapid and complete.

Alewives, another anadromous fish species, commanded an extensive fishery in Narragansett Bay from the mid-1800s to the turn of the century. But by the early 1900s this commercial fishery was declining rapidly, and it was essentially abandoned by 1930 (Figure 7.1). This species, like the salmon, travels up the estuary to spawn, but it is not as reliant as salmon upon gaining access to the upper reaches of tributaries to successfully reproduce. Although damming of tributaries may have influenced alewife stocks, the fishery's failure is generally attributed to overfishing (Goode, 1887). During the spring alewife runs, fish traps were placed throughout Narragansett Bay, particularly in the East and West passages and the mouth of Sakonnet Bay. These fish traps were often placed so densely that it was virtually impossible for any alewives to reach the upper bay without becoming lodged in one (Goode, 1887). Alewives have not been

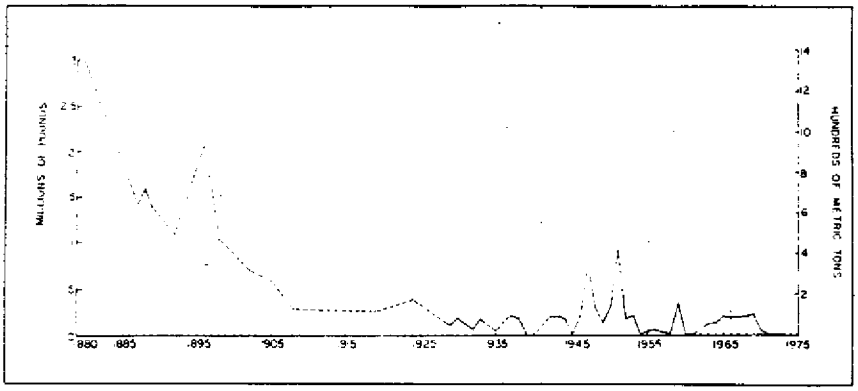


***Figure 7.1** Trends in the Rhode Island Alewife fishery since 1880, showing the steady decline in landings over time. Taken from Olsen and Stevenson (1975).*

fished on a commercial basis in Narragansett Bay waters since the fishery's collapse. Since the late 1950s, however, alewives have begun to return to Narragansett Bay in increasing numbers, and have often been noted in the Providence and Seekonk rivers. Spawning now occurs in some tributaries of the bay, and the species appears to be re-populating itself as a springtime visitor to Narragansett Bay waters.

Links to Water Quality

It is apparent that the collapse of Narragansett Bay fisheries for anadromous species is not directly attributable to water quality degradation in the estuary. Overfishing took a rapid toll on the populations of these fishes as they moved through the bay to spawn, and loss of access to spawning areas, at least for salmon, prevented the rapidly depleted adult stocks from replacing themselves. In the case of the alewife fishery, water quality degradation in the Providence and Seekonk rivers may have caused a loss of suitable spawning habitat, but extraordinary fishing pressure apparently was the main cause of the extinction of the commercial fishery.

Migratory Fisheries

Menhaden were an important commercial fishery in the bay; and they and striped bass are the two migratory species that have been most extensively studied. Menhaden travel up and down the Atlantic seaboard, moving into estuaries and coastal bays to spawn and to feed upon the plankton abundant in these regions. Narragansett Bay is an important spawning area for this species; especially the upper bay and Mount Hope Bay, where larval menhaden are found in their greatest abundances (Matthiessen, 1974). Menhaden move into bay waters in the early spring to spawn, and prior to 1880 their arrival triggered the setting of fish traps throughout the bay. As seining became more popular, fish traps were employed mainly at the mouth of the bay to catch the fish as they entered the estuary.

Large harvests of menhaden were taken prior to the turn of the century, but the fishery essentially failed in the late 1880s (Figure 7.2). As with the alewife, overfishing by the numerous fish traps lining the shores of the bay apparently caused the fishery's decline (Goode, 1887). The fishery has cycled since then but has not produced harvests to rival those of the late 1800s even in most recent years. Menhaden fishing still takes

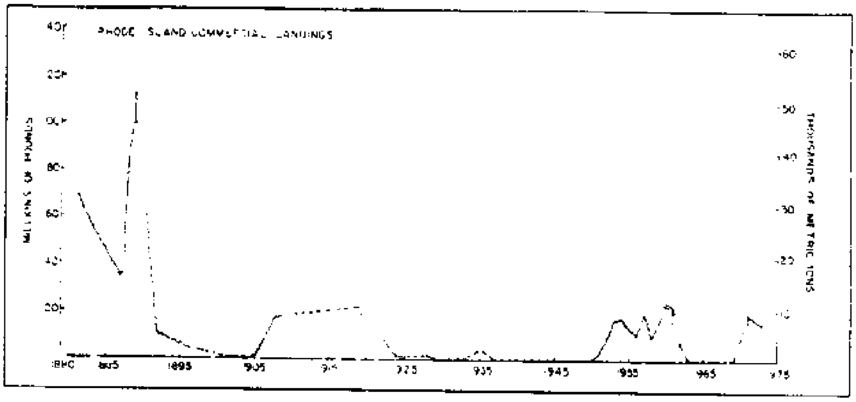


Figure 7.2 Trends in the Rhode Island menhaden fishery since 1880, showing the rapid decline of the fishery, with only sporadic landings after the turn of the century. Taken from Olsen and Stevenson (1975).

place today, but mainly by out-of-state vessels which follow the schools of fish along the Atlantic Coast.

Nicholson (1971) notes that a decline in the menhaden fishery all along the Atlantic seaboard during the late 1960s was a direct result of increased fishing pressures. Poor stock recruitment was noted during the decline, indicating that the Atlantic spawning stock was below optimum size. Overfishing of the stocks during this critical time period reduced the potential breeding stock, resulting in a decline in the fishery which to date has not revived itself. Oviatt (1977) found the 1976 year class of menhaden entering Narragansett Bay to be immature fish generally less than three years of age. Apparently these fish were unable to spawn, contributing further to the decline of the fishery. Increased fishing effort for menhaden, intensifying when the West Coast anchovy fisheries failed during the 1970s, could account for depleted stocks, considering the 80% capture efficiency reported for Narragansett Bay purse seiners (Ganz, 1975).

