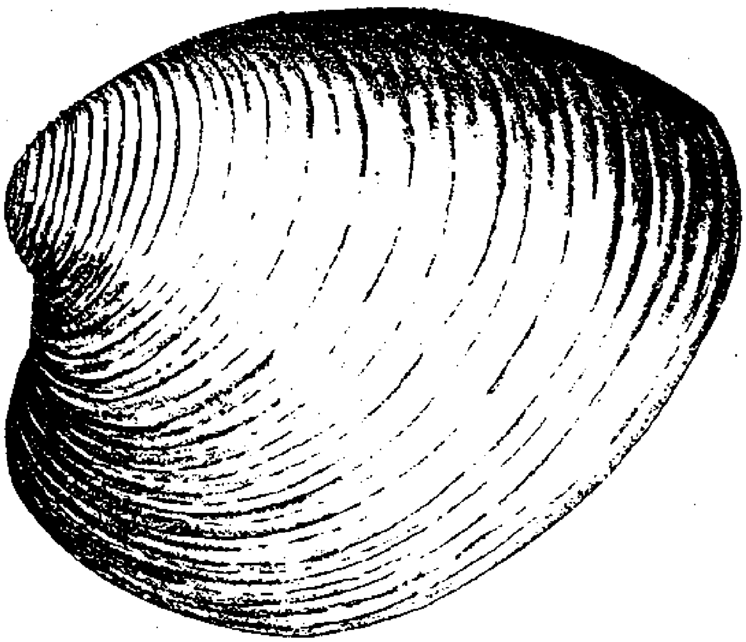
A SPECIES PROFILE OF THE QUAHOG IN RHODE ISLAND

Sheldon D. Pratt
Arthur R. Ganz
Michael A. Rice

1992



Rhode Island Sea Grant

Rhode Island Cooperative Extension

A Species Profile of the Quahog in Rhode Island

Sheldon D. Pratt
Graduate School of Oceanography
The University of Rhode Island
Narragansett, RI 02882-1107

Arthur R. Ganz
Division of Fish and Wildlife
Department of Environmental Management
State of Rhode Island
Stedman Government Center
Wakefield, RI 02879

Michael A. Rice
Department of Fisheries, Animal and Veterinary Science
The University of Rhode Island
Kingston, RI 02881

Prepared for
Rhode Island Sea Grant Program

April, 1992
$10.00

Major funding for this report has been provided by Rhode Island Sea Grant Marine Advisory Service under grant number NA-89-AA-D-SG-082. This is Rhode Island Sea Grant publication RIU-T-92-001 (P-1272). Partial funding of this report was provided through Rhode Island Cooperative Extension and the Rhode Island Agricultural Experiment station project H-840. This is publication 2726 of the College of Resource Development, The University of Rhode Island.

Table of Contents

A Species Profile of the Quahogs

1. Introduction

The quahog is a resource of major economic importance in Rhode Island. It is also the most important commercial species that is managed solely by the state. Most of the catch comes from Narragansett Bay. Throughout the state large areas of potentially productive beds are closed because of poor water quality. The need to protect areas presently harvested and to expand harvested areas has been an important argument in recent and projected future upgrading of sewage treatment in Rhode Island.

During the first phase of the Narragansett Bay Project (NBP) (1985-1990), a series of studies were supported on quahog abundance in closed portions of the Bay and on the condition of quahogs in closed and open parts of the Bay. The NBP also supported literature reviews of important pollutants in the waters, sediments, and organisms of the Bay. While summary reports have been completed on the safety of quahogs for consumption (Kipp 1991a; 1991b) and problems of contamination by pathogenic microbes (Roman 1990), the NBP reports are often large, do not focus specifically on quahogs, and, in some cases, need additional interpretation to be of use to fishery managers.

The Rhode Island Department of Environmental Management, Division of Fish and Wildlife, Marine Fisheries Section is presently preparing species profiles of important marine finfish. These profiles bring together information that will be accessible to fishermen and fisheries managers and that will identify data gaps that might be the subject of future research.

Funding by Rhode Island Sea Grant has made it possible for The University of Rhode Island staff with long-term interests in quahog biology to synthesize information in a form that can be combined with data from DEM to provide a species profile. URI research has emphasized quahog biology, including natural history, physiology, ecological aspects and the effects of pollution. Division of Fish and Wildlife research has emphasized the population ecology and the fishery. There are large numbers of quahog fishermen who take an active interest in the management of their fishery. It is hoped that this profile will become a source of information to these individuals, as well as to fisheries managers and environmental planners.

Acknowledgements

The authors wish to acknowledge the assistance of Sgt. Anne D. Holst of the DEM Division of Enforcement, who provided information about enforcement activities. A special thanks to Ms. Carole Jaworski of the Rhode Island Sea Grant Communications office for her editorial comments on the manuscript.

2. Introduction to the Species (Stanley and DeWitt 1983; Abbott 1974)

2.1 Nomenclature

Scientific name - Mercenaria mercenaria (Linné 1758); before 1957 - Venus mercenaria Linne (Wells 1957a). Mercenaria mercenaria notata (Say) is a form with brown zigzag mottling on the exterior of its shell (Chanley 1961).

Common name - The recognized malacological common name is "northern quahog." It is known as "quahog" or "quahaug" in the northern United States; "hard clam" in the southern United States and in most research reports. In Rhode Island, market names include "littlenecks," describing the smallest legally sold animals (>48mm valve length); "cherrystones" for intermediate-sized animals (>60mm valve length; and "chowder quahogs" for larger animals (>75mm valve length). In other localities outside Rhode Island, the name "cherrystone" can refer to the smallest legally harvested animals. Other market names include "topnecks" and "top cherries" for intermediate-sized animals.

2.2 Taxonomy (Barnes 1974; Pechenik 1991)

Kingdom - Animalia
Phylum - Mollusca
Class - Bivalvia (Pelecypoda)
Subclass - Lamellibranchiata
Order - Heterodonta
Family - Veneridae
Genus - Mercenaria
Species - Mercenaria mercenaria (L.)

2.3 Range - Intertidal and subtidal bottom to depth of about 15m (50 feet) from the Gulf of St. Lawrence to Florida. Subspecies M. mercenaria texana is found in the Gulf of Mexico (Craig and Bright, 1986). Quahogs are most abundant from Massachusetts to Virginia.

2.4 Identification - Quahogs attain sizes up to 130mm (5 inches) in length, are ovate-trigonal in shape, and have heavy and thick shells. Sculpture of the shell consists of concentric lines of growth. In juveniles, these concentric ridges are shelf-like and well separated. The shell interior is white with variable degrees of purple staining, especially along the inner posterior shell margin. Usually there are fine teeth along the ventral inner margins of the shell. The thin periostracum differs in color from tan to black, depending on substrate type.

2.4.1 Mercenaria mercenaria subspecies notata

M. mercenaria subspecies notata is a variant with chestnut-brown zigzag lines (frequently chevron-shaped) on the outside of the shell. This form is found throughout the range of the northern quahog (Abbott 1974). Chanley (1961) demonstrated that the *notata* color pattern is controlled by a single gene or by closely linked genes that are inherited as a unit. The zigzag shell pattern is the heterozygous form found in individuals with one gene of a pair positive for *notata*. Homozygous individuals with two *notata* genes are almost solidly colored chestnut-brown with wide light bands running from the umbo to the ventral margin.

In two southern field studies, heterozygous *M. m. notata* were found in 0.77% and 1.12% of populations (Humphrey and Walker 1982). The frequencies of the *notata* form in Rhode Island is not known but is probably not more than 1%. Individuals with markings are most easily detected among light-colored young individuals growing in sandy areas. Markings may be present but not detectable in larger individuals with black or eroded shells.

