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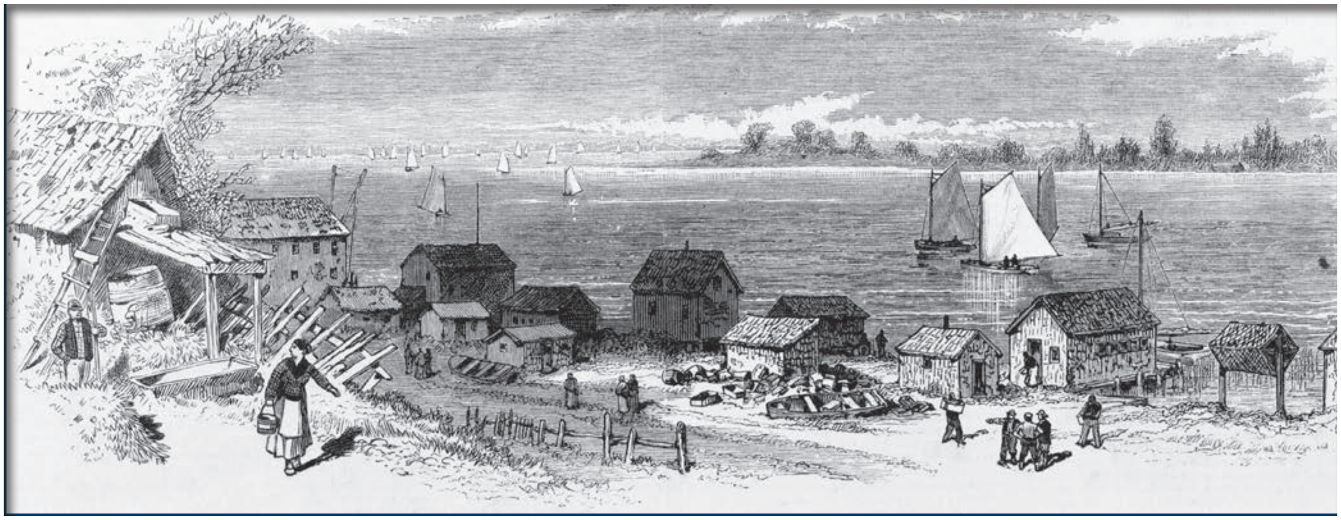
Imprint of the Past:

Ecological History of Greenwich Bay, Rhode Island



Office of Research and Development
National Health and Environmental Effects Research Laboratory, Atlantic Ecology Division

Front cover: *General View of Scalloptown, East Greenwich, and the Fishing Grounds*
Back cover: *Interior of a Scallop Shanty – "Cutting Scallops" for the Market*

Wood engravings from Frank Leslie's Illustrated Newspaper (Leslie's Weekly), Nov. 14, 1877. (Rhode Island Historical Society, RHi X35799)

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Abstract

Because environmental problems are often caused by an accumulation of impacts over several decades or even centuries, it is necessary to look at the environmental history of an area to understand what happened and why, before solutions can be devised. This case study of Greenwich Bay, a small sub-estuary of Narragansett Bay, describes the connection between the development in the watershed and the ecology of the bay. We divided the cultural history of the Greenwich Bay area into five time periods (Pre-Colonial, before 1650; Colonial, c. 1650 to c. 1750; Maritime, c. 1730 to c. 1820; Industrial, c. 1800 to c. 1945; and Suburbanization, c. 1945 to present) and described the ecological effects associated with each. During the first three periods, ecological effects occurred but were minimal. Major ecological effects occurred in the last 150 years. During the Industrial Period, the increase in people and industries resulted in bacterial pollution and shellfish bed closures, chemical pollution, and obstruction of anadromous fish runs by dams. Overfishing in all of Narragansett Bay reduced fish stocks. During the Suburbanization Period, the bay was affected by more bacterial pollution, increased nitrogen input, eutrophication, low oxygen, fish kills, and loss of eelgrass and scallops. This historical analysis of Greenwich Bay provides an opportunity to inform scientists, managers, and citizens about the consequences of development and gives environmental managers a foundation on which to make informed decisions for the future.

Key words: historical ecology; ecological history; environmental history; Greenwich Bay, RI

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Acknowledgements

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Source of section head images and quotes. Executive Summary (p. vii), left to right - Fishermen's shanties along East Greenwich waterfront (East Greenwich Historic Preservation Society); Beach and Break Water, Nausauket, RI (postcard, Rhode Island Historical Society, RHi X17 1245); Apponaug Mill with workers (Warwick Historical Society). Introduction (p. 1) – aerial view of Greenwich Cove (photograph by Christopher Deacutis, Narragansett Bay Estuary Program). Pre-Colonial Period (p. 5) – aerial photograph altered to simulate how the watershed would have looked when mostly wooded with pristine beaches and water. Colonial Period (p. 9) – stone wall photograph by Carol E. Pesch. Maritime Period (p. 11) – etching of East Greenwich waterfront (East Greenwich Historic Preservation Society). Industrial Period (p. 15) – Greenwich Worsted Mills, 1918, just over the town line in Warwick, RI (East Greenwich Historic Preservation Society). Suburbanization Period (p. 33) – aerial view of houses in Oakland Beach, Warwick (photograph by Christopher Deacutis, Narragansett Bay Estuary Program). Summary (p. 43) – aerial view of Buttonwoods and Brush Neck Coves (photograph by Christopher Deacutis, Narragansett Bay Estuary Program); quote from: McPartland, M.R. 1960. The History of East Greenwich, Rhode Island 1677-1960: with Related Genealogy, p. 188 [27]. Quotes: p. viii, Mark R. Tercek. 2012. The Nature Conservancy Magazine, Issue 3, p. 9; p. 14, D.H. Greene. 1877. History of the Town of East Greenwich and Adjacent Territory from 1677 to 1877, p. 2 [51].

Executive Summary

To formulate solutions for environmental problems, research scientists and managers have to understand the ecological conditions in the area of interest. Because environmental problems are often caused by an accumulation of impacts over several decades or even centuries, it is necessary to look at the environmental history of an area to understand what happened and why, before solutions can be devised. Further, it is important to understand true baseline conditions, and not just what is in recent memory. Historical information can be used in the process of developing a system-wide approach to set realistic management goals based on understanding current ecological conditions and knowing what ecological habitats and organisms existed in the past.

Greenwich Bay, a small sub-estuary of Narragansett Bay, Rhode Island, provides a unique and interesting case study of estuarine changes over time. Yet, the history of human influences on Greenwich Bay is not atypical or unusual for estuaries on the U.S. Atlantic coast. To better understand this system, the cultural history of the local area was divided into five time periods that corresponded to the human activities in the watershed at those times. Within each time period, the activities and their associated ecological effects were researched and reported. The dates of these periods are approximate, and the activities in the periods overlap. In the earliest time period, the Pre-Colonial (before 1650), the native peoples utilized the abundant natural resources available in Greenwich Bay and its watershed—fish, shellfish, mammals, plants, trees, clay deposits, seagrass, and fresh water. They modified the terrestrial habitat by clearing underbrush from the woods to facilitate hunting. They took shellfish from the bay, and the decrease in oyster shell size, over time, at an archeological site indicates that human harvesting may have affected populations of shellfish. However, the ecological effects of prehistoric peoples and Native Americans on Greenwich Bay were probably minimal.

In the Colonial Period (c. 1650 to c. 1750), the settlers in the watershed cleared land, planted crops, and grazed animals. The amount of land cleared during this period probably increased the amount of sediment entering the bay. During the Maritime Period (c. 1730 to c. 1820), the waters of Greenwich Bay became important as a means of transportation for trading purposes. There were some changes, although not major, to the coastline as wharfs were built and shorelines were hardened. As more land was cleared there was evidence of increased sediment entering the bay.

During the Industrial Period (c. 1800 to c. 1945), especially after 1850, human activity had measurable ecological effects on Greenwich Bay. The 13-fold increase in human population resulted in a dramatic increase in the amount of sewage. The bay waters became polluted with fecal bacteria, and areas of the bay were closed to shellfishing. Industries in the watershed polluted the bay with chemicals. Episodes of low oxygen occurred in sections of the bay. Dams built on brooks obstructed the passage of anadromous fish.

In the Suburbanization Period (c. 1945 to present), the ecological effects on the bay resulted primarily from the continuously increasing number of people in the watershed. The population in the watershed doubled, and farmland was converted to residential and commercial uses. Bacterial contamination in the bay caused more areas to be closed to shellfishing and caused some beach-closure days. Increased input of nitrogen to the bay resulted in eutrophication, which caused low oxygen at times during the summer months, and which in turn caused fish kills. Eelgrass declined and is no longer found in the bay. Scallops do not grow in the bay anymore.

This case study describes the connection between the development in the watershed and the ecology of Greenwich Bay, and allows us to appreciate the natural resources that were present in the bay before the major impacts of the last 150 years. On an ecological time scale, people have short memories. Today, citizens of the watershed see the abundant quahog harvests, but probably don't know that less than one hundred years ago the bay bottom was covered with eelgrass (suggesting that the bay water was much clearer) and the bay was a productive scallop area. Environmental conditions have been changing since initial settlement; the direction of those changes in the future, whether toward a cleaner, healthier environment or toward continued degradation, will depend on the management decisions made at local and regional levels. This historical analysis of Greenwich Bay provides an opportunity to inform the scientists, managers, and citizens about the consequences of development and gives environmental managers a foundation on which to make informed decisions for the future.

"Nature provides the food, water and air we need to survive, but it also nourishes our spirits through the places we call home and the landscapes, waters and wildlife that inspire us."

Mark R. Tercek

Introduction

This narrative tells the story of Greenwich Bay—the story of the people who lived and worked on the land around the bay, and the story of the effects of their activities on the bay. Five hundred years ago, the land surrounding Greenwich Bay was wooded and bustled with abundant wildlife—deer, bear, turkeys, other birds, rodents, and other small animals. The waters of the bay teemed with abundant fish and shellfish—sturgeon, striped bass, salmon, shad, oysters, scallops, soft-shell clams, and quahogs. These resources supported the Native American people living in the watershed. Today, the watershed is a suburban landscape of housing developments and commercial property, and the quality of the bay water has been compromised—shellfish beds are closed due to bacterial contamination, eelgrass and scallops no longer grow in the bay, dams on streams block anadromous fish migrations, and low dissolved oxygen levels in summer have caused fish kills. How did these changes come about, and why is this history important?

The activities of people and industries affect the environment, and often the changes are negative. The U.S. Environmental Protection Agency (EPA) has a mission to protect human health and the environment. EPA's original approach to research and manage pollution problems was by "command and control"—the method of regulating specific chemicals at discharge sites. Research was conducted on individual pollutants and their effects on particular species in each separate medium—water, air, or land—to set water quality criteria or air quality standards (concentrations of pollutants and pathogens that are intended to protect biological organisms and human health), which the states would then implement. After criteria were developed for some of the worst pollutants and after pretreatment of industrial waste was mandated, EPA adopted a more comprehensive approach to solve environmental problems. About two decades ago, EPA began an effort in community-based environmental protection [1]. This approach was based on a consensus-building process among the stakeholders (local planners, zoning officials, local business people, state and federal environmental managers, and citizens) to identify local environmental problems, evaluate community priorities, plan and implement solutions, and assess the results. The focus was on more than just the effluents at the end of a pipe because environmental problems are often caused by interaction between pollutants from different sources and can affect large portions of a watershed (the area drained by a river system).

Current environmental problems are more complex and challenging. Increased nitrogen loading, climate change, sea-level rise, and invasive species are complex issues that affect ecological conditions and require creative solutions. Recently, EPA's Office of Research and Development has adopted a multidisciplinary approach to focus on complex environmental problems of broad national interest [2]. The emphasis of this research is to provide solutions that are sustainable, and responsive to the needs of multiple stakeholder groups. This requires scientists and managers to understand ecological conditions in the affected area. Because environmental problems are often the result of impacts accumulated over several decades or even centuries, managers need to look at the environmental history of an area in order to understand what happened and why, before solutions can be devised.

Historical analysis of ecological consequences is a valuable tool in solving environmental problems [3, 4]. Current ecological conditions are the result of events that have occurred over decades or even centuries. Small impacts over time can be additive. Historical studies help us understand the connection between what happens on land and the condition of adjacent water bodies. These studies also help us recognize that some decisions and their accompanying actions can cause long-term environmental consequences, and thus these studies can help environmental managers make informed decisions. Historical information can be used to set realistic management goals based on an understanding of current ecological conditions and a knowledge of past ecological habitats and organisms [5, 6]. Historical studies help scientists realize that while current ecological conditions were certainly different several hundred years ago, conditions might have been very different as little as fifty years ago. Historical studies can be used to inform stakeholder groups and to engage them in a dialog about important issues. Because many people have a strong interest in where they live, historical studies can be used to engage the public in discussions of the environmental issues they face in their home towns.

Greenwich Bay is a shallow embayment on the western side of Narragansett Bay, Rhode Island, USA (Fig. 1). The bay with its five coves covers about five square miles (13 km^2). It is surrounded on the north, west, and south by the towns of Warwick and East Greenwich. Most of the 21-square mile (54.6 km^2) watershed lies within Warwick (79.6%), with smaller portions in East Greenwich (10.6%) and West Warwick (9.8%).

Greenwich Bay is an estuary, a place where fresh water and salt water mix. The largest freshwater inputs come from Hardig Brook, its tributaries, and Gorton Pond via Apponaug Brook (33%), which empty into Apponaug Cove, and the Maskerchugg River and its tributaries (30%), which empty into Greenwich Cove (Fig. 1). The remaining fresh water comes from smaller streams, the East Greenwich Waste Water Treatment Facility, surface runoff, ground water flow, and stormwater outfalls [7]. Salt water enters Greenwich Bay from Narragansett Bay on incoming tides and mixes with the fresh water. In

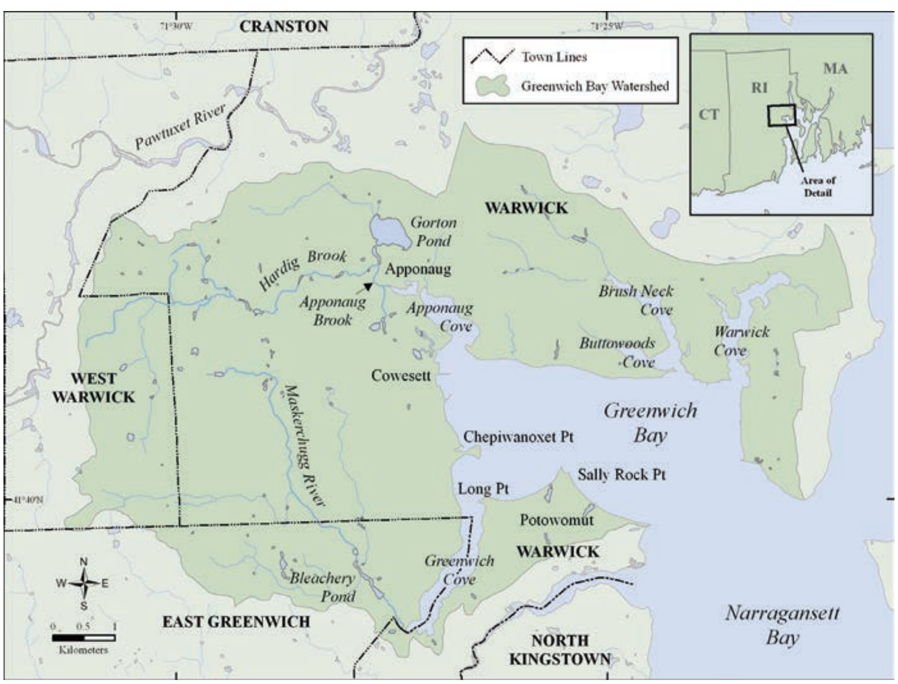


Figure 1. The watershed of Greenwich Bay, which is located on the west side of Narragansett Bay, includes sections of three towns, Warwick, East Greenwich, and West Warwick.

addition to tidal exchanges, wind conditions can affect the exchange of water with Narragansett Bay. Strong southwesterly winds can trap water in Greenwich Bay and thus minimize the exchange of water [8]. Models that simulate tidal movement and winds have show that, under certain conditions, water from upper Narragansett Bay is swept around Warwick Neck and into Greenwich Bay [9]. Thus, in addition to freshwater inputs from the surrounding watershed, Greenwich Bay is affected by Narragansett Bay water.

The geology of Greenwich Bay and its watershed was shaped by glaciers. Rhode Island coastal estuaries were formed as the glaciers in the last ice age (16,000 years ago) retreated, and the melting waters caused the sea level to rise and flood the land. Sediment deposited by the melting ice formed the features of coastal Rhode Island, Narragansett Bay, and Greenwich Bay. As the glacier melted, Greenwich Bay was part of a river system that drained eastward into a glacial lake located in present-day Narragansett Bay. The western shore of Greenwich Bay is composed of coarse-grained sediments that were deposited in front of the ice sheet as it retreated [10]. Land masses on the southern (Potowomut) and northern shores of Greenwich Bay are deltas that formed as meltwater drained eastward [11]. Marine waters entered Greenwich Bay between 6500 and 5000 years before present (BP) [12, 13]. In the term BP, "present" was standardized to be 1950, so 5000 BP is about 3050 BC. The rate of sea-level rise declined between 3000 and 300 years BP and Greenwich Bay stabilized as a low-energy depositional environment [11, 13]. The Greenwich Bay sub-systems on the northern side (Apponaug, Buttonwoods, Brush Neck, and Warwick Coves) were likely formed either by erosion of material by seasonal ground water discharge [11] or were part of an organized post-glacial river system [12]. The sources and paths of ground water to Greenwich Bay are important because ground water has been identified as a potential source of nitrogen to the bay [7, 14].

Greenwich Bay's historic heritage provides a unique sense of place [7]. The bay has attracted people to live along its protected shore for thousands of years. Throughout history, residents have relied on shellfish for food and economic purposes—first oysters, then scallops, and now quahogs. Colonial settlers were attracted by the availability of suitable land and access to marine resources. During the eighteenth century, the waterfront at East Greenwich developed as a harbor for trade and fishing. Textile mills were built in East Greenwich and Apponaug during the Industrial Revolution. Hotels, picnic areas, a campground, an amusement park, and beaches at Oakland Beach and Buttonwoods, along the bay's northern shore, provided recreation during the nineteenth century. Many historic homes and buildings can be seen throughout the watershed, especially in East Greenwich, Apponaug, and Buttonwoods.

Residents and businesses in the Greenwich Bay watershed played a part in some historical events of national significance. Warwick residents participated in the burning of the British revenue schooner *Gaspee* in 1772 in the lead-up to the American Revolution. Members of the Kentish Guards, a state militia formed in East Greenwich in 1774, participated in the American Revolution. General James Mitchell Varnum of East Greenwich served in the Continental Army, and Potowomut resident General Nathanael Greene was George Washington's second-in-command during the Revolution [15]. Civil War General George Sears Greene of Apponaug led the heroic defense of Culp's Hill at Gettysburg [16]. A factory on Chepiwanoxet Point manufactured seaplanes for the U.S. Navy during World War I, and a shipyard on Greenwich Cove built Coast Guard Picket boats in the early 1900s and Sub-Chaser boats during World War II.

Today, a large portion of the watershed is developed; in 2003-2004, 64% of the watershed consisted of commercial, industrial and built land, including 43% residential development. Almost 25% of the bay shoreline is devoted to recreation [7]. The bay, with its many marinas, attracts recreational boaters and is also home to a small fleet of commercial fisherman. Three beaches (Oakland Beach, Warwick City Park, and Goddard Memorial State Park), four golf courses (two public, two private), and walking trails in three parks (Warwick City Park, Goddard Memorial State Park, and Chepiwanoxet Point) provide recreational opportunities for the public.

Greenwich Bay provides habitat for many species. Bottom sediments serve as habitat for shellfish, including quahogs (*Mercenaria mercenaria*), soft-shell clams (*Mya arenaria*), oysters (*Crassostrea virginica*) and blue mussels (*Mytilus edulis*). Resident and migratory species of finfish are found in the bay. A study by the Rhode Island Department of Environmental Management (RIDEM) identified 41 species of juvenile and adult fish in Greenwich Bay [17], and the bay's protected coves serve as spawning areas for several species of finfish [7]. The bay's wetlands also provide valuable ecosystem services. Tidal and freshwater wetlands provide habitat for fish and other wildlife. Wetlands act as gigantic filters, removing sediments, chemical pollutants, and nutrients, thus helping to improve water quality. Coastal wetlands help protect the shoreline from erosion during storms, and preserve areas of scenic beauty. Greenwich Bay provides habitat for migrating birds, wintering waterfowl, and permanent nesting bird species. Sandy beaches along the bay are used as nesting places by coastal birds, as haul-out places for harbor seals, and as spawning sites for horseshoe crabs. The variety of natural habitats that exist in a healthy Greenwich Bay provides support for the many valued native species that depend on these habitats and also provides support for the recreational and commercial activities of the people in the watershed.

Events in the past two decades have brought attention to the declining condition of Greenwich Bay waters and the resulting threats to the watershed's historic and economic heritage. In 1993, the bay was closed to shellfishing because of bacterial pollution—it is now open conditionally—and in August 2003, a massive fish kill occurred due to low dissolved oxygen levels. It should be noted, however, that degradation of the bay and its watershed has not just been caused by recent human activities, but is the result of the cumulative effects of human activities that have occurred over the past one hundred and fifty years.

Much has been written about the cultural history of the Greenwich Bay watershed, and many scientific studies have been conducted in Greenwich Bay. The narrative that follows is a summary of the cultural history of the Greenwich Bay watershed and the ecological effects that history had on the bay and watershed. To organize and present this information, we divided the cultural history into five time periods (Pre-Colonial, Colonial, Maritime, Industrial, and Suburbanization) that corresponded to the human activities in the watershed, and then determined the ecological effects of the activities within each period. The dates of these periods are approximate, and many activities overlap two or more periods.

