CHAPTER 12.

Human Impacts on Narragansett Bay

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Figure 12.1. Circa 1920 penny postcard depicting Slater Mill and subsequent industrialization on the Blackstone River. *Photo from USGenWeb Archives*.

Human Impacts on Narragansett Bay

Once considered the most industrialized estuary in the world, Narragansett Bay has endured a long history of human impacts—some transient, some dynamic, some chronic, and some historic yet persistent. Human impacts are numerous and vary widely temporally, spatially, and functionally. It may be safe to say that every ecological function of Narragansett Bay has been directly or indirectly impacted by human activity. To list and provide detailed information on every historic impact to the Bay is well beyond the scope of this chapter, and would certainly fill an entire book. What follows, therefore, is a brief history of consequential human activities on Narragansett Bay and a discussion of the major anthropogenic impacts that affect the present ecology, value, and aesthetics of the Bay.

Prehistoric Human Use

The first evidence of post-glacial human occupation in the Narragansett Bay watershed is located on Conanicut Island and dates back roughly 5,000 years. Two Algonquin tribes, the Narragansetts of the West Bay and the Wampanoags of the East Bay, subsisted off of the resources within and surrounding the Bay. Natives numbered approximately 8,000 in total. The Algonquins may have had a minor ecological impact on Narragansett Bay and the surrounding upland habitats, harvesting fish and shellfish, hunting keystone species, and clearing land for subsistence farming by burning. However, from an ecological perspective, influences of native peoples were relatively minor and the precolonial environment is thus generally considered to be the natural background condition (e.g., King et al., 1995; Nixon, 1995).

Preindustrial Use

European colonists first settled the Narragansett Bay watershed in 1636 along the shores of the Providence River (Keller, 1996). Colonization spread quickly south along the East Bay to Aquidneck Island, and down the West Bay to Wickford. The temperate climate, long growing season, and loamy soils along the immediate coast of Rhode Island and southern Massachusetts were ideal for farming, and coastal land along the upper Bay was extensively cleared for agriculture and lumber production during the 17th and 18th centuries. Agriculture was the dominant coastal land use in the Narragansett Bay watershed until population growth and demand for labor housing associated with industrialization and urbanization became prevalent in the early 1900s. Land clearing and agriculture have historically and presently affected the water column and benthic quality of the Narragansett Bay and its tributaries by contributing to nutrient loading and siltation.

Finfish and shellfish fisheries have historically been major sources of sustenance and income for inhabitants of the Narragansett Bay watershed from early colonial times until present. Narragansett Bay was a rich fishing ground until the mid-1800s, when pelagic and anadromous fish stocks succumbed to the pressures of trap fishing and industrialization, respectively (Oviatt et al., 2003). Heavy, persistent fishing pressure and practices have, in part, caused many Bay stocks to dwindle, and the finfishery has shifted primarily to coastal waters outside of the estuary. Today, the shellfishery is the most important commercial fishery in the Bay (DeAlteris et al., 2000).

The natural deep channels and protected harbors of Narragansett Bay were ideally suited to support the shipping trades. As early as the 1700s, Rhode Island ports were involved in a lucrative shipping trade of crops, slaves, and rum with Europe, South America, Africa, and the West Indies (Childress et al., 1996). In 1853, the Army Corps of Engineers dredged a 3 m (10-foot) deep, 30 m (100-foot) wide channel into the Port of Providence to allow for the entry of large freight vessels. By 1965, Providence was the fourth largest port in New England. Regular marine shipping continues with the present importation of fossil fuels and automobiles (Harrington, 2000). Presently, approximately 13 million tons of cargo are imported into Narragansett Bay each year (U.S. Army Corps of Engineers, 2005). Shipping has led to modifications of the shoreline, driven the dredging of deepwater channels, and introduced invasive marine species from foreign bilge water and bottom fouling.

Industrialization

Historians often credit Slater Mill as being the birthplace of the Industrial Revolution in America. This textile mill was constructed by Samuel Slater in 1793 on the Blackstone River—one of the two main tributaries to Narragansett Bay—and was powered by damming the river to create a millpond that reserved the potential energy of the descending water for controlled and constant availability (Fig. 12.1). The success of the mill spawned 19th century entrepreneurs to build small and large mills on nearly every tributary to the Bay. Metal milling operations arose to supply the demand for textile machinery, followed by the manufacture of items of precious metals. As mill dams were constructed, they constricted water flow and fish passage on virtually all tributaries to the Bay, which has had numerous ecological effects, including the decimation of anadromous fish populations. By 1900, hundreds of Narragansett Bay watershed textile and metal mills were using Bay tributary waters for power, processing, and washing of materials, and for direct waste discharge. And, with the invention of the steam turbine, many industries replaced hydropower with more flexible fossil fuel power, which introduced various hydrocarbon-derived pollutants into the Bay system. Overall, the numerous consequences of industrialization to Narragansett Bay included severely polluted waters and sediments and greatly debilitated hydrologic and biological processes.

Figure 12.2. Military installation on Gould Island in the lower East Passage. This site housed a torpedo testing facility during the mid-20th century and is now largely reclaimed by vegetation. *Photo from the National Archives*.

Population Growth and Sprawl

During the 1800s, the population of Rhode Island was growing faster than any other New England state. The livelihood of residents that once depended largely on the exploitation of local resources was shifting to manufacturing and export. Between 1860 and 1920, the population of Rhode Island tripled, and industrial employment doubled (Harrington, 2000). During that period, immigrants came to America to labor on public works projects or in the textile mills and metals factories. Meanwhile, agriculture declined as the work force shifted from fields to factories and urbanization began.

As commerce and population grew with the industrialization and urbanization of the watershed so did the need for infrastructure, in the form of streets, dredged waterways, railroads, and urban sewage systems. In 1870 the city of Providence constructed a sewer system that conveyed the city's sewage through a series of 65 sewer outfalls directly into Providence's rivers and harbor. Processing of Providence sewage by chemical precipitation began in 1901 at Field's Point, but the plant was already inadequate to keep up with the growing population by 1910 (Nixon, 1995). The city then began dumping large quantities of precipitated sludge into Narragansett Bay, just east of Prudence Island, which continued until 1950 (Nixon, 1995).