Several researchers have suggested that *M. m. notata* quahogs could be used to identify experimental stocks selected for traits such as rapid growth. The majority of cultured quahog stock produced in New England have *notata* markings, but no difference in growth rate or viability have been detected between cultured *notata* and cultured non-*notata* stocks.

2.5 Related species - *Arctica islandica*, the ocean quahog or mahogany clam, also reaches 130mm in valve length, but is circular in outline, and has a thick black periostracum. It is abundant on the continental shelf, and extends into deep portions of the East Passage of Narragansett Bay.

Pitar morrhuanus, the false quahog, widgeon clam or duck foot clam, reaches 40mm (1.5 inches) in valve length. It is similar to small quahog but has a muddy periostracum and no shelf-like juvenile ridges. The inner surfaces of the shell are gray, and they do not have marginal teeth. They are found in the deeper portions of Narragansett Bay, especially in clayey, silty sediments (Pratt 1953).

The southern quahog, *Mercenaria campechiensis*, is very similar to the northern quahog, but it ranges from southern New Jersey to Mexico. The external shell sculpture of *M. campechensis* is rougher in texture than *M. mercenaria*. There is evidence of hybrids between the two species, especially in the southern range of the northern quahog (Dillon and Manzi 1989).

3. Natural History

3.1 Anatomy

3.1.1 Gross anatomy

Shell parts and tissues referred to in this report are identified in a series of illustrations taken from Shuster (1969) and Pechenik (1991) (Figure 1). The illustration of the shell exterior is oriented in the position of animals within the sediment with the posterior siphons at the sediment surface. On the exterior of the shell, concentric ridges are thin and elevated in juveniles and often eroded away in the umbo region of adults. The lunule is a heart-shaped depression that can be seen along the anterior face. The periostracum is the thin proteinaceous layer covering the outside of the shell (yellow in young individuals in sand, black in quahogs from muddy bottom, and often eroded from the umbo of older individuals).

Features of the shell interior include a toothed margin, the pallial line where the mantle is attached to the shell, muscle scars, hinge teeth, and the flexible ligament that holds the shells together. The shell is usually nacreous (pearly) outside the pallial line (middle layer) and chalky within it (inner homogeneous layer).

The mantle lines the interior of each shell. The mantle secretes the shell and forms the siphons. Note that the mantle does not have contact with the shell at the muscle scars and thus cannot secrete shell at that location.

The gills cover the dorsal portion of the body mass. The transverse section shows that they are double and within the space between body and mantle. The muscular foot is ventral. The mouth is opposite the siphons so is downward when the animal is in feeding position. The palps manipulate food caught by the gills and carry it to the mouth.

Within the viseral mass food enters the stomach where digestion begins with enzymes released by the crystalline style, a gelatinous rod seen in fresh quahogs. Food particles are digested and taken up within the digestive gland (liver), which is surrounded by gonad tissues. The intestine leaves the body through the pericardial cavity and the heart. The kidney is located behind and beneath the pericardial cavity. The heart and kidney form a dark area at the top of the viseral mass.

3.1.2 Shell

3.1.2.1 Size conversions A variety of shell measurements have been used in scientific studies and in management of the fishery. The following conversions from Stanley and DeWitt (1983) are used to convert from one

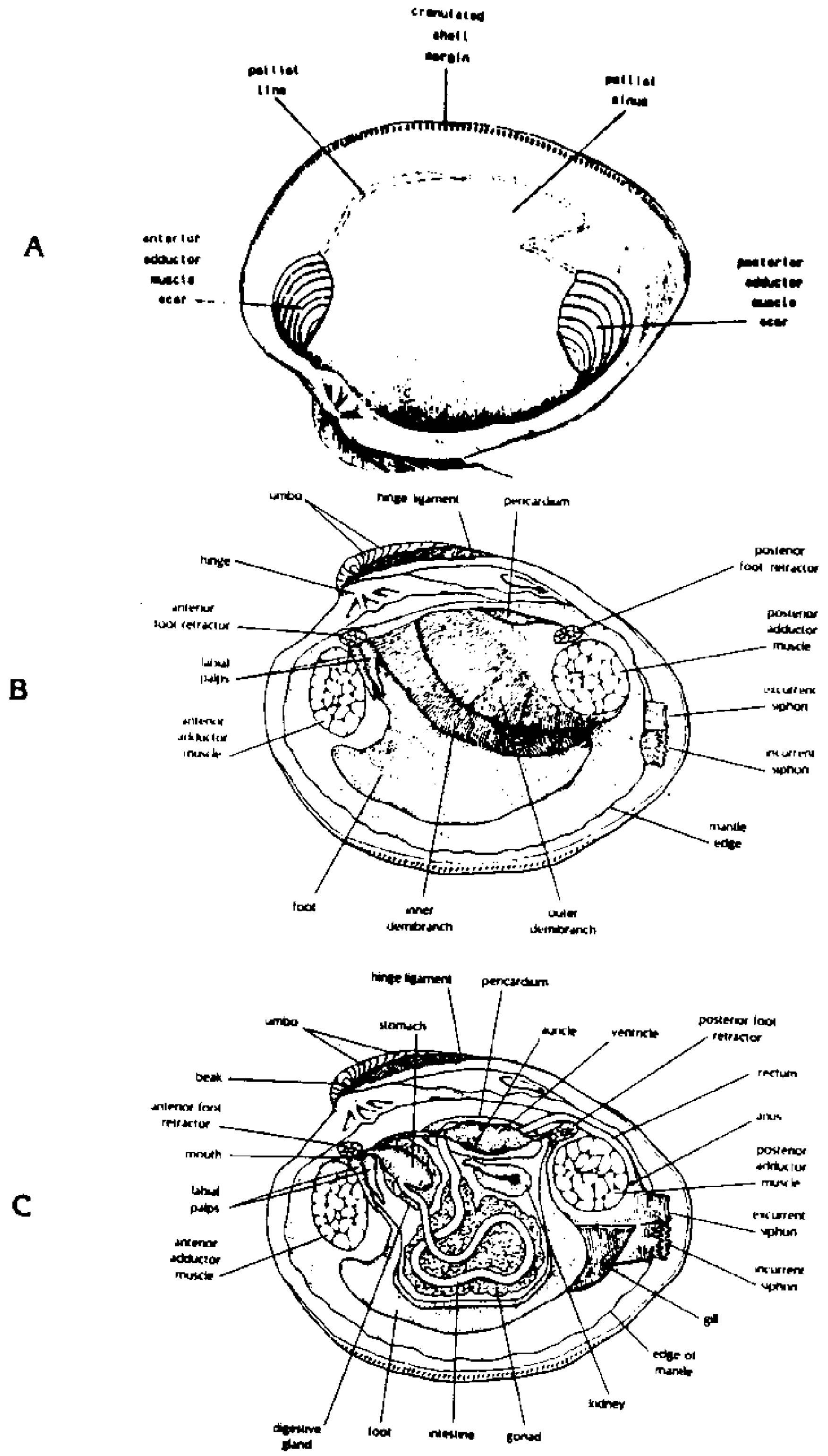


Figure 1. Gross anatomy of the quahog, *Mercenaria mercenaria*. A. Interior of left valve showing muscle scars. From Shuster (1969). B. Right valve with left mantle removed to reveal external morphology of the soft tissues. From Pechenik (1991). C. Right valve with viscera partially dissected to reveal internal organs. From Pechenik (1991).

measure to another when site-specific information is not available. Conversions will introduce inaccuracies when populations with slightly different body forms are compared (see Section 4.2.5).

to convert	multiply by
width to length	1.90
length to width	0.53
height to length	1.25
length to height	0.80
width to height	1.52
height to width	0.66

3.1.2.2 Growth lines

External -- North of Virginia quahogs develop a groove or "break" in the shell during cessation of growth in the winter. In young individuals, these exterior lines are often clear enough to provide reliable ages. In most older quahogs, winter breaks are obscured by shell erosion, additional breaks from other causes, and crowding of breaks.