Bluefish and striped bass are also migratory species, and although they are of only limited commercial importance at present, both are extremely desirable and important as part of the sportfishery catch. Local sportfishermen have tended to blame poor year classes of bluefish and striped bass on overfishing of menhaden stocks in the bay, which are a major food source for these sportfish. However, Oviatt (1977) calculated the biomass of striped bass, bluefish, and menhaden and the percentage of menhaden eaten by these two predatory species during the 1975–76 season and concluded that commercial fishing efforts for menhaden in Narragansett Bay cannot account for declining stocks of bluefish or striped bass, or for the lean years often noted for these species in the bay. Figure 7.3 shows landings of menhaden, bluefish, and striped bass in Rhode Island waters and reflects the lack of correlation between menhaden and bass/bluefish abundances. The catch size limits imposed for striped bass over the past six years has resulted in recent dramatic improvements in the condition of the stock, and increases in size of fish, as well as their overall abundance.

Links to Water Quality

The patterns of abundance exhibited by exploited migratory fish species in Narragansett Bay do not seem to be caused by water quality degradation. The plight of the striped bass has been widely studied and publicized, and their decline is apparently due mainly to habitat degradation in their major spawning areas (e.g., Chesapeake Bay and the Hudson River) rather than to local conditions in Narragansett Bay; although

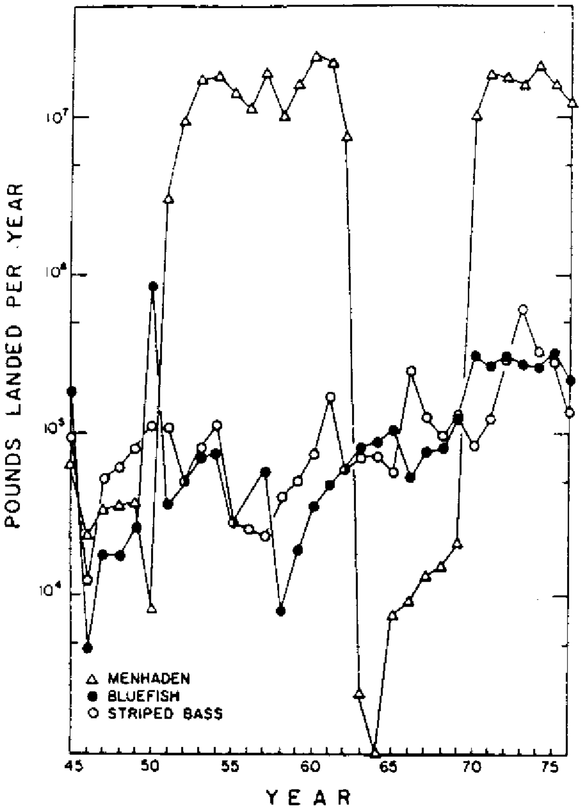


***Figure 7.3** Rhode Island landings of menhaden, bluefish, and striped bass since 1945, showing the lack of relationship between menhaden abundances and those of bluefish and striped bass. Taken from Oviatt (1977).*

fishing pressure in Rhode Island may exaggerate the stress upon the species by further reducing the potential breeding stock. The modern intensive fishery for menhaden, not only in Narragansett Bay but all along the Atlantic seaboard, apparently depleted the parent stock to the point of poor breeding and recruitment success, causing a collapse of menhaden fisheries up and down the Atlantic coast. Water quality degradation apparently was not a direct cause of this collapse.

Bay-Based Fisheries

The winter flounder (*Pseudopleuronectes americanus*), the only commercially valuable finfish resource that is bay-based for at least part of its life cycle, is also an important component of the recreational catch. Although most flounder are caught by commercial trawlers outside of the bay, the winter flounder is dependent upon the bay for spawning success and early life stage development. Therefore population trends that may be due to changes in water quality would be more likely to show up in flounder than in other less bay dependent finfish.

An excellent long-term record of winter flounder abundance exists in weekly trawl samples collected by researchers at the University of Rhode Island Graduate School of Oceanography. The trawl samples were initiated in 1959 and have continued on a weekly basis using similar methods through the present day. The GSO trawl survey collects from two stations: Fox Island, located north of the Jamestown Bridge, and Whale Rock, where the bay meets Rhode Island Sound (Figure 1.1). Due to the long duration of the survey and the consistency of sampling methods, this database provides an excellent opportunity to observe winter flounder abundances over three decades, without the vagaries introduced through commercial catch records.

The winter flounder exhibits strong seasonality in the pattern of its abundance in the bay; adults travel into the estuary during late fall and spawn in the upper estuary during late winter and early spring (Jeffries et al., in press; Figure 7.4 - bottom). The adults then move offshore for the summer to complete the annual cycle (Saila, 1961). Juveniles and larvae are found in great abundance in the upper bay and Providence River (Matthiessen, 1974). The larvae are most abundant in the upper bay during summer months, a time when water quality is typically at its seasonal worst (i.e., highest temperature, lowest dissolved oxygen).

A survey conducted by Jeffries and Johnson (1974) found an 86% decline in relative abundance of winter flounder between 1968 and 1974 (Figure 7.4 - middle). The species then increased until 1979, when it entered another decline lasting through 1986 (Jeffries and Terceiro, 1985; Jeffries et al., 1988). Commercial catch records (Figure 7.4 - top), though they include flounder caught both inside and outside Narragansett Bay, reflect the same overall pattern of abundance shown in the Fox Island trawl surveys, suggesting that the pattern of abundance in Narragansett Bay was also noted in other fishing areas, and that the cause of these changes were representative of winter flounder populations in the region.

Although the causes for these cycles are not fully known, Jeffries and Terceiro (1985) suggest they are a result of climatic warming and predators in Narragansett Bay. Jeffries and Terceiro's conclusion—cold winters mean good flounder recruitment; warm winters poor—is supported by Buckley and Caldarone's (1988) finding that young-of-the-year winter flounder growth and condition are a function of the local environment and not pollution-related. *Neomysis americana*, an epibenthic mysid that is a predator of larval and juvenile winter flounder, shows an opposing pattern—that is, better growth in warm winters (Jeffries and Terceiro, 1985). Therefore, warm winters may bring not only poor spawning success, but also increased predation by *N. americana* due to early larval set of flounder. Recent years have seen milder winters overall, which may affect winter flounder recruitment in upcoming years. Jeffries et al. (in press) have developed a model, based upon climate and predators, for winter flounder abundance in Narragansett Bay. Their model can predict future abundances over short time spans with 60–75% accuracy. It correctly predicted an increase in abundance during 1987, and should be useful in short-term future management of this species in the bay.