Research Methods

For the cultural history of the watershed, we found written histories of Warwick and East Greenwich in town libraries and online. We searched for historical maps of Warwick and East Greenwich in libraries, town halls, and online. Population statistics were taken from the U.S. Census reports. Historical photographs were obtained from historical societies and private collections. We used a geographic information system (GIS) to compare coastlines and wetlands from historical maps to present-day maps. Locations of former industries were determined from written histories and from the Sanborn Fire Insurance Maps (1884 to 1941). Ecological information about Greenwich Bay was found in historical state and federal reports, scientific publications, and the Greenwich Bay Special Area Management Plan [7].

We used GIS to create the maps contained in this report. GIS and Rhode Island Geographic Information System (RIGIS) data layers were used to calculate various features: area of bay and watershed, portion of towns in the watershed, land use, population of the watershed, length of hardened shoreline, and area of impervious surface. To evaluate the growth of marinas, we used GIS to measure the length of docks in historical aerial photographs of Greenwich Bay (RIGIS historical aerial photographs, 1939 to 2003).

Pre-Colonial Period – before 1650

Native Americans

Native Americans occupied the area surrounding Greenwich Bay for thousands of years before Europeans arrived. During the period between 8000 and 3000 years ago, there was an increase in native people in the Rhode Island area [18]. The earliest people were migratory hunters, living in small bands and following herds of animals [18]. Evidence from archeological sites around Narragansett Bay has shown that natives settled in villages along the coastline, especially at protected sites like Greenwich Cove, from around 3000 to 500 years ago. These native peoples hunted game and gathered shellfish and wild plants. Stone materials not native to Rhode Island found at some archeological sites indicate that early people in Rhode Island had contact with other communities in New England [18]. In the period just prior to European settlement, four Native American groups, the Shawomets, Cowesetts, Potowomuts and Pawtuxets, all under the domination of the Narragansett tribe, occupied the land around Greenwich Bay [15].

The archeological sites that have been excavated around Narragansett Bay and Greenwich Bay give some idea of the resources utilized by the native people. The Sweet Meadow Brook site near Apponaug had been occupied for about 1600 years starting about 100 BC [15]. Excavation of the site in the late 1950s yielded remains of shellfish and deer, stone tools, and bowls made of soapstone, which probably came from quarries in Cranston [15]. At a site on the southern shore of Greenwich Cove, evidence of shellfish (oyster) use first appeared around 2700 BP, and on Potowomut Neck shells were dated to about 2300 BP [19]. Some archeologists believe that the intensive harvesting of shellfish started after the coast stabilized and marshes and mud flats developed, which would have been after about 4000 to 5000 BP in New England [19, 20].

Analysis of the artifacts at the Greenwich Cove archeological site showed that as time progressed more resources were utilized by the native people [19]. Over the time period represented by this site (about 2700 to 400 BP), seven species of shellfish were found in the midden; four of these—quahog, soft-shell clam, oyster, and bay scallop—accounted for 99.5% (by weight) of the shells recovered, while ribbed mussel, channeled whelk and slipper shell comprised the rest. The pattern of shellfish utilization changed over the time period this site was occupied. Initially, around 2700 BP, oyster shells predominated (60% of total number of shells), but oyster abundance dropped to 16% by 2000 BP and stayed at about that level for the next 1500 years. When oyster abundance declined, soft-shell clam increased from 24% to between 60 and 70% of the total number of shells, while quahog remained at about 20% or less. The author of this study, David Bernstein, proposed that a likely explanation of the shift in abundance from oyster to soft-shell clams was sedimentation in Greenwich Cove, which probably started when the rate of sea-level rise slowed in the third millennium BP [19]. Oysters need a hard substrate, whereas clams and quahogs inhabit soft bottoms. Based on estimates of the weight of meat (an indication of nutritional value), Bernstein concluded that oyster was the most important shellfish from 2700 to 2000 BP, but oyster, quahog, and soft-shell clams were about of equal nutritional importance after about 2000 BP. The size of shells found in the midden decreased in the last period before

European contact (1000 to 400 BP); Bernstein suggested that the smaller size shellfish could have resulted from human harvesting pressure or from some environmental change [19].

Other animal remains found in the Greenwich Cove midden were: three reptile species, four fish species, five bird species, and thirteen mammal species (Table 1) [19]. The bones of birds and fish are smaller and more delicate than those of mammals and are not preserved as well; this probably accounted for fewer reported numbers of these species. Based on estimates of available meat, calculated from the number of bones found in the midden, Bernstein concluded that white-tailed deer was a major food source [19]. As with the shellfish, an increase in the number of animal species was found as time progressed, an indication that the native people were utilizing an increased number of food resources.

Plant material deteriorates more rapidly than shells and bones; remnants of only two plant species, hickory nuts and acorns, were found at the Greenwich Cove site [19]. However, fifteen species of potentially edible plants gathered from the wild have been found at seven other archeological sites on the western side of Narragansett Bay. Based on analysis of the plants found at these other sites, Bernstein concluded that hickory nuts were the most important plant food. Pollen grains of domesticated plants such as corn were not found during the prehistoric period at the Narragansett Bay sites, although they were found after European arrival [19, 21]. Bernstein and several other archeologists [22, 23] concluded that agriculture in the Greenwich Bay watershed was probably an activity that developed after European contact. This archeological evidence does not agree with written historical accounts by the first European visitors of natives growing corn and beans. However, archeological evidence from other Rhode Island sites supports this conclusion; a small number of corn kernels and bean seeds have been found at only two sites in Rhode Island (in Cranston and on Point Judith Pond in Narragansett) [18]. Archeologists speculate that the resources of the woodlands and bay provided enough food and other necessities without having to expend the labor to grow food [18].

Some historians have described the movements of native people in southern New England as

Table 1. List of species found at the Greenwich Cove archeology site, from Bernstein [19].

Shellfish	Fish
Quahog—*Mercenaria mercenaria*	Weakfish—*Cynoscion regalis*
Soft-shell clam—*Mya arenaria*	Tautog—*Tautoga onitis*
Oyster—*Crassostrea virginica*	Sea robin—*Prionotus sp.*
Bay scallop—*Aequipecten irradians*	Sand shark—*Carcharias littoralis*
Channeled whelk—*Busycon canaliculatum*	**Mammals**
Slipper shell—*Crepidula fornicata*	White-tailed deer—*Odocoileus virginianus*
Ribbed mussel—*Modiolus demissus*	Eastern chipmunk—*Tamias stratus*
Reptiles	Eastern grey squirrel—*Sciurus carolinensis*
Snake—*Natricinae cf. Thamnophis sp.*	Beaver—*Castor canadensis*
Turtles, pond, marsh and box (Emydidae)	Rabbit—*Sylvilagus sp.*
Stinkpot turtle—*Sternotherus odoratus*	Raccoon—*Procyon lotor*
Birds	Black bear—*Ursus americanus*
Turkey—*Meleagris gallopavo*	Marten—*Martes americana*
Thick-billed murre—*Uria lomvia*	River otter—*Lutra canadensis*
Razorbill—*Alca torda torda*	Striped skunk—*Mephitis mephitis nigra*
Hawk—*Accipiter sp.*	Canid—*Canis sp.*
Sandhill crane—*Grus canadensis*	Red fox—*Vulpes vulpes fulva*
	Gray fox—*Urocyon cinereoargentus*

living along the coast in the warmer months to fish and collect shellfish, then moving inland in winter to hunt. Analysis of quahog shells and deer teeth can reveal generally what season the animal died and therefore, when a site was occupied. Analysis of the quahog shells and deer teeth indicated that the sites at Greenwich Cove and Lambert Farm, in the Cowesett section of Warwick, were probably occupied for most or all of the year [19, 24], while a nearby site on Potowomut Neck was occupied only from summer to late fall [25, 26]. Data from other Narragansett Bay and southern New England sites also suggested that movement of the native peoples from coast to inland could have been overestimated; they probably made limited moves from one coastal site to another to take advantage of the resources available [19]. Another important resource near the site at the head of Greenwich Cove was a freshwater spring. This spring, located along the Pequot Trail near present-day Post and Forge Roads, was an excellent source of fresh water for the Native Americans and later the colonists. In Colonial times, Roger Williams named the spring, Elizabeth Spring, in honor of Elizabeth Read, second wife of Rhode Island Governor John Winthrop [27] .

Europeans Visit

Giovanni Verrazzano was the first European known to have visited Narragansett Bay. In 1524, he spent fifteen days exploring the area. Verrazzano found the land "as pleasant as I can possibly describe" [28]. He wrote that the shores of the bay were bordered by open fields and wooded areas clear of brush [18, 28]. Verrazzano listed some of the trees, fruit, and animals he and his crew saw: "oaks, cypresses, and others unknown in our Europe"; "Lucullian apples (cherries), plums and filberts, and many kinds of fruit different from ours"; "stags, deer, and lynx and other species" [28]. He wrote that the natives lived in villages, in circular houses crafted from bent saplings and covered by woven straw mats [18, 28].

The pollen record at the Greenwich Cove archeological site indicates that substantial land clearing occurred before European contact; there was a shift in percentages of tree pollen to grass and shrub pollen indicative of land clearing, and also a lack of non-native species [19, 21]. Verrazzano's description, along with the archeological pollen record showing a lack of domesticated plants, suggests that land clearing was done for hunting rather than for agricultural purposes. Cleared land would have increased the carrying capacity of the land for white-tailed deer and some other species that the native people were utilizing as food [19, 29]. There is evidence that the Native Americans managed the landscape by burning underbrush to make the woods passable; however, David Foster and his co-authors [30] have concluded that burning was most likely to have occurred much less frequently than annually (William Wood, 1634) or "every spring and fall" (Thomas Morton, 1632) that has been written about and often cited by other authors. Surface fires, even if not frequent, can affect forest structure, composition, and ecosystem function [30]. Fire kills the undergrowth and small trees, damages less fire-resistant species, and results in an open understory and an increase of fire-resistant trees such as oaks, hickories, and birches.

From the time of Verrazzano's visit to Narragansett Bay in 1524 to the early 1600s, there was no real attempt to establish any settlements, but European explorers and traders made contacts in New England. These traders brought diseases that were deadly to the Native Americans; between 1616 and 1619, epidemics killed many natives, destroying villages and altering the social structure between the tribes [18]. However, the Narragansetts, who occupied the area west of Narragansett Bay, did not suffer from these epidemics and that left them in a position of power. In the early 1600s, the Narragansett Tribe might have had as many as 40,000 people [18].

In the early 1600s the Dutch had established trade with the Native American tribes along the southern coasts of Connecticut, Rhode Island, and Massachusetts [31]. In exchange for furs, primarily beaver, the Dutch supplied the natives with blankets, cloth, kettles, knives, axes, guns, and trinkets. By 1630 the center of the fur trade had shifted to trading posts on land [31]. In 1639, a trading post was established by Richard Smith on the Pequot Trail (present-day Post

Road) at Wickford, south of Greenwich Bay [31]. In 1642 and 1643, two more trading posts were established nearby (by Roger Williams and John Wilcox) [31]. The Narragansetts were deeply involved in the fur trade. Goods to barter and European coins were in short supply so the Narragansetts provided wampum—shell beads, white made from periwinkle, purple made from quahog—to use as currency [32]. Before trading with Europeans the Narragansetts had made wampum in small quantities to use with other natives for special exchanges (long distance trade, ransom, tribute, or to settle a feud) [18]. One local historian speculates that Nausauket, the northern shore of Greenwich Bay between Apponaug and Brush Neck Coves, was a location where wampum was made because of the large deposits of shell dust found there [32].

Beaver pelts were highly desirable in Europe, and large numbers of pelts were acquired in trade. For example, between 1623 and 1633, 10,000 beaver skins annually were obtained from the Connecticut River fur trade [31]. Beavers are not migratory, so the beaver populations along the coast were quickly exploited. By 1660, fur trade along the western shore of Narragansett Bay had declined [31].

Beavers and their removal due to the fur trade had an effect on the ecology of New England and probably on the Greenwich Bay watershed. Before European settlement, beavers occupied all of Canada and most of the continental United States [33]. Almost every stream in New York and probably New England had beavers [34]. The numerous beaver dams created ponds and wetlands, which resulted in a landscape that was much wetter than it is today [33]. Beaver dams retain sediment and decrease stream flow. Beavers also change the vegetation [33]. As deciduous trees are cut by beavers along streams, the riparian zone initially becomes more open, with shrubs the dominant vegetation. Then species of trees not used by beavers, for example spruce and fir, grow and become the dominant stream-side vegetation. When beavers abandon a pond, sediment continues to collect behind the dam and a beaver meadow is formed. Eventually a new stream bed cuts through the meadow and drains the area [33]. When large numbers of beavers were removed, the land became much drier, and water flow in streams and rivers increased, causing more sediment to wash downstream. Although the Greenwich Bay watershed is small and has limited rivers and streams (Fig. 1), beaver bones found at the archeological site at Greenwich Cove are evidence that beavers were present. The loss of beavers in the early 1600s probably increased the amount of sediment washed into the coves of Greenwich Bay.

Summary of Pre-Colonial Period

In the Pre-Colonial Period (before 1650), the native people utilized the abundant natural resources available in Greenwich Bay and its watershed. During the late prehistoric period (after 3000 BP), the native inhabitants of the watershed continued “to expand and diversify the available resource base” [19]. They used the traditional foods—deer, shellfish, and nuts—throughout this time period but continued to add new resources to their diet. Trees were used for fuel, for building shelters, and for making canoes. Deer skins were used for clothing and shelters. Springs supplied clean water. Marsh grasses were used to make baskets and mats, clay deposits to make ceramic pots, and shell, bone, and stone to make a wide variety of tools [18]. For the most part Native Americans settled year-round on the coast to take advantage of the marine resources and cleared the forest of underbrush to improve hunting of deer and small animals. Burning of underbrush could have affected the forest composition and structure, but the forests were still an impressive resource when the colonists arrived [35]. Archeologists working in the area of Narragansett Bay postulate that land management and the utilization of increased number of species occurred because of an increase in the population just before European contact. In the last period before European contact (1000 to 400 BP), the decrease in shell size at the Greenwich Cove archeological site indicates that the local populations of shellfish could have been affected by human harvesting. Loss of beavers (due to the fur trade), and consequently beaver dams, might have caused an increase in the amount of sediment entering the bay. However, the ecological effect of prehistoric peoples and Native Americans on Greenwich Bay were minimal compared to what was to come.

Colonial Period – c. 1650 to c. 1750

First Settlers

The first European settlement on Narragansett Bay was established at Providence in 1636 by Roger Williams, who came from the Bay Colony (Massachusetts). Two years later Aquidneck Island was purchased from the Native Americans and a settlement established. The third settlement in Rhode Island, the first in the Greenwich Bay watershed, was Warwick. In January 1643, Samuel Gorton bought about 90 sq. miles of land, the Shawomet Purchase, which included most of present-day Warwick, West Warwick, and Coventry, from the Indian sachems Miantonomi and Pomham [15]. The initial settlement at Mill Creek was short-lived, but Gorton returned and settled near the head of Warwick Cove in 1647; the town was chartered as one of the four towns in Providence Plantations in 1648 [15]. In 1654, Warwick purchased the rest of Potowomut Neck from Taccomanan, the local sachem [15]. Potowomut was divided into shares but none of the owners moved there initially because it was a favorite hunting ground for the Native Americans. However, the colonists harvested hay from the meadows on Potowomut Neck and shipped it across the bay to Old Warwick, at the head of Warwick Cove [15].

Conflicts with the Native Americans kept the first settlements in the Greenwich Bay watershed small. Between 1647 and 1676, settlement in Warwick was confined to a small village at the head of Warwick Cove and the "four mile common"—the area from the village to present-day Apponaug [15]. It was not until after King Philip's War (1675-76), when many Native Americans were killed and the tribes' power destroyed, that colonial settlement around Greenwich Bay increased. The town of Greenwich, which included present-day East and West Greenwich, was incorporated in 1677. Cowesett Farms, on the western end of Greenwich Bay, was divided into parcels in 1684. Settlers moved to Potowomut Neck starting in 1684 [15].

Subsistence Farmers

The early settlers in the watershed were subsistence farmers. They cleared land to raise livestock (cattle, sheep, and hogs) and to grow food crops like corn, beans and squash. They left some land for woodlots and planted some land as orchards for apple cider. Farming practices resulted in an open landscape of pastures, hay fields, wetland meadows, tilled land, stone walls, and scattered but intensively cut wooded areas [36]. The early dirt roads were often muddy and impassable so transport by water (larger rivers or the bay) was common. A source of clean fresh water was important to the early settlers; most homesteads were built near a running stream or spring, and a steadily running stream was valuable as a source of power for grist and saw mills [37]. Small villages built up around these mills.

In 1696 John Micarter built a fulling mill at Apponaug and a village was established there. Fulling, the process of scouring woven woolen cloth to make it stronger, requires "fuller's earth" or clay, which separates oil and grease from sheep's wool, and a good supply of clean water. Apponaug was the site of both: soil in the area contained fuller's earth, and Gorton Pond and Apponaug Brook supplied plenty of clean water [38]. The early fulling mills consisted of a wheel with pestles and stampers on it. Cloth was placed in a trough with fuller's earth, beaten with the pestles, and then rinsed clean. The proprietors of Warwick gave John Micarter permission to dig "a trench at the entrance of Kekamewit [Apponaug] brooke [sic] to raise it sufficiently" and "to raise Cowesett [Gorton] pond two feet if the occasion be for it" [32].

Population

It is difficult to assess the exact human population of the watershed because population records are kept by town, not by watershed. Before 1740, the population of the towns was small and the land area large. From 1708 to 1730 the population of Warwick (which included present-day Warwick, West Warwick, and Coventry) increased by about two and a half times, from 480 to 1,178, and the population of Greenwich (which included present-day East and West Greenwich) increased about five times, from 240 to 1,223 [39]. Prior to 1740, before West Greenwich split off from East Greenwich (1740) and Coventry split off from Warwick (1741), only a small percentage of land from each town was in the watershed, 3.3% for Greenwich and 18.3% for Warwick. Thus, assuming a fairly even distribution of people within each town, the population of the watershed during the Colonial Period was small.

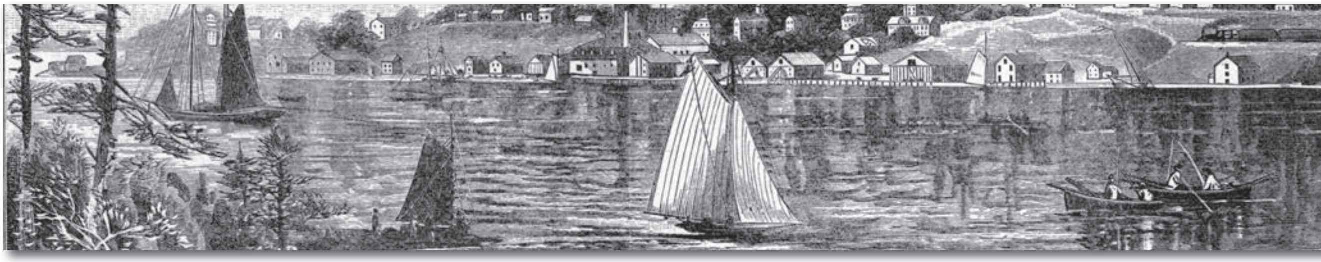
Fishing Resources

Just as the Native Americans relied on fish and shellfish, so did the colonists. The importance of fishing was reflected in colonial documents. The 1663 charter granted by King Charles II of England, incorporating the colony of Rhode Island and Providence Plantations, included a public right to harvest fish and shellfish [40, 41]. In 1719, "the Warwick assembly empowered the town council to protect and improve fishing in their rivers, forbidding the setting of weirs, dams or nets" that would impede the migration of fish up the rivers [40]. In 1731, the Rhode Island colony passed an act to encourage the cod and whale fisheries by offering a bounty of 5 shillings a quintal (hundredweight or 100 lb) for codfish, 5 shillings for a barrel of whale oil, and one penny a pound for whale bone [40]. In East Greenwich two laws were passed to protect oysters [40]. Colonists were harvesting oysters in large quantities for just the shells, which were burned to produce lime for making masonry mortar. The Colonial Assembly thought this was wasteful, and in 1734, an act was passed to prevent the harvesting of oysters strictly for the shells. By 1766, it was recognized that oyster beds were being over fished, and an act forbidding the taking of oysters by drags or any other way except tongs was passed [40]. No data on oysters in Greenwich Bay exist so it is not known how abundant they were during the Colonial Period. Quahogs were valued by the colonists for their meat and shells, which were used as scrapers, paint-holders, and spoons [40].

Summary of the Colonial Period

During colonial settlement (c. 1650 to c. 1750), land clearing most likely would have caused ecological effects on the bay and its watershed. Land clearing can change the stability and filtering capacity of soil and can cause increased erosion, resulting in increased input of sediment and nutrients into adjacent water bodies. Alterations in the hydrology can also influence vegetation on land. There are no measurements of the amount of land cleared in the watershed, but estimates of forest area have been made for the whole state. About 90-95% of Rhode Island was forested in the early 1600s before colonial settlement [42]. According to one estimate, Rhode Island had about 78% of its area as forest in 1700, about 57% in 1790, about 54% in 1820, and a minimum of about 34% in 1850 [42]. Other researchers estimated that about one third of forested land in the state was cleared by 1700, about 65% by the late 1700s, and about 75% by the mid 1800s [43]. In a study of sedimentation rates in upper Chesapeake Bay, the highest sedimentation rates coincided with major storms and with intensive land clearing when more than 20% of the watershed was deforested and cultivated [44]. Although we don't have data for the watershed, it is very likely that by 1700 more than 20% of the Greenwich Bay watershed was cleared, and thus sedimentation rates would have increased. Although there is no specific mention of a dam on Apponaug Brook, John Micarter had permission to alter the stream, and it is likely that a dam was built at the site of his fulling mill in Apponaug. This would have been the first dam in the watershed. These early dams were usually low and not permanent, thus the effect on streams and fish would have been transient.