Internal -- A cross section of the shell tip shows that the most growth over time takes place in the outer shell layer in increments perpendicular to the shell surface (Figure 2). Simple cutting and polishing of the shell is adequate to allow ageing by counting dark winter bands. Sectioned and polished shells were used in a Bay-wide study of quahog growth by Jones et al. (1989). Microscopic daily growth bands (between the dark winter bands) can usually be counted in individuals from about two to 10 years old. A maximum amount of detail can be seen in thin sections and acetate peels of sectioned shells. The daily bands are very useful in confirmation of winter bands (preceded and followed by progressively smaller and larger daily bands) and in establishing the time of year of maximum growth and the timing of breaks caused by environmental stress. It is often difficult to determine the size of individuals at the end of their first season of growth. Grizzle and Lutz (1988) found that seasonal growth patterns were absent in the first year and often obscured in the second. In older individuals, erosion may damage evidence of early growth. Annual growth bands, but not daily bands, can be seen in sections of the hinge plate. Hinge plate sections can be made more rapidly than whole-shell sections and were used by Pratt (1988) in research on Narragansett Bay quahogs. For a more complete treatment of the use and methods determining molluscan growth lines, refer to Rhoads and Panella (1970), Kennish (1980), or Kennish et al. (1980).

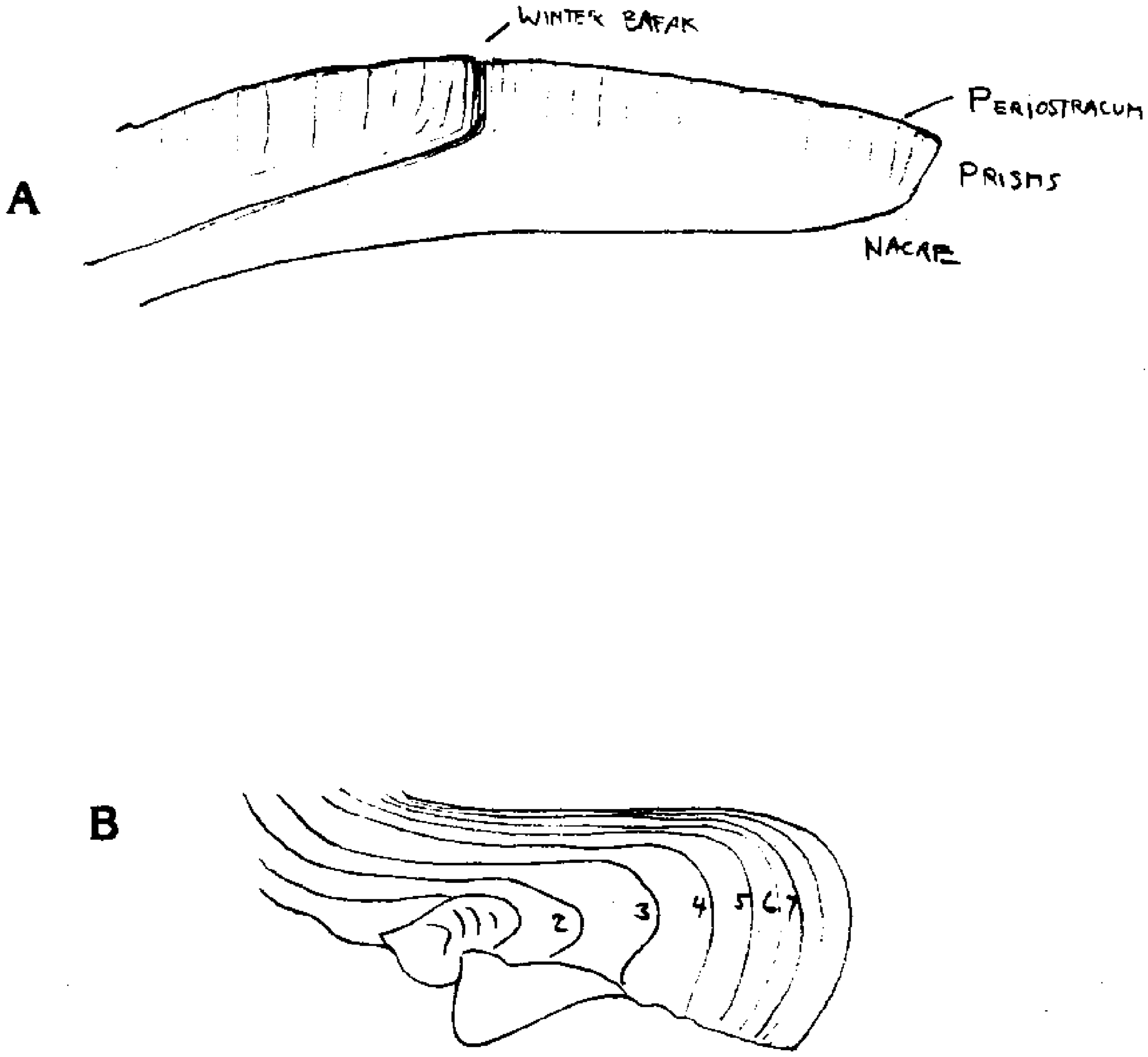


Figure 2. Sectioned quahog shells showing incremental growth bands. A. Schematic cross section of a quahog shell tip. Microscopic daily growth increments occur between annual winter growth breaks. B. Cross section through the hinge plate of a 9 to 11-year-old quahog. Winter break lines are obscure in the first year and become crowded after about seven years.

3.2 Life History

3.2.1 Spawning Release of gametes by quahogs is strongly dependent on temperature. In detailed studies in New Jersey, Carriker (1961) found that the median daily spawning temperature was 25.7°C (range 22° to 30°C) and occurred during a two- to three-day period of increasing temperature. In England, spawning was found to take place at 18°-20°C (Mitchell 1974). When threshold temperatures are reached, males release their sperm. Pheromones associated with the sperm act to stimulate release of eggs by the females (Nelson and Haskin 1949). The largest release of eggs is during the initial spawning event, but may continue at low levels for 2 to 2.5 months (Ansell 1967). Spawning is most intense during neap tides, presumably because higher water temperatures are reached (Carriker 1961). Diamond (1981) examined gametogenic cycles in quahogs at four locations in Narragansett Bay in monthly collections over a year. She found evidence of peak egg release in May and September at Sabin Point and in June and September at Dutch Island Harbor.

Quahogs do not exhibit reproductive senescence as they attain large sizes at advanced age (Bricelj 1979; Peterson 1983; 1986). Data from Bricelj and Malouf (1980) show that a large (>90mm valve length) female may be 40 years old or more but still be capable of producing several million viable eggs (Figure 3).

Eggs are spherical, 70-78 μm in diameter, and with closely-packed yolk granules (Belding 1931; Loosanoff and Davis 1963). Quahog eggs have a gelatinous capsule not present in other marine mollusks (Loosanoff and Davis 1950). After eggs are released through the excurrent siphon, the capsule swells to 3.2 times the egg diameter. This capsule may impart buoyancy and increase the dispersal of eggs (Stanley and DeWitt 1983). Spermatozoa are able to penetrate the capsule and fertilize the egg. An embryo develops rapidly after fertilization and after ten hours develops cilia and escapes into the water as a gastrula.

3.2.2 Larval Ecology The gastrula embryo develops into a trochophore larva 18 to 24 hours after initial fertilization (Loosanoff and Davis 1963). The digestive tract of the trochophore is not completely developed, so it does not feed on particulate food. Carriker (1952) found that early stage larvae concentrate at about 1 m below the surface during daylight and are more evenly dispersed through the water column at night.