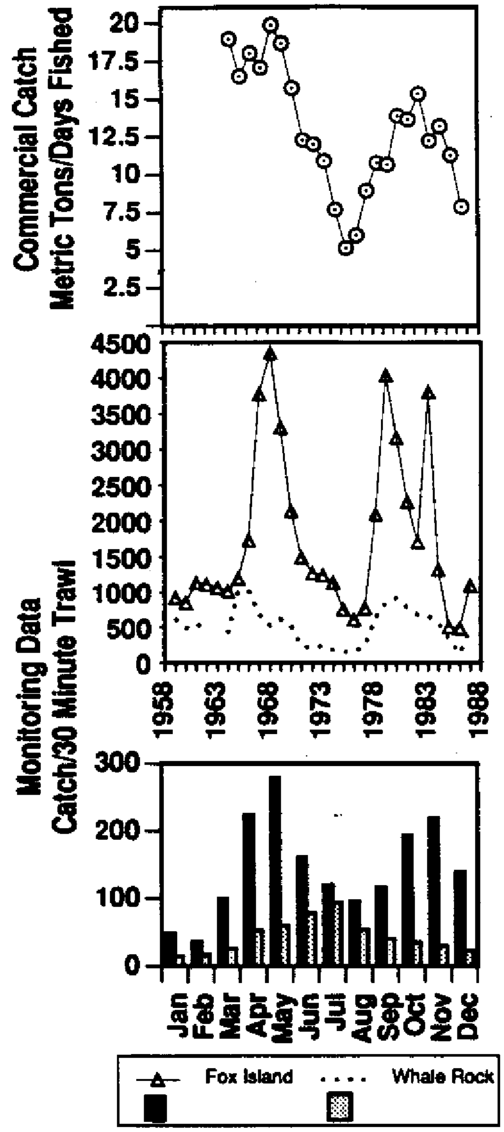


Figure 7.4 Trends in Rhode Island winter flounder abundance since 1958 for commercial (Rhode Island) and monitoring trawl landings conducted in Narragansett Bay, both which reflect fishing effort. Note the similarity between commercial landings (top) and trawl survey landings (middle). Seasonal abundance of winter flounder in Narragansett Bay is also shown (bottom). Data from NMFS catch statistics and Jeffries et al. (1988).

Links to Water Quality

Of all the finfish species described in this chapter, the winter flounder would be expected to be the most susceptible to water quality degradation—not only because environmentally sensitive larval and juvenile life stages are dependent upon the more polluted upper bay, but also because the flounder feed upon benthic organisms, which are most likely to contain toxins concentrated in the sediments. Yet the observed fluctuations in winter flounder populations seem not to be tied to the concentrations of pollutants common in the upper bay. Buckley and Caldarone (1988) found no correlation between juvenile winter flounder size, liver weight, or biochemical composition and any known pollutant gradient that has been well studied in Narragansett Bay (see Chapters 4 and 5). Population fluctuations of winter flounder seem to be linked to cycles of predators and to other physical variables that are driven by climatic change in the bay.

Summary—Finfisheries

Overall, it appears that water quality degradation has not been a major determining factor in the cycles of abundance observed in any Narragansett Bay finfishery. The general habitat degradation in the Providence and Seekonk rivers, as evidenced by the reports of filthy, and commonly anoxic, conditions, may have assisted in speeding the depletion of fish stocks in the late 19th and early 20th centuries, but cannot be cited as the major culprit in their demise over the last three decades.

The driving blow that tumbled every Narragansett Bay finfishery except for winter flounder was apparently overfishing to the point where the parent stock was not able to produce enough young that could successfully run the gamut of dams, predators, diseases, and generally degraded conditions to survive and reproduce. For migratory species, this pattern was evidenced up and down the Eastern Seaboard, further evidence that degraded conditions solely in Narragansett Bay were not a likely cause of the collapse of an entire species.

For a variety of reasons, fishing pressure for many non-sport species has decreased tremendously in the past 30–50 years within Narragansett Bay. Technological improvements in gear from hand nets, to fish traps, to the otter trawl and purse seine allowed for the more efficient harvest of finfishes in Narragansett Bay and in offshore waters. As bay-based fish resources began to be depleted, new technology took the new fishing technology offshore in search of more abundant stocks. In other cases—for example, the lobster fishery—new technology lured fishermen offshore to more lucrative fishing grounds, leaving Narragansett Bay stocks to the smaller commercial operator.

Yet, in spite of this decreased fishing pressure, most species have not returned to the bay in numbers close to those reported at the height of fishing success. The reasons for this limited rebound are many, and differ for different species, but water quality in Narragansett Bay does not seem to be the limiting factor. Migratory species still move up and down the Atlantic seaboard, experiencing a variety of water quality conditions in their travels, and they are also heavily fished in the open ocean. Anadromous species still face a multitude of dams on the tributaries of Narragansett Bay, keeping spawning grounds isolated from use. Present work to restore stocks of anadromous fishes, especially Atlantic salmon, through the introduction of fish ladders in tributaries are experiencing only limited success. Population abundance of the winter flounder, the only true bay-based finfish of commercial importance, seems to be driven by the related factors of climate and predator populations, as well as fishing pressure, but not water quality or otherwise perceived degraded conditions in the bay.

Shellfisheries

The two most economically important shellfish species in Narragansett Bay have historically been the American oyster (*Crassostrea virginica*) and the hard clam (*Mercenaria mercenaria*). At present no commercial fishery exists for oysters in Narragansett Bay waters, but hard clams constitute a major bay-based fishery. A number of other shellfisheries have existed in Narragansett Bay, on both commercial and recreational scales. At present, soft-shell clams, blue mussels, several species of conch, and surf clams are fished recreationally within Narragansett Bay.

The Oyster Industry

From the early 1880s to 1920, oysters were the most important shellfishery within Narragansett Bay. Native oysters were originally used to feed swine or burned to produce lime, but by 1830 two fisheries for oysters existed: (1) harvest by private individuals who stored them and used them for food during the winter, and (2) harvest by full-time commercial oystermen who sold their product to shucking houses (Kochiss, 1974). The commercial harvest grew rapidly and natural spawning stocks dwindled, to the point where in the 1860s oyster seed stock had to be imported from the Chesapeake Bay into Narragansett Bay to keep pace with a consumer demand that outpaced the ability of natural populations to replace themselves.