Maritime Period – c. 1730 to c. 1820



Although agriculture continued to sustain the population of the watershed, a number of factors influenced the growth of maritime activities. In the 1690s, the Rhode Island colony granted commissions to privateers, who were allowed to keep nine-tenths of the spoils obtained from attacking French and Spanish ships; young men from the farms were attracted to this seafaring life. In the mid 1700s, the population along the coast was reaching its natural limits for agriculture as good land for farming became scarce [45]. The agricultural economy had fostered other trades: tanners, coopers, weavers, blacksmiths, and shipbuilders [46]. As farming became more successful there was a need to transport the excess farm goods. Small sloops were used along the coast to move goods to and from larger ports. Coastal trade was centered in the smaller ports like East Greenwich and Apponaug, while larger ports like Newport, Providence and Bristol were involved in overseas trade. By 1790, the state of Rhode Island had successful shipbuilding, rope making, rum distilling, and iron industries, which all had grown to support the maritime economy [45].

Maritime Activities in Apponaug Village

Although Greenwich Bay didn't have a large port, Apponaug and East Greenwich were the sites of shipbuilding and participated in local coastal trade. In the late 1700s and early 1800s, sloops and schooners were built in Apponaug [32]. Jacob Greene & Company, a store and shipping center located on Apponaug Cove, imported coal and black sand, which was used in making anchors in the family's forges in Coventry and on Potowomut Neck, and shipped the finished anchors. In the late 1800s, a local historian wrote that "Apponaug Cove in early times, was several feet deeper than at present, sloops of fifteen tons burden found no difficulty entering it, and approaching the store of Jacob Green & Co." [32]. A study conducted in the 1980s documented the filling in of upper Apponaug Cove; the researchers found that the upper cove was a depositional area where silty sand had been deposited over a long period of time from before colonization until the cove was developed [47]. The surface sediments in the cove contained coal, coal ash, and clumps of pigment that had been deposited since industrialization of the area [47]. In the upper cove a layer of red-brown organic matter 2 to 4 inches thick occurred at a depth of 10 to 12 inches in the sediment. This layer was probably sawdust and contained higher levels of metals and lead than the surface layer. The researchers reported that this layer was deposited in the early to mid 1800s. The shipbuilding and a saw mill located in Apponaug were likely sources of the sawdust and metals [47].

Other commercial ventures located in Apponaug included a saw mill, a blacksmith shop, and a grist mill. In 1796, a tide mill, for grinding corn and other grains, was built near the bridge on Post Road near the head of the cove. The Rhode Island General Assembly gave permission to build the mill "provided that the mill dam be made and erected with suitable waste-gates for venting superfluous water, and in such a manner as not to back the water or otherwise injure the mills" upstream [32]. The grist mill owner also had to "leave open at all proper times, a suitable passage, not less than sixteen feet wide, in the small dam, for the passage of rafts and boats up and down said river" [32].

Maritime Activities in East Greenwich

The village in East Greenwich was also the site of shipbuilding, shipping, and maritime related activities. When the town was platted, two pieces of land on the waterfront were set aside for shipyards [48]. In 1725, one piece at the foot of Queen Street was given to a ship carpenter provided he would "improve said land in building of ships" [49]. From 1773 to 1821 eighteen sailing ships were built in East Greenwich [50]. In 1765 a ropewalk, which produced rope for maritime activities, was located on Rope Walk Hill in the area of Castle Street overlooking Greenwich Cove. One historian wrote that the ropewalk was an important business when East Greenwich was a prosperous commercial port and that "the air around [the ropewalk] was filled with the agreeable odor of tar, with which the ropes were saturated to protect them from salt water" [51]. For a short time, 1809 to 1812, there was a whale oil works at the foot of Division Street [51].

Wharfs were built along the coastline in East Greenwich to accommodate shipping activities and to stabilize the shoreline. Before 1790, the lower end of King Street had been an open dock and the tide flowed up as far as the present railroad bridge [51]. Vast quantities of sand were being washed down King Street. To retard the filling in of the cove with this sand, the Town Council "ordered a wharf 100 feet long and 40 feet wide built there" [52]. Figure 2 shows the wharf at the foot of King Street on an 1836 map, the earliest accurate map of the coastline. Wharfs were also present along the coast north of King Street to Division Street as indicated by the artificially straight lines on the map. Fish, farm, and timber products were shipped from the wharfs in East Greenwich. In the late 1700s, Division Street was rebuilt as a major road extending inland so farmers could more easily bring products to the harbor [52].

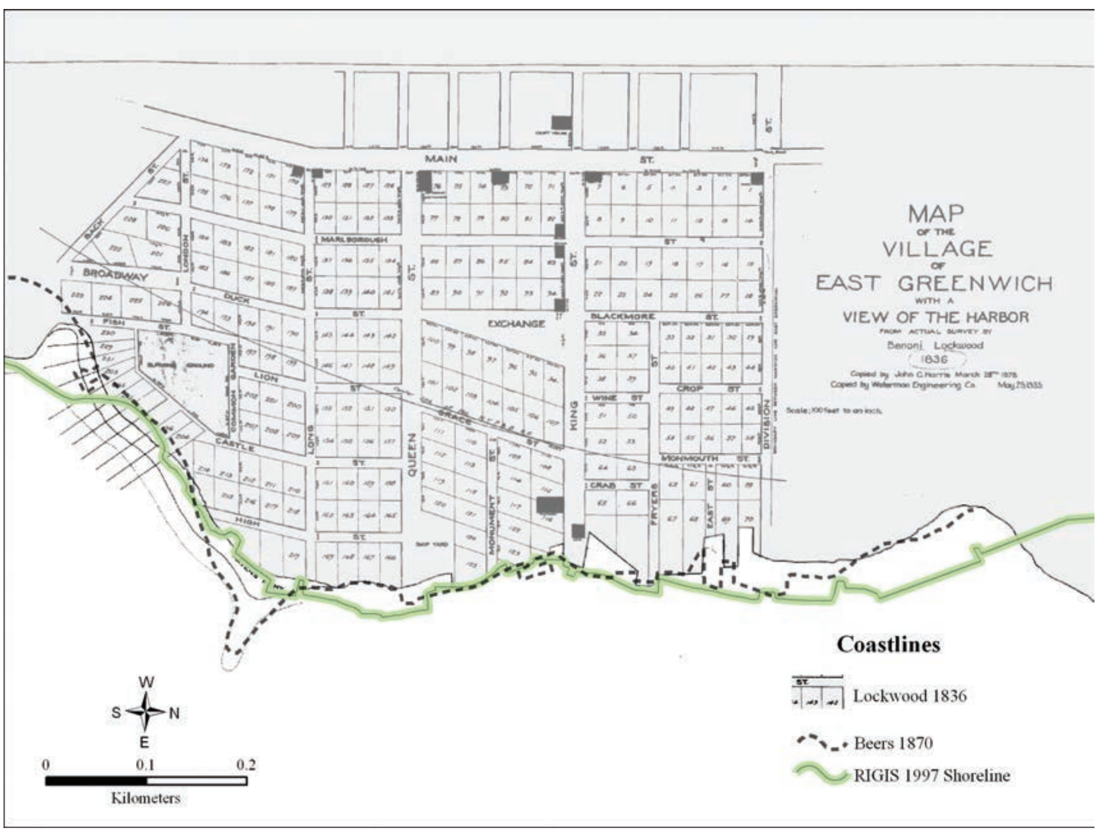


Figure 2. Greenwich Cove shoreline at East Greenwich for three dates. The map of the village was made by Benoni Lockwood in 1836 [149]. The 1870 coastline is from the Atlas of the State of Rhode Island and Providence Plantations by D.G. Beers [63]. The 1997 coastline is from RIGIS, 1:5000 town boundaries.

The American Revolution (1775–1783) interrupted maritime trade, but merchants took advantage of the opportunity by providing goods needed during the war. Since British ships were patrolling Narragansett Bay, overland transport of goods became important, and the villages in Apponaug and East Greenwich prospered because of their location on Post Road [53]. The maritime economy recovered quickly after the Revolution, but was slowed again during the Embargo of 1807 and the War of 1812.

Population

From 1748 to 1820 the population of the town of Warwick increased by about 100% (from 1,782 to 3,643) and East Greenwich by about 45% (from 1,044 to 1,519). Since population numbers are kept by town, we estimated the population of the watershed using the "proportion of road length" method, which is based on a study that showed higher population density is related to road density or length [54]. From 1748 to 1820 the estimated population of the total watershed increased about 88% (from 1,013 to 1,907). Although both Warwick and East Greenwich were adjacent to Greenwich Bay, the towns grew at different rates and acquired their own unique characteristics. Warwick's diverse geography—beaches along Greenwich and Narragansett Bay, and waterfalls on the Pawtuxet River—resulted in the establishment of a number of villages with no real town center [15]; whereas the village on Greenwich Cove became the town center for East Greenwich.

Fisheries

Few data are available about the state of fisheries in Greenwich Bay in the eighteenth century; however, a personal description of Apponaug Cove at about 1800 exists. In a letter dated 1846, but written about his childhood, Oliver C. Wilber described Apponaug Cove: "Its bridge [at Post Road] with the tide constantly ebbing and flowing under it, the nettles, silk weed, eel grass, the mud flats, the narrow crooked channels of the cove, the clams, quahogs, scallops, mussels, winkles, razors, snails, five-fingers, fiddler crabs, large crabs, horse feet, road fish, grunters, sharks, dogfish, bass, menhaden, squiteague, tautog, scup, skipjacks, flatfish, flounders, eels, mummachogs [sic] that abounded in its waters" [47]. Historian D. H. Greene wrote in 1877, that one hundred years ago (1770s) oysters were so abundant in Greenwich Bay that "the inhabitants were in the habit of laying in an [sic] hundred bushels each for winter consumption" [51].

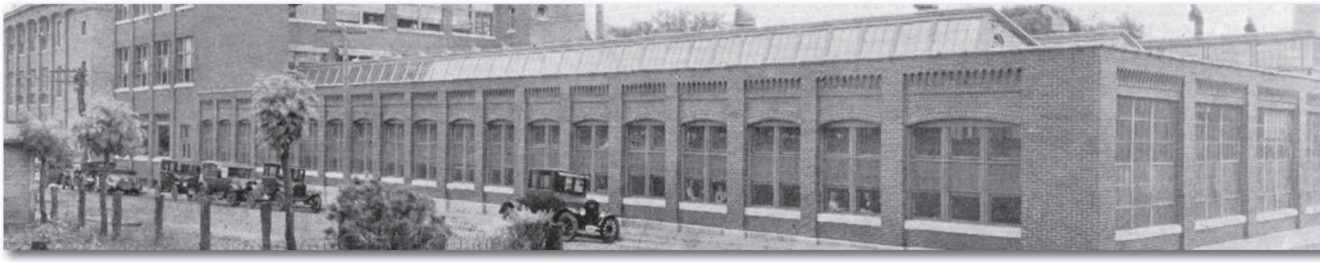
Summary of the Maritime Period

During the Maritime Period (c. 1730 to c. 1820) more land was cleared to accommodate the growing population, and there were some changes in the shoreline. We don't have specific data for the watershed, but in 1700 about 78% of the land in Rhode Island was forested, and by 1820 only 54% was forested [42]. As mentioned above, evidence of sedimentation in Apponaug Cove was noted by a historian [32] and confirmed by a scientific study [47]. By 1836 the East Greenwich shoreline was filled in places and hardened by wharfs. More changes in the shoreline occurred later, as shown in Figure 2.

"The excellence and safety of the harbor was a strong inducement for men of energy and business habits to settle on its shores."

D. H. Greene

Industrial Period – c. 1800 to c. 1945



The Industrial Revolution started in Britain in the late eighteenth century when major changes in agriculture, manufacturing, transportation, mining, and technology had profound effects on economic, social and cultural conditions. The Industrial Revolution spread to Rhode Island in 1790 with the opening of Slater Mill in Pawtucket, the first cotton mill run by water power in the country. Topography and climate in Rhode Island were ideal for textile manufacturing [45]. Many narrow streams were amenable to dam construction for water power, and the fairly even seasonal distribution of rain provided water for power year-round. The soft water was good for washing and bleaching cloth, and dyes took easily. Also, the relatively high humidity kept the fibers supple for spinning without breaking [45]. The textile industry was dominant in Rhode Island's economy from 1800 to the mid-1900s [46]. Base and precious metal industries, which were located primarily in Providence, were also important to the state's economy [46]. Many of these industries produced machinery for the textile mills. The capital and business skills accumulated during the Maritime Period put Rhode Island merchants in a good position to finance the emerging textile industry [46].

Industries in the Watershed

In Warwick a number of textile mills were built in the 1790s and early 1800s. Most of the mills were built along the Pawtuxet River, outside the Greenwich Bay watershed. Within the watershed, a cotton mill was located in Apponaug in 1809 at the site of the former fulling mill (Fig. 3). Over the years this textile mill expanded, changed ownership, and was known most recently as the Apponaug Company. Between 1920 and 1928, Apponaug Company replaced almost all the old mill buildings, in spite of difficult economic times. The New England textile industry was not doing well; however, Apponaug Company was expanding because it had "specialized in developing innovative dyeing, printing, and finishing techniques" [15]. Skilled color chemists and a good supply of clear water from Gorton Pond enabled the Apponaug Company to enlarge its business [53]. It was a leader in producing synthetic and synthetic-natural blend fabrics and was the first company in the U.S. to produce wash and wear no-iron fabric [15]. Despite these successes,

Apponaug Company, 1917. The mill at Apponaug operated under various names: Manchester Manufacturing Company, 1809 to 1850s; Oriental Print Works, 1859 to 1883; Apponaug Print Works, 1896 to 1913; and Apponaug Company, 1913 to 1958. These old buildings were replaced in the 1920s as the mill expanded under the direction of Alfred J. Lustig, a skilled chemist and president of the company. With new innovations in dyeing, finishing, and fabric blends, Apponaug Company became a leader in the textile industry. (Warwick Historical Society)

Apponaug Company closed in 1958, and a fire in 1969 destroyed most of the buildings [38].

Several textile mills and textile-related companies were located in East Greenwich within the Greenwich Bay watershed (Table 2, Fig. 3). The largest and longest operating textile company in East Greenwich was the Greene Dale Bleachery, which opened in 1840 on the Maskerchugg River near the head of Greenwich Cove [55]. Generations of residents, many of them skilled immigrants, worked at the Bleachery [50]. This textile finishing plant operated under various names until it was closed in 1960. At one time there were 14 buildings [55], but today the only reminder of this once large mill complex is Bleachery Pond.

Other early industries in East Greenwich included metalworking companies, coal and lumber yards, and shipyards (Table 2, Fig. 3). The 1891 Sanborn Fire Insurance Map [56] showed a boat builder on the shore just north of Division Street. Over the years it was called by a number of names—Saunders Boat Yard, F.S. Nock, Inc., Harris & Parsons Inc., Beetle Boat Co., and since 1966, Norton's Shipyard & Marina, one of the larger marinas on Greenwich Bay

Table 2. Early textile and metalworking industries within the Greenwich Bay watershed in East Greenwich and in the section of Warwick just north of the town line.

Name	Location	Start	End Date	Comments	References
Textiles					
Dawson Mill	Main & Division St.	1790	Early 1800s	First cotton print works in the country	[52]
East Greenwich Manufacturing Co. 1	King & Water St.	1828	1920s	First steam powered cotton mill in RI	[46]
Pollard Mill 2	Division & Duane St.	1836	1941	Woolen mill, dye house	[46] [55]
Phoenix Woolen Co. Yarn Mill 3	King & Duke St.	1870	Early 1890s	Dye house, carding and spinning	[62] [56] [63]
Union Mill (later Orion Mill)	Greene, Liberty, Union, & Main St.	1836	1894	Made broad cloth, printed cloth	[55]
Providence Drysalters 4	Greene, Liberty, Union, & Main St.	1894	1939	Made paper coatings, textile chemicals, soap	[55]
Hercules Powder	Greene, Liberty, Union, & Main St.	1939	1946	Division of E.I. DuPont - made dyes used in WWII uniforms	[55]
Farrington Mill 5	Foot of Division St.	1905	c. 1940	Made dextrin for calico printing, cloth finishes, adhesives for shoes	[55]
Green Dale Bleachery 6	Post Rd & Cedar Ave	1840	1960	Textile finishing plant	[55]
Metalworking					
Asa Arnold Machine Shop	Marlborough & Division St.	1845	c. 1870	Made machinery for textile mills, and for making fishing nets	[49] [55]
Ferricup Metal Corp.	Foot of Division St.	1889	1905	Metalworking and plating	[55]
Boston Wire Stitcher 7	Division & Duane St.	1904	1946	Made wire staples	[55]

1 also operated under other names: Shore Mill, Bay Mill, and Elizabeth Mill [55]

2 also operated under other names: Phoenix Mill, Greenwich Worsted Mill, and Greenwich Mills

3 unnamed dye house on 1870 Beers map [63]; Phoenix Woolen Co. Yarn Mill on 1884 and 1891 Sanborn maps [62, 56]

4 Providence Drysalters and then Hercules Powder successively occupied the buildings of Union/Orion Mill

5 Farrington Mill occupied Ferricup Metal Corporation building in 1905

6 during this time also operated under other names: Bolton Manufacturing, Bourne Bleachery, Greenwich Bleachery, and Greenwich Printing and Dyeing Company

7 Boston Wire Stitcher was the precursor of Bostitch. After a short period located elsewhere, Bostitch moved, in 1957, to its present location on Route 2 in East Greenwich.

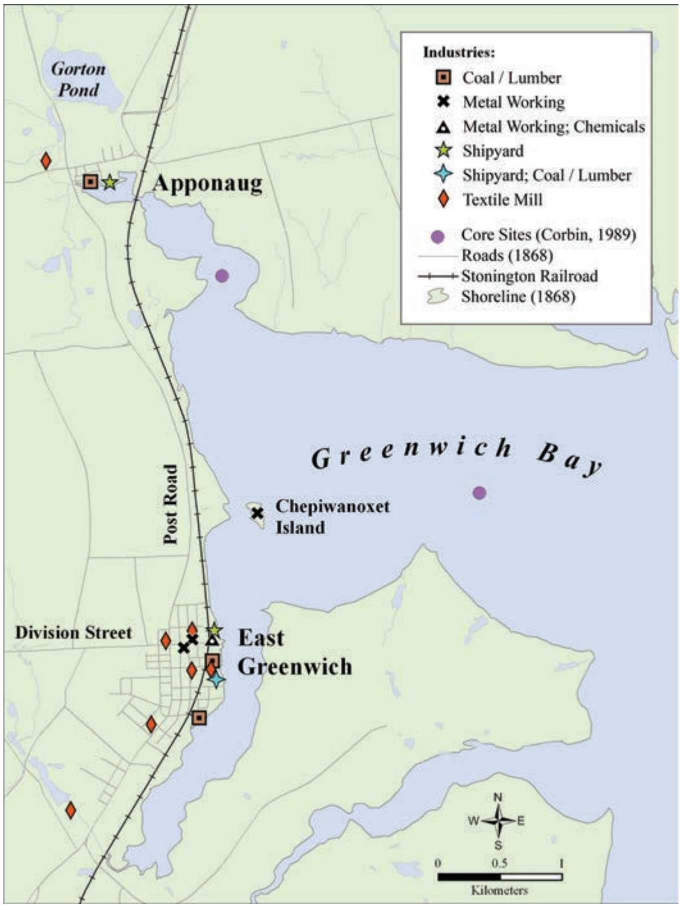


Figure 3. Location of industries in the Greenwich Bay watershed from 1800 to about 1920. Coastline and roads are from two 1868 maps [150, 151]. Core sites mark the location of the 2 sediment cores taken by Corbin [78].

The Bleachery, East Greenwich. Today, no trace of this large mill complex remains. A church, a small office building, and trees now occupy the site at the corner of Post Road and Cedar Avenue. (Bruce MacGunnigle, private collection)

Inside the Green Dale Bleachery. Generations of residents worked here. (East Greenwich Historic Preservation Society)

[57, 58]. From 1900 to 1926, when the shipyard was owned by Mr. Nock, Coast Guard Picket boats were built there [58]. During World War II, the shipyard then known as Harris & Parsons, built eight Sub-Chaser boats for the war effort [58]. In 1909 the East Greenwich Yacht Club was established just south of this shipyard.

Another industry in the Greenwich Bay watershed, the Gallaudet Engineering Company, was established in 1910 to build airplanes. The founder Edson Gallaudet, a contemporary of the Wright Brothers, was experimenting in aerodynamics in the late 1890s. The company was located on Chepiwanoxet Point, formerly an island (Fig. 3). About 1915, fill was dumped into the marsh and a causeway was built that connected the island to the mainland to facilitate access to the factory [59]. In 1917 the company reorganized as Gallaudet Aircraft

Postcard of Gallaudet Aircraft Corporation. This company, which was built on Chepiwanoxet Point in 1915, made sea-planes for the U.S. Navy during World War I. The buildings were lost in the 1938 hurricane. The site is now maintained as an undeveloped park by the city of Warwick.
(Bruce MacGunnigle, private collection)

Corporation and built seaplanes for the U.S. Navy for use in World War I [60, 61]. The company was bought by Consolidated Aircraft in 1923 and moved to Buffalo [61]. Until the 1960s Chepiwanoxet Point was the site of an industrial area and marina [7]. In 1994, Warwick bought the property to protect it from development, and it is now maintained as an undeveloped public park [7].