Larvae enter the veliger stage about 48 hours after initial fertilization when they secrete a thin transparent shell and a ciliated velum forms. The velum acts to capture particulate food and provide for locomotion. The digestive tract of the veliger larvae is fully developed. The veliger has greater swimming ability than the trochophore. Veligers are able to move 7 to 8 cm/minute vertically and may be able to control horizontal

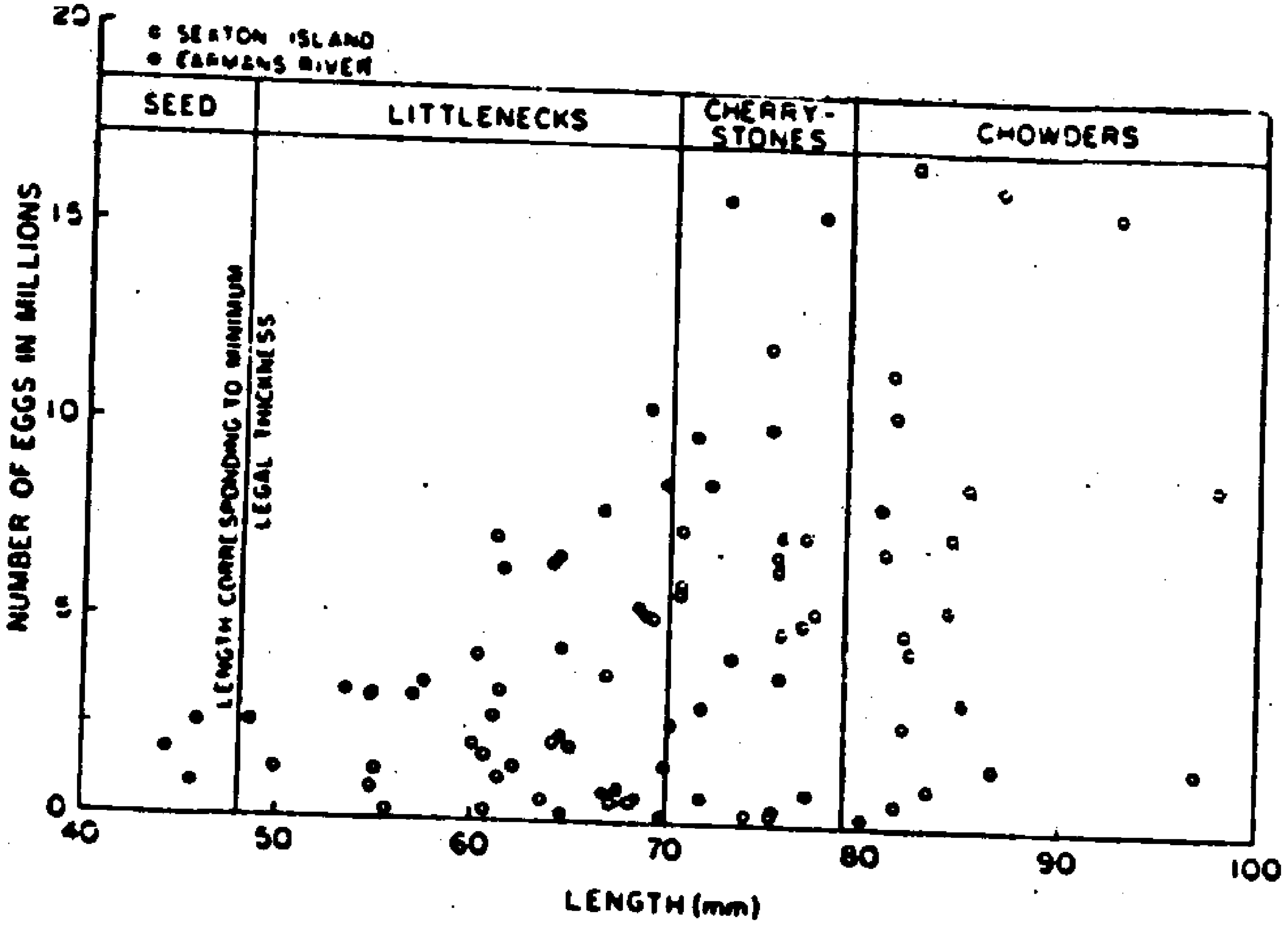


Figure 3. The relationship between total egg production and shell length of hard clams from Great South Bay, New York. From Bricelj and Malouf (1980).

displacement by choice of vertical level in the water column, taking advantage of varying current velocities (Mileikovsky 1973). Carriker (1961) found that vertical migration was stimulated by turbulence. Veliger densities over 500 individuals/L have been recorded in some estuaries (Stanley and DeWitt 1983). In Narragansett Bay, Landers (1954) followed larval density in weekly samples from Wickford Harbor and Greenwich Bay over two summers. He found that spawning usually began in May, peaked in July, and lasted until August-October. Only about one-tenth of early larvae survived to the pre-settlement stages. The density of mature larvae varied from 16 individuals/L to 0.3 /L, depending on season and location. Two peaks of abundance were found one year but not the other. In a recent study of mollusk larvae in Narragansett Bay, quahog larvae could not be distinguished from other species found in low abundance (P. Fofonoff, GSO, personal communication). If quahog larvae had been present in large numbers, they probably could have been identified. The low density of larvae in Narragansett Bay and the extended period in which they are present makes them difficult to monitor.

The last larval stage prior to settlement and metamorphosis is the pediveliger. The pediveliger stage retains the velum, but a foot and byssal gland begin to develop. In addition, there is a switch in behavior from a light-seeking to dark-seeking behavior. Larvae that are able to metamorphose also exhibit a substrate-seeking behavior. See Pechenik (1990) for a discussion of the events associated with invertebrate larval settlement and metamorphosis.

The duration of the planktonic larval stages is temperature dependent. Metamorphoses into a seed clam occurs at 16-30 days at 18°C, 11-22 days at 24°C, and 7-16 days at 30°C (Loosanoff et al. 1951). The size at which quahog pediveligers become capable of metamorphosis ranges from 175-240μm in shell length, but most commonly, this competency to metamorphose occurs when larvae are 200-215μm in length (Loosanoff 1959; Loosanoff and Davis 1963).

3.2.3 Juvenile Stage The juvenile stage begins when the pediveliger larva settles to the sediments and metamorphoses. At metamorphosis, there are profound anatomical and physiological changes that occur that make return to the water column impossible. One of these major changes is the loss of the ciliated velum. Metamorphosis does not take place at salinities below 17.5 to 20 ppt (Castagna and Chanley 1973). Carriker (1952, 1961) found that hard surfaces covered by a thin layer of detritus or mud are preferred for setting. Butman (1987) provides an excellent review of factors influencing the settlement of soft-bottom invertebrates, including quahogs.

In the first year after settlement and metamorphosis, the juvenile byssal gland secretes a thread that anchors the clam to shell or rock particles. Seed quahogs have been observed to move laterally through the sediment during their second summer and then re-attach by a byssal thread for a period. The juvenile quahogs become free burrowing at a length of about 10mm (Burbanck et al. 1956).

It is difficult to estimate typical set densities for quahogs because of the high variance over time and space and because of continuous mortality. Carriker (1961) reported sets exceeding 125/m^2 in good habitat in Delaware. Dow and Wallace (1955) reported on an extraordinary set of 270,000/m^2 in Maine. No major studies have been made of spat set in Narragansett Bay, although small individuals are reported in some macrobenthos community studies. These studies have sampled small areas (0.1-0.5 m^2) using fine mesh sieves (0.25 to 1.0mm). In most of these studies, quahog densities were low and variable. Maximum densities reported were 215/m^2 (n = 3) south of Field's Point, and 260/m^2 (n = 1) off Mount View (Pratt, unpublished data), and 140/m^2 off Calf Pasture Point (Pratt 1977)

3.2.4 Adult The adult quahog remains in a small area throughout its life, but thre is some horizontal and vertical movement within the sediments. Chestnut (1951) found an average of 5 cm and a maximum of 15 cm of lateral movement in 38 days. Kerswill (1941) found maximum movement of 30 cm in two months by sublegal individuals (20-30 mm long). Adult quahogs bury deeper in sand (mean depth 2 cm) than in mud (mean depth 1 cm), and small adults burrow deeper than larger ones (Stanley 1975). Quahogs can escape upward after being buried by 10 to 50 cm of sediment, if the material is not very compact (Belding 1931; Glude and Landers 1953; Kranz 1974).