Military Occupation

Since the establishment of the Continental Navy in 1775, the U.S. military has occupied various key strategic areas within Narragansett Bay—mostly prominent coastal points and nearly every Bay island—to protect the security of the Bay's civilians as well as valuable resources. Many of these outposts began as forts to house cannons and guns to stop penetration of Bay waters by enemy ships. Over time, the Navy developed numerous in-Bay sites as huge military ports, torpedo development facilities, shipbuilding operations, and naval air stations

(U.S. Navy, 2005, Fig. 12.2). Military operations modified coastal lands and shorelines as necessary to meet their changing needs. During the early and mid-1900s, the Navy developed at least 6,000 acres of coastal lands along 31 miles of the Narragansett Bay shoreline, which included the filling of at least 400 acres of the Bay to expand Quonset Point Air Station (U.S. Navy, 2005). Military waste, including hazardous pollutants, was routinely disposed of in coastal landfills and salt marshes, which at that time were generally considered valueless. Navy dumpsites are responsible for at least seven identified superfund sites in Rhode Island (EPA, 2005). The Navy also used the Bay waters extensively as a training ground and as a testing site for maritime weaponry, including torpedoes and mines, some of which remain on the seafloor.

Anthropogenic Impacts to Narragansett Bay

Physical and Hydrologic Modifications

The physical structure, hydrology, temperature, and chemistry of Narragansett Bay have been greatly affected since colonization of the watershed in the 1700s. Development of the watershed and industrialization of the tributaries were and are the basic anthropogenic forces altering the natural physical processes that drive the Bay's estuarine functions. Modifications to the watershed for transportation, industry, residence, and infrastructure, in the forms of damming of tributaries, impoundment of salt marshes, construction of hard shoreline and roadways, dredging, canalization and diversion of waterways, filling of wetlands and shorelines, withdrawal of fresh water, massive inputs of effluent, and removal of vegetative coastal and riparian buffers all contribute to changes in Bay flow patterns, salinity, temperature, and tidal influence.

Physical modifications have been directly imposed on virtually all systems of Narragansett Bay, including the tributaries, coastal wetlands, and the seafloor. Over 1,100 dams have been constructed on virtually every tributary to the Bay, mostly to support numerous small and large mills within the watershed (Hale, 1988). Most of these delinquent dams remain as relics. Over 680 ha (1,700 acres) (48 percent) of estuarine marshes have been ditched and/or impounded, and over one-third of all coastal wetland buffer area (150 m buffer zone) has been developed (Tiner et al., 2004). In total, 52 percent (214.5 km) of Narragansett Bay's shoreline has been developed into hardened shoreline (derived from RIGIS, 2006). From 1950 to 1990, 15 percent of estuarine wetlands were lost (mostly due to filling), including 124 ha of coastal marshes (Tiner et al., 2004). In deepwater habitats, three major dredged channels are maintained to connect the deep river valleys of the Bay with major ports on the Providence and Taunton rivers and in Quonset Point. The Providence River channel, the largest of the three, is 27 km long and at the time of construction it was 183 m (600 feet) wide and 12 m (40 feet) deep, running through surrounding waters ranging from zero to 12 m (1 to 40 feet) deep.

Water withdrawals from the Bay and its tributaries for residential, industrial, and power production uses have affected temperatures, salinities, and flow patterns in the Bay. Most notably, the Brayton Point Station, the largest coal-fired power plant in the Northeast, has been extracting, warming, and reintroducing seawater to the Mount Hope Bay (the northeast sub-embayment of Narragansett Bay) since 1986. The plant has been permitted to cycle up to 1.45 billion gallons per day (BGD) through a once-through cooling system with a maximum output temperature of 95 F and a maximum change in temperature of +22 F (Massachusetts Department of Environmental Protection (MADEP), 2002). The current average discharge plume of the plant (0.98 BGD) causes a rise of over 1.5 F (MADEP maximum standard) over background temperature to 2,350 ha (60 percent) of Mount Hope Bay (MADEP, 2002). In total, Brayton Point Station cycles the equivalent of the entire contents of Mount Hope Bay approximately every 21 days (J. Quinn, personal communication).

Physical anthropogenic changes in the surrounding watershed further impact Narragansett Bay by affecting the natural hydrography. By 1995 over 30 percent of the watershed was developed including nearly 6,000 miles of public roads. Several of the urbanized subwatersheds within Narragansett Bay contain more than 15 percent impervious surface, which is an EPA benchmark for ecologically impaired watersheds (Crawley, 2000). Due to the relatively small natural input of fresh water to Narragansett Bay (2.4 billion gallons, less than 1 percent of total Bay volume, entering daily), wastewater inputs comprise a relatively large percentage (more than 4 percent) of the total freshwater inputs.

In effect, physical development of the surrounding watershed contributes to the pollution of the Narragansett Bay in nearly every aspect, but most directly it creates urban runoff. Urban runoff is the flash runoff of surface water from a watershed due to highly impervious surfaces quickly channeling water off of the watershed and into the receiving water body. With the high velocity and lack of impounding structure in urban areas, any pollutants entrained in the runoff are carried, usually through specifically designed conduits, directly into the receiving water bodies without natural filtration processes offered by vegetated riparian areas (Fig. 12.3). Urban runoff contributes to pathogen, toxic metal, and hydrocarbon pollution in the Bay.

In addition to contributing indirectly to pollution impacts, physical changes to the hydrology and structure of the Bay's tributaries, coastlines, and bottom have had several direct impacts on Narragansett Bay's ecology. Loss of estuarine wetlands directly reduces critical habitat for a variety of nekton and avian species and reduces the filtering effect on watershed runoff. Impoundment of Narragansett Bay wetlands has been found to lead to the widespread establishment of invasive vegetation due to lowering marsh salinities (Bertness, 1999). From 1950 to 1990, 97 ha of marsh were overtaken by the invasive reed *Phragmites australis* (Tiner et al., 2004). Impoundment also often results in degraded nekton assemblages within marshes (Raposa and Roman, 2003). The damming of tributaries has led to the downfall of anadromous fish stocks, beginning with the extirpation of Atlantic salmon (*Salmo salar*) by 1830, and continuing with a chronic demise in once robust river herring (*Alosa* spp.) runs (NBEP, 2006). Currently, only 18 of the historic 45 runs still support anadromous fish. Damming also raises the temperature of waters entering the Bay, traps and concentrates polluted sediments, buffers natural flow variations, and alters the compositions of riverine flora and fauna (Erkan, 2002). The ongoing maintenance of miles of dredged deepwater channels also affects the Bay's ecosystem health. Dredging causes a direct loss of benthos and also reintroduces buried toxins, such as heavy metals and synthetic organic compounds, to the living water column and aerobic benthic zones.