Population

Industrialization changed the social structure and pattern of development of the watershed. The population in the towns increased greatly during this time as people moved into the area to work in the mills and other industries. Many of the workers were immigrants (Irish, Swedish, French-Canadians, and others) and this influx changed the ethnic makeup of the villages. Until the mid 1800s, the settlers had been mostly of English origin. In East Greenwich, Swedish immigrants settled by Rector and West Streets, an area called “Sweedie Hill,” and Italians occupied houses along Duke, Queen, King, and Marlborough Streets [52]. Apponaug village expanded due to the influx of mill workers, and became Warwick’s civic center when the town hall was moved there in 1835 from Old Warwick, at the head of Warwick Cove. Between 1810 and 1910 the population of Warwick increased about seven-fold (3,757 to 26,629), while East Greenwich’s population increased only about two-fold (1,530 to 3,420) (Fig. 4). At the turn of the century most of Warwick’s industry was located in the western third of the town along the Pawtuxet River, while the eastern portion (in the Greenwich Bay watershed) was primarily agricultural, shore resorts, and the start of some suburban plats [15]. In 1913, the different needs of the citizens in the two sections of Warwick led to a division of the town; the western section split off to form West Warwick. Warwick’s population dropped in the 1920 census after the split, but quickly recovered; by 1950 Warwick’s population was 43,028. East Greenwich was expanding more slowly, and had only 4,923 residents in 1950. Between 1810 and 1950, the estimated population in the watershed increased 13-fold from about 1,900 to 25,500 (Fig. 5).

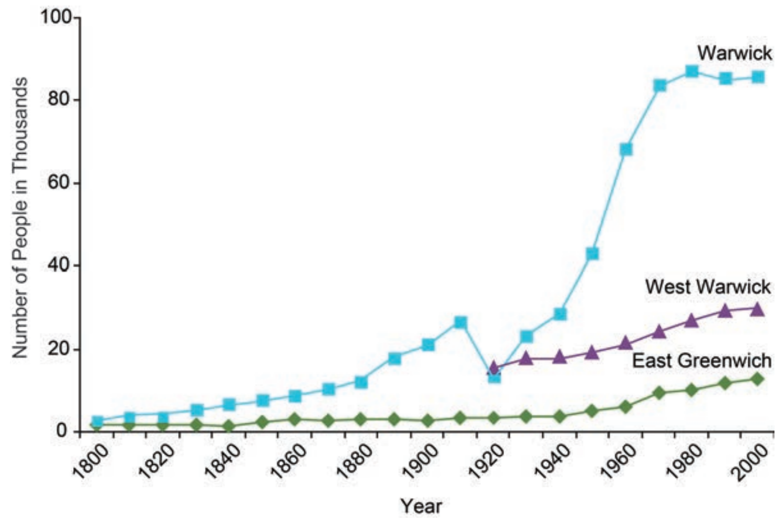


Figure 4. Population of the three towns surrounding Greenwich Bay from 1800 to 2000.

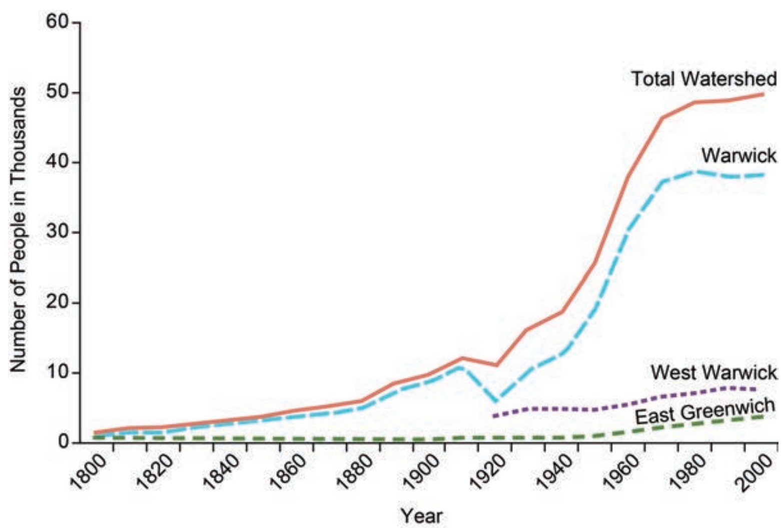


Figure 5. Estimated population of Greenwich Bay watershed and the portions of the towns within the watershed. Population estimates were made based on the proportion of roads within the watershed (see text).

Transportation

Patterns of transportation within the watershed changed during the early 1800s, and that had an effect on businesses and settlement. In 1816, the New London Turnpike (a toll road) was built from Providence to New London, Connecticut. From New London goods and people traveled to New York by boat. The New London Turnpike followed a route through western Rhode Island that bypassed the villages of Apponaug and East Greenwich [52]. In 1837 the Stonington Railroad was completed, connecting Providence to Stonington, Connecticut. The section of the railroad through the watershed ran parallel to Post Road, going through East Greenwich and Apponaug; this brought a focus back to these villages that had been missing when travel had been along the New London Turnpike [52]. Goods and people traveled from Boston to Stonington by rail and then by boat to New York. The railroad eliminated much of the need for marine transport along the coast. In 1893, requests to the U.S. Army Chief of Engineers to dredge Apponaug and Greenwich Coves to permit deeper draft boats into the harbors were refused because there was little commercial need. The coal and cotton destined for the mills on the Pawtuxet River in Warwick were being unloaded in Providence Harbor and transported by rail [64]. However, two years earlier, the Army Engineers had dredged the sand bar off Long Point at the mouth of Greenwich Cove to straighten and widen the channel and make navigation easier [65].

The process of building the railroad had ecological and social consequences for Greenwich Bay and its watershed. Extensive excavations were made through two hills in East Greenwich (Rope Walk Hill and Meeting House Hill) to make a level grade for the railroad tracks [52]. Most likely, sediment was washed down the hill into Greenwich Cove during this excavation. A railroad bridge was constructed across the upper section of Apponaug Cove. Fill was used at the site of the bridge and narrowed the opening across the cove forming an inner and outer section of the cove. The constriction of the bridge accelerated the tidal flow under it,

Railroad bridge crossing King Street, East Greenwich. King Street, which goes down the hill to the waterfront, was the main street in East Greenwich until the time of the Civil War. King Street lies between two hills, Meeting House Hill to the north and Rope Walk Hill to the south. Excavation through these hills for the railroad caused sediment to wash down into the cove. (Bruce MacGunnigle, private collection)

scouring sand from the channel and depositing it in a bar west of the bridge [47]. Pollution from coal-burning locomotives probably led to higher concentrations of lead, zinc, and copper in the soil along the railroad and water at the bridge [66]. The railroad also influenced the social fabric of the both communities because many Irish immigrants were brought in to build it.

Local railroads and trolleys had an effect on the pattern of development in the watershed, and led to the beginning of suburban development in Warwick [15]. As the population of Providence increased with increasing industrialization, there was a need for factory workers to have a place to spend their day off. Warwick became that place. Steam boats had been bringing workers for day trips to Rocky Point (outside the watershed) and to Nausauket (Buttonwoods) on the north shore of Greenwich Bay for picnicking, bathing, clamming, and holding clambakes since the mid 1800s. In 1865 the Union Railroad (using horse-drawn vehicles) was established from Providence to Warwick, making travel easier. The Warwick Railroad, completed in 1874, branched off the Stonington Railroad at Cranston, and ran south on Warwick Neck, across the mouth of Warwick Cove to Oakland Beach. In 1881, it was extended across the mouth of Brush Neck Cove to Buttonwoods. In the early 1900s the railroad was replaced by an electric trolley line.

Aerial photo of Oakland Beach, c. 1920. The Warwick Railroad carried passengers across the trestles at the mouth of Warwick Cove (top right) to Oakland Beach and then across the mouth of Brush Neck Cove (middle left) to Buttonwoods. Passenger service on the trolley ended in 1935, and the 1938 hurricane destroyed the trestles. The 1938 hurricane also destroyed the amusement park and many shorefront buildings. (Warwick Historical Society)

Trolley crossing Warwick Cove. About 1900 the trains to Oakland Beach were replaced by electrified trolleys. The middle section of the trestle over Warwick Cove was a drawbridge that allowed boats to pass. (Warwick Historical Society)

The railroads and trolleys facilitated the development of the shore resorts. The Oakland Beach Hotel was built in the early 1870s and amusement attractions were added, but few summer houses were built until the trolley made travel more convenient [15]. In 1871, the congregation of Providence's Cranston Street Baptist Church bought land at Nausauket to establish a summer colony. They formed the Buttonwoods Beach Association, built the Buttonwoods Hotel, and established a cottage colony modeled after the Methodist campground at Oak Bluffs, Martha's Vineyard [16]. The concept of Buttonwoods was to provide summer recreational and religious activities in a "wholesome, respectable environment," in contrast to the livelier summer playground at Oakland Beach [16]. Around the turn of the century, Buttonwoods Campground was established west of Buttonwoods Beach Association by philanthropist Henry Warner Budlong as a place for working-class city residents to enjoy summer by the shore [16]. Wealthy families built country estates on Warwick Neck [15]. In the early 1900s, Buttonwoods began to transition from a summer colony to a year-round community. This pattern of expansion in the late 1800s and early 1900s was the precursor of the urbanization that boomed after the end of World War II [15].

One area of the watershed that was saved from intense development was Potowomut Neck, which was located south of Greenwich Bay and not conveniently reached by trolley lines. Land on Potowomut had been owned by the members of the Greene family since Colonial times. In the late 1700s ownership passed to the Brown and Ives families, and later to their relatives, the Russell and Goddard families. These wealthy families established estates there. In 1876, the Russell family built their home, The Oaks, on land located in present-day Goddard Memorial State Park. Henry Russell liked trees. He raised evergreen tree seedlings and planted them along the eastern bank of Greenwich Cove, and planted oak and other hardwood trees on the estate [27]. In 1911, Robert H.I. Goddard inherited The Oaks from his cousin, Mrs. Russell. In 1927, Goddard's son and daughter donated The Oaks and surrounding property to the State of Rhode Island to be used as a public recreational park in memory of their father [27]. Today, the tree-lined eastern shoreline of Greenwich Cove is in sharp contrast to the marinas and commercial development on the western (East Greenwich) side. The 489-acre park, which includes a nine-hole golf course, picnic areas, beach, and riding trails, is a popular attraction in the watershed.

Buttonwoods Beach, c. late 1800s. This scene looking west shows Promenade Avenue running along the shore with a grassy area and beach to the left (south) of the then dirt road. The Buttonwoods Hotel (with flag, on right) was located at the head of Beach Park Avenue. Land at Buttonwoods was eroded during the 1938 hurricane. As a result, today, the beach at Buttonwoods is essentially gone, and the shoreline has been hardened. (Picturesque America, 1872)

Infrastructure

The increase in population and industrialization brought a need for infrastructure within the watershed. Until the 1880s, drinking water in the watershed was supplied by springs or wells, but the increasing population created a need to supply water to the more densely populated villages. In 1886, the East Greenwich Water Company laid cast iron pipes from a large well near the Hunt River to East Greenwich village [67]. In 1890, the Warwick and Coventry Water Company was established to supply water to Apponaug and Crompton, and in 1929, Warwick developed a city-wide water distribution system [66]. By 1950 the water demand had grown and the county-wide Kent County Water Authority was formed by purchasing three private companies—Warwick and Coventry Water Company, East Greenwich Water Company, and Pawtuxet Valley Water Company [68]. An abundant supply of water permitted people to install water closets (toilets) in their homes. This new convenience caused health problems in densely built areas. Before sewers were installed, water closets were connected to cesspools, which frequently overflowed as the soil became saturated with the increased flow of piped-in water [69].

With the increased number of people and the availability of recently piped-in water, sewers were proposed for East Greenwich in 1893 (Fig. 6) [70]. The proposed plan placed a sewer on every street in the area bounded by First Avenue, Kenyon Avenue, Division and William Streets, and the shoreline of Greenwich Cove. Overflows were planned at the foot of Division Street, the foot of King Street, at the location of the present wastewater treatment facility (WWTF), and at the foot of Rocky Hollow Road. The plan was implemented in stages. The first sewer lines were installed in 1896 and 1897 [71, 72]. More sewer lines were added over time (Fig. 6). The outfall for the sewer lines emptied directly into Greenwich Cove at the foot of King Street. In 1928 the first WWTF was built, and an interceptor line connected the sewer lines to the plant. The original plant provided primary treatment of sewage—Imhoff tanks for the settlement of solids and anaerobic digestion of sludge [73]. The outflow from the plant was into Greenwich Cove. The WWTF was upgraded in 1956 to a secondary treatment facility with trickling filters and chlorination [73]. Sewers and a WWTF were not installed in Warwick until 1965. However, the Warwick WWTF, on the Pawtuxet River, and the first sewer lines in Warwick were outside the Greenwich Bay watershed.

Pollution

Industries offer jobs and economic benefits, but can pollute the air, water, and land. Before the enactment of environmental regulations in the 1970s, industries disposed of wastes directly into nearby water bodies or sewers, and emitted chemicals into the air. Textile companies were the sources of a variety of chemical pollutants. Wastewater from bleaching and dyeing processes contained metals (in the dyes and mordants), acids, and bleaches. The machinery in textile mills was a source of grease and oils. Metalworking industries and shipyards were sources of metals, acids, and petroleum hydrocarbons (organic compounds found in

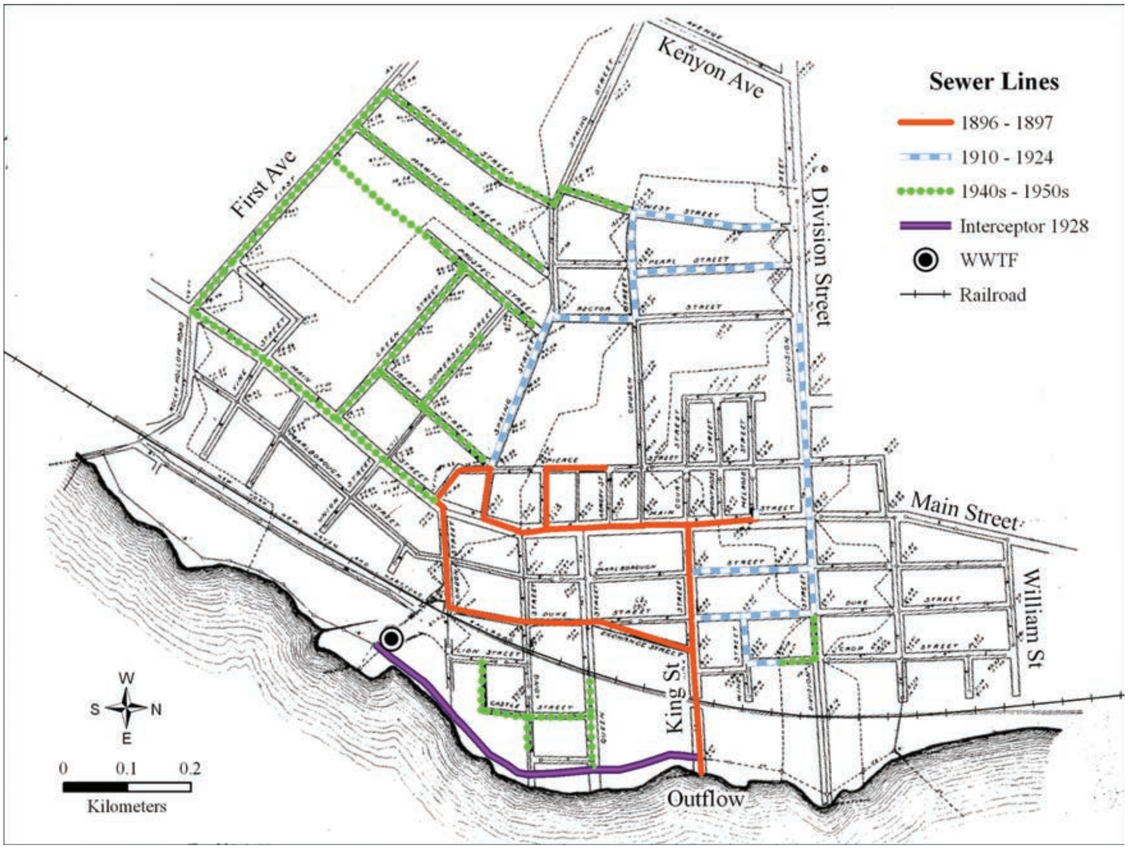


Figure 6. Sewer lines in East Greenwich installed from 1896 to the 1950s. The base map is the Preliminary Plan for a System of Sewers at East Greenwich, Rhode Island, 1893 [70]. Sewer lines shown for the various dates are from maps located in the Clerk's Office, East Greenwich Town Hall. The interceptor line and first wastewater treatment plant (WWTP) were built in 1928. Before 1928 the sewer lines emptied directly into Greenwich Cove.

oils, petroleum fuels, solvents, and grease). Industries also emitted polycyclic aromatic hydrocarbons (PAHs) from wood and coal combustion [74], and arsenic [75] and mercury [76] from coal combustion. Many of the mills in East Greenwich used steam-power to run the machinery, and burned coal to produce the steam [50]. The increase in people and industries within the watershed increased the sewage and chemicals flowing into Greenwich Bay. Historical data have shown that between 1800 and 1945 the sediments in the bay were contaminated, and water quality of the bay was affected by chemical pollution, bacterial pollution, and in Apponaug Cove, hypoxia (low oxygen levels).

The first study of pollution in Greenwich Bay, conducted in 1861 by the Rhode Island Shellfish Commission, cited pollution of the water by textile companies as a problem [66]. Goode and Associates [40] wrote about Apponaug Cove—"of late years the (fishing) business has largely decreased. The fishermen claim that chemicals and refuse from the large print-works have driven away the fish and killed every clam in the immediate vicinity of the town." Chemicals used in textile companies before the 1930s include: alumina, copper, iron, zinc, nickel, lead, chromium, tin, barium, magnesium, and acids [66]. When interviewed in 1980, retired workers from the Apponaug Company said most of the plant's liquid waste was disposed of in Apponaug Brook, which emptied into the head of Apponaug Cove [47]. The workers listed chemical wastes that were generated in the latter years of the plant's operation: bleaches and oxidizing agents, organic chemicals, pigments and mordants containing metals, and oils from the machinery [47]. A resident of the watershed remembers as a child (in the 1950s) seeing the color of Apponaug Cove water as "whatever dye color the Apponaug Mill was using that day" [77]. In Greenwich Cove there were similar stories: "kids in the 1930s and 1940s used to work (Greenwich) Cove for extra money, but they never knew what color the shellfish were going to be—it all depended on what color the Bleachery (a textile finishing plant) was using that day" [77]. The shipyards and metalworking companies in East Greenwich, Apponaug, and on Chepiwanoxet Point were likely sources of metals and petroleum hydrocarbons. The Industrial Period was a time of significant unregulated pollution input to Greenwich Bay.

Sediment Contamination

Sediments record the history of contamination in estuaries. Many contaminants adsorb to sediment particles, which get moved by currents and settle in areas of low water flow. Contaminants in surface sediments generally reflect recent events, whereas contaminants found deeper in the sediment correspond to past events. Sediment cores can be used to reveal the history of contamination. The cores are sliced horizontally and the slices are analyzed for contaminants and markers (to determine age). Various methods are used to determine the age of the core slices. When the concentrations of contaminants in the core slices are plotted by date, the resulting profile shows the history of contamination in the estuary. This is not an exact science; sediments can be eroded and resuspended, or disturbed by benthic animals, and the dating is not exact. However, sediment profiles can indicate an approximate history of contamination, particularly when taken from a relatively undisturbed site.