Quahog reproduction and fecundity have been studied in detail in Great South Bay, Long Island (Bricelj and Malouf 1980). They found equal sex ratios at all ages: first reproduction in a female at 33.1mm length, 17.6mm width and in a male at 36.7mm length, 19.2mm width (both sublegal), and large variability in egg production for a given size range. The maximum number of eggs produced by any individual in a size class increased from 2.4 million for sublegal to over 15 million for cherrystones and chowders (Figure 3). No differences could be found in fecundity or larval survival in individuals from favorable and unfavorable growing areas.

The distribution of adult quahogs in Narragansett Bay is very patchy. In most areas of the Bay, quahog densities rarely exceed five individuals/m^2 (Saila et al. 1967). Areas of high quahog abundance in Narragansett Bay can have as many as 190 adults/m^2 (Rice et al. 1989). A more comprehensive treatment of quahog population characteristics in Narragansett Bay will be given in the fisheries stock analysis section of this report (Section 4.2.1)

3.3 Ecology and Environmental Requirements

3.3.1 Food and feeding Food availability is an important determinant of quahog growth. Like other filter-feeding bivalves, quahogs obtain phytoplankton, heterotrophic micro-organisms, and mineral and organic particles from suspension (Walne 1972), as well as being capable of deriving nutrition from dissolved organic material from seawater (Rice and Stephens 1988). Growth depends on the volume and quality of food obtained.

3.3.1.1 Food quantity and quality Since quahogs are filter feeders, food availability is directly tied to the primary productivity of phytoplankton. In their review of phytoplankton in Narragansett Bay, Hinga et al. (1989) concluded that annual primary productivity values are similar to those found in other major East Coast estuaries. They found that productivity increased by about a factor of three from the lower West Passage to the Providence River. They also found that chlorophyll concentration and phytoplankton cell numbers increased by about three times from lower to upper Bay.

Since quahogs only feed at water temperatures above 10°C (50°F) (Allard 1988), the quality and availability during the warm months is important. Pratt (1965) described cycles of alternate dominance by diatoms and flagellates in Narragansett Bay. In a "typical" year, diatoms bloom in winter and spring, decline in late spring, and may bloom for brief periods in the fall. Flagellates dominate in late spring-early summer. Standing crop of all phytoplankton is less during the winter. In their review, Hinga et al. (1989) found that there were many exceptions to the simple pattern described above. For example, in Mount Hope Bay and the Providence River, phytoplankton densities are not significantly reduced in the summer versus the winter.

In a frequently cited study carried out in Narragansett Bay, Pratt and Campbell (1956) found that quahog growth was positively related to the abundance of "small" diatoms (less than 15 µm) and not to flagellates or larger diatoms. Skeletonema costatum was by far the most abundant small diatom, but based on their data it was difficult to say whether S. costatum, or small diatoms in general, were especially good food sources because other environmental factors affecting growth rate were not ruled out.

Attention was drawn to the food value of different phytoplankton species during the 1950s when it was found that small Nannochloris atomus algae growing in nitrogen-rich duck farm effluent in Long Island had little nutrient value. Bass (1983) determined that N. atomus passed through quahogs undigested. Feeding studies with cultured phytoplankton have found large differences in the food value of different species, toxicity in some species, and variable results depending on culture techniques (Walne 1970). Quahogs in natural waters have the opportunity to feed on a variety of species, including many nutritious forms and some which might complement each other, as suggested by Epifanio (1979).

Food quality would be of concern if there were a bloom of a toxic species or persistent dominance by an indigestible species. The Providence River is the most likely location for dominance by low food value phytoplankton species. Only two long term studies of phytoplankton include this area. Mitchell-Innes (1973) monitored three stations from outside Pawtuxet Cove to Whale Rock (1968-1969). Smayda (1988) sampled seven stations from Field's Point to Fox Island between July 1985 and June 1986 following the May 1985 brown tide outbreak. Mitchell-Innes (1973) observed brief intense blooms of Nannochloris spp and reduced densities of diatoms in summer samples at the Pawtuxet station. Phytoplankton at Nayatt Point was similar to that found in the rest of Narragansett Bay. Smayda (1988) did not report Nannochloris spp in the Providence River. While this might indicate improvement since 1969, relatively large numbers could have been masked by brown tide (Aureococcus anophageferens) cells. The brown tide organism, which appeared to be suppressed by high nutrient levels, decreased in abundance from mid-Bay to the upper Bay. This suggested that the demarkation between pollution-affected and normal habitat may be between these portions of the Bay (Smayda, personal communication). The Smayda study (1988) found that total phytoplankton biomass increased in upper Narragansett Bay as nutrient levels rose, but decreased at Field's Point, possibly due to a toxic effect. S. costatum was present at high density from Bullock Point to Warwick Neck and at much reduced density at Field's Point. Pratt et al. (1987) hypothesized that the slow growth rate of quahogs observed in the Providence River could be due to food quality rather to the direct effect of pollutants, but the data of Smayda (1988) suggests that quahogs in the mid- and lower-Providence River are presently in the same nutritional regime as is found in the upper Bay.

During the 1985 outbreak of A. anophageferens (brown tide), there was an extensive mortality of blue mussels. These mussels failed to feed when levels were high and did not digest the organism at low levels. The mussels died because they ceased feeding and thus could not nutritionally satisfy their metabolic demands (Tracey et al. 1988). The lower metabolism of quahogs appeared to reduce the effects of the bloom, and no mortality or significant decrease in condition was observed by DEM personnel (R. Sisson, personal communication). Shells of quahogs collected between March 1984 and July 1985 have been archived by DEM for possible analysis of growth during the outbreak.

In the typical seasonal cycle, S. costatum levels are reduced in the summer. This could be a cause of the reduction in growth rate after July reported by Pratt (1953) and Pratt and Campbell (1956). Ansell (1968) speculated that quahog production in Narragansett Bay would increase if higher temperatures made it possible for feeding to take place during the peak of S. costatum abundance. At this time it, is not possible to determine whether absence of small diatoms, presence of flagellates, high temperature, or reproductive status causes slowed growth in mid-summer.

Horizontal seston flux -- A number of studies (e.g. Walne 1970) have shown that much higher laboratory concentrations of good quality phytoplankton are required to produce growth rates in quahogs comparable to field growth rates. The explanation for this phenomenon is that most laboratory culture systems work with a fixed volume of water, and the quahogs must filter and use what is in that fixed volume. By contast, in the field situation, water currents are delivering phytoplankton and other particulates to the animals. By virtue of the water movement past the animals, they are exposed to larger volumes of water, and therefore larger quantities of potential food, even though the absolute concentration (mg/L) may be much lower than the laboratory concentrations. Recent work (Grizzle and Morin 1989; Grizzle and Lutz 1989) have shown that quahog growth is very closely tied to "horizontal seston flux," which they define as the product of seston concentration (mg/L) and current speed (L/sec) flowing past the animals.