Nutrient Loading

For over a century, Narragansett Bay has been receiving a substantial loading of anthropogenic nutrients, most notably in various forms of nitrogen and phosphorus. Nutrient inputs are specifically correlated with the widespread use of running water, which began in the late 1800s (Nixon et al., 2005). The two major sources of nutrient inputs to Narragansett Bay are the major public wastewater treatment facilities (WWTFs) that discharge directly into the Bay and the major tributaries (riverine input), which act to combine nutrients from upstream WWTFs, individual sewage disposal systems (ISDSs), and runoff from their respective contributing sub-watersheds. Total riverine input is the major source of nitrogen entering the Bay (Nixon et al., 2005). However, if all WWTFs are taken into account, including those discharging into rivers, WWTFs currently contribute approximately 70 percent of the total nitrogen load entering the Bay, while runoff carrying nutrients from atmospheric deposition and agriculture contributes most of the balance (22 percent and 6 percent, respectively; Nixon et al., 2005). Direct atmospheric and groundwater sources are thought to be minor (Carey et al., 2005).

Figure 12.3. A highly modified and industrialized upper reach of the Providence River in Narragansett Bay. Note highway storm drain pipes discharging directly into the river. *Photo from NBNERR photo library.*

Currently, total inputs from Narragansett Bay's five major tributaries contribute 1.5 times the nitrogen and 2.7 times the phosphorus to the Bay as the three combined largest WWTFs (Field's Point, Bucklin Point, and East Providence), dispensing an estimated 2,590 metric tons (MT) of total nitrogen and 271 metric tons of total phosphorus per year into the Bay (Nixon et al., 2005). Nitrogen enters the Bay from rivers mainly in the form of dissolved inorganic nitrogen, mostly derived from WWTF discharges during high river flow periods in spring and in fall storms (Carey et al., 2005). Phosphorus enters from rivers mostly in the forms of inorganic phosphate and particulate phosphorus (Nixon et al., 2005).

Over 290,000 cubic meters per day of effluent enter Narragansett Bay directly from the three large sewage treatment facilities. Nixon et al. (2005) estimated that, combined, the three big WWTFs contribute 1,650 MT and 120 MT per year of total nitrogen and phosphorus, respectively. Nitrogen inputs from major WWTFs have changed little since

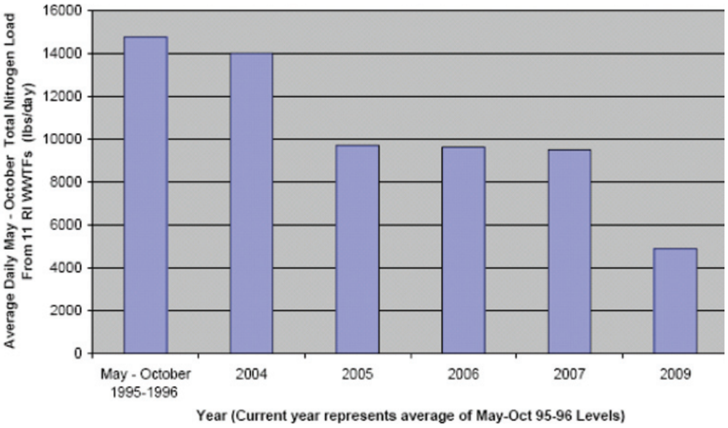

Figure 12.4. Projected yearly reductions in nitrogen loads from major Rhode Island WWTFs on Narragansett Bay. *Reproduced from RIDEM, 2005.*

the mid-1970s, with reduced inputs from the Field's Point facility being offset by increased inputs from the Bucklin Point facility, while phosphorus inputs have decreased significantly during that time. Nitrogen enters mainly in the form of ammonia (approximately 60 percent) followed by organic nitrogen and nitrites/nitrates, while the state of phosphorus entering has not been determined for sewage effluent (Nixon et al., 2005).

Nutrient loading is considered by some ecologists to be the most serious and widespread pollution impact currently occurring in Narragansett Bay, decreasing benthic biodiversity and altering valuable ecosystem functions (e.g., Deacutis, 1998; Carey et al., 2005). Nitrogen is considered the limiting nutrient to primary production in the Bay, while phosphorus and other nutrients may have lesser effects on certain ecosystem processes (Carey et al., 2005). Overloading the Bay with these nutrients has led to widespread eutrophication (over-production in primary producers such as phytoplankton and macroalgae, especially *Ulva* sp.), primarily in the upper reaches. This has ultimately impacted the ecology of much of the Bay ecosystem. One impact is high turbidity, which remains a primary cause in the stress or complete elimination of eelgrass (*Zostera marina*) from historic areas (visit *www.edc.uri.edu/restoration/html/intro/sea.htm*). Eelgrass forms an important Bay habitat type that provides cover for many juvenile and adult marine species and thus its decline has had ascending trophic effects on the ecosystem.

Another effect of eutrophication on Narragansett Bay is the regular seasonal occurrence of hypoxic and anoxic events, especially in areas of the upper Bay near the sources of nutrients. Middle and lower Bay segments are subject to periodic and infrequent hypoxic events, respectively (Carey et al., 2005). Habitats subjected to regular oxygen depletion have been degraded, with shifts in benthos from expected diverse faunal assemblages of large species such as American lobster (*Homarus americanus*), crabs, and mantis shrimp (*Squilla empusa*) to depauperate assemblages of small, short-lived worms and clams (Deacutis, 1998; Carey et al., 2005). Hypoxic and anoxic events have also been responsible for recent fish kills in the Bay (e.g., RIDEM, 2003; RIDEM, 2004).

The Rhode Island Governor's Commission enacted a "Plan for Managing Nutrient Loadings to Rhode Island Waters" (RI General Law 46-1-3(25)) in 2004 to reduce, by 50 percent, dissolved nutrients entering the Bay from 11 major WWTFs by 2009 (RIDEM, 2005; Fig. 12.4). This is expected to result in a 48 percent reduction in total summertime nitrogen loads to the Bay (Carey et al., 2005). Reduction of nutrients has been shown to restore expected ecological functions to estuarine systems (Mallin et al., 2005). Scientists expect a recovery of diversity and productivity in the degraded benthos of the upper Bay in response to lower nutrient loads, but are uncertain whether it will lead to a rebound in eelgrass abundance (Carey et al., 2005).