Analysis of sediment cores has shown that the sediment in Greenwich Bay is contaminated with metals and organic compounds. Two researchers examined metal contaminants in sediment cores taken from Apponaug Cove and the middle of Greenwich Bay (Fig. 3) [66, 78]. They both found that contaminants in the Apponaug Cove core matched the history of anthropogenic input from the textile mill in Apponaug. The Greenwich Bay core also reflected the history of contaminants from the mill in Apponaug, but because it was further from the mill, the concentrations of contaminants were lower, and it also contained contaminants from other sources. For example, in the core from Apponaug Cove the concentration of chromium, a metal used in textile dyes and mordants, started to rise above background concentration between 1870 and 1880 (Fig. 7). After 1880 the concentration increased more rapidly, with a decrease about 1910, followed by an increase to 1920, dipped in the 1930s, reached a maximum concentration about 1950,

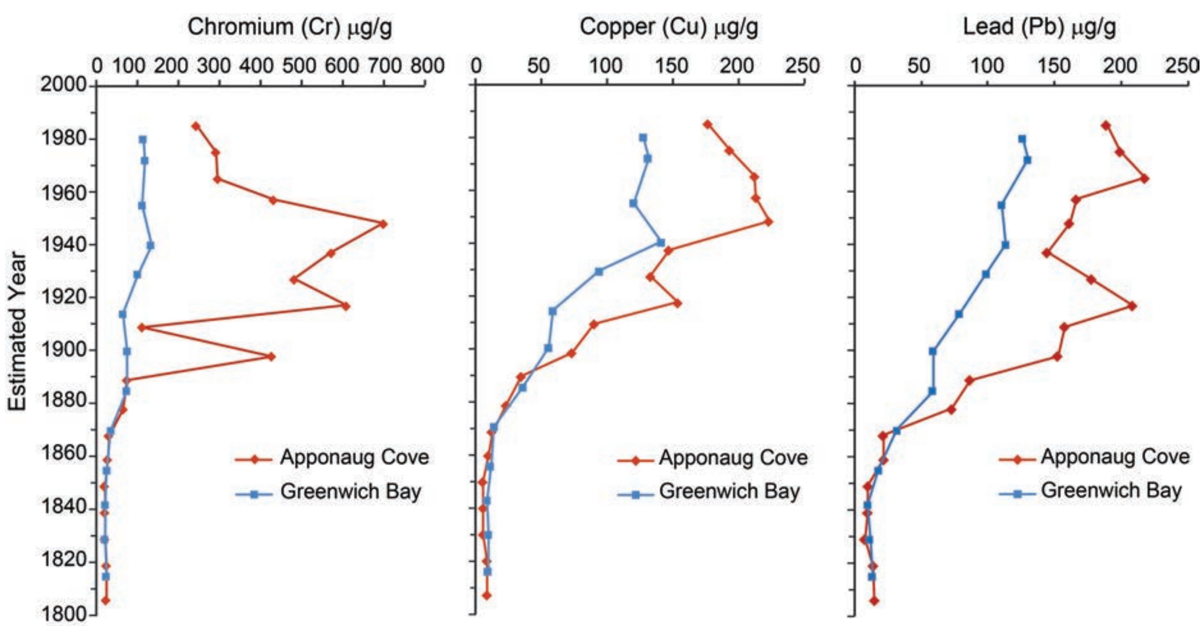


Figure 7. Profiles of chromium, copper, and lead concentrations in sediment cores taken from Apponaug Cove and Greenwich Bay. Data from Corbin [78].

and then decreased rapidly to the top of the core (1980s). This profile reflects the expansion of the mill in the late 1800s, an unexplained dip about 1910 followed by a rise, the economic recession and replacement of most of the mill buildings in the 1920s and 1930s, and the end of the mill operation in 1958. The sediment profile for copper, another metal used in textile dyeing, was similar: the copper concentration increased in the late 1800s, dipped in the 1920s and 1930s, reached the maximum concentration about 1950, and then decreased (Fig. 7). The core from the middle of Greenwich Bay also showed increases in chromium and copper concentrations in the late 1800s and had maximum concentrations in 1940-50; but the maximum concentrations were lower, about 5-fold for chromium and one half for copper, than those in Apponaug Cove (Fig. 7). Chromium readily binds to sediment particles. So chromium discharged from the mill in the wastewater would bind to sediment particles, which settled out in Apponaug Cove, leaving less chromium to reach the middle of Greenwich Bay. Copper does not bind as readily to sediment particulates, so more copper would be carried further from the mill. This might account for the smaller difference in maximum concentrations of copper for the two cores. The concentrations of chromium and copper in the Greenwich Bay core decreased only slightly from the maximum concentration, indicating that there were other sources of these metals besides the mill in Apponaug. Sediments in the middle of Greenwich Bay were also exposed to contaminants from the East Greenwich WWTF and industries in East Greenwich and on Chepiwanoxet Point.

The concentration of lead started increasing in the cores in the 1870s and continued to increase (steadily in the Greenwich Bay core but more variably in the Apponaug Cove core) until about the 1970s, when there was a small decrease to the top of the core (Fig. 7). Lead was used in textile production, but the textile industry was not a major source of this metal. In the late 1800s, lead, and also copper, started to increase rapidly in the environment from the burning of coal [79]. Leaded gasoline, a major source of lead, was used from the 1920s to the 1970s. The slight decrease in lead at the surface of the cores probably resulted from the phaseout of leaded gasoline that began in 1973. Grab samples of surface sediments, taken in various locations in Greenwich Bay in 2003 [80], had concentrations of chromium, copper, and lead that were similar to the concentrations at the top of the cores taken in the 1980s, indicating no major change, decrease or increase, for these particular contaminants. Data from one grab sample taken in the middle of Greenwich Bay are shown in Figure 13 (on the sediment quality line).

How do the concentrations of metals in Greenwich Bay sediments compare with those from other locations in Narragansett Bay? Table 3 lists the highest concentrations of chromium, copper, and lead in the Apponaug and Greenwich Bay cores and the concentrations of those metals that were found at four other locations from the same study [78] during the same time periods (1940-50s for chromium and copper, 1970-80s for lead). With the exception of the chromium concentration in the Apponaug Cove core, the concentrations of metals in the Greenwich Bay and Apponaug Cove cores were two to three times higher than those from two relatively clean stations mid bay (Calf Pasture Point, Ohio Ledge), but considerably lower

Table 3. Comparison of historical metal concentrations in sediment cores from Greenwich Bay and Narragansett Bay. The highest concentrations in the Apponaug and Greenwich Bay cores are listed. Values for chromium and copper for these two cores date from the 1940-50s, and values for lead are from the 1970-80s. Concentrations for the other four cores are taken from similar time periods (1950s for chromium and copper, and 1970-80s for lead). The upper Narragansett Bay sampling locations were in close proximity to Providence, a major industrial area. Data are from Corbin [78].

Location	Chromium µg/g	Copper µg/g	Lead µg/g
Upper Narragansett Bay			
Seekonk River	850	2558	812
Fox Point	490	1625	517
Greenwich Bay			
Apponaug Cove	701	223	218
Greenwich Bay	134	142	130
Mid-Narragansett Bay			
Ohio Ledge	66	85	68
Calf Pasture Point	76	95	51

than concentrations measured in the upper Narragansett Bay cores (Seekonk River, Fox Point), which were taken near Providence, a highly industrialized area (Table 3). This is consistent with a number of scientific studies that have analyzed concentrations of pollutants in Narragansett Bay sediments, showing a gradient of concentrations down bay with the highest concentrations in the upper bay closest to Providence, a highly industrialized and urban area, and the lowest concentrations at the mouth of the bay [78, 80, 81].

Organic compounds have also been measured in sediments in Greenwich Bay, including the same two sediment cores from Apponaug Cove and the middle of Greenwich Bay mentioned above [82]. In both cores, sediment profiles of polychlorinated biphenyls (PCBs, produced from 1929 to 1977), PAHs (by-products of petroleum processing and incomplete combustion of fossil fuels), and aliphatic hydrocarbons (another class of organic compounds) each reached a maximum concentration below the surface and then decreased to the surface (1980s). This indicates that input of these contaminants has been declining, most likely due to improved wastewater treatment, a change in public attitude toward releasing petroleum wastes into the environment, and a ban on PCBs in 1978. Concentrations of these organic compounds were considerable lower (3 to 10-fold) in Apponaug Cove and Greenwich Bay than those measured in cores from upper Narragansett Bay. Another group of researchers measured organic compounds in a different core from Apponaug Cove [83]. The distribution of chemicals in this core indicated that there was a disturbance in the deposition of sediments at this particular site, but the results indicated past contamination of the sediment with DDT (a pesticide produced from 1940 to 1972), PCBs, and PAHs.

How have the contaminants in the sediment affected quahogs? Quahogs live in soft sediment and filter particulates from the water, so they can be exposed to contaminants in a number of ways: dissolved in the water, attached to particulate material in the water, attached to sediments resuspended from the bottom, or dissolved in the sediment pore water. Several studies were conducted in the 1980s and 1990s that measured contaminant levels in quahogs from Narragansett Bay. An analysis of the data from three of these studies concluded that metal levels in quahogs from different areas of Narragansett Bay, including a station in Greenwich Bay, were fairly uniform despite large differences in concentrations of the metals in the overlying water and sediment [84]. An exception was the concentration of copper, cadmium, and lead in quahogs from Providence River. The Providence River quahogs had concentrations of these three metals that were two to three times higher than the bay-wide averages [84]. In a study of organic compounds in quahogs, sampled in 1985 and 1986 from four areas in mid to upper Narragansett Bay and from Mount Hope Bay, Greenwich Bay quahogs had the lowest concentrations of PCBs and PAHs [85]. Compared to the four other areas, Greenwich Bay quahogs had mid-level concentrations of DDTs, chlordane (a pesticide used from 1948 to 1988), and benzotriazoles (BZTs, synthetic chemicals produced by a company in Rhode Island from 1963 to 1986). But concentrations of all the organic compounds measured in this study were significantly lower in Greenwich Bay quahogs than in those from the Providence River [85].

Other studies have used these data to assess the risk from a public health point of view—are the shellfish safe to eat? In 1981, an evaluation of metal levels in quahogs for the whole state concluded that lead in quahogs from the Providence River might be a public health hazard; however, no FDA or Rhode Island State limit exists for lead [86]. Quahogs sampled in 1987 from various locations in Narragansett Bay (including Apponaug Cove, Sally Rock in Greenwich Bay, and Providence River) had concentrations of PCBs well below the FDA action level of 2.0 μg/g (the concentration above which the seafood is considered unsafe and will be removed from market) [87]. In 1992, another assessment of quahogs from all of Narragansett Bay, including the upper bay, concluded that nickel and mercury levels "appeared to be of marginal rather than serious concern" and a preliminary analysis indicated that PCBs and PAHs (both carcinogens) are "likely to be at the margin of concern rather than seriously exceeding acceptable levels" [88]. But there were problems with the methodology used in this assessment—it did not include a good assessment of the amount of quahogs eaten [89]. A recent study of mercury in Narragansett Bay sediments and biota found that the concentration of total mercury in quahogs sampled from various places in the bay, including Greenwich Bay, was very low, well below the FDA action level for methyl mercury (concentration of total mercury includes methyl mercury, which is the most toxic form of mercury and accumulates in seafood, particularly in fish at the top of the food chain) [90]. A more thorough assessment of risk concluded that there were no immediate health threats associated with an average level of consumption of quahogs from any area of Narragansett Bay, although eating large quantities could increase the risk of cancer to unacceptable levels [89]. The greatest risk for adverse health effects was associated with eating large quantities of quahogs from the Providence River, primarily due to contamination with PAHs, PCBs, and cadmium [89]. Fortunately, the quahogs that might pose a health risk from chemical contaminants are found in areas that are permanently closed to shellfishing because of bacterial contamination, so the public is not exposed when eating legally harvested quahogs.

Water Quality – Bacteria and Oxygen

The increasing number of people who moved into the Greenwich Bay watershed during the Industrial Period caused bacterial pollution of bay waters. Sewer lines to handle this increase in population were first installed in East Greenwich in 1896 and 1897, and emptied directly into Greenwich Cove. A sewage treatment plant, built in 1928, provided only primary treatment, and the liquid waste emptied directly into the cove. Human waste entered upper Apponaug Cove via Apponaug Brook; Rhode Island Division of Water Pollution surveys from 1927 to 1951 described gross pollution and bacterial contamination in upper Apponaug Cove [47]. Maps dated 1936 show shellfish beds in Apponaug Cove closed to shellfishing because of water quality [66]. By 1946, Apponaug and Greenwich Coves were permanently closed to shellfishing because of fecal contamination [7].

There is some historical evidence of low oxygen in Apponaug Cove. Investigations conducted in the summers of 1922 and 1923 found Apponaug Brook "practically devoid of oxygen and badly discolored with dyes and other industrial wastes" from the Apponaug Company [91]. The zone of pollution extended out into Greenwich Bay, and fishermen working in the bay complained about the water quality. Other historical data recorded low dissolved oxygen in inner Apponaug Cove; oxygen concentrations averaged 30% of saturation in August 1924, and there were anoxic areas in July and August 1926 [92]. A "red tide" algal bloom and massive fish kill [93], thought to be linked in part to pollution [94], was reported in Narragansett Bay and Greenwich Bay as early as 1898.

Fisheries

In the mid 1800s, a number of events led to the demand for more fish, resulting in an economic boom for the fishing industry on the East Coast: rapid growth of the country, use of railroads and ice to transport fresh fish to cities, recognition of fish oil as a valuable product, and use of uncooked fish as manure. By the early 1870s, it was recognized that the fish stocks in Rhode Island and Massachusetts were declining. In 1871, a bill was passed in the United States Congress to appoint a commissioner of fish and fisheries "for the protection and preservation of the food fishes of the coast of the United States" [95]. Spencer F. Baird was appointed the first U.S. fish commissioner and was authorized to conduct an inquiry into the state of fisheries in Rhode Island and Massachusetts. In his report, Baird concluded that there was "an alarming decrease of the shore fisheries" [95]. He wrote that the decline of some species had started at the beginning of the nineteenth century but was more rapid during the twenty years prior to his inquiry. He attributed the recent rapid decline to the increased use of fish traps and pounds. Fish traps were set along the shore in early spring and caught whole schools of fish (e.g. alewives, tautog, mackerel, menhaden, scup, sea bass, bluefish, and squiteague) as they moved along the coast and into Narragansett Bay and Buzzards Bay, Massachusetts, to spawn. The hook-and-line fishermen blamed the trap fishermen for the

Year	Greenwich Bay	Total for Rhode Island
1881	nd	20
1882	nd	25
1898	nd	119
1899	2	121
1902	6	161
1903	8	195
1904	5	220
1905	8	240
1906	11	249
1907	12	271
1908	13	271
1909	11	277
1910	16	283
1911	15	277
1912	nd	261
1922	nd	127

Table 4. Number of fish traps in Rhode Island waters at the turn of the twentieth century. Data from the Annual Reports of the Commissions of Inland Fisheries, Rhode Island [97]. The number of traps set in Greenwich Bay was not available for all years (nd = no data).

decrease in fish. In 1871, legislation was proposed in the Rhode Island General Assembly to prohibit fish traps in Narragansett Bay in order to preserve the right of each individual to fish and not infringe upon the rights of others, and to conserve the fish stocks. Even though the right to fish is guaranteed in the Rhode Island charter, the legislation to prohibit fish traps did not pass; however, some restrictions were placed on the use of the traps. Fish traps in Narragansett Bay proliferated, with some traps set in Greenwich Bay by 1899 (Table 4). The number of traps in Greenwich Bay peaked at sixteen in 1910 (Fig. 8). After 1910, the number of traps in all state waters declined. Large numbers of scup were caught in the traps, including the traps set in Greenwich Bay [96].

George Goode, Assistant Director of the U.S. National Museum, and his associates described the fisheries of Greenwich Bay in 1880 [40]. They reported that Apponaug and East Greenwich had active fishing fleets (Table 5). Fish—bluefish, squiteague, tautog, flounders and scup—were caught by hand-lines, seines, and gill-nets. Fyke nets were set along the

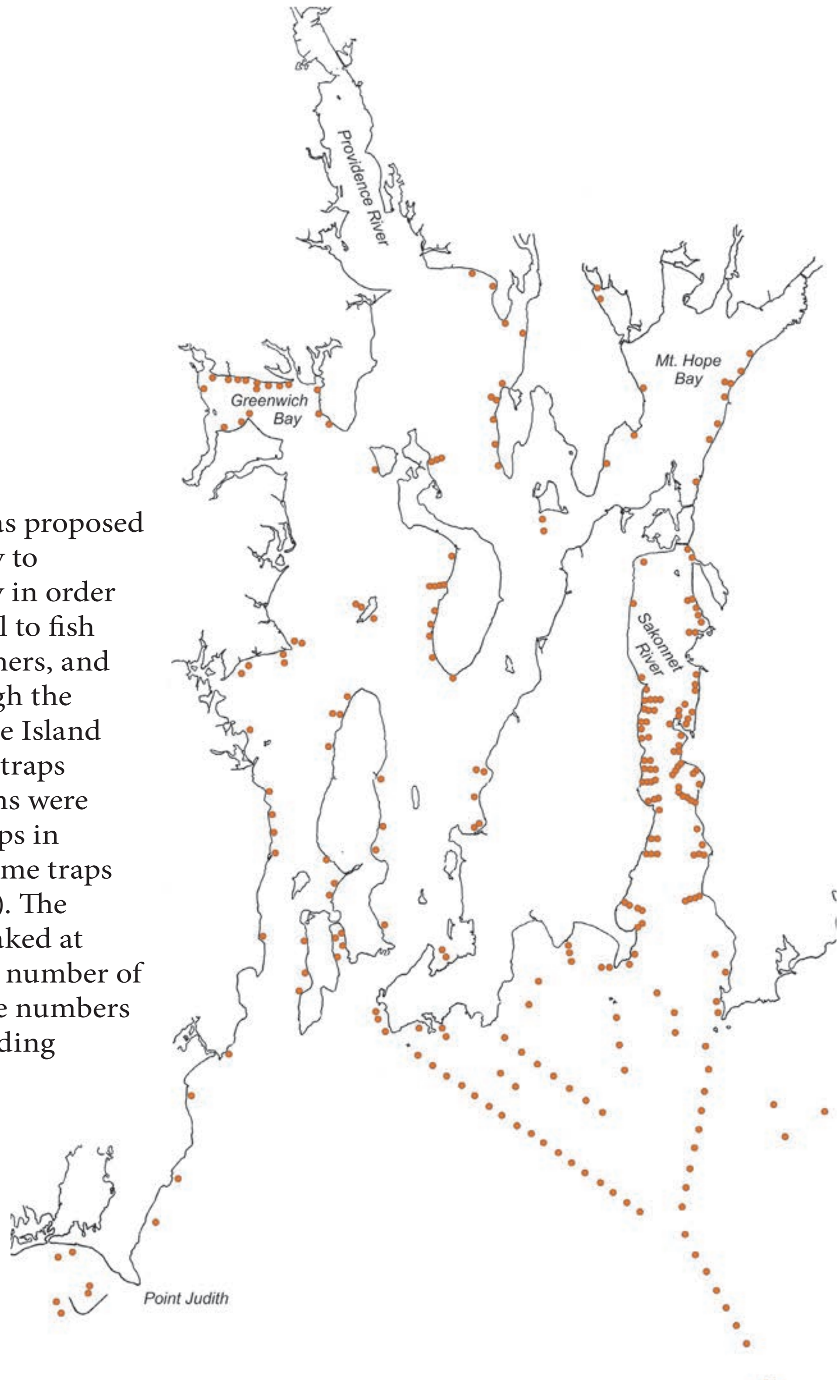


Figure 8. Map of fish traps in Narragansett Bay in 1910. Map redrawn from the Forty-first Annual Report of the Commissioners of Inland Fisheries [152].

shore of Greenwich Bay in the winter under the ice. Soft-shell clams and scallops were leading fishery products. Scallop beds in Greenwich Bay were the most productive in Narragansett Bay. In 1865, the scallop harvest from East Greenwich and Warwick comprised 86% of the scallop harvest for the whole state (Table 6). The scallop beds surrounded Chepiwanoxet Island and extended along the northern and southern shores of the bay. Scallops were dredged from September 15 to May 15. Soft-shell clams, which inhabit soft bottoms in the intertidal to subtidal zones, were dug close to shore year round. Most of the soft-shell clams harvested in the summer were used in the clam bakes held at the beach resorts—Rocky Point, Buttonwoods, Oakland Beach. Although oysters had been abundant in earlier times and laws had been passed in East Greenwich to preserve the oyster fishery, by 1865 few oysters were landed by fisherman in East Greenwich and Warwick (Table 6), and these oysters were most likely harvested from Narragansett Bay, not Greenwich Bay. Goode and Associates reported that by 1880 Narragansett Bay had "almost ceased to yield marketable oysters of natural growth…" [40]. Writing in 1877, the historian D.H. Greene also mentioned the scarcity of oysters and the abundance of scallops in Greenwich Bay at that time [51].

As the oyster fishery collapsed, the hard clam, or quahog, became more important. Quahogs were harvested commercially in the 1800s but were not a significant part of the commercial fishery until the 1930s and 1940s [41]. In 1865 quahog harvest for the whole state accounted for only 7.5% of the total shellfish catch (Table 6) [40]. Commercial quahog harvest in Rhode Island peaked in the 1950s at over five million pounds and then declined to less than one million pounds in the 1970s (Fig. 9) [98]. The increase in the quahog harvest from 1920 to the 1950s was due to the opening of new fishing areas that were no longer used for oysters [99] and the increased use of outboard motors that enabled fishermen to cover

Table 5. Fishing resources and catch in Apponaug and East Greenwich in 1880 (nd = no data) [40, p. 306].

	Apponaug	East Greenwich
Resources		
Sail boats	9	16
Small boats	30	12
Scallop/clam dredges	36	75
Seines	4	4
Gill nets	nd	11
Fyke-nets	nd	100
Catch		
Scallops	3300 (gallons)	6000 (bushels)
Clams (bushels)	6000	4000
Fresh fish (pounds)	37,500	125,000

Table 6. Shellfishing products (number of bushels) reported for 1865[1] [40, p. 286].

	Warwick	East Greenwich	Total for State
Clams	9,127	1,415	31,697
Quahogs	2,953	339	9,241
Scallops	1,627	6,635	9,653
Oysters	242	13	71,894

[1] numbers presented by a committee of the general assembly of Rhode Island for 1865, with a note that the amounts probably should be doubled [40].

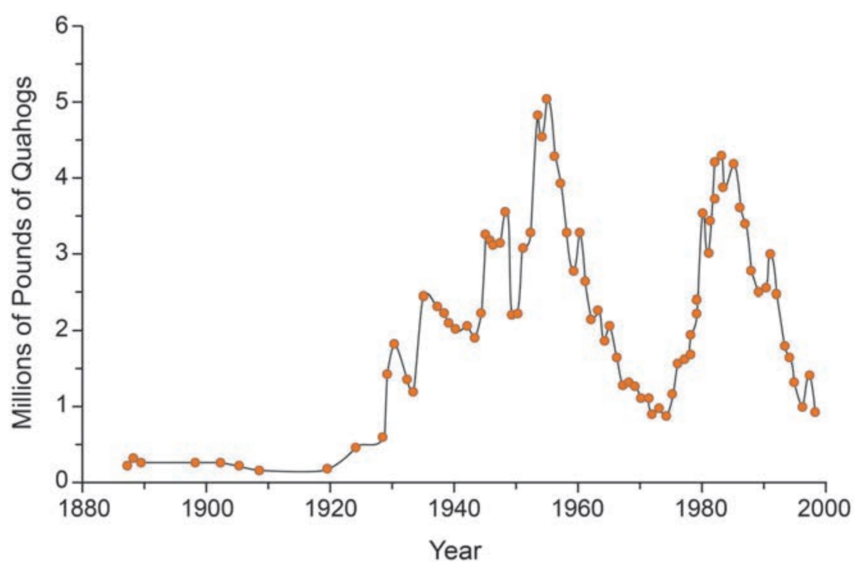


Figure 9. Commercial quahog harvest from Narragansett Bay. Figure redrawn from DeAlteris et al. [98].

larger areas [41]. The decline in harvest between the 1950s and 1970s was due primarily to pollution in upper Narragansett Bay that closed prime shellfishing grounds [100]. Quahog harvest information specifically for Greenwich Bay is not available, but quahogs were abundant in Greenwich Bay, and there was an active quahog fishery there. Conditions in Greenwich Bay favored good production of quahogs: nutrient-rich freshwater input, abundant phytoplankton, sand and mud bottom [77], and a low number of competing species [101]. Shallow depths in Greenwich Bay and protection from winter winds made harvesting of quahogs easier there.