Once oysters began to be imported to the bay, oyster spat were seeded for growout mainly in the lower bay, harvested when ready, and then exported from the bay. Natural oyster beds in the Seekonk River were kept open as public ground, but it was a common practice for commercial oyster growers to remove small oysters from this area to plant on privately leased tracts downbay.

The practice of downbay growout stemmed from two causes: (1) since large areas of the best oyster-growing grounds in the Providence and Seekonk rivers were open to public harvest, oystermen could increase their profit by removing oysters from public tracts to private tracts downbay; and (2) oysters were moved to higher-salinity waters because they grew better there, produced a better-flavored meat, and lost the "greenish" meat color common to Seekonk River oysters.

Harvests continued to slowly increase throughout the 1860–1880 period. A population boom of starfishes, predators on oysters, caused a drop and leveling off in the oyster harvest during 1866 and again in the late 1880s, but the industry responded with starfish removal practices and recovered quickly. The oyster market continued to grow rapidly from 1890 through 1900 as demand for succulent Narragansett Bay oysters increased. With this came rapid expansion of the oyster-culturing system throughout Narragansett Bay. Great Bed (once located south of Field's Point), was one of the prime oyster-growing sites. It was abandoned by 1895 due to contamination of the oyster crop with the oily residue of the coal gasification plant, and was later filled in the expansion of the Providence port facilities. The oyster industry moved further downbay, away from the industrial sprawl and into

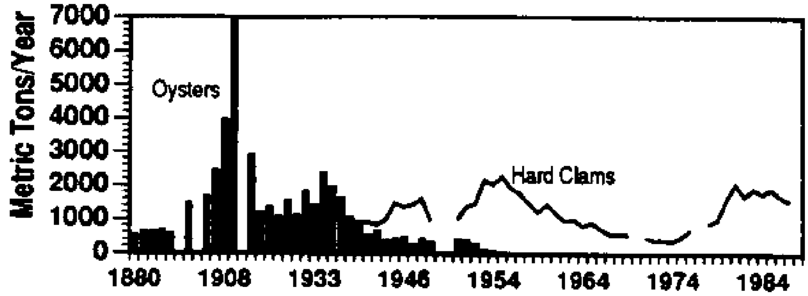


***Figure 7.5** Trends in oyster and hard clam landings in Narragansett Bay since 1880. Note that the hard clam fishery does not begin to prosper in the bay until the oyster fishery began its demise in 1910. Data from Reports to the Commissioner of Shellfisheries and NMFS catch statistics.*

downbay sites where conditions produced better oyster growth and flavor.

The lease of deep-water bottom opened the door for a major boom in the oyster industry between 1900 and 1910 (Figure 7.5). At the industry peak in 1910, more than 8,500 ha of bottom were leased for culture of imported oyster seed and more than 7,000 metric tons of oysters were harvested (Figure 7.5). Shortly afterwards, the industry went into a rapid decline caused by several factors, primarily financial. Rising lease fees became an increasing financial drain as they rose over time. Longer hours were required to work the now more expensive downbay sites, reducing the profit margin on the harvested oysters. Successive years of poor spat sets in Chesapeake Bay and Long Island Sound between 1910 and 1920 drove up the price of imported seed stock, yet the growers had no alternatives for getting seed stock since Narragansett Bay's limited natural oyster stocks had been depleted in the 1880s by overfishing. Ultimately, the oyster growing process simply became too unprofitable to sustain itself.

Both acres leased and landings were reduced to levels found in the 1880s, prior to the large expansion of the industry (Figures 7.5). A slight rebound occurred during the mid-1930s, but then the final two nails were put in the oyster industry's coffin: the economic effects of the Great Depression, and the physical damage caused by the 1938 hurricane, were more than the economics of the industry could handle, and the oyster industry completely failed in Narragansett Bay.

Links to Water Quality

The oyster industry in Narragansett Bay declined and became extinct primarily for economic reasons—the profit return to the oystermen was not sufficient to offset the lease fees, seed stock prices, loss to predators, and growout of their stocks in harder-to-work lower bay waters. Overfishing of natural stock in the upper bay and habitat degradation due to dredging and filling in the Providence and Seekonk rivers were also factors in the eventual decline of the industry.

However, it must be stressed that the oyster fishery in the bay was essentially a put-and-take phenomenon. The upper bay, although once having plentiful oysters, was not conducive to oyster propagation and recruitment due to its high salinity waters, particularly after freshwater input to the upper bay was limited by damming of all major tributaries for industrial purposes. The natural oyster stocks originally found in the upper bay could not support a major fishery due to these environmental constraints. The high salinity waters however, did provide good conditions for the rapid growth of succulent oysters. The natural fishery therefore was replaced with massive aquaculture operations for the grow out of oyster seed stock. Present day oyster stocks are very limited in Narragansett Bay, due to both environmental (salinity) and habitat (water depth) limitations on propagation and recruitment of juvenile oysters.

The Hard Clam Fishery

During the reign of the oyster industry, hard clams, although abundant and readily available, were of secondary importance as a commercial fishery; but after the failure of the oyster industry in the early 1900s, hard clams became increasingly important, increasing from 907 metric tons landed in 1928 to 2267 metric tons in 1955. The substantial expansion of the hard clam fishery during this period was related to the opening of new clamming areas where oyster grounds were formerly leased (Pratt, 1988; Figure 7.5). The initial growth of the hard clam fishery therefore, was a direct result of clamming on once unavailable bottom, as well as a shift in effort from the culturing of oysters to the harvest of natural clam populations in Narragansett Bay. The harvest of hard clams declined between 1955 and 1974, apparently due to over-exploitation of the stock, and possibly also to failure of the depleted stocks to properly recruit (Pratt, 1988).

A second marked increase in hard clam landings occurred around 1974. This increase was apparently due to the introduction of a new harvesting technology: the bull rake. The bull rake allowed clammers to work a wider variety of bottom covers, and, more important, enabled them to work in deeper waters. With the advent of the bull rake, the workable depth jumped from 13 feet (the maximum depth that could be worked with hand tongs) to 26 feet, increasing the total amount of workable bottom available in the bay by nearly a factor of two (Pratt, 1988). Clam harvests peaked in 1984 at 2,000 metric tons, and have since declined to 1,100 metric tons in 1989 (Figure 7.6). As of 1989, there were approximately 2,000 Rhode Island residents who held clamming licenses (Figure 7.6). Of these, 40% (800 people) were employed in the hard clam fishery on a full-time basis, the remainder being part-time or weekend clammers (Migliore, pers. comm.).