Toxic Metals

The sediments and waters of Narragansett Bay have been contaminated with a variety of anthropogenic metals contributed by numerous sources over the course of developed history. Significant inputs of metals to Narragansett Bay began as industrialization led to prevalent machinery and jewelry base-metal industries on Narragansett Bay tributaries during the mid-1800s. Metal-rich manufacturing wastes from these and other industries were dumped directly into the Bay and its tributaries until about 1910, when the Field's Point treatment facility began treating combined household, street runoff, and industrial effluent (Nixon, 1995). From 1909 to 1950, metal-laden solids were precipitated from the Field's Point effluent and dumped directly into the mid-Bay, just south of Prudence Island (Nixon, 1995). As a result, various anthropogenic metals are known to exist throughout the Bay in various levels of concern. These include arsenic, cadmium, chromium, copper, iron, lead, manganese, mercury, nickel, selenium, silver, and zinc. All facets of industrialization and subsequent urbanization of the

	Year					
	1900[a]	1925[a]	1950[a]	1986[b]	1988[b]	1993[c]
Cd	<1.3	<1.4	1.9	0.6 (0.14)	0.6	<0.1
Cr	13	17	22	2.3	1.2	1.4
Cu	54	76	104	35 (18-23)	6.8	6.4
Pb	15	16	22	5.9 (1.8)	3.3	0.9
Ni	<31	<51	71	40 (20)	23	15
Zn	90	125	171	54	25	6.6
Ag				1.8		0.4

Table 12.1. Partial reproduction from Nixon (2005) presenting a comparison of estimated inputs of various metals to Narragansett Bay from the Fields Point WWTF in metric tons per year.

watershed, including fossil fuel use, the widespread use of automobiles, construction, street paving, and indoor plumbing, contributed to a snowballing of metal inputs, peaking around the 1950s when environmental regulations began to be implemented (Table 12.1).

Metals have entered Narragansett Bay through several interconnected modes: riverine inputs, WWTF discharges, direct point and nonpoint discharges, and direct atmospheric deposition. Rivers and WWTFs have historically been, and remain, the main sources of metal inputs into Narragansett Bay, while direct atmospheric deposition has been a significant source of only lead, mostly during the leaded gas era (Nixon, 1995). River and upstream inputs increased with urbanization of the watershed, as metals from atmospheric deposition and automobile byproducts were efficiently and quickly transported from the roofs, streets, and sidewalks of urban areas into the tributaries in the form of urban runoff. Narragansett Bay tributaries also carry the discharges of some 22 WWTFs and numerous industries (RIDEM, 2003). Rivers currently contribute the most cadmium, lead, zinc, copper, nickel, and chromium, while WWTFs contribute the highest amount of silver (Nixon, 1995).

Due to environmental regulations imposed in recent decades, metal inputs to Narragansett Bay have diminished, but high concentrations of these contaminants remain buried in Bay sediments. Decreases in inputs have resulted from air and water pollution legislation, the shift from wood and coal to oil and natural gas, application of stack emission reduction devices, removal of lead from gasoline, termination of sludge-dumping in the Bay, upgrading of WWTFs, and the loss of primary metal industries in the watershed (King et al., 1998; Greene and Deacutis, 2000; Nixon, 1995). In fact, Nixon (1995) estimated that fewer metals were entering the Bay from watershed discharges than from the open ocean. However, high concentrations of persistent metals remain within bottom sediments in many areas of the Bay and its tributaries. King et al. (1995) found the dam-impounded sediments of the Bay's major tributaries often exceeded the "effects range–median" (ERM) sediment quality guidelines (EPA Sediment Effect Concentrations: "a level above which indicates frequent adverse biological effects") for cadmium, chromium, copper, lead, nickel, silver, and zinc. Some of these concentrations were among the highest ever observed in the United States. They also noted that large areas of the upper Bay also exceeded sediment quality guidelines. Overall, the National Status and Trends Program, conducted by NOAA in 1989, found Narragansett Bay to rank among the top 20 most contaminated embayments in the country for mercury, selenium, and silver, as well as ranking sixth of 72 for copper, eighth of 45 for lead, and 21st of 145 for nickel contamination in *M. edulis* flesh concentrations (Keller et al., 1996). In more recent studies, King et al. (2003) found concentrations of several metals to be above "effects range–low" (ERL) values in the sediments around a remediated military superfund site near Quonset Point, while Hanson et al. (2002) found similar results in the sediments at Potter Cove in the NBNERR North Prudence Unit.

In general, the highest concentrations of metals in the sediments of Narragansett Bay are located near historic sources in the upper Bay and decrease exponentially with distance down-Bay (King et al., 1995). Core samples collected by King et al. (1995) suggest that as sediments are disturbed by such processes as bioturbation or dredging, metals are resuspended and transported down the Bay with the net flow of the estuary; thus, areas away from the source are becoming more contaminated, while upstream areas are becoming less contaminated (Ely and Trew Crist, 2001).

Sediments contaminated with metals can have harmful effects on marine and human life, but knowledge of the extent of direct effects on Bay life is limited, due to confounding factors such as nutrient loading, Bay warming, and the complex nature of effective bioavailability. Metals vary widely in toxicity, bioavailability, and the degree in which they are bioaccumulated, depending on various physical factors such as temperature, salinity, and sediment composition. Because metal inputs have dramatically declined, most Bay metals are remnants of historic sources, buried in the sediments in reduced states and are not readily bioavailable. In general, metals in the sediments most directly affect shellfish and other burrowing fauna. King et al. (1995) found a weak relationship between sediment concentrations and flesh concentrations in *M. mercenaria* for copper and cadmium, and no relationship for nickel, chromium, or lead, but they observed a stronger correlation between *M. mercenaria* tissues and effective water-column metal concentrations (likely due to increased bioavailability of oxidized metals), which has implications for dredging and dam remediation projects. RIDEM (2004) does not consider current levels of toxic metals buried in Bay sediments to pose an immediate public human health threat, primarily because contaminated areas exist mostly in the upper reaches of the Bay where shellfishing is already banned due to sewage contamination.