A section of the waterfront in East Greenwich known as Scalloptown was the center of Greenwich Bay fishing activity for over a century (Fig. 10). The shorefront east of Rope Walk Hill, from King Street to London Street, had been designated as "shore lots" by the East Greenwich Proprietors to be used for "fishing purposes and wharfing" [102]. Starting in the first half of the 1800s, a haphazard cluster of small houses, shanties, and boathouses were built by fishermen. By the turn of the century Scalloptown had become a social problem with reports of illegal and immoral activity. In 1913 the Town Council condemned many of the buildings, and in 1926 a fire destroyed most of the rest of the houses [102]. Further damage of shoreline buildings occurred in the 1938 hurricane, but some of the boathouses were rebuilt and Scalloptown is still the center of commercial shellfishing in Greenwich Bay.

South Water Street, East Greenwich, c. 1930s. Scalloptown shanties were home for some in lean times. A fire in 1926 and the 1938 hurricane destroyed the Scalloptown shanties and boathouses. (Drew collection, courtesy of East Greenwich Historic Preservation Society)

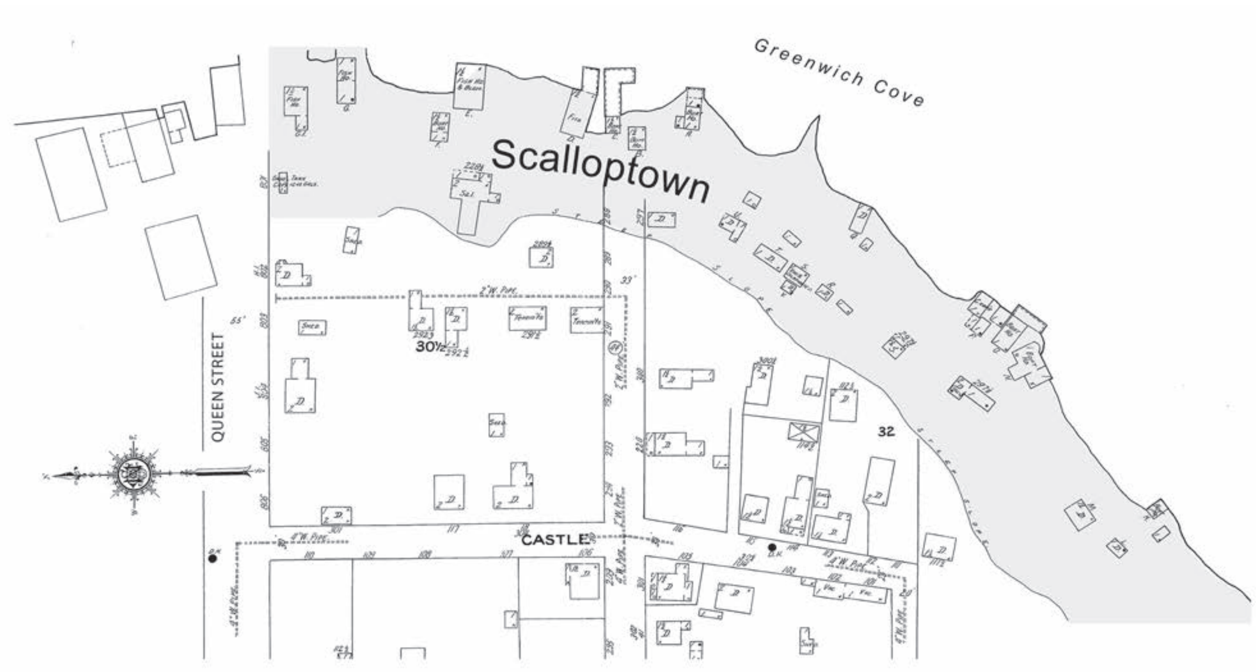


Figure 10. The 1910 Sanborn Fire Insurance map [153] shows the boathouses and buildings along the East Greenwich shore in the area known as Scalloptown. Shading and the label "Scalloptown" was added to this section of the map.

Seagrass

Seagrass beds serve as nursery and feeding grounds for fish, shellfish, and wildlife. Seagrasses are important in maintaining the physical, chemical, and biological integrity of coastal ecosystems [103, 104]. In the 1800s and early 1900s, eelgrass (*Zostera marina* L.), the species of seagrass most common in New England coastal waters, was prevalent throughout Narragansett Bay [105]. Seagrasses are often associated with scallop beds. Goode's [40] description of fisheries in Greenwich Bay in 1880 included scallop beds, and it is likely that eelgrass was located in those same places—surrounding Chepiwanoxet Island and extending along the northern and southern shores of the bay. Later evidence of eelgrass in Greenwich Bay supports that assumption. On a 1913 survey map, eelgrass was indicated in the southeastern part of Apponaug Cove, north of Chepiwanoxet Island, and along the northern and southern shores of Greenwich Bay [105]. According to old-time shellfishermen, eelgrass was found up to a depth of 15 feet in most of Greenwich Bay before the 1938 hurricane [105]. During the early 1930s eelgrass abruptly disappeared from much of the American and European Atlantic coasts [106] and presumably disappeared from Greenwich Bay. The die-off was attributed to "wasting disease" that was thought to be caused by a fungus. By the 1940s eelgrass was beginning to come back in selected areas, including Greenwich Bay. In the 1940s and 1950s, old-time shellfishermen remembered seeing eelgrass north of Chepiwanoxet Point and along the southern shore west of Sally Rock Point [105].

Dams and Fish

During the Industrial Revolution, dams were built on rivers to provide an inexpensive source of power or a source of water for commercial processing (for example, finishing and dyeing textiles). Anadromous fish, such as alewives, blueback herring, American shad, and Atlantic salmon, spend most of their lives in marine waters but return to fresh water during the spring to spawn. Dams that block their passage upstream can result in extirpation of local fish populations [107]. Dams also can alter the characteristics of streams; they can raise water temperatures, concentrate sediment and pollutants, buffer the normal water level fluctuations, and alter species composition [107]. The effect of dams on native fish populations seemed not to be considered at this time, although in the early 1700s Warwick forbid the setting of weir, nets, and dams that would impede the movement of fish upriver. Dams were built on some streams that empty into Greenwich Bay. In 1865, a dam was built on Apponaug Brook at Gorton Pond near the textile mill. In East Greenwich, a dam was built on the Maskerchugg River forming Bleachery Pond, probably in 1840 when the Green Dale Bleachery was built. More dams were added later; from the 1950s to the 1970s, a number of dams were built to create farm ponds and recreational ponds. By 2010, there were two dams on Apponaug Brook, nine dams on Hardig Brook, and seven dams on the Maskerchugg River [108].

Anadromous fish were plentiful in Narragansett Bay in the 1600s [109]. By the late 1800s, two species of anadromous fish (sturgeon and salmon) were disappearing [40]. In 1875, the Rhode Island Commissioners of Inland Fisheries were concerned about river herring, stating that "in olden time, the herring swarmed in every stream" [110]. Their report mentioned the problem of dams blocking streams and urged that some legislation be passed to protect herring. In 1880, alewives (*Alosa pseudoharengus*) were still plentiful in Rhode Island waters and were the third largest annual catch of fish, after menhaden and scup [111]. However, by 1960 there were no significant landings of anadromous fish in Narragansett Bay [111]. In 1993, a fish survey found that Greenwich Bay was a valuable habitat for river herring and still supported populations of alewives and blueback herring (*Alosa aestivalis*) [17]. Alewives spawn in upper Brush Neck Cove, but dams obstruct river herring runs on the Maskerchugg River and Apponaug and Hardig Brooks [107]. A recent study, which assessed the suitability of restoring anadromous fish, found that the Maskerchugg River and Apponaug and Hardig Brooks had suitable habitat for alewives and blueback herring; however, a low restoration priority was given to the dam at Bleachery Pond on the Maskerchugg River because of the height of the dam [107]. The

Bleachery Pond Dam, postcard postmarked Oct 14, 1908. The height of Bleachery Pond dam, 16 feet, gives it a low priority for restoration of the anadromous fish run on the Maskerchugg River. Today the East Greenwich Muncipal Land Trust manages 5.5 acres of land at Bleachery Pond. Walking paths are accessible from the northern side of the Maskerchugg River near Post Road. (Bruce MacGunnigle, private collection)

Gorton Pond Dam on Apponaug Brook only partially obstructs fish passage, and restoration to this fish run was given a high priority [107].

Natural Hazards – Hurricanes

Natural hazards cause damage to property and natural resources, can cause injuries and fatalities, and can interrupt business. The most significant natural hazards for Greenwich Bay are hurricanes and nor'easters [7]. The hurricane of 1938 was the worst hurricane to hit Rhode Island in recent times, and it had devastating affects on Greenwich Bay. The low lying areas of Warwick and East Greenwich were flooded with a storm surge that was 13 feet above the normal high tide line [75]. Many waterfront buildings in East Greenwich and Warwick were damaged or washed away. The shanties, docks, and boats at Scalloptown were left in a jumble of broken wood. State-wide, the town of Warwick sustained the most property damage; over seven hundred permanent homes and hundreds of summer houses were destroyed [112]. Damage along the northern shore of Greenwich Bay was extensive. At Oakland Beach waterfront houses, the amusement park, Oakland Beach Yacht Club, and other landmarks were destroyed. Damage there was so great that some homeowners did not rebuild. The trolley trestles across Warwick and Brush Neck Coves were destroyed. At Buttonwoods the bank along Promenade Avenue, which ran along the waterfront, was eroded [112]. Land was lost on the eastern end of the Buttonwoods peninsula, and Promenade Avenue was damaged so badly there that the eastern end of the road was not rebuilt [113]. After the hurricane, a seawall was built along the western end of Promenade Avenue to protect the road from more erosion.

An earlier hurricane, the Great Gale of 1815, caused damage in Rhode Island and southern New England [114]. During that storm, a surge of water moved up Narragansett Bay; it flooded Providence and swept vessels over wharfs and into the streets. Throughout southern New England coastal flooding damaged buildings and boats, large trees were uprooted, and agricultural crops were ruined by wind and salt spray. Undoubtedly, flooding occurred in Greenwich Bay, but in 1815 there were few waterfront buildings along the northern shore where a storm surge would have caused the most damage, as it did in 1938.

In 1954, Rhode Island was hit by another significant storm, Hurricane Carol. Oakland

Beach sustained the greatest damage in Greenwich Bay; but homes and boats were also lost at Arnold's Neck, Chepiwanoxet, and Potowomut, and flash floods damaged sections of Apponaug [112]. Although no major hurricanes have hit Rhode Island since 1954, four smaller storms have occurred: tropical storm Diane, 1955; and hurricanes Donna, 1960; Gloria, 1985; and Bob, 1991. A National Hurricane Center model has identified Oakland Beach, Buttonwoods, and Potowomut as areas at high risk for coastal flooding from storm surge [7].

West end of Oakland Beach – then and now. The post card (above) depicts the beach front houses in the early 20th century. The tower for the circle swing ride at Oakland Amusement Park can be seen in the background. These houses were destroyed in the 1938 hurricane and were not rebuilt. (Warwick Historical Society). Today there are no houses along the west end shore of Oakland Beach. (Photo left by Carol Pesch)

Summary of the Industrial Period

During the Industrial Period (c. 1800 to c. 1945) unregulated industries in the watershed polluted Greenwich Bay waters and sediments with metals and organic chemicals. Concentrations of some metals in bay sediments corresponded to the activities of a large textile mill in Apponaug, but also indicated other sources within the watershed. Increased human population caused an increase in the amount of sewage. Sewer lines installed in East Greenwich emptied directly into Greenwich Cove. The first WWTF in East Greenwich, built in 1928, had only primary treatment. Overflowing privy vaults and cesspools added to the bacterial problem in the watershed. Greenwich and Apponaug Coves were polluted with fecal bacteria and closed to shellfishing. Episodes of low oxygen occurred in Apponaug Cove. Building of the Stonington Railroad contributed to sedimentation in Greenwich Cove. The railroad bridge across Apponaug Cove formed an inner cove section, changing patterns in water circulation and sedimentation. Dams built on Apponaug and Hardig Brooks and the Maskerchugg River obstructed the passage of anadromous fish. By the 1870s fish stocks in Narragansett Bay, and presumably Greenwich Bay, were declining due to overfishing. Few oysters were harvested in Greenwich Bay, and the oyster fishery in Narragansett Bay collapsed by the late 1800s. Scallops were plentiful in Greenwich Bay in the the late 1800s, but disappeared in the first half of the 1900s with the disappearance of eelgrass. Industrialization had negative effects on the ecology of Greenwich Bay.

Suburbanization Period – c. 1945 to present

The pattern of suburbanization (development of human population outside of cities) set in the early 1900s was followed with a boom in development after the end of World War II. The GI Bill made home ownership available to returning servicemen and fueled the growth of suburban neighborhoods [7]. Farm land, already cleared and generally flat, was well-suited for building housing developments. Summer houses were converted to year-round homes. From 1940 to 1970 the population in Warwick increased almost 3-fold, East Greenwich population increased about 2.5-fold, and West Warwick population increased about 1.3-fold (Fig. 4). Overall, from 1970 to 2000, the population leveled off compared to growth in the previous 30 years: East Greenwich's population increased 1.4-fold, while Warwick's and West Warwick's increased slightly (Fig. 4). From 1950 to 2000, the estimated population in the watershed doubled, from an estimated 25,500 to 49,400 (Fig. 5).

Land Use

Land use data prior to 1988 are poor or non-existent, so it is difficult to compare loss of agricultural land from 1950 to present, but it was substantial. Specific categories in the newest land use data set (2003-2004) were different from previous years, so we could not compare those to past years. Comparison of land use within the watershed from 1988 to 1995 showed that developed land increased, from 59.5% to 62%, while undeveloped land decreased (40.5% to 37.9%) [7]. By 1995, only about 3% of the land in the watershed was categorized as agricultural, 17.9% as forest, and 9% as wetlands; whereas, 62% was classified as developed—46% residential, and 16% commercial and industrial [7]. By 2004, human-made impervious surfaces (buildings and paved surfaces such as roads, sidewalks, driveways, parking lots) accounted for 29% of the Greenwich Bay watershed (calculated from RIGIS impervious surface data layer based on imagery taken in 2003-2004) (Fig. 11). Watersheds that contain greater than 15% impervious surfaces are considered by

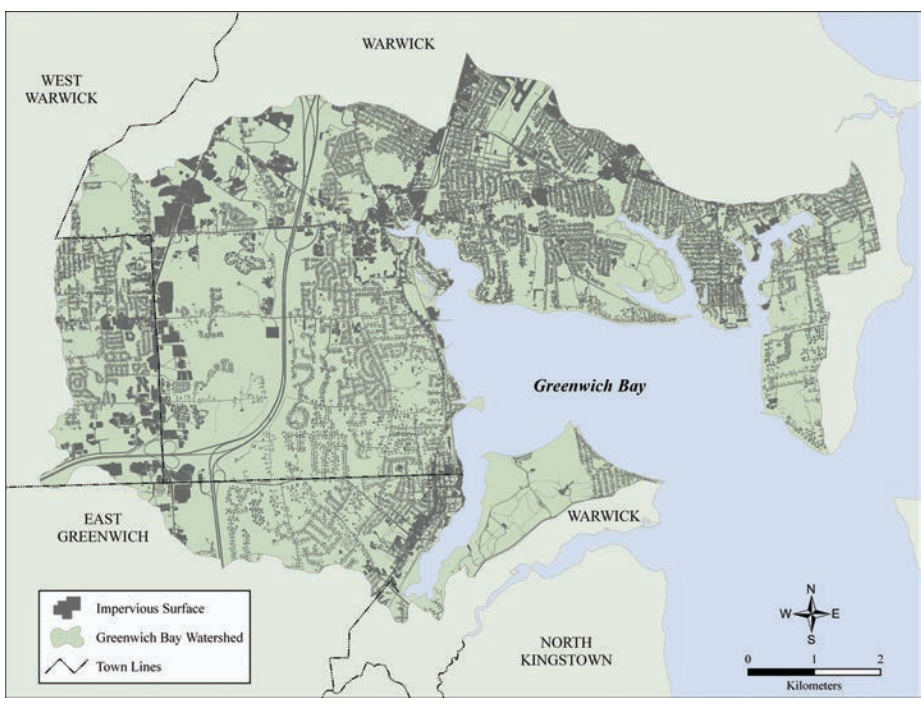


Figure 11. Impervious surfaces (pavement) accounted for 29% of the Greenwich Bay watershed in 2004 (RIGIS impervious surface data layer).

EPA as beginning to "suffer negative ecological effects" [115]. Impervious surfaces cause rain and runoff to flow quickly, via storm drains, into adjacent water bodies instead of slowly seeping into the ground where runoff is filtered and is available to recharge ground water aquifers.

Land use along the shore has a direct influence on fish, wildlife, and water quality. Wetlands and vegetated buffers trap sediment, pollutants, and nutrients, and thus, improve water quality by decreasing the amount of contaminants that reach the bay. Wetlands and vegetated buffers protect the shore from storm erosion and provide habitat for wildlife. In addition, coastal wetlands protect the shore from flooding, provide habitat for fish, and provide opportunities for recreation—fishing, shellfishing, and bird-watching. Land use along Greenwich Bay's 25.8-mile coastline was similar to the whole watershed. By 2003, 57% of the land within a 500-foot buffer of the shore was developed—47% residential, and 10% commercial and industrial [7]. The undeveloped shoreline was composed of 26% forest, 8% wetlands, and 4% vegetated. A study conducted in 2005 identified 14 miles along Greenwich Bay coast as potential vegetated buffer restoration sites, with the areas along Potowomut Neck and Cedar Tree Point as having the most potential [116].

Greenwich Bay has never had extensive coastal wetlands. Its coastal wetlands are primarily fringe marshes along the shores of the coves. The largest tidal wetlands are along Baker Creek and Marys Creek in the northwestern portion of the bay. Shoreline development is the primary cause of destruction of vegetated buffers and coastal wetlands. We were able to measure the loss of coastal wetlands in Greenwich Bay by comparing the wetlands shown on maps from 1868 to those delineated in the 2003 National Wetland Inventory [117]. Our comparison showed a 40% loss of coastal wetlands, from 249 acres in 1868 to 148 acres in 2003. Most of the loss occurred in the fringe wetlands in Apponaug, Brush Neck, Buttonwoods, and Warwick Coves. The larger tidal wetlands along Baker and Marys Creeks still exist, although they have been impacted: Baker Creek by vegetation change, and Marys Creek by vegetation change, tidal restriction, ditching, fill, debris, and stormwater discharge [117]. These two wetlands, as well as impacted fringe marshes along the coves, have been identified as potential restoration sites [7, 117].

By 1996, 24% of the shoreline of Greenwich Bay had been hardened by built structures such as bulkheads, revetments, and bridge abutments (RIGIS hardened shoreline data). Also there were 4,180 ft of breakwaters, jetties, and groins that extended into bay waters. Hardened structures, such as revetments, can protect the immediate shoreline, but they alter water circulation and erosion patterns, trap potential beach sediment, and consequently can affect other nearby shoreline areas. Groins were built at Oakland, Buttonwoods, and Cedar Tree Point beaches to trap sand and have slowed the erosion process there [7]. But these beaches, which were battered by previous hurricanes, will be increasingly prone to erosion due to sea-level rise and more intense storms, which are expected with climate change. Estimates for sea-level rise in Rhode Island range from 17 to 34 inches by the year 2100 [7]. Shoreline structures provide protection during moderate storms, but the presence of hardened structures often provides a false sense of security for protection from damage during severe storms. Hardened structures also affect shoreline habitat. Some species of fish spawn in near-shore

Baker Creek is one of the larger tidal wetlands in Greenwich Bay. (Photo by Christopher Deacutis, Narragansett Bay Estuary Program)

Marys Creek wetlands have been impacted by vegetation change, tidal restriction, ditching, filling, and stormwater discharge. (Photo by Christopher Deacutis, Narragansett Bay Estuary Program)

areas and coastal wetlands, so loss of these areas by hardening of the shoreline decreases the amount of habitat available for these species.

Water Quality

Increases in population and commercial activity during the Suburbanization Period affected the water quality of Greenwich Bay. Water quality in the bay continued to decline: bay waters were further contaminated by fecal bacteria, nitrogen inputs increased, and there were episodes of low dissolved oxygen [7]. According to water quality testing in 2010, Greenwich Bay and all five of its coves did not meet the Rhode Island Water Quality Standards for one of the seven designated use categories, fish and wildlife habitat, because of excessive nitrogen and low dissolved oxygen [118]. Two freshwater brooks within the watershed were also listed as not supporting the standards for fish and wildlife habitat: Hardig Brook and its tributaries did not meet the standard for lead, and the Maskerchugg River did not meet the standards for cadmium [118].

Bacterial Contamination

The major pathway for fecal bacteria to enter bay waters is thought to be via storm drains [7]. Surface water runoff carries bacteria from pets and wildlife into storm drains that empty directly into the bay. Bacteria also reach bay waters from failing individual septic systems within the watershed. Another possible source of bacteria is from illegal boat discharges.