Some portion of the recent increase in hard clam landings can be attributed to the conditional opening of extensive and densely populated clam beds in the upper bay that were previously closed due to excessive fecal coliform contamination. Presently, the water over these beds is considered unsatisfactory only during wet weather periods. When 1 inch or more of rain is received within 24

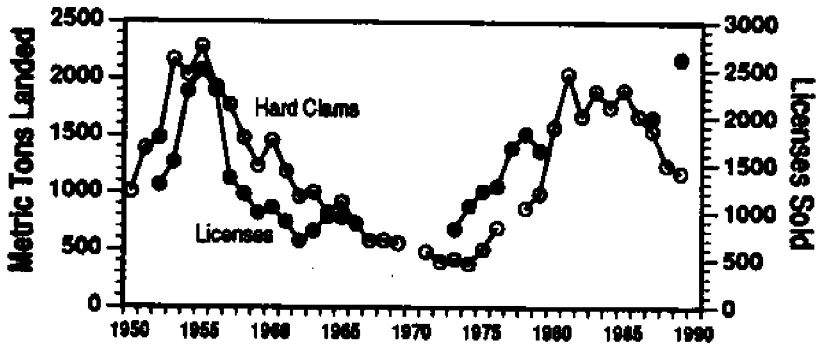


Figure 7.6 Hard clam landings and shellfish licenses sold since 1950 in Rhode Island. Licenses sold are used as a proxy to fishing effort, but do not distinguish between part-time and full-time fishermen. Note the close correlation between effort and landings through 1988, when landings continue to decline despite increased effort. Data from NMFS catch statistics and RIDEM shellfishing permit records.

hours, Conditional Areas A and B (see Figure 5.1) are closed to shellfishing for a 7-day period. If additional rain falls before the 7-day purge is completed, the beds remain closed for 10 days following the most recent rain event. When 0.5 to 1 inch of rain falls, only Conditional Area A is closed. Because of this closing schedule, the conditional beds in the upper bay are closed on average 50% of the year and have been for the last 20 years.

The shellfishing area closures however, do not mean that shellfish are being depleted by pollution. A recent hard clam survey conducted in closed and conditional areas of the Providence River and upper bay by Pratt et al. (1988) found clam distributions to be similar to those reported during earlier surveys in 1957 (Stringer, 1959) and 1965 (Saila et al., 1967), indicating that 30 years of exposure to upper bay pollutants has apparently not affected hard clam population distribution. Pratt et al. (1988) also found good numbers of smaller clams in the upper bay and Providence River, suggesting that conditions have been suitable for spat settlement in the recent past. The authors note some size/growth limitations in sampled clams (e.g., smaller than normal size at a given age), which might be due to upper bay pollutants or more probably to high clam densities within the beds.

Improved water quality in the upper bay has led to the suggestion that some of the conditionally closed clam beds be opened on a permanent basis. This idea has met with much opposition from the bay's clammers, who claim that the opening of these areas would cause a glut of clam meats on the market, attract new fishermen, lower prices, and decrease profits to the point where the industry would no longer be a worthwhile way to make a living. At present no new areas have been opened on a permanent basis in the upper bay (other than the Conditionally Managed Areas A and B), and harvests are expected, despite recent decreases in clam landings, to remain stable at present levels.

Recently, concern has been mounting over the potential of hard clams to harbor pathogenic viruses that are not detectable using the present analytical method for fecal coliform testing. If new pathogen indicators are adopted, it is possible that this could lead to closure of some currently open shellfish beds, and adversely affect the fishery. These changes however, despite their potential effect on the fishery, will not affect the abundance of hard clams, only their marketability.

Concern has also recently been expressed about concentrations of metals in clam tissues, but metal contamination is unlikely to cause significant problems to the industry in light of overall decreases in metals discharged into the bay as well as recent testing that showed metal concentrations in clam tissues to fall below both state and federal alert levels for human consumption.

Links to Water Quality

As with the oyster industry, water quality affects the hard clam fishery by limiting the area available to the fishermen when waters are not meeting fecal coliform bacteria standards, but apparently has little direct effect upon the clams. The increases and decreases observed in the commercial landings data mainly reflect overfishing and changes in technology, which are then constrained by the economic/political atmosphere surrounding the fishery, and the extent of bay bottom available for harvest to clammers on a continual basis. Further evidence of non-water quality directed changes is seen from the various studies that show hard clam abundances have not changed dramatically in the bay since the 1940s, despite very degraded water quality during the late 1940s in the upper bay, and a continual improvement in water quality since the start of the 1950s. Water quality in Narragansett Bay can therefore be considered a factor which influences where fishing effort is expended, but does not directly influence abundances of hard clams in the bay.

Over-exploitation of the hard clam resource apparently drives the commercial landings recorded, as is seen through declining landings in recent years, despite increased fishing effort and the conditional opening of once permanently closed shellfish beds. The effect that water quality has on influencing commercial landings of hard clams in Narragansett Bay, if any, is masked by the effort expended by clammers and exploitation of hard clam resources.

References

Bender, M., D. Kester, D. Cullen, J. Quinn, W. King, D. Phelps and C. Hunt. 1988. Trace metal pollutants in Narragansett Bay waters, sediments, and shellfish. Narragansett Bay Project, Providence, RI.

Bicknell, T.W. 1920. The History of the State of Rhode Island and the Providence Plantations. The American Historical Society. New York, NY

Black, D.E., D.K. Phelps and R.L. Lapan. 1988. The effect of inherited contamination on egg and larval winter flounder, *Pseudopleuronectes americanus*. EPA Region I, Narragansett Bay Laboratory, Narragansett, RI.

Boehn, P.D. and J.G. Quinn. 1977. The persistence of chronically accumulated hydrocarbons in the hard shell clam *Mercenaria mercenaria*. *Mar. Biol.* 44:227-233.

Boothroyd, J. and A. Al-Saud. 1978. Survey of the susceptibility of the Narragansett Bay shoreline to erosion. Unpubl. manuscript, Coastal Resources Center, Univ. Rhode Island, Narragansett, RI.

Bricker, S.B. 1990. The history of metals pollution in Narragansett Bay as recorded by salt marsh sediments. PhD Thesis. University of Rhode Island GSO, Narragansett, RI. 355pp.

Brown, M., L. Kossin and H. Ward. 1987. Narragansett Bay issue assessment: Public perceptions. Narragansett Bay Project Current Report. Providence, RI.