Petroleum Hydrocarbons and Polycyclic Aromatic Hydrocarbons

Petroleum hydrocarbons (PHCs) encompass the total suite of hydrocarbon compounds derived from petroleum oil, while polycyclic aromatic hydrocarbons (PAHs) are toxic constituents of PHCs, created during PHC combustion. PHCs and PAHs enter Narragansett Bay primarily through chronic urban runoff that is introduced to Bay waters via combined WWTFs and rivers, although direct atmospheric deposition and direct industrial discharge may also be significant contributors (Latimer and Quinn, 1998; Hartmann et al., 2004). Large accidental spills only constitute about 2 percent of all oil entering the Bay (Keller et al., 1996). Major chronic sources of PHCs are thought to originate primarily from used crankcase oil, either being illegally discharged directly into the environment or from runoff carrying roadway oil into storm drains (Latimer and Quinn, 1998). In addition to pervasive crankcase oil, Latimer and Quinn (1998) also found a high incidence of No. 2 and No. 6 fuel oil constituents in riverine samples, as well as gasoline or kerosene-like components in the Moshassuck River, which likely result from leaking tanks or spillage. Significant PAH inputs currently originate in the Bay's watershed as both petrogenic (from petroleum) and pyrogenic (from combustion) hydrocarbons. Creosote (from treated piles and bulkheads), coal combustion (possibly from two power plants on the Taunton River in Massachusetts), and diesel exhaust are thought to be the major contributors (Hartmann et al., 2003). Higher molecular weight species are most likely to settle in Bay sediments.

Annual loads of total PHCs to Narragansett Bay are estimated to be 420 MT, including approximately 240 MT dry-season chronic inputs (150 MT from WWTF, 64 MT from rivers, and 27 MT from other surface water sources) and approximately 180 MT of wet-weather and other event-driven inputs (Latimer and Quinn, 1993). Total input is roughly the equivalent 128,000 gallons of oil per year, but, due to considerable pyrogenic sources, contains a much higher aromatic (PAH) fraction (Latimer and Quinn, 1993). Hartmann et al. (2006) ran sediment grab-sample transects (41 samples total) down both the East and West passages and found that PAH concentrations were highest at the industrialized head of the Bay and lowest toward the mouth, suggesting urban runoff and WWTF sources, with the Barrington, Taunton, and Seekonk/Providence rivers having the highest values.

In 1993, annual loads of total PHCs in Narragansett Bay were estimated to be 37±17 micrograms per liter (μg l^{-1}) in the Bay's main-stem rivers—substantially higher than the reference level of 10 μg l^{-1} reported in prior studies to be harmful to certain biota, including the American lobster—a locally valuable commercial species. Eighty-six percent of samples were above that value. Hartmann et al. (2006) found a mean concentration of PAHs in the sediments of the Narragansett Bay of 21 micrograms per gram (μg g^{-1}), which was well above ERL (4.02 μg g^{-1}) sediment quality guidelines. Overall, 73 percent (30) of their stations exceeded ERL values, while 12 percent (5) were above the ERM guideline of 44.8 μg g^{-1}. Toxicity of each hydrocarbon component varies, but chronic exposures to total hydrocarbons have shown effects in winter flounder physiology at concentrations of 1 μg g^{-1} and on benthic macrofauna communities at 0.09–0.18 μg g^{-1} (Keller et al., 1996).

The various components of PHCs contain a wide range of compounds that are highly toxic to marine and human life, with aromatic and mid-weight components (such as diesel due to its high aromatic fraction and persistent physical properties) being the most toxic (Clark, 2001). Pruell et al. (1984) found that *M. mercenaria* samples purchased at Rhode Island commercial seafood stores—which the authors presumed were locally caught—were contaminated with levels of biogenic hydrocarbons that exceeded levels found in samples from a control site in the lower Bay. King et al. (1993) found a strong correlation between sediment concentrations and tissue concentrations of PAHs among Narragansett Bay *M. mercenaria*. Although PAHs are considered to be carcinogenic, no state—Massachusetts or Rhode Island—or federal standards are set for concentrations of any PHCs in seafood (Pruell et al., 1984; J. Migliore, personal communication).

Synthetic Organic Compounds

Synthetic organic compounds are anthropogenic, potent, and generally highly conservative pollutants that are composed of a wide range of organochlorines and other halogenated hydrocarbons. They include industrial solvents, chlorofluorocarbons (CFCs), flame-retardants, polychlorinated biphenyls (PCBs), and pesticides such as DDT, '-drins', lindane, hexochlorobenzene (HCB), toxophene, and dioxins (Clark, 2001). Synthetic organic contaminants enter Narragansett Bay from a wide range of sources, including rivers, point sources, atmospheric deposition and spills, and adsorb to particulate matter that settles to the seafloor, where it can remain in the sediments almost indefinitely (Quinn and King, personal communication). Many of these compounds were extensively produced and utilized in and around the Narragansett Bay watershed in support of modern agriculture and infrastructure systems during the mid-1900s. In response to worldwide environmental and human health impacts brought to light mostly during the 1960s, production and use of most of these compounds has been highly regulated or halted since the 1970s and 1980s (Clark, 2001). Although PCBs and DDT have been banned from sale in the United States, they both remain measurable in Narragansett Bay waters (Keller et al., 1996).

The most notable suite of synthetic organic compounds currently affecting Narragansett Bay is PCBs, which were produced mainly for use in electrical capacitors and transformers. The Blackstone River is by far the greatest contributor of PCBs, carrying 93 percent of total PCBs entering the Bay from rivers (Latimer et al., 1990; J.G. Quinn, personal communication). Latimer et al. (1991) and Quinn and King (personal communication) found that PCB levels in sediments were highest in the industrialized source areas in the extreme upper Bay and decreased in a linear fashion down-Bay due to sediment transport, with 90 percent of contaminants accumulated in the Providence River (Latimer and Quinn, 1996, Fig. 12.5). King et al. (1995) found that sediments in the Seekonk River and northern and middle sections of the Providence River contain concentrations exceeding ERM quality guidelines. Mid-bay areas situated near point sources such as in Newport and Quonset Point also contain elevated levels of PCBs. Latimer et al. (1996) found mean PCB concentrations in Narragansett Bay sediments of 390 ppm, ranging from about 1,000 ppm in the Providence River to less than 10 ppm near the mouth of the Bay. Total annual flux to the sediments of the Bay is approximately 0.1 MT (J.G. Quinn, personal communication). Quinn and King (personal communication) also found high concentrations of the flame suppressant polybrominated diphenyl ether (PBDE) in the sediments in Pawtuxet Cove and at Bucklin Point in the Upper Bay. PBDE is structurally similar to PCBs and is believed to have similar function and toxicity.