Fecal contamination of bay waters has led to shellfish bed closures. By 1946, Apponaug and Greenwich Coves were permanently closed to shellfishing. Warwick Cove and the Cowesett shore were added to the permanently closed areas by 1972, Brush Neck Cove was closed by 1990, and Buttonwoods Cove was closed by 2004 [7]. In December 1992 heavy precipitation caused violations of the shellfish fecal-coliform standard, and in January 1993 the whole bay was closed to shellfishing to allow time to reclassify the waters [119]. In 1994 Greenwich Bay (but not the coves, and an area south of Apponaug Cove) was conditionally opened to shellfishing during dry weather (0.5 inches of rain in 24 hours will close an area for 7 days). As of May 2010, 313 acres of Greenwich Bay that had been permanently closed were re-classified as conditionally approved, indicating that conditions appeared to be improving [120]. But a year later in May 2011, 46 of these acres (near Baker Creek) were permanently closed again, indicating the need to continue implementing programs that prevent bacteria from reaching the bay [121]. Quahog populations in the closed areas have thrived. To take advantage of this resource, RIDEM started a transplant program in the late 1970s. Initially, quahogs were moved from Greenwich Cove to western Greenwich Bay [122]. Currently, quahogs are harvested from the contaminated coves (Greenwich, Apponaug and Warwick) and moved to clean areas in Narragansett Bay where they are protected from harvest for at least six months to allow the quahogs to cleanse themselves[123]. The Rhode Island Department of Health monitors the transplanted quahogs for fecal coliform bacteria and seven metals at the time of the move and again six months later, before harvest, to ensure they are safe to eat [123]. Bacterial pollution clearly affects shellfisheries in Greenwich Bay, and also in Narragansett Bay.

Fecal contamination of bay waters has also led to beach closures. The Rhode Island Department of Health monitors bacterial levels during the summer beach season at the three public beaches in Greenwich Bay—Goddard Memorial Park State Beach, Warwick City Park Beach, and Oakland Beach. From 1998 to 2010 most of these beaches had some closure days due to unhealthy bacterial counts, usually after wet weather (Table 7) [124].

Table 7. Number of beach closure days for three public beaches in Greenwich Bay. Data from the Rhode Island Department of Health [124].

Year	Warwick City Park	Goddard Park	Oakland Beach
1998	27	14	31
1999	0	7	0
2000	0	16	10
2001	19	28	12
2002	15	7	12
2003	23	21	66
2004	5	0	11
2005	7	2	7
2006	17	10	15
2007	3	1	7
2008	15	1	15
2009	12	10	17
2010	2	5	5

Effects of Nutrients

Nutrients—nitrogen and phosphorus—stimulate plant growth and are necessary for healthy ecosystems. However, when human activities increase nutrients to excessive levels, a series of negative ecological effects can result. Eutrophication, the excessive growth of algae, causes low dissolved oxygen in bottom waters as the algae die, sink to the bottom, and use up the available oxygen in the process of decaying. Low dissolved oxygen levels can drastically affect aquatic organisms, killing or driving off most of the larger animals. This simplified story is actually much more complex in nature, where several highly variable factors can critically affect the process.

Sources of Nitrogen

In estuarine systems, nitrogen is the primary nutrient that stimulates plant growth [125], and excess nitrogen can cause severe problems. Nitrogen enters Greenwich Bay from freshwater streams, storm drains, ground water, wastewater from the East Greenwich WWTF, atmospheric deposition, and tidal exchange from Narragansett Bay [7]. Old cesspools, failing individual septic systems, and synthetic fertilizers (used extensively after 1950) are sources of nitrogen in ground water. In 2006 the East Greenwich WWTF was upgraded to tertiary treatment to remove nitrogen from its wastewater. Recently, researchers, using modeling techniques and estimating mass budgets of nitrogen, have suggested that a major source of nitrogen to Greenwich Bay is coming from Narragansett Bay. Steve Granger and his co-authors at the University of Rhode Island Graduate School of Oceanography (GSO) estimated that the amount of dissolved inorganic nitrogen entering Greenwich Bay from Narragansett Bay was about equal to the amount entering from the Greenwich Bay watershed (ground water, streams, and WWTF), while the amount from atmospheric deposition was considerably less [126]. Mark Brush, also from GSO, estimated that a larger contribution of nitrogen was coming from Narragansett Bay, about four times the amount from the watershed [127]. In the latest study, Peter DiMilla and his co-authors estimated that the largest source of dissolved inorganic nitrogen to Greenwich Bay was Narragansett Bay (54%), while sources from the watershed totaled 44% (21% from streams, 12% from ground water, 7% from the East Greenwich WWTF in 2004 and 2005 before the tertiary upgrade, and 4% from storm drains), and atmospheric deposition was small, 2% [14]. The amount of nitrogen entering Greenwich Bay remains open to research and debate, but it is clear that Greenwich Bay receives a considerable nitrogen input from Narragansett Bay.

Narragansett Bay, especially the upper bay, receives a considerable nitrogen load from its densely populated watershed. Upper Narragansett Bay shows the negative effects of excessive levels of nitrogen—dense macroalgal mats, summertime hypoxia, and benthic community changes [128]. Nitrogen enters the upper bay directly from three large WWTFs (Field's Point, Bucklin Point, East Providence) and from the rivers that enter the upper bay (Blackstone River with three WWTFs; Ten Mile River with two WWTFs; Woonasquatucket and Moshassuck Rivers with one WWTF; and Pawtuxet River with three WWTFs, Warwick, West Warwick, and Cranston) [129-131]. Although sewers and WWTFs keep nitrogen from entering ground water and streams, the effect of sewage systems is to concentrate nitrogen and potentially increase the proportion of nitrogen reaching the receiving waters [131].

Until the late 1800s, nitrogen input to upper Narragansett Bay was low; in 1865, a U.S. Coast Guard survey of the Providence River found eelgrass growing there, evidence of clear water and thus low nitrogen [130]. After the installation of Providence's public water supply system in 1871 and a sewage treatment facility at Field's Point in 1892, the input of nitrogen to upper Narragansett Bay increased greatly. One estimate of total nitrogen input to Narragansett Bay indicated about a 10-fold increase from 1865 to 1925, and then another 20% increase before leveling off in the 1980s [130]. Another research group estimated that nitrogen input to Narragansett Bay increased 250% from 1850 to 2000 [132]. Their model showed that nitrogen input to the upper bay increased far more than to the lower bay, and that the source of nitrogen shifted dramatically over time from animal (livestock) waste, which was dispersed over land, to human waste, which is concentrated at sewage treatment facilities. They estimated that in 1850 18% of nitrogen input to the bay was from human waste, 51% from animal wastes (horses, cows, sheep, and hogs), a negligible amount from fertilizer, and 31% from atmospheric deposition. Whereas, the estimates of nitrogen input for 2000 were: 51% from human wastes delivered through sewers, 14% from human waste from septic systems and cesspools, 2% from animal waste, 13% from fertilizer, and 20% from atmospheric deposition [132]. Given the exchange of water between Narragansett Bay and Greenwich Bay, water from upper Narragansett Bay has the potential to increase the amount of nitrogen in Greenwich Bay.

Effects of Nitrogen Pollution on Seagrass

Symptoms of eutrophication recorded in Greenwich Bay include: increased phytoplankton and macroalgal (seaweed) biomass [126], increased low dissolved oxygen in summer months [126], odor problems and decreased aesthetic quality [133], and loss of eelgrass [105, 134]. Eelgrass has specific light requirements and loss of eelgrass world-wide has been attributed in part to reduced light availability due to eutrophication [135, 136]. Eelgrass had been abundant in Greenwich Bay in the late 1800s and first half of the 1900s. According to personal interviews, eelgrass was just seen in limited areas of Greenwich Bay in the second half of the twentieth century: in the 1960s, between the mouth of Brush Neck and Warwick Coves and west of Sally Rock Point; in the 1970s to 1990s, north of Chepiwanoxet Point and west of Sally Rock Point [105]. A survey of eelgrass in Rhode Island waters conducted in 2006 found no eelgrass in Greenwich Bay [134]. However, since 2008 patches of another species of seagrass, *Ruppia maritima* L. (widgeongrass), have been noted on the northern shore of Greenwich Bay, extending west from the mouth of Apponaug Cove for about a quarter of a mile [137].

Effects of Nitrogen Pollution on Oxygen

Low dissolved oxygen (DO) occurs mostly in the summer, when conditions favor stratification of the water column, with less dense fresh water floating over denser salt water. These conditions occur with hot temperatures, low wind, and small tides that result in minimal mixing of the water column. Without mixing, the organisms near the bottom use up the oxygen, and hypoxia (low oxygen, less than 2 mg/L) or anoxia (no oxygen) can occur. Low DO concentrations affect aquatic organisms and can result in foul odors as sediments and water turn sulfidic. Dissolved oxygen concentrations of less than 4.8 mg/L for extended periods result in reduced abundance and diversity of aquatic life [138]. Fish and shellfish kills can occur at DO concentrations below 1.0 mg/L. In the 1920s, some low DO events had been recorded in Apponaug Cove. In recent years, there have been more recorded incidents of low oxygen in Greenwich Bay, mostly in the western end and in Apponaug Cove. Rhode Island Department of Environmental Management reported anoxic conditions in Apponaug Cove bottom waters in August 1986 due to a sudden die off of macroalgae [92]. A large fish kill (over 400 winter flounder) occurred at the mouth of Apponaug Cove in June 1989 [92]. Samples of DO taken in the summer months of 1995 to 1997 recorded low oxygen concentrations (less than 2 mg/L) in the near-bottom waters of Greenwich and Apponaug Coves and the extreme western end of Greenwich Bay [126]. RIDEM reported small fish kills in Greenwich Bay in July 1998 and 1999 and June 2001 [133]. A large fish kill occurred in Greenwich Bay on August 20, 2003. It was estimated that over one million animals died, primarily juvenile menhaden, but also small crabs, grass shrimp, tautog, horseshoe crabs, and American eels. Several weeks later, a large number of soft-shell clams died [133].

In Greenwich Bay wind conditions are an important factor in creating conditions that led to low oxygen levels. As early as the 1950s, researchers observed that during the summer, strong southwesterly winds were more important in moving sediment and plankton in Greenwich Bay than were tides [139]. A recent study indicated that southwesterly winds cause separate gyres in the western and eastern section of Greenwich Bay that trap the water in the bay and increase the residence time (time water remains in the bay) ten-fold over no wind conditions [140]. The severe hypoxic events in Greenwich Bay are likely the result of poor exchange of water with Narragansett Bay under these wind conditions [8]. Other studies also show the influence of Narragansett Bay water on Greenwich Bay. A model that simulated wind and tidal movement showed that, under certain meteorological conditions, water from upper Narragansett Bay flows around Warwick Neck and into Greenwich Bay [9]. Another model indicated that hypoxic events in Greenwich Bay were linked to low DO water entering the bay from upper Narragansett Bay [127]. The interactions between Greenwich Bay waters and Narragansett Bay waters are complex and variable, yet it is evident that water quality in Greenwich Bay deteriorated from 1945 to the present.

Response to Deteriorating Water Quality

What was the response to the deteriorating water quality conditions in Greenwich Bay during the Suburbanization Period? To correct bacterial pollution in the bay, sewer systems were extended and upgraded. Both East Greenwich and Warwick worked to improve their sewage treatment systems. In 1956, East Greenwich extended its sewer lines to include the Hill and Harbor District and added secondary treatment (trickling filters and chlorination) to its WWTF. In 1974, the sewer lines were extended further west as far as Route 2. In 1989, the capacity of the WWTF was expanded and the plant was upgraded to advanced secondary treatment. In the 1990s, the sewer lines were extended further to include most of the area east of Route 2. In 2004, the East Greenwich WWTF stopped using chlorination and used ultraviolet light to disinfect the wastewater. And in 2006, the WWTF was upgraded to tertiary treatment to remove nitrogen from the wastewater [73].

In 1965, Warwick completed building a WWTF with secondary treatment on the Pawtuxet River and installed a small core of sewer lines, all outside the watershed. After the 1992-93 closure of Greenwich Bay to shellfishing due to bacterial contamination, Warwick voters approved a bond issue to upgrade the WWTF and to expand the sewer system. Further upgrades and expansions of Warwick's sewage system occurred after the massive fish kill in 2003. An upgrade of Warwick's WWTF to tertiary treatment was completed in 2004. From 2006 to 2011, Warwick Sewer Authority worked on sewer construction projects in 13 neighborhoods, many of these adjacent to Greenwich Bay [141]. The Warwick Sewer Authority Facilities Plan of 2011 lists nine more future sewer construction projects. In 2006, the Warwick Sewer Authority implemented the Mandatory Sewer Connection Program. This program required all residents in sewered areas that are at high risk for bacteria and nutrients to reach Greenwich Bay to connect to the sewer lines by 2015. The five areas identified as having the greatest risk were the areas around Brush Neck Cove, Apponaug Cove, Warwick Cove, Buttonwoods Cove, and the west side of the bay along Post Road [141]. As of July 1, 2011, there were 12,141 available sewer line connections with 9,089 properties connected within the Warwick section of the watershed. Since some of the sewer connections (1,536) front vacant lots, the connection rate to sewers within the watershed was 85.7% [142]. However, there are still 6,933 houses within the watershed that do not have access to sewers and rely on septic systems or cesspools for disposal of domestic wastewater [143].

Closure of the bay to shellfishing in 1993 prompted the formation of the Greenwich Bay Initiative (GBI). The purpose of this program, involving many agencies and organizations, was to assess the physical conditions within the watershed and their impact on the water quality of Greenwich Bay. The fish kill in 2003 and the desire to continue the work of the GBI led to the creation of the Greenwich Bay Special Area Management Plan [7] to assess the condition of the bay, identify sources of pollution, and make recommendations on how to "work with communities to restore, protect, and balance the uses of Greenwich Bay" [144]. While much work remains to be done, history has shown that the public is willing to invest in infrastructure to improve water quality in Greenwich Bay.

Fisheries

There have been effects on the fisheries in Greenwich Bay besides those of water quality. By 1981 overfishing had deteriorated the quahog fishery in Greenwich Bay [145]. To restore the fishery, RIDEM declared Greenwich Bay a shellfish management area, closed it to shellfishing for two years, and restocked the bay with transplants from Greenwich Cove. When Greenwich Bay was reopened in the winter of 1982-83, the quahog fishery was managed by reducing the daily catch limit and limiting commercial fishing from boats to just the winter months [145].

Fish abundance data for just Greenwich Bay are limited. In 1993, a study by RIDEM indentified 41 species of juvenile and adult fish in Greenwich Bay. The most abundant species were bait fish, but several other species of interest to recreational fishermen (alewife, bluefish, winter flounder, striped bass, and tautog) were considered common. A study that used fish data collected in Narragansett Bay showed that, in general, fish stocks declined during the second half of the twentieth century [111]. Comparison of the contents of fish trawls taken in 1960 and 2000, showed that abundance and species composition of fish in Narragansett Bay changed over this time [111]. Abundance of northern species, such as winter flounder and northern sea robin, decreased. Abundance of all bottom fish (for example, tautog, flounders, skate, sea robins) decreased, while abundance of some pelagic fish, such as bluefish and butter fish (but not scup), increased. As the bottom fish decreased, blue crabs, lady crabs, cancer crabs, and lobsters increased. These changes may be the result of fishing pressure, climate (warmer winter water temperatures), or both [111]. Although these data are from Narragansett Bay, similar changes most likely occurred in Greenwich Bay.

Marinas and Boating

Greenwich Bay and its coastline historically have been important for boating-related commercial and recreational activities, and the increased population during the Suburbanization Period brought many more recreational boaters to the bay. From 1978 to 2005, the number of marinas and yacht clubs in Greenwich Bay increased from 19 to 33, and the number of boat slips increased from 2,391 to 3,419 [7]. To see the increase in marinas from an earlier time, 1950, we looked at historical aerial photos (RIGIS, 1939 to 2003). Since not all the photographs were clear enough to count individual boat slips we measured dock length as an indicator of growth in marinas and boating (Fig. 12). The 1939 aerial photographs had no docks, only five large boats (probably at a shipyard) on the northern shore of Greenwich Cove, and numerous moorings in Greenwich,

In the last half of the twentieth century, marinas have filled Warwick Cove. (Photo by Christopher Deacutis, Narragansett Bay Estuary Program)

Apponaug, Warwick, and Brush Neck Coves. It is not surprising that no docks were visible in the 1939 aerial photographs because docks in Greenwich Bay had been badly damaged in the 1938 hurricane, which subjected the bay to flood tides 13 feet above normal high water [77]. The number of linear dock feet, which included marinas, yacht clubs, and commercial and private docks, increased 37-fold from 1,143 ft in 1951 to 42,716 ft in 2003. Most of the docks were in marinas (62% in 1951, 82% in 1962, and 87 to 96% in later years). Warwick Cove had the greatest linear feet of docks, 47% of the total in 2003.

What are the effects of boating and marinas on the bay? The majority of boats using Greenwich Bay are power boats [146]. Power boats can be noisy (disrupting birds and other fauna) and disturb bottom sediments and aquatic vegetation in shallow areas. Petroleum hydrocarbons from boat engine exhaust and oily bilges can pollute the water and sediment. Discharge of sewage from boats can introduce disease-carrying bacteria and viruses to the water. Greenwich Bay is a no-discharge area for boats, and marinas have pump-out stations, but illegal discharge probably still occurs. Sewage from boats is worse than from other sources because it is more concentrated, and might contain treatment chemicals that disinfect the waste or control odors [147].

The concentration of boats at marinas can cause pollution problems. The construction of a marina limits water circulation, and thus concentrates pollutants in the water column and sediment [147]. Chemicals used in boat maintenance (oil, acid from batteries and cleaning compounds, surfactants, and solvents) can wash down into the water if best management procedures are not used to contain them [147]. Potentially toxic metals can be released from a number of marine operations: copper and tributyltin (banned since 2003) in antifouling paint; arsenic in boat paint pigments; and arsenic, chromium, and copper from docks, pilings and other structures built with chromated copper arsenate-treated wood [147]. Spills of gasoline, diesel fuel, and oil while fueling, petroleum hydrocarbons from boat engine exhaust, and oily bilge water can contaminate water and sediments. A study of PAHs (compounds commonly found in petroleum oils) in surface sediments in Warwick, Brush Neck, Apponaug, and Greenwich Coves found that the cove sediments had higher concentrations than sediment taken from the middle of Greenwich Bay [81]. The concentrations of PAHs in cove

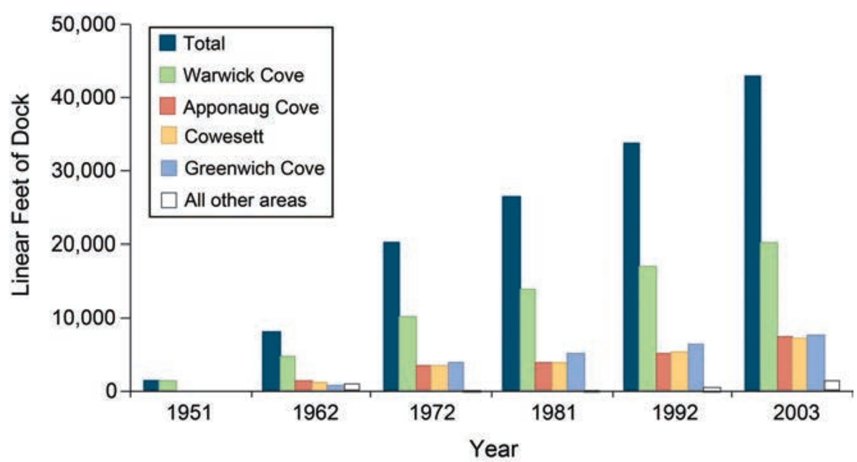


Figure 12. Length of docks (marinas, yacht clubs, commercial, and private docks) in Greenwich Bay measured from historical aerial photographs (RIGIS).

sediments were above the concentration at which occasional adverse biological effects could be expected [81]. Concentrations of PAHs are generally higher in coves than the open bay because the coves are closer to the potential sources—marinas, runoff, and sewers.

When marinas are built, habitat is lost. On the shore, wetlands and vegetated buffers are destroyed, and in the water, bottom fauna (for example shellfish) is disrupted by the initial building of docks and by regular maintenance dredging. The hard surfaces of docks, pilings, and other structures provide habitat for fouling organisms that otherwise would not have been there. The ecological effects of marinas have not been well studied. A study in Wickford Harbor, RI, comparing a marina area to a small salt marsh cove found no major differences in a number of ecological indicators measured; however, concentrations of copper (from antifouling paint) in sediments were higher in the marina area [148]. The fish species were found to be just as diverse at both areas. The fouling communities on the docks at the marinas appeared to be a source of food for the small fish, but did increase the oxygen demand of the marina cove water [148]. Shellfishing is not permitted at marinas but this has had a positive effect on the quahogs in Greenwich Bay. The shellfish beds under the marinas serve as a source of brood stock for the rest of the bay [7]. Other positive aspects of marinas include providing recreational boating opportunities, adding to the economy, and providing pump-out facilities for boats.

The increase in the number of marinas and the sizes of boats popular today has increased the need for dredging the marinas and the channels to them. There are three federal channels in Greenwich Bay: the entrance to Greenwich Cove, last dredged in 1891; Warwick Cove, last dredged in 1966; and Apponaug Cove, last dredged in 1963. The dredge spoils from the 1963 dredging of Apponaug Cove were used to fill a tidal flat that now serves as a parking lot for recreational boaters and fishermen [47]. The channel in Apponaug Cove is shallower than its authorized depth, but is a low priority for dredging because the cove is used primarily for recreational, not commercial, uses. The channel in Warwick Cove is at depth, but according to boaters the current channel location is dangerous to navigate [7]. The ecological issues with dredging are the turbidity that is created during dredging and the options for disposal of the dredged material. Turbidity can negatively affect shellfish, fish (especially during breeding season), and seagrass beds, and can change the bottom substrate. Options for disposal of dredged materials within Greenwich Bay are limited [7]. The material used for beach nourishment has to be relatively clean and of a certain grain size [7]. Sediments from marinas need to be tested for contaminants, and disposal options can be expensive.