Brubaker, K. and T. Hamblett. 1989. Hope for Mount Hope Bay. Save The Bay Special Report, Providence, RI. 43 pp.

Buckley, L.J. and E.M. Caldarone. 1988. Recent growth and biochemical composition of juvenile, young-of-year winter flounder from different areas of Narragansett Bay. Final report to the Narragansett Bay Project, Rpt. No. NBP-89-14, Providence, RI. 40 pp.

Carson, R. 1962. Silent Spring. Fawcett Books; New York, NY.

Chinman, R.A. and S.W. Nixon. 1985. Depth-area-volume relationships in Narragansett Bay. Rhode Island Sea Grant #87. Narragansett, RI. 64 pp.

Christensen, E.J., C.E. Olney and T.F. Bidleman. 1979. Comparison of dry and wet surfaces for collecting organochlorine dry deposition. *Bull. Environ. Contam. Toxicol.* 23:196-202.

Collins, C. and S. Sedgwick. 1979. Recreational boating in Rhode Island coastal waters: A look forward. Rhode Island Sea Grant #75. Narragansett, RI. 76 pp.

Conley, P.T. 1986. An Album of Rhode Island History, 1636–1986. Donning Co., VA. 288 pp.

Conley, P.T. and P. Campbell. 1982. Providence: A pictorial history. Donning Co. Publ., Norfolk, VA.

Doering, P.H., L. Weber, W.M. Warren, G. Hoffman, K. Schweitzer, M.E.Q. Pilson, C.A. Oviatt, J.D. Cullen and C.W. Brown. 1988. Monitoring of the Providence and Seekonk rivers for trace metals and associated parameters. SPRAY Cruises I–VI, MERL, Narragansett, RI.

Dunwell, S. 1978. The run of the mill. David R. Godine Publ. Boston, MA. 300 pp.

Eisler, R., R.L. Lapan, Jr., G. Telek, E.W. Davey, A. Soper and M. Barry. 1977. Survey of metals in the sediments near Quonset Point, RI. *Mar. Poll. Bull.* 57:260-264.

Fall River Sewage Treatment Plant. 1983-1989. Facility NPDES monitoring records.

Frithsen, J.B. 1989. The benthic communities within Narragansett Bay. Narragansett Bay Project, Providence, RI. Report #NBP-90-28.

Ganz, A.R. 1975. Observations on the Narragansett Bay menhaden fishery. Rhode Island Dept. of Natural Resources, Div. of Fish and Wildlife, Marine Fish. Section., Leaflet No. 45. 21 pp.

Goldberg, E.D., E. Gamble, J.J. Griffin, and M. Koide. 1977. Pollution history of Narragansett Bay as recorded in its sediments. Est. and Coast. Mar. Sci. 5: 549-561.

Goode, G.B. 1887. The fisheries and fishery industry of the United States. U.S. Dept. of the Interior, Comm. Fish and Fisheries, Washington, DC.

Gorham, F.P. 1911. Report to the Rhode Island Commissioners of Shell Fisheries, Annual Report. Providence, RI.

Hale, S.O. 1980. Narragansett Bay: A friend's perspective. Rhode Island Sea Grant #42. Narragansett, RI. 122 pp.

Haley, J.W. 1939. The Old Stone Bank History of Rhode Island. Providence Institute for Savings. Providence, RI.

Halvorsen, W.L. and W.E. Gardiner. 1976. Atlas of Rhode Island salt marshes. Rhode Island Sea Grant #44. Narragansett, RI.

Haynes, T. 1989. Florida's Indian River is major player in clam industry. *National Fisherman* 70(2):10-11.

Hennessey, T. and D.D. Robadue, Jr. 1986. The governance of estuaries: Agenda setting and institutional choice in Narragansett Bay. First Nat. Symp. Soc. Sci. and Res. Mgmt, Oregon, May 12-16, 1986.

Hicks, S.D., H.A. Debaugh, Jr. and L.E. Hickman, Jr. 1983. Sea level variations for the United States 1855–1980. U.S. Dept. of Commerce, NOAA, NOS, Rockville, MD. 170 pp.

Hinga, K.R., R. Rice, A. Keller, N.F. Lewis and K. Dadey. 1988. A review of Narragansett Bay phytoplankton data: Status and trends. Narragansett Bay Project, Providence, RI.

Hoffman, E.J. 1987. Pollution inputs. In: Narragansett Bay: Issues, resources, status and management. NOAA Estuary-of-the-Month Seminar Series No. 1. U.S. Dept. of Commerce, NOAA, Washington, DC. pp. 31-69.

Hoffman, E.J. 1988. The first year of the Narragansett Bay Project: Results and recommendations. Report to the Narragansett Bay Project, Providence, RI.

Hoffman, E.J., J.S. Latimer, G.L. Mills, C.G. Carey, and J.G. Quinn. 1984. Pathways of pollutant entry into Narragansett Bay. In: Hydrocarbons and other pollutants in urban runoff and combined sewer overflows, E.J. Hoffman and J.G. Quinn (eds). NOAA Oceans Assessment Division. pp 1–73.

Hunt, C.D. unpublished data from analyses of Ohio Ledge and Dutch Island subtidal sediment cores.

Jeffries, H.P., S.S. Hale and A.A. Keller. 1988. Historical data assessment: Finfishes of the Narragansett Bay area. Report 1988-1. Graduate School of Oceanography, University of Rhode Island, Narragansett, RI.

Jeffries, H.P., A.A. Keller, and S.S. Hale. In Press. Predicting winter flounder (*Pseudopleuronectes americanus*) abundances by time series analysis. *Can. Jour. Fish. Aquat. Sci.*

Jeffries, H.P. and M. Terceiro. 1985. Cycle of changing abundances in the fishes of the Narragansett Bay area. *Mar. Ecol. Prog. Ser.* 25:239-244.

Jeffries, H.P. and W.C. Johnson. 1974. Seasonal distributions of bottom fishes in the Narragansett Bay area: Seven-year variation in the abundance of winter flounder (*Pseudopleuronectes americanus*). *J. Fish. Res. Board Can.* 31:1057-1066.

Kochiss, J.M. 1974. Oystering from New York to Boston. Wesleyan Univ. Press, Middletown, CT. 251 pp.

Kremer, J.N. and S.W. Nixon. 1978. A coastal marine ecosystem: Simulation and analysis. Ecological Studies, Vol. 24, Springer-Verlag, Heidelberg. 210 pp.