Synthetic organic compounds are considered the most highly toxic and mutinogenic of all marine pollutants. They are a particular threat to species in higher trophic levels, as they tend to bioaccumulate and biomagnify in fatty tissues (Clark, 2001). However, because their effects are not typically acute, little is known about their direct impacts on Bay or human life. King et al. (2005) found a strong correlation between surface sediment concentrations and tissue concentrations in *M. mercenaria* for five organic compounds including benzotriazoles and PCBs. Jeon and Oviatt (1991; in Keller et al., 1996) assessed concentrations of toxic contaminants in Narragansett Bay blue mussel, quahog, and winter flounder and found that PCB concentrations were generally higher in tissues of animals in the upper Bay. Of 42 coastal sites ranked for contamination by NOAA in 1989, Narragansett Bay ranked 14th for PCB concentrations in flounder. Strong correlations between PCB burdens and liver disease in winter flounder have since been revealed (Keller et al., 1996).

Another notable environmental consequence of synthetic organic pollution is that it limits riverine restorations, specifically the removal of relic dams, due to high concentrations in impounded sediments. High costs of removing and disposing of contaminated sediments are often prohibitive to riparian restoration efforts in the Narragansett Bay watershed (T. Ardito, personal communication).

Aquatic Nuisance Species

Historically, nonindigenous marine species (or aquatic nuisance species) have entered Narragansett Bay mainly through passive introduction via the shipping trades. The primary vector has been bilge water effluence, although ship fouling, aquaculture importation, and ornamental escape may have been instrumental for certain species (Narragansett Bay Estuary Program (NBEP), 2005; Cute and Hobbs, 2000; Massachusetts Invasive Species Working Group (MAISWG), 2002). Estuaries are generally considered the most vulnerable waters to invasion of aquatic nuisance species due to the extended time international ships spend in estuarine ports. Narragansett Bay, as a net importer of goods, supports less ballasted incoming international shipping traffic than many major ports, and is thus considered by some to have a relatively low risk of invasion

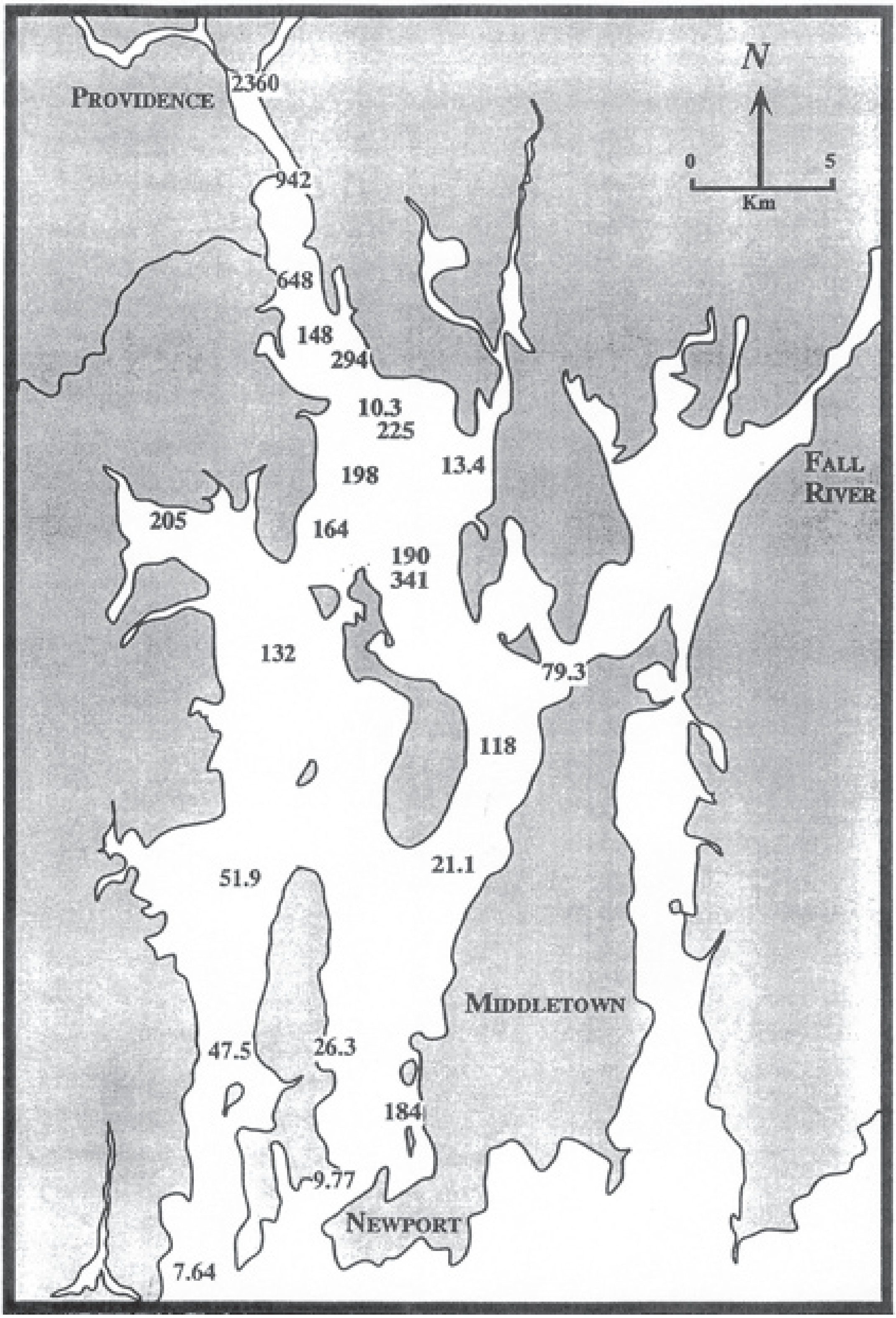

Figure 12.5). A reproduction from King et al. (1995) depicting concentrations of total PCBs (ng/g) in the surface sediments of Narragansett Bay. Note that the concentrations are highest in the industrialized upper Bay and diminish while moving down the Bay (a trend that holds for most contaminants in the Bay).