Summary of Suburbanization Period

During the Suburbanization Period (c. 1945 to present), the ecological effects on Greenwich Bay were caused primarily by the increased number of people in the watershed. Farmland was converted to residential and commercial uses, causing an increase in the amount of impervious surfaces in the watershed. More people meant more sewage, more individual septic systems, more stormwater, and thus more bacteria to contaminate the bay. Bacterial contamination caused additional areas to be closed to shellfishing and caused some beach-closure days. Increased input of nitrogen to the bay resulted in eutrophication and low oxygen at times during the summer months, which caused fish kills. Eelgrass, an important habitat for scallops and other biota, declined and is no longer found in the bay. Scallops are gone. Overfishing depleted the quahogs in Greenwich Bay; however, management of this fishery restored its viability. Hardened shorelines and groins have helped protect the northern shoreline of Greenwich Bay from erosion, but may give residents a false sense of security for protection from major storms. The increase in number and size of marinas has contributed to an increase in hardened shoreline, destruction of vegetated buffers and fringe wetlands, affected water circulation patterns around the docks and slips, and contributed to sediment pollution in the marina areas.

In the 1890s, a shipyard was located on the shore of Greenwich Cove just north of Division Street. Over the years it was known by a number of different names. In the early 1900s, it was called Nock's Shipyard, as depicted in this postcard. Chepiwanoxet Island is visible in the background. (Bruce MacGunnigle, private collection)

This contemporary photograph shows Norton's Shipyard & Marina, which is now located at the same site. The Norton family has owned the shipyard since 1966. The docks have been extended and the boats are considerably larger now. About 1915, fill was added and a causeway built to connect Chepiwanoxet Island to the mainland. Chepiwanoxet Point is visible in the background. (Photograph by John Butler)

Summary

The presence of humans has clearly had ecological effects on Greenwich Bay and its watershed, especially in the last 150 years. The major events and known ecological effects are summarized in Table 8 and Figure 13. In the Pre-Colonial Period (before 1650), the native people utilized the abundant natural resources available in Greenwich Bay and its watershed—fish, shellfish, mammals, plants, trees, clay deposits, and fresh water. They modified the terrestrial habitat by clearing underbrush from the woods to facilitate hunting. The decrease in shell size found at an archeological site indicates that populations of shellfish could have been affected by human harvesting. In the early 1600s, loss of beavers, due to the fur trade, and consequently loss of their dams might have caused an increase in sediment in the coves. However, the ecological effects of prehistoric peoples and Native Americans on Greenwich Bay were probably minimal. There are no published scientific studies that show that this human activity had a measurable effect on the bay.

During the Colonial Period (c. 1650 to c. 1750) the settlers in the watershed cleared land, planted crops, and grazed animals. They utilized the natural resources of the bay and watershed; they fished, collected shellfish, and harvested salt marsh hay for their livestock.

Table 8. Summary of the major ecological effects of development on Greenwich Bay.

Pre-Colonial Period – before 1650	
• Natives cleared underbrush	Minimal impact
• Utilized marine resources, fish, shellfish	Minimal impact
• Fur trade, loss of beaver	Might have increased sedimentation in coves
Colonial Period – c. 1650 to c. 1750	
• Cleared land, farmed	Probably increased sedimentation
Maritime Period – c. 1730 to c. 1820	
• Cleared more land	Evidence of sedimentation in Apponaug Cove
• Built wharfs	Some changes to shoreline, loss of habitat
Industrial Period – c. 1800 to c. 1945	
• Population increased, more sewage	Bacterial contamination; shellfish bed closures
• Industries	Chemical contamination of water and sediments
• Built dams	Obstructed anadromous fish runs in streams
• Building of Stonington Railroad	Contributed to sedimentation
• Overfishing in Narragansett Bay	Depleted fish stocks, probably also in Greenwich Bay
Suburbanization Period – c. 1945 to present	
• Population doubled, more sewage	Bacterial contamination; shellfish bed and beach closures
• Nitrogen input increased	Eutrophication; low DO; loss of eelgrass and scallops; fish kills
• Development of shoreline areas	Loss of natural shallow water habitats and vegetated buffers

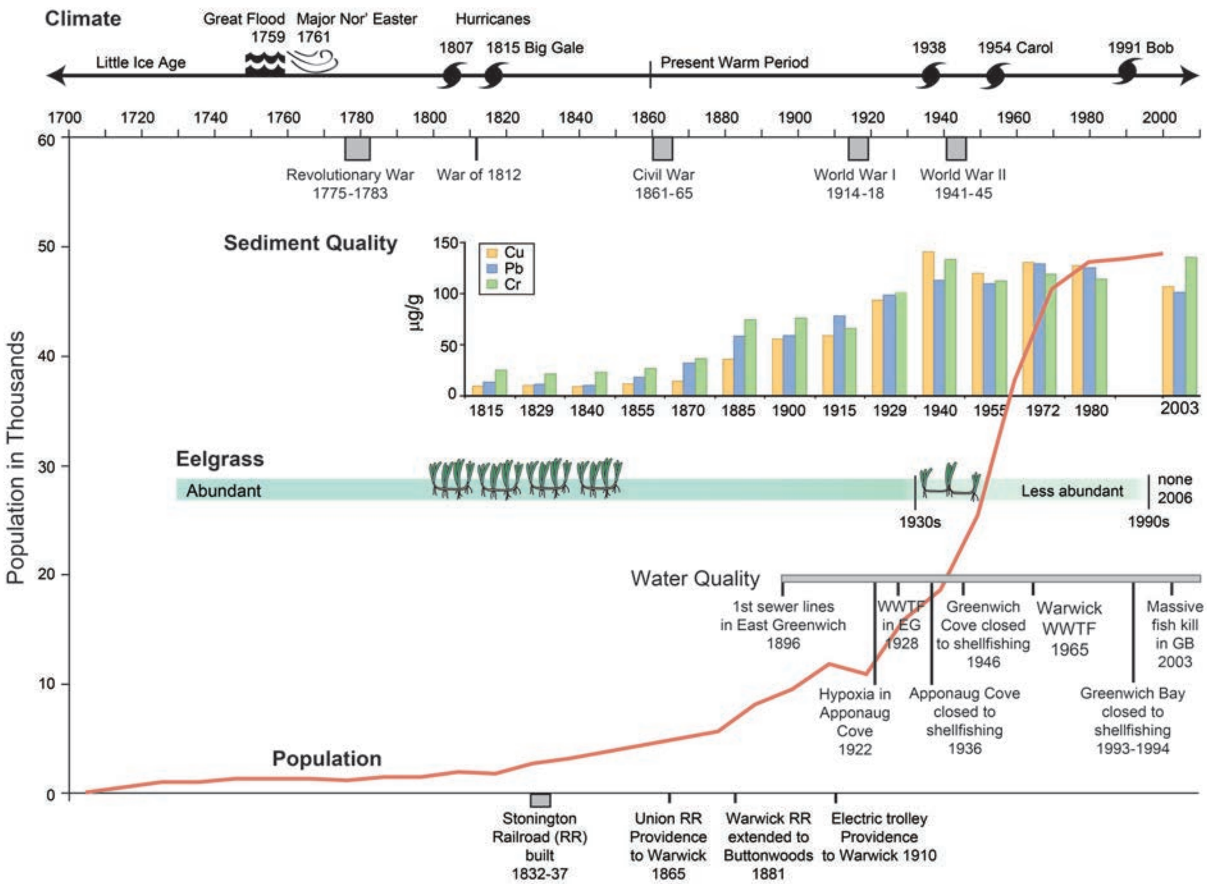


Figure 13. Timeline showing the population of the Greenwich Bay watershed, local and national events, and some environmental trends in the bay. Population was estimated for the watershed using the road density method (see text). Metal concentrations for 1815 to 1980 are from a core taken in the middle of Greenwich Bay [78]. Metal concentrations for 2003 are from a surface grab sample (BSP 233) taken in the middle of Greenwich Bay [81].

They maintained woodlots for firewood and lumber. Fresh water from springs and wells supplied them with drinking water. The amount of land cleared during this period probably increased sedimentation in the bay.

As the land for farms became limited within the watershed, the maritime economy grew. During the Maritime Period (c. 1730 to c. 1820) the waters of Greenwich Bay became more important as a means of transportation. There were some changes, although not major, to the coastline as wharfs were built and shorelines hardened. As more land was cleared there was evidence of increased sedimentation, especially in upper Apponaug Cove.

During the Industrial Period (c. 1800 to c. 1945), especially after 1850, human activity caused measurable ecological effects on Greenwich Bay (Fig. 13). From 1810 to 1950, the estimated population of the watershed increased 13-fold. This caused a great increase in the amount of sewage. Sewer lines were installed in the densely populated section of East Greenwich. Water was piped into homes, which probably caused privy vaults and cesspools to overflow. The bay waters became polluted with fecal bacteria, and Greenwich and Apponaug Coves were closed to shellfishing. Industries in the watershed polluted the bay with chemicals. Episodes of low oxygen occurred in Apponaug Cove. Building of the Stonington Railroad probably contributed to sedimentation in Greenwich Cove. The upper end of Apponaug Cove was divided by the railroad bridge, causing changes in circulation and sedimentation patterns. Dams built on Apponaug and Hardig Brooks and the Maskerchugg River obstructed the passage of anadromous fish. Overfishing depleted the fish stocks in Narragansett Bay and probably affected fish in Greenwich Bay.

During the Suburbanization Period (c. 1945 to present) the ecological effects on the bay were caused primarily by the increased number of people in the watershed. From 1950 to 2000 the population in the watershed doubled. Farmland was converted to residential and commercial uses. The large increase in population led to more sewage, more individual septic systems, more stormwater runoff, and thus, more bacteria to contaminate the bay. Bacterial contamination caused additional areas to be closed to shellfishing and also caused some beach-closure days. Increased input of nitrogen to the bay resulted in eutrophication, which caused low oxygen at times during the summer months, which in turn caused fish kills. Eelgrass, an important habitat for scallops, declined and is no longer found in the bay. Scallops are also gone. These ecological problems prompted the formation, in 1993, of the Greenwich Bay Initiative (GBI), which assessed the physical conditions in the watershed and their effect on water quality. In 2005, efforts started with the GBI were continued with the creation of the Greenwich Bay Special Area Management Plan that updated the assessment of physical conditions in the watershed, identified pollution sources, and included recommendations for restoring and protecting Greenwich Bay. Recent models of water circulation patterns indicated that under certain conditions water from upper Narragansett Bay could be swept into Greenwich Bay and probably affect some conditions, such as the amount of nitrogen in the bay. This suggests that in addition to managing pollution within the Greenwich Bay watershed, better management of environmental conditions in Narragansett Bay, especially in the upper bay, is needed to protect waters in Greenwich Bay.

Studies of environmental history are important. This ecological history of Greenwich Bay enables us to see the connection between development in the watershed and effects on the ecology of the bay. People have short memories. Today, citizens of the watershed see the abundant quahog harvests, but they might not know that over one hundred years ago the bay was filled with eelgrass and had a productive scallop fishery. This history allows us to appreciate the natural resources that were present in the bay before the major impacts of the last 150 years. Environmental conditions have been changing since initial European settlement, and we can expect additional changes in the future. Sea-level rise (more flooding), climate change (increase in severity of storms, warmer water temperatures), and contamination from chemicals of emerging concern (see Appendix B) will pose new challenges. The response to these challenges, whether toward a cleaner, healthier environment or toward continued degradation, will depend on the management decisions made at the local and regional levels. The plans for the continuing improvements to Warwick's sewage system, along with the other recommendations in the Greenwich Bay Special Area Management Plan, and improvements in water quality in upper Narragansett Bay could prevent or decrease negative ecological impacts in the future. This historical analysis of Greenwich Bay provides information for scientists, managers, and citizens on the consequences of development and gives managers a foundation on which to make informed decisions for the future.

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Appendix A: Short How-to Guide on Historical Reconstruction of Ecological Effects

Visit the area – Drive around the area and get to know the residential, commercial, and industrial areas. Look for old buildings and learn the location of the "old section" of town. Also look for the undeveloped areas and parks.

Become familiar with local history – Use the resources at local libraries, local historical societies, and online to learn the local cultural history. State historical preservation commissions may also have written reports on individual towns. Initially, concentrate on sources that give the big picture. You can go back and get the details later. A great deal of written material can now be found online using Google, Google Books, and other search engines. The full text of older books that are out of copyright can sometimes be found online (try Google Books).

Look at old maps of the area – Locate facilities (local library, local and state historical societies, university libraries, state library, and state archives) that have historical maps of the area of interest. Search online for digital versions of old maps. Panoramic or bird's eye view maps, generally dating from the mid 1800s to 1920s, are useful to get a feeling of development and topography of the town or city depicted. To assess changes in coastlines and wetland area, compare those features on older maps to current maps. This can be done by using a geographic information system (GIS). Some useful web sites are: NOAA Office of Coast Survey Historical Maps and Charts (http://www.nauticalcharts.noaa.gov/csdl/ctp/abstract.htm); Library of Congress Map Collection - panoramic maps, Sanborn Fire Insurance Maps, and many others (http://memory.loc.gov/ammem/gmdhtml/gmdhome.html); and Historic Maps of New England (http://docs.unh.edu/nhtopos/nhtopos.htm).

Photographs – Look at old photographs of the area to see what the area looked like in the early 1900s. Historical societies are usually good sources of old photographs. Some publishing companies (e.g. Arcadia Publishing) have published books on local or regional history with many old photographs. Some state geographic information systems (e.g. Rhode Island GIS) have historical aerial photographs.

Research former industries – Local boards of trade reports and town or city directories list industries and businesses. The Sanborn Fire Insurance Maps show locations of former industries and may indicate the industrial processes or types of materials stored in the buildings (see the Library of Congress Map Collection listed above for Sanborn Maps). History books written in the late 1800s about specific local areas usually have sections on the early businesses and manufacturers.

Research city and state health reports – Check state libraries or search online for state or city Department of Health reports to learn of "nuisances" (odor problems from sewage or other sources) or outbreaks of diseases that may be related to environmental conditions. For example, an outbreak of typhoid in New Bedford, MA in 1900 to 1903 was caused by consumption of contaminated shellfish.

Research city, state, and government engineering reports – Search online or check state libraries for old engineering reports and check city halls for Board of Public Works and Department of Engineering reports to learn about possible environmental effects.

Census Reports – The federal government has conducted a census every 10 years since 1790. The census is divided into "schedules" with different kinds of information: the population schedule has data about households; the agricultural schedule has data about crops and land use; and the manufacturing schedule has data about raw materials, labor, and factory production. The later censuses, after 1850, tend to have more data. States may also have conducted censuses in other years. Census reports can be found in state archives or state libraries, and often at university or large public libraries.

Newspapers – Old newspaper articles are a good way to see what issues were important to residents. Check local newspapers to see if they maintain a library of past articles. Newspaper articles can often be found on microfilm at local libraries. Google News Archives has listings of some old newspaper articles.

Find scientific data – Conduct a literature search for historical scientific information. If sediment cores have been taken in the area, the report may include information about past contaminants and vegetation (from pollen analysis). The reference listed below has a chapter on where to find historical written records, including those containing ecological information.

Make a time line – Make a time line with population and significant local, regional, and national events. Add time series data such as number of industries, fish and shellfish landings, contamination data, and any environmental data that shows changes over time. A time line will help put local events in perspective and give an understanding of why development occurred as it did. It will also help to identify time periods associated with development and the resulting environmental effects.

Each area has its own unique history – Use that as a guide to identify the environmental effects associated with development of the area.

Reference – A useful book on where to find information is "The Historical Ecology Handbook: A Restorationist's Guide to Reference Ecosystems" edited by Dave Egan and Evelyn A. Howell, 2001, Island Press. There are chapters on where to find written records, maps and photographs, and land survey reports, as well as chapters on tools used to reconstruct historic ecosystems, and four case studies.

Appendix B: Contaminants in the Environment

There are two issues to consider about environmental contaminants: fate —what happens to the contaminant when released to the environment; and effect—what kind of damage is done. Some contaminants are short-lived and affect only the immediate area for a short time, while others persist in the environment for decades. Chemical contaminants can remain at the area of release or can be transported to other locations. For example, some chemicals adsorb to soil particles and persist there for decades; while other chemicals leach into the ground water or adjacent streams, rivers, and lakes, and are transported away from the site of disposal. Soil type also affects the fate of chemicals. For example, sand is highly permeable, so water can pass through it readily and carry contaminants into the ground water. Clays are less permeable (liquids filter through slowly), so surface runoff carries the contaminants into nearby water bodies. Many chemicals adsorb to the organic fraction of soils. Chemicals dumped into water bodies may be adsorbed by the bottom sediments, and persist for decades. Chemical contaminants emitted into the air can be carried miles by prevailing winds.

The effect of any chemical contaminant depends on its toxicity and the quantity released. At high concentrations, contaminants dumped into water bodies can cause acute toxicity (death) to aquatic organisms, whereas, at lower concentrations they can cause chronic effects, such as decreased growth rate, reduced number of offspring, nervous system disorders, or accumulate in the tissues of the exposed organisms. Edible species can accumulate high enough concentrations of certain chemicals that they pose a threat to human health. For example, large fish at the top of the food chain accumulate mercury, and consumption of these fish should be limited, especially by children, pregnant women, and people with certain health issues. Since some species of plants and animals are more sensitive than others, pollutants can cause changes in the species composition by affecting the more sensitive species, while the more tolerant ones survive.

The fate and effect of groups of contaminants can be described in general terms; the particular effect of a contaminant depends on the individual chemical or mix of chemicals, the amount released, and the physical characteristics of the disposal site. The general characteristics of some groups of chemicals are listed below. Some, but not all, of the individual chemicals within these categories are regulated (i.e., the amount that can be released into the environment is limited).

Emerging Contaminants (or contaminants of emerging concern) are new chemicals or chemicals that have been used for decades, but only recently have been found to be widespread, in small amounts, in ground water and water bodies. New analytical techniques have enabled scientists to measure extremely small amounts of these chemicals in the environment. Emerging contaminants are often present in pharmaceutical or personal care products, such as detergents, fragrances, prescription and nonprescription drugs, veterinary drugs, disinfectants, cosmetics, lotions, and insect repellents. Sources of these chemicals are runoff from agricultural land, wastewater from sewage treatment facilities, and discharge from individual septic systems. These chemicals are not environmentally regulated, and sewage treatment facilities are not designed to remove them. The risks of emerging contaminants to public health and the environment are uncertain because the concentrations are low, but they are often designed to be biologically active. Two classes of these chemicals are especially troubling: endocrine disrupters and antibiotics. Endocrine disrupters mimic hormones. In living organisms, only small amounts of hormones are needed to control metabolic activity. Sexual abnormalities have been found in fish in streams with endocrine disrupters. With the addition of antibiotics to the environment, there is a risk of developing antibiotic resistant strains of bacteria, as well as inadvertently changing natural communities of bacteria, which could result in unknown consequences.

Metals can be toxic and can be accumulated by organisms. Metals absorb to sediments, persist in the environment, and have been widely used in many industrial processes. Cadmium, lead, mercury, and arsenic are some of the more commonly known metals that cause health problems. Children are particularly susceptible to metal toxicity because of the routes of exposure (e.g. putting things in their mouths, crawling around on the floor), their rapidly developing bodies, and small size.

Petroleum hydrocarbons are comprised of hundreds of organic compounds derived from petroleum. Toxicity and persistence depend on the particular fraction of petroleum. Some petroleum fractions are volatile (evaporate easily), and although these compounds are toxic, they usually are not harmful to organisms because they do not persist in the environment. Whereas, other fractions are not very reactive, persist in the environment, and are toxic. Oils and grease are general terms for some petroleum hydrocarbons.

Pesticides are chemicals that prevent, destroy, or repel any pest. The term pesticide refers to insecticides, herbicides, fungicides, also plant regulators, defoliants, or desiccants, and any other chemical used to control pests. Pesticides are used commercially on farms and nurseries, and by exterminators and lawn care companies, but are also available for household use. These chemicals are deliberately designed to be toxic and affect both target and non-target species.

Phenols are a particular group of organic chemicals that vary in toxicity and tend to be less persistent in the environment.

Solvent is a term that indicates a group of chemicals distinguished by their industrial use, not chemical structure. They are usually organic chemicals. Solvents vary in toxicity and persistence in the environment.

Acids can cause acute effects in the immediate vicinity of disposal, however, acids are quickly buffered and generally do not persist in the environment.

Cyanides are highly toxic and persistent in the environment. They were used by a number of industries in the 1800s but are now regulated.

Caustic cleaning agents are highly toxic. They can cause acute effects in the immediate disposal area, but do not persist in the environment.

Biological waste can cause acute, short-term effects when disposed in water. Biological waste contains organic matter, which consumes dissolved oxygen (DO) when it decomposes. The amount of DO in waters can be lowered so much that resident plants and animals cannot survive.

Nutrients, nitrogen and phosphorus, are natural chemicals. They stimulate plant growth and are necessary for healthy ecosystems. However, when human activities increase nutrients to excessive levels, a series of negative ecological effects can result. Too much nitrogen in marine waters or phosphorus in fresh water causes eutrophication, the excessive growth of algae. Eutrophication causes low dissolved oxygen in bottom waters as the algae die, sink to the bottom, and use up the oxygen in the process of decaying. Low dissolved oxygen levels can affect aquatic organisms and cause fish kills.

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