Latimer, J.S. 1988. A review of the major research done in Rhode Island on polychlorinated biphenyls in water, atmosphere, sediment, and biota from 1970–1986. Narragansett Bay Project, Providence, RI.

Lee, V. 1986a. Comparative estuaries water quality profiles. Unpubl. manuscript, Coastal Resources Center, Univ. Rhode Island, Narragansett, RI.

Lee, V. 1986b. Narragansett Bay water quality profile. Unpubl. manuscript, Coastal Resources Center, Univ. Rhode Island, Narragansett, RI.

Maguire Group, Inc. 1987. Phase I: Combined sewer overflow in the city of Fall River, Massachusetts. Prepared for the Fall River Sewer Commission. Waltham, MA.

Marine Research, Inc. 1974–1990. Brayton Point investigations quarterly progress reports. Falmouth, MA.

Massachusetts Department of Environmental Quality Engineering. 1975. Blackstone River water quality management plan update. Div. Water Poll. Control, Westborough, MA.

Massachusetts Department of Environmental Quality Engineering. 1980. The Blackstone River, Part A—water quality data. Div. Water Poll. Control, Westborough, MA.

Massachusetts Department of Environmental Quality Engineering. 1984. Blackstone River water quality management plan update. Div. Water Poll. Control, Westborough, MA.

Matthiessen, G.C. 1974. Rome Point Investigations, Narragansett Bay Ichthyoplankton Survey. Final report of Marine Research Inc., Falmouth, MA, to Narragansett Electric Co.

McGinn, J.M. 1981. A sediment control plan for the Blackstone River. Dept. Env. Qual. Eng., Office of Planning and Program Management, Boston, MA.

McLoughlin, W.G. 1978. Rhode Island: A bicentennial history. W.W. Norton and Co., New York.

McMaster, R.L. 1960. Sediments of Narragansett Bay system and Rhode Island. *J. Sedim. Petrol.* 30:249-274.

Mead, A.D. 1898. *Peridinium* and the 'Red Water' in Narragansett Bay. *Science* 8(203):707-709.

Metcalf & Eddy. 1990. Narragansett Bay Combined Sewer Overflows. Report submitted to USEPA Region I and The Narragansett Bay Project, Providence, RI.

Migliore, J. Rhode Island Dept. Env. Management, Water Resources Div. Pers. Comm.

Narragansett Bay Commission. 1989. Industrial pretreatment program annual report. October 1988–September 1989. Narragansett Bay Commission, Providence, RI.

Narragansett Bay Project. 1987, 1989, 1990. Status report on the Narragansett Bay Project. Narragansett Bay Project, Providence, RI.

Narragansett Times. 1988. 16 December.

National Marine Fisheries Service. 1880–1985. Marine Fisheries Landings Records, New England, Region I, Boston, MA.

National Pollution Discharge Elimination System (NPDES). US EPA, Region I, Boston, MA.

Needham, B. and D. Robadue, Jr. 1990. Historical review of water quality management and pollution abatement in Narragansett Bay. Narragansett Bay Project, Providence, RI.

New England Econometrics. 1988. Rhode Island: Economic annual report 1988. New England Business, Ann. Rpt. pp. 1RI-32RI.

Nicholson, W.R. 1971. Changes in catch and effort in the Atlantic menhaden purse seine fishery 1940–68. *Fish. Bull.* 69:765-781.

Nixon, S.W. In Preparation. Univ. Rhode Island GSO, Narragansett, RI

Nixon, S.W. 1991. Recent metal inputs to Narragansett Bay. Final Report to the Narragansett Bay Project, Providence, RI. 57 pp.

Nixon, S.W. 1990. A history of metal inputs to Narragansett Bay. Narragansett Bay Project, Providence, RI. 69 pp.

Nixon, S.W. 1989. An extraordinary red tide and fish kill in Narragansett Bay. In E. Carpenter, M. Bricelj and E.M. Cosper (eds)., Unusual algal blooms, Springer lecture notes on coastal and estuarine studies. Springer-Verlag, New York.

Nixon, S.W. 1987. Overview. In: Narragansett Bay: Issues, resources, status and management. NOAA Estuary-of-the-Month Seminar Series No. 1. U.S. Dept. of Commerce, NOAA, Washington, DC. pp. 7-16.

Nixon, S.W., C.D. Hunt and B.L. Nowicki. 1986. The retention of nutrients (C, N, P), heavy metals (Mn, Cd, Pb, Cu), and petroleum hydrocarbons in Narragansett Bay. In: P. Lasserre and J.M. Martins (eds.), Biogeochemical processes at the land-sea boundary. Elsevier Press, Amsterdam. pp. 99-122.

Nixon, S.W. and M.E.Q. Pilson. 1984. Estuarine total system metabolism and organic exchange calculated from nutrient ratios: An example from Narragansett Bay. In: V.S. Kennedy (ed.), The Estuary As A Filter. Academic Press, New York. pp. 261-290.

Nixon, S.W. 1983. Estuarine ecology: A comparative and experimental analysis using 14 estuaries and the MERL microcosms. Final report to U.S. EPA, Chesapeake Bay Program, Grant No. X-003259-01. Boston, MA.

Nixon, S.W. Unpublished dissovled oxygen data for Seekonk and Providence Rivers.

NOAA. 1985. National estuarine inventory data atlas: Vol. 2, Land use characteristics. U.S. Dept. of Commerce, Nat. Ocean. Atmos. Admin., Washington, DC.

NOAA. 1987a. Land use characteristics. National estuarine inventory data atlas, U.S. Dept. of Commerce, Nat. Ocean. Atmos. Admin., Washington, DC.

NOAA. 1987b. Marine recreational statistics for the Atlantic and Gulf coasts. U.S. Dept. of Commerce, Washington, DC.

Olsen, S. and V. Lee. 1979. A summary and preliminary evaluation of data pertaining to the water quality of upper Narragansett Bay. Coastal Resources Center, Univ. Rhode Island, Narragansett, RI. 189 pp.

Olsen, S., D.D. Robadue, Jr., and V. Lee. 1980. An interpretive atlas of Narragansett Bay. Rhode Island Sea Grant #40, Narragansett RI. 82 pp.

Olsen, S.B. and D.K. Stevenson. 1975. Commercial marine fish and fisheries of Rhode Island. Rhode Island Sea Grant #34, Narragansett, RI. 117 pp.

Oviatt, C.A. 1977. Menhaden, sport fish and fishermen. Rhode Island Sea Grant #60. Narragansett, RI.