3.3.1.2 Suspended sediment In very turbid estuaries, or where dredging or erosion increases turbidity, there is often concern as to potential effects of suspended sediment on bivalves. Bricelj and Malouf (1984) found that 5 mg/L silt had no effect on filtration rates of quahogs, but 20 mg/L and 40 mg/L silt reduced particle filtration by 31% and 52% respectively. The reduction of particle filtration rate in turbid water is greater in quahogs than in oysters, blue mussels, or surf clams. This reduction in filtration may impair food acquisition and overall nutritional state of quahogs. Bricelj et al. (1984) found no effect in growth of juvenile shells at silt levels up to 44 mg/L. Tissue growth was not affected by 25 mg/L silt but was reduced by 16% in 44 mg/L silt. In a recent study, Turner and Miller (1991) found that filtration rates and shell growth rates of quahogs were depressed in simulated storm events in which suspended sediment levels reached 193 mg/L. Murphy (1985) found that quahogs were excluded from areas where sediments were unstable and suspended sediment concentrations were high.

When total concentrations of organic and inorganic particles (seston) is high, bivalves are unable to ingest all the material captured and will reject the excess as pseudofeces. To illustrate this, Murphy (1985) reported inhibition of shell growth of juvenile quahogs at a total seston concentration of 23 mg/L. Bricelj and Malouf (1984) found that the threshold for pseudofeces production in quahogs was about 10 mg/L seston in the water column. They found that the effect of loss of food through pseudofeces production was minimized by efficient sorting of algae from silt on the gills and labial palps (78% of captured algae was retained, and >70% of the silt rejected). Some silt is ingested and there is absorption of organic matter from silty detritus.

Total seston levels in the open waters of Narragansett Bay are relatively low. Morton (1967) reported a Bay-wide near-bottom sediment load of 3.7 mg/L. In samples taken 1 m off the bottom of the Providence River and the upper Bay in January to April, Bisagni (1976) found an average of 3.2 mg/L seston (maximum 6.9 mg/L). A high value obtained during a storm at the Graduate School of Oceanography dock (South Ferry Road, Narragansett) was only 7.4 mg/L seston (S. Pratt, unpublished data). Embayments in Narragansett Bay generally have higher seston levels than the open Bay. For example, Nixon et al. (1973) found seston levels of about 20 mg/L throughout the summer in Wickford Harbor. Seston loads in shallow waters close to marshes or where waves can resuspend bottom sediments may be similar to those measured in Great South Bay, Long Island by Bricelj et al (1984) -- (organic particles: about 10 mg/L; inorganic particles varying from less then 10 mg/L to 126 mg/L in a severe storm). In Charlestown Pond, Pratt (1978) found levels of 1.5 to 5.4 mg/L total seston in samples taken from April-June. The New England Power Corporation (NEPC) (1976) found levels of 3.2 to 25 mg/L in the pond in December and February and 21 to 105 mg/L during a winter storm.

It is unlikely that effects of high sediment loads on quahog growth or distribution can be detected in shallow waters of Rhode Island because inhibiting levels would only be reached for short periods of time, and food supply is generally abundant. Bricelj et al (1984) suggested avoidance of waters with sediment concentrations above 30-40 mg/L for quahog culture. Given these guidelines, there would be very few areas in Rhode Island coastal waters in which high near-bottom turbidity might have measurable effects on quahog productivity.

3.3.2 Predators Predation was thought to be a problem in Narragansett Bay during cycles of high starfish abundance in the past, but in recent years, there has been little perception that predation is a threat to the fishery. Nevertheless, on the basis of research in other regions, it can be assumed that predation is an important determinant of the survival of spat and small clams in the Bay (MacKenzie 1977, 1979; Malinowski and Whitlatch 1988).

In the following subsections, information is given on predators that may affect quahog abundance in the Bay. There are no data available that quantify the effect of predators on natural populations of quahogs in Narragansett Bay.

3.3.2.1 Crabs The xanthid crabs are small estuarine species with large crushing claws marked by dark tips. They prefer muddy bottom with shells or pebbles, but are found in most habitats. One of this group, *Neopanopeus sayi* (*texana* in older literature), is very abundant in Narragansett Bay and is probably a major predator of small bivalves, including quahogs. The first report on the rate of predation by *N. sayi* on small quahogs was published by Landers (1954) from work done in Wickford, Rhode Island. In laboratory experiments, he found that crabs 15mm (0.6 inch) across consumed quahogs less than 10mm long (0.4 inch) at a rate of 5/day at summer temperatures. Little or no predation was observed if the clams were more than 15mm long or if temperature was below 12°C. In a field planting of 2,000 seed clams, there was circumstantial evidence that mud crabs ate 86% within a year. Oyster drills appeared to have eaten only 0.6% of the planted seed clams. MacKenzie (1977) found that adult *N. sayi* could eat seed clams at a rate of 14/hour in the absence of sediment. In sand, the crabs would bury themselves to reach clams, which they ate at a rate of 1.6/day. The closely related *Panopeus herbstii* is present in small numbers in the Bay. Whetstone and Eversole (1981) determined that the ability of *P. herbstii* to crush clams decreased rapidly with clam sizes over 20 mm (0.78 inch) and at temperatures below 17°C. Flagg and Malouf (1983) calculated that the existing population of *N. sayi* in Great South Bay, Long Island, could consume about 20 seed clams/m^2/day which would soon destroy any aquaculture planting. Experiments with gravel overlays, which are effective in protecting clams from blue crabs in the Virginia area, resulted in attraction of mud crabs and increased predation. Oyster toadfish living near the experimental plots eat crabs and increased clam survival from 5% to 80%. Gibbons and Castagna (1985) found toadfish to be useful in crab control in net-covered seed-growing areas. In Narragansett Bay, *N. sayi* are eaten by toadfish and probably also by tautog.

In addition to mud crabs, other species of crabs are destructive to juvenile quahogs. The green crab, *Carcinus maenas*, has been very destructive to intertidal softshell clam stocks in northern New England. It does not appear to be as destructive to quahogs in Narragansett Bay, but research in England shows that it can be a potential quahog predator (Walne and Dean 1972). *C. maenus* is found in the salt ponds and in the Narrow River (A. Ganz, personal observation) and on mussel beds. The rock crab, *Cancer irroratus*, is found on sandy and silty sand bottoms, especially in the lower Bay. MacKenzie (1977) found that in the absence of sediment, juvenile C. irroratus crabs could eat 1 mm seed clams at a rate of 30/hour, while adults could eat 8-10mm clams at 29/hour. In sand, the C. irroratus dug up small quahogs and ate them at a rate of 100/day. Where blue crabs, Callinectes sapidus, are abundant on the mid-Atlantic and southeast Atlantic coasts, they are the major predator of small quahogs (Arnold, 1984). Because Rhode Island is near the northern edge of the blue crab range, they are much less abundant here and their numbers are highly variable from year to year. Blue crabs are most abundant in the summer in warm shallow areas with freshwater input and move into deeper parts of the Bay in the winter. The lady crab or calico crab, Ovalipes ocellatus, a close relative of the blue crab, lives on fine sand bottoms, especially in the lower Bay. Like the blue crab, it has a very high level of activity and rapidly consumes seed clams in laboratory tests.

3.3.2.2 Starfish The starfish, Asterias forbesi, has been an important predator of shellfish in the Bay in the past, and its control was a major expense in oyster farming operations. Starfish have great destructive potential even as very small individuals. In 1898, Mead (1901) studied starfish on softshell clam and oyster beds in the upper Bay. He describes the "reign of terror" of a 1 mm wide starfish that ate 50 softshell clams in six days and increased in size by 300%. He also found that starfish settled from the water column several weeks before their prey so that they were prepared to feed heavily on spat. Additionally, he found that they could complete their life cycle in one year. The rapid growth of starfish helps to explain the sudden shifts in shellfish densities reported by oystermen and found in state surveys (see section 4.2.1 on management surveys). Starfish distribution in the Bay was mapped in the fall and winter of 1935 (Galtsoff and Loosanoff 1939)(103 and 80 dredge stations). Starfish were only caught within the boundaries of Narragansett Bay, and they were concentrated in the East Passage near Dyer Island, Hog Island, and Mount Hope Bridge. More recently, Doering (1976, 1981, 1982) studied predation of quahogs by A. forbesi in laboratory and field experiments. He found peaks of starfish feeding in the fall and spring, a short period of inactivity in the winter, and a longer period of inactivity throughout the summer (Doering 1981). In the same study, he observed that large clams could be opened by groups of starfish. He found that deep burrowing gave measurable protection from starfish (Doering 1982).