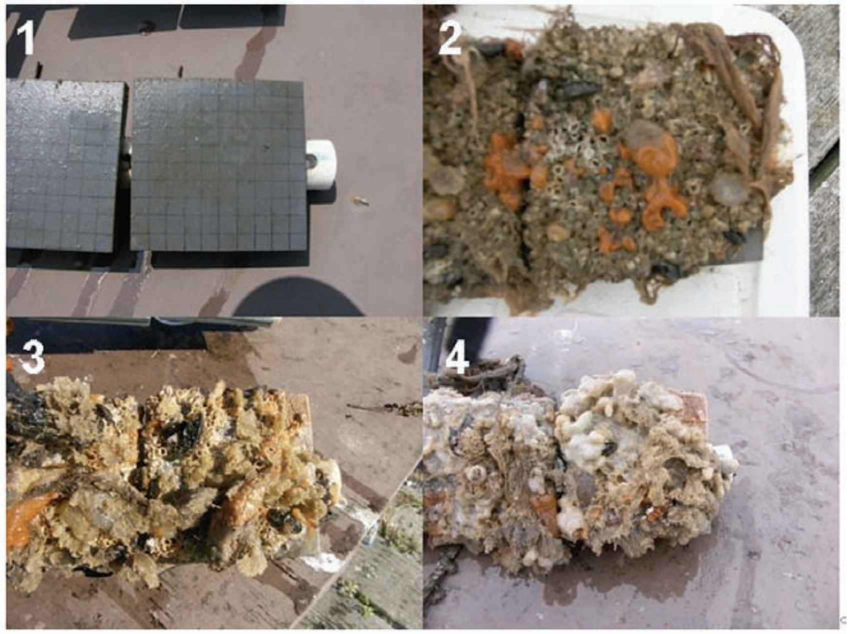

Figure 12.6. A time-series account of species recruitment on a Whitlatch settling plate set off the T-wharf in the NBNERR in 2005 by URI graduate student Linda Auker. Note how expected species such as barnacles (*Semibalanus balanoides*) and blue mussels (*Mytilus edulis*) are almost entirely overtaken by invasive tunicates. *Photo from NBNERR photo library.*

(NBEP, 2005). Others consider the Bay ecosystem to be at a high risk of invasion due to recent glacial history resulting in an under-saturated ecosystem (e.g., Bertness, 1999). Cute and Hobbs (2000) found that rates of invasion within Narragansett Bay have generally been increasing since 1900, which follows regional and global trends (NBEP, 2005).

Several aquatic nuisance species are widespread and abundant in Narragansett Bay. These include long-time invasives such as the common periwinkle (*Littorina littorea*), which was introduced from Europe circa 1840, and the green crab (*Carcinus maenas*), which was introduced from Europe circa 1841; and recent introductions such as the red seaweed *Grateloupia turuturu*, which was introduced from the West Pacific circa 1996, and the Asian shore crab (*Hemigrapsus sanguineus*), which was introduced from the West Pacific circa 1988 (Cute and Hobbs, 2000) and currently is showing rapid growth around Prudence Island (NBEP, 2005).

The only known formal inventory of aquatic nuisance species in Narragansett Bay is a rapid assessment of floating dock fouling communities that was conducted over a four-day period in 2000 (Cute and Hobbs, 2000). Of 149 species catalogued during that assessment, 22 species in 11 phyla were determined to be nonindigenous, while 17 species in four phyla were determined to be cryptogenic (of undetermined origin). Due to the nature of the assessment, all nonindigenous species found were either seaweeds or sessile invertebrates, with the exceptions of the green crab and the Asian shore crab.

The MAISWG (2002) compiled a list of problematic marine invaders and marine species of concern for the Massachusetts Aquatic Invasive Species Management Plan. Problematic invaders occurring in Narragansett Bay include green crab; Asian shore crab; lace bryozoan (*Membranipora membranacea*); the green alga dead-man's fingers (*Codium fragile* var. *tomentosoides*); six tunicates including *Styela clava, S. canopus, Diplosoma listerianum, Asciliella aspersa, Botryllus schlosseri,* and *Botrylloides violaceous*; and numerous shellfish pathogens including MSX (*Haplosporidian nelsoni*), SSO (*H. costalis*), Dermocystidium (*Perkinsus marinus*), and QPX, an unidentified quahog parasite. Threatening species, those that are not yet present but pose considerable threats to native ecosystems, include the veined rapa whelk (*Rapana vanosa*) from Japan; Nori (*Porphyra yezoensis*), an edible Asian red alga commercially cultivated in the Gulf of Maine; the Chinese mitten crab (*Eriocheir sinensis*); the intentionally cultivated Pacific oyster (*Crassostrea gigas*); and the "killer algae" *Caulerpa taxifolia*, which is an escaped ornamental alga associated with marine aquaria (MAISWG, 2002).

Aquatic invasive species have had long-term, wide-ranging effects on Narragansett Bay ecosystems and on fisheries. Significant impacts are community changes due to competitive dominance and predation and transmission of disease. For example, the ubiquitous green crab is known to compete with native crabs for food resources, and prey upon the commercially important clam species *Mya arenaria* and *Mytilus edulis* (Flimlin and Beal, 1993). Since its introduction, the green crab has become one of the most dominant omnivorous shoreline consumers in the Northeast. The common periwinkle is the most abundant grazer in the Bay's intertidal habitats and has effectively driven the ecology of all Bay cobble and rock beach ecosystems via top-down control of algae and seaweeds and displacement of expected species (Bertness, 1999; Fig. 12.6). The alga dead man's fingers has also been found to affect cobble beach communities by contributing to the dislodgement of cobbles due to increased drag, and introduced tunicates are responsible for the displacement of native fouling organisms (Bertness, 1999). The invasive shellfish parasites MSX and *Dermocystidium* have been implicated in the continued scarcity of the once abundant and economically important native, the American oyster (*Crassostrea virginica*), in Narragansett Bay (RIDEM, 2004b).

Extraction of Biotic Resources

Since the 1800s finfish and shellfish in Narragansett Bay have been greatly affected, both in community composition and abundance, by fishing. Commercial fishing practices have evolved from early gears, such as the small trap, hand-line, hand dredge and tong, and small surface net, to massive, modern, efficient, and potentially destructive gears, such as the otter trawl, hydraulic dredge, long-line, and gillnet. Recreational fishing has also persisted throughout the period. A drop in finfish stock has driven most commercial finfishing out of the Bay and into coastal waters, while Bay shellfishing and recreational fishing remain important. Commercial fisheries data have been used to indicate fish abundance and community composition, and, coupled with trawl data captured by the RIDEM from 1960 to 2000, have shed light on fish populations and the effects of fisheries on the Bay.