Oviatt, C.A. 1981. Some aspects of water quality and pollution sources to the Providence River. Report to Region I EPA, Narragansett, RI.

Pilson, M.E.Q. 1985. On the residence time of water in Narragansett Bay. *Estuaries* 8:2-14.

Pilson, M.E.Q. 1989. Aspects of climate around Narragansett Bay. Univ. Rhode Island, Narragansett, RI. 29 pp.

Pratt, D.M. and D.A. Campbell. 1956. Environmental factors affecting growth in *Venus mercenaria*. *Limnol. Oceanogr.* 1:2-17.

Pratt, S.D. 1988. Status of the hard clam fishery in Narragansett Bay. Final report to the Narragansett Bay Project, Providence, RI.

Pratt, S.D., B.K. Martin and S.B. Saila. 1988. Status of the hard clam in the Providence River and Mount Hope Bay. Narragansett Bay Project, Providence, RI. 88 pp.

Providence City Engineer. 1891, 1893. Annual Report to the city of Providence. Providence, RI.

Pruell, R.J. and C.B. Norwood. 1989. Organic contaminants in quahogs, *Mercenaria mercenaria*, collected from Narragansett Bay. Final report to the Narragansett Bay Project, Providence, RI.

Quinn, J.G. 1988. A review of the major research studies on petroleum hydrocarbons and polycyclic aromatic hydrocarbons in Narragansett Bay. Narragansett Bay Project, Providence, RI.

Rhode Island Board of Health. 1894, 1905, 1910, 1912. Annual report to the city of Providence. Providence, RI.

Rhode Island Board of Purification of Waters. 1921, 1922, 1925. Report to the city of Providence. Providence, RI.

Rhode Island Bureau of the Census and Population Statistics. 1790-1990. Providence, RI.

Rhode Island Commissioners of Shell Fisheries. 1891, 1905, 1906, 1911, 1922, 1924. Annual report. Providence, RI.

Rhode Island Department of Environmental Management. 1986, 1988. The state of the state's waters—Rhode Island. A Report to Congress-PL 92-500 305b. Div. Water Resources, Providence, RI.

Rhode Island Department of Health. 1923, 1947, 1955, 1956. Dissolved oxygen surveys of Narragansett Bay. Providence, RI.

Rhode Island Department of Health. 1934, 1936, 1956, 1957. Annual report. Providence, RI.

Rhode Island Geographic Information Service (RIGIS). 1990. University of Rhode Island Dept. of Geology, Kingston, RI.

Rhode Island Pollution Discharge Elimination Systems Permits (RIPDES). 1985–1989. RIDEM Permitting Data. Providence, RI.

Rhode Island Statewide Planning and Employment Statistics, Govenor's Office, Providence, RI.

Ries, K.G. 1990. Estimating surface-water runoff to Narragansett Bay, Rhode Island and Massachusetts. USGS Water-Resources Investigations Rpt. 89–4164.

Rippey, S.R. and W.D. Watkins. 1987. Mount Hope Bay sanitary survey—microbiological. Final Report to U.S. FDA - Northeast Tech. Ser. Unit, Davisville, RI

Robadue, D.D., Jr. 1986. Port development in the city of Providence. Unpubl. manuscript, Coastal Resources Center, Univ. Rhode Island, Narragansett, RI.

Robadue, D.D., Jr. and J. Parker. 1986. Recreation in Narragansett Bay. Unpubl. manuscript, Coastal Resources Center, Univ. Rhode Island, Narragansett, RI. 24 pp.

Roman, C.T. 1989. Pathogens in Narragansett Bay: Issues, inputs and improvement options. Narragansett Bay Project, Providence, RI.

Saila, S.B. 1961. A study of winter flounder movements. *Limnol. Oceanogr.* 6:292-298.

Saila, S.B., J.M. Flowers and M.T. Cannario. 1967. Factors affecting the relativie abundance of *Mercenaria mercenaria* in the Providence River, Rhode Island. *Proc. Natl. Shellfish. Assoc.* 57:83-89.

Santschi, P.H., S.W. Nixon, M. Pilson and C. Hunt. 1984. Accumulations of sediments, trace metals (Pb, Cu) and total hydrocarbons in Narragansett Bay, Rhode Island. *Estuar. Coast. Mar. Sci.* 19:427-449.

Sarle, O.P. 1911. In: Annual report Commissioner of Shell Fisheries, State of Rhode Island, Providence, RI.

Save The Bay. 1988. Long-range plan: 1989–1991. Save The Bay, Providence, RI.

Smayda, T.J. 1984. Variation in long-term changes in Narragansett Bay, a phytoplankton-based coastal marine ecosystem: Relevance to field monitoring for pollution assessment. In: H.H. White (Ed.), Concepts in marine pollution measurements. Maryland Sea Grant College, Univ. Maryland, MD. pp 663-679.

Snow, E.M. 1855. Statistics on causes of Asiatic cholera. Rockefeller Library, Brown Library, Collection of Special Documents. Providence, RI.

Snow, E.M. 1865. Report to the Board of Health on Asiatic cholera in the city of Providence. Ann. Rpt. RI Board of Health, Providence, RI.

Spaulding, M. 1987. Circulation dynamics. In: Narragansett Bay: Issues, resources, status and management. NOAA Estuary-of-the-Month Seminar Series No. 1. U.S. Dept. of Commerce, NOAA, Washington, DC. pp. 71-146.

Spaulding, M. Pers. Comm. Univ. Rhode Island Department of Ocean Engineering, Kingston, RI

Stringer, L.D. 1959. The population abundance and effect of sediment on the hard clam. Hurricane damage control. Narragansett Bay and vicinity. U.S.D.I. - F.W.S., Boston, MA.

Sweet, A.W. 1915. A sanitary survey of the Seekonk River. Ph.D. thesis, Brown University, Providence, RI. 141 pp.

U.S. Army Corps of Engineers. 1959. Effects of proposed hurricane barriers on water quality of Narragansett Bay. U.S. Dept. Health, Education, and Welfare, Regions I and II. New York. 48 pp.

U.S. Bureau of the Census. Population Statistics and Census Reports. Washington, DC.

Wang, X. and M.L. Spaulding. 1985. A tidal prism flushing model of Narragansett Bay. Univ. Rhode Island, Dept. of Ocean Engineering, Narragansett, RI.

Willis, J. 1988. Recreational boating facilities. Rhode Island Coastal Resources Management Council, Oliver Stedman Office Building, Wakefield, RI. 9 pp.