It has been known for some time that starfish populations are quite cyclic in abundance. Burkenroad (1946) concluded from oyster company records and newspaper reports that starfish followed a regular cycle of abundance of about 14 years (Figure 4). During a period of relatively high starfish abundance (1959-1962), the state

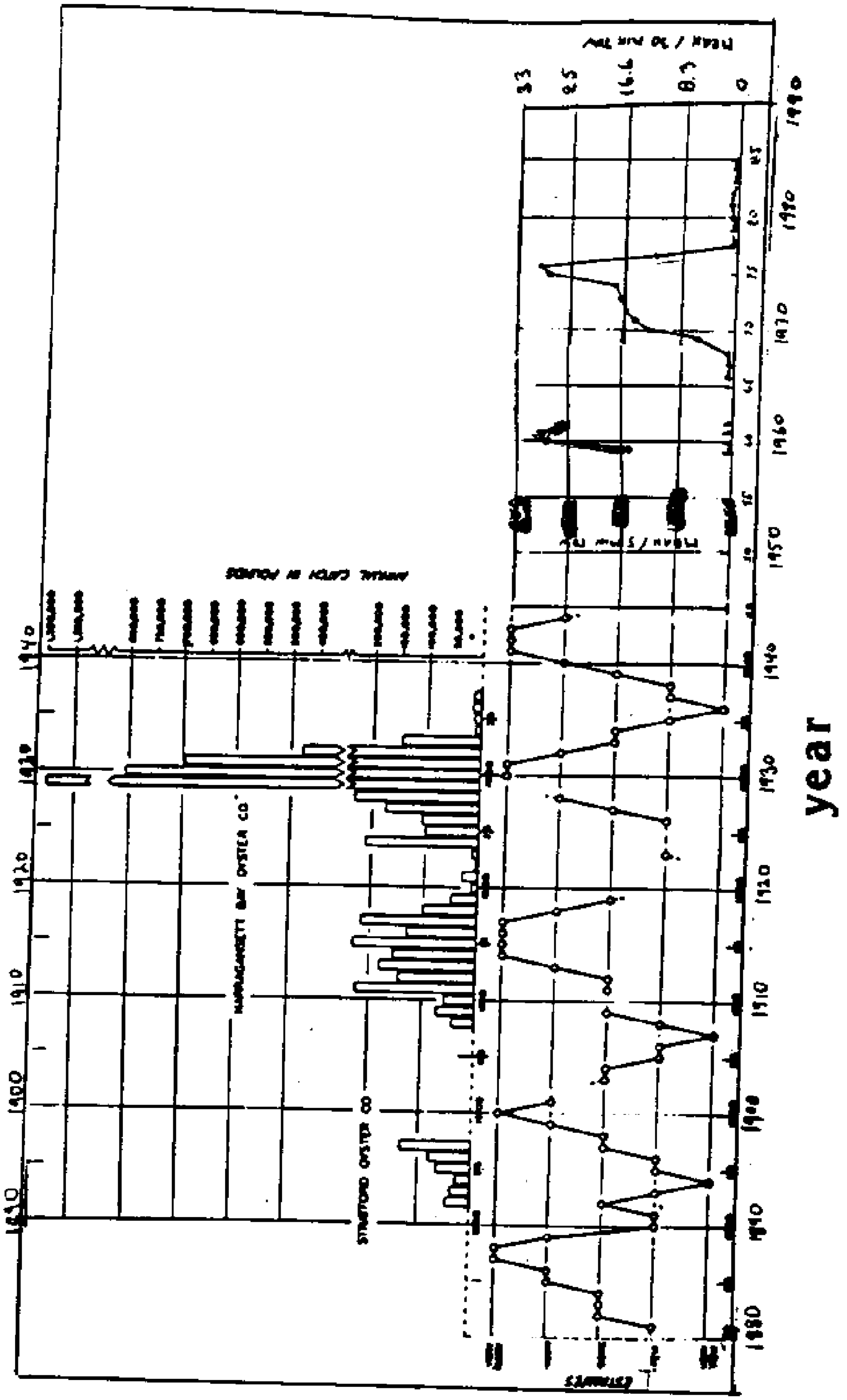


Figure 4. Cycles of seastar, Asterias forbesi, abundance in Narragansett Bay. Data from Burkenroad (1946); Canario (1962); Terciero (1985).

of Rhode Island conducted four annual surveys to plan possible predator control measures and to learn about their natural behavior patterns. Collections were made at 84 stations throughout the Bay during the winter (when starfish are inactive) using a sea scallop dredge. The width of each starfish caught was recorded in centimeters. Survey data are given in Campbell and Dalpe (1960b) and Canario (1962). In 1960, starfish concentrations were found off Wickford, Davisville, Colt Drive, east of Hog Island, south of the Kickamuit River, south of Old Stone Bridge, and off Portsmouth. As many as 2,523 were caught in one five-minute tow. Starfish were not abundant in Greenwich Bay and the Providence River. In 1961, populations were generally more dispersed, although concentrations were noted in Dutch Island Harbor and off Fogland Point (Canario 1963b). In that year, densities throughout the Sakonnet River had increased. Starfish surveys were discontinued by the state after 1962, presumably because of decreased densities. Long-term weekly otter trawl data from the West Passage (Terceiro 1985) shows a low density of starfish from 1966-1968, a steady increase until 1976, and then a rapid decline. Starfish catches have remained low from 1978 to the mid-1980s. These weekly otter trawl surveys off Fox Island and Whale Rock in the West Passage (Jeffries et al. 1986) have been continued into the 1990s. The low level of starfish, beginning in 1978, continues to the present time (Figure 6). If starfish abundance is cyclic, an increase may be overdue. Studies are necessary to understand the factors controlling starfish population densities. In addition, a monitoring plan might be designed to provide early warning of starfish population increases. Such surveys could be most useful in local areas before transplants are carried out, thus preventing loss of transplanted stock on the sediment surface prior to reburrowing.

It is not clear that any control measures are available in case of future starfish population increases. In some cases, quicklime (CaO) has been applied to control dense starfish populations on oyster beds (MacKenzie 1977). This treatment is lethal to the starfish because it causes burns on the epidermis, which eventually become infected. Extreme care should be taken if this method of starfish control is selected. This is because the quicklime is also lethal to other marine life and may adversely affect water chemistry by way of its high alkalinity. There are alternatives to this drastic treatment. In Long Island, operators of leased shellfish beds hydraulicly dredge with the hope of making the bottom unsuitable for recently metamorphosed starfish. Starfish have few natural enemies. However, it has been shown that the spider crab, Libinia emarginata, eats them one leg at a time (Aldrich 1976). Although low population numbers of the spider crabs probably keeps them from being a controlling predator, their value as a starfish predator argues for their preservation in shellfish management areas.

3.3.2.3 Gastropod Mollusks In Narragansett Bay, the conch, or channeled whelk (*Busycon canaliculatum*), feeds almost exclusively on quahogs as an adult. It feeds by rasping or breaking the clam shell with its own shell and is most active at night. Conchs are found on fine sand and silty sand bottoms in open parts of the Bay where they are subject to a pot fishery. Sisson (1972) studied conchs off Wickford where he found a small inshore-offshore seasonal movement. He found that they were inactive in the winter and remained buried and inactive over long periods of time in the summer as well. Conchs, unlike crabs and drills, are able to attack adult clams. Peterson (1982) found that they selected the largest prey available. Scattered adult conchs seem to be little threat to the clam fishery since they attack less valuable large clams and eat at a slow rate (1 quahog/20 days, Carriker 1951). However, in areas where they are abundant, such as Great South Bay, conchs can rapidly destroy 25mm clams that are safe from other predators (Flagg and Malouf 1983).