Oviatt et al. (2003) analyzed historic and current fisheries and trawl data to explore trends and formulate hypotheses in finfish abundance and community structure in Narragansett Bay over time. Rhode Island fishery survey data compiled from the 1860s and the mid-1900s revealed a shift in target species from primarily in-Bay species to a mix of in-Bay and offshore species. More recently, RIDEM trawl surveys conducted within Narragansett Bay revealed that overall biomass of demersal species has decreased by a factor of four in recent times. Biomass of pelagic species changed little, but species composition has shifted, with a decrease in scup biomass and an increase in bluefish, butterfish, and bay anchovy biomass. Historically important codfish, tautog, and alewife populations no longer support distinct commercial fisheries due to drastically reduced numbers (Oviatt et al., 2003).

The Narragansett Bay shellfish fishery has persisted since early times, but also with shifts in targeted species from the American oyster, the soft-shelled clam (*Mya arenaria*), and the bay scallop (*Argopecten irradians*) to the American lobster and the quahog more recently (Fig. 12.7). Oviatt et al. (2003) theorize that this shift may be associated with competitive release resulting from changes in demersal finfish assemblages, with the shift in harvest being a direct reaction to population shifts in respective species. Currently, approximately 8 million pounds of quahogs are extracted from Bay waters annually (see *NBEP.org*). Overall, it is estimated that shellfish biomass has dropped 17 percent since 1960 and 88 percent since 1898 (Oviatt et al., 2003).

Both direct and indirect harvesting pressures have been implicated as instrumental factors driving finfish and shellfish population shifts in Narragansett Bay. Oviatt et al. (2003) estimated that between the mid-1800s and mid-1900s, finfish catches within Narragansett Bay actually exceeded the Bay's capacity for production, and fish populations were apparently repopulating the Bay from nearby offshore waters. Currently, due to recent heavy fishing pressure in these nearby offshore waters, those populations no longer exist. Fish trapping, which was the most highly utilized and effective harvesting method employed in early times, is thought to have affected target populations while otherwise minimally impacting the environ-

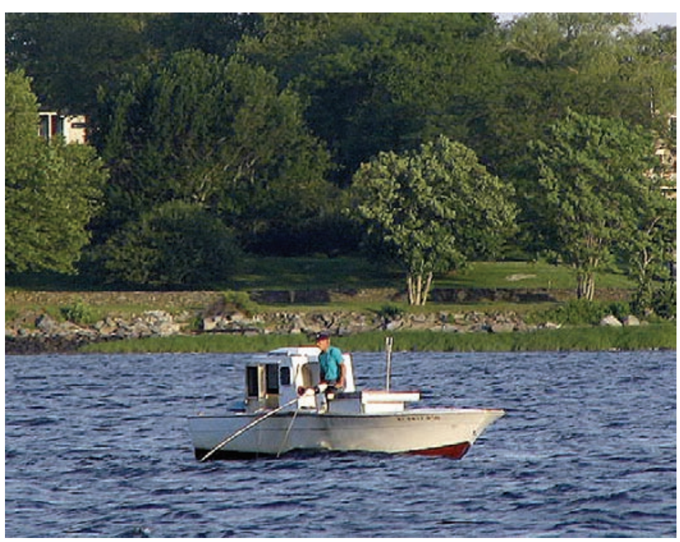

Figure 12.7. A quahog fisherman digging from a small, modern, commercial skiff in upper Narragansett Bay. Inconsistent with trends in sophisticated modern gear, quahogs are harvested manually with a long hand rake known as a bullrake or by diving. *Photo from NBNERR photo library.*

ment (Oviatt et al., 2003). However, efficient but destructive commercial fishing practices of the last century, especially scallop dredging and trawling, have greatly impacted benthic habitat, which in turn may have effected the recruitment of various commercial species, including the once commercially important bay scallop. Relative abundance of total fish yield has declined an estimated 81 percent since 1891, attributed mostly to impacts of trawl fishing in the past 40 years (Oviatt et al. 2003). The dynamics between fishing pressure and populations of target species are tightly intertwined in such a small ecosystem as Narragansett Bay, yet direct relationships are often confounded by many other natural and anthropogenic factors, such as extreme weather events, siltation, warming, impasse, toxins, hypoxia, and disease, many of which may act synergistically (DeAlteris et al., 2000). Thus, harvest restrictions imposed within the last century have had limited success in restoring target populations.

Summary

A long history of human exploitation has affected virtually every ecological function in Narragansett Bay and its watershed. Sources of degradation and pollution are centered in and around industrial and residential growth centers, mostly in the upper Bay near the Providence and Fall River metropolitan areas, although effects are often widespread. There is a distinct gradient in nearly all contaminants, ranging from high levels of contamination in the upper Bay to relatively low levels in the lower Bay. For persistent contaminants buried within Bay sediments, this gradient is slowly moving down-Bay as sediments are resuspended by activities such as dredging, trawling, and bioturbidation, and resettle in lower reaches. Modifications to natural hydrologic systems have directly affected or facilitated environmental degradation throughout the Narragansett Bay watershed. Widespread damming, watershed urbanization, and diversion, canalization, and dredging of waterways have directly contributed to fish impasse, urban runoff, and habitat loss, while indirectly contributing to water and sediment pollution.

Nutrient loading perhaps has the greatest immediate impact on Narragansett Bay ecology, having ascending trophic effects on all biota and direct effects on certain benthic species through oxygen depletion associated with eutrophication. Nutrients enter the Bay primarily through WWTF effluent, both directly and via riverine transport. Steps are currently being taken to reduce nutrient loading to the Bay by 50 percent by 2009, but under changing climate conditions, these reductions could have as-yet-unknown consequences on Bay productivity. Persistent pollutants, such as metals, synthetic organic compounds, and PHCs also enter the Bay through direct WWTF discharge and riverine sources, but are also attributed to urban runoff. Sediments in the upper reaches of Narragansett Bay and its main-stem rivers contain some of the highest concentrations of persistent contaminants on record, yet due to current limited bioavailability, have limited immediate impacts on Bay life. They do, however, limit hydrologic restoration efforts, especially riparian restoration, due to the probability of resuspension.

The Narragansett Bay ecosystem has also responded to direct anthropogenic inputs and withdrawals of biota. Aquatic nuisance species, introduced primarily through fouling and bilge exhaust associated with the shipping trades, have been affecting trophic dynamics since the 1800s. Currently, exotic shellfish diseases are impacting economically important species, such as the American oyster. A long history of persistent fishing has also affected Bay ecology through direct extraction and ascending and cascading trophic consequences. Efficient, but sometimes destructive, modern fishing practices are thought to also directly degrade benthic systems.

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