In addition to channel whelks, oyster drills and moon snails are potential quahog predators. They bore a hole through the shell to gain access to the soft tissues. The rough oyster drill (*Eupleura caudata*) and the smooth oyster drill (*Urosalpinx cinerea*) were serious predators on oysters when they were grown in Narragansett Bay, and they attack small quahogs in Long Island and New Jersey (MacKenzie 1977). The moon snails, *Polinices duplicatus*, and *Lunatia heros*, are important predators on sandy bottoms. The holes that they drill in a clam's shell can be differentiated from those made by oyster drills because they are "countersunk" rather than straight-sided.

3.3.3 Pathology Disease is important as it can affect the productivity and marketability of quahog stocks. Diseases in quahogs may result from natural causes or by pollutants or changes caused by man. In most cases, it is difficult to identify specific causitive agents or to determine field exposures to possible agents, but there have been a few studies that have been able to focus on specific quahog diseases.

Most pathologic conditions can be detected by microscopic examination of fixed and stained tissues. Histologic examination can also give information on the timing and success of reproduction and on the animal's nutritional status, which can be of use in interpreting apparent pathological effects.

Two quantitative studies have been made in which quahogs from large areas of Narragansett Bay were histologically examined. There have been other studies,

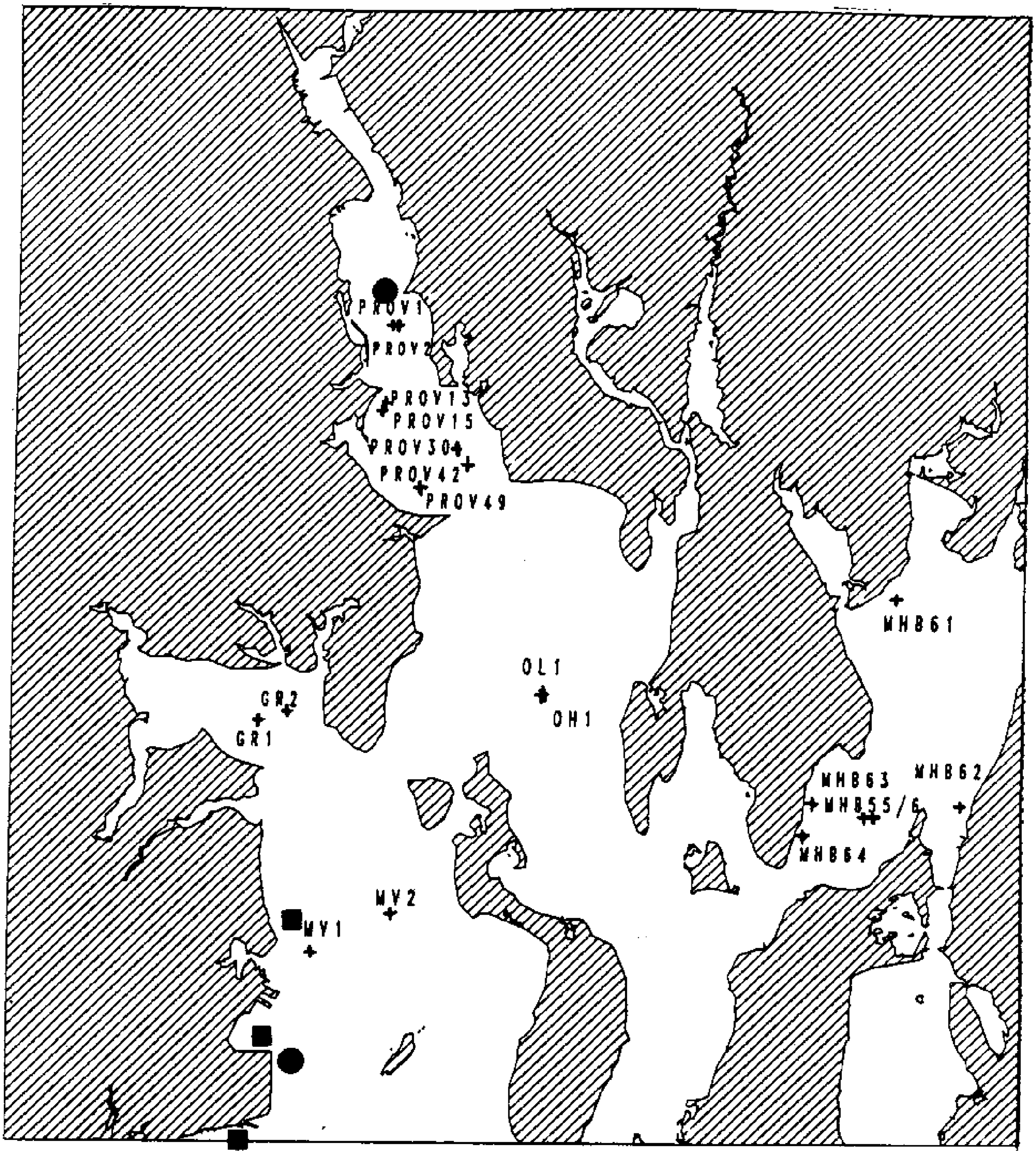


Figure 5. Location of stations sampled in quahog histopathology studies. Squares (Brown 1977); circles (Diamond 1981) (Bay Campus and Dutch Island stations not shown); crosses (Kern 1990). Kern stations were also sampled for tissue metals (Thibault/Bubly 1990) and organic contaminants (Pruell et al 1988).

but they have been restricted to much smaller areas or to single sample periods. Diamond (1981) examined animals from Sabin Point and three stations in West Passage (Figure 5) at monthly intervals over a year. Kern (1986) examined quahogs from the Providence River and mid- and upper Bay collected in November and June. Data from the reports has been condensed (Tables 1 and 2) to provide a basis for comparison. Neoplasia, kidney concretions, and tissue color (reported as ceriod pigment and as lipofuscin) are discussed separately. All but one of the remaining conditions listed were found at low incidence, had no consistent changes along the pollution gradient, and would not lead to mortality.

Necrosis listed by Kern (1986), referred to dead and decomposing individuals. Although the total number of dead animals was small (10), all were found in the June collection (2.14% prevalence). Affected animals were found in all Bay sub-areas. Kern found no evidence of the cause of mortalities among living animals.

During the brown tide bloom in the summer of 1985, quahogs and four other species of suspension-feeding mollusks were collected from sites between Jamestown and Conimicut Point and subjected to histopathologic examination (Yevich 1985). All species had an increased mucous cell response, a reaction to any irritant. Of the species examined, *Pitar morrhuanus* had the most extensive histopathologic changes and were in a moribund condition. Quahogs were the least affected species, showing little histopathology other than the mucous cell response.

Neoplasia - A number of researchers have found incidences of cancer-like proliferation of cells in a small number of quahogs. Diamond (1981) found gonodal neoplasia at two stations in the lower West Passage (7%, 7.6%) but not at Sabin Point or Quonset Point. Kern (1986) found gonodal tumors in a total of four individuals and a sarcoma resembling the hematopoietic neoplastic disease of softshell clams (n = 963). In 1969 and 1970, Barry and Yevich (1972) found ovarian and testicular gonodal neoplasia in quahogs from Rose Island (East Passage), with incidences in respective years of 4% and 3.7% in females, 0% and 1.4% in males. Brown (1977) found no neoplasia in animals from three sites off Quonset/Davisville (n = 156).

It is clear that neoplastic disease is not a problem with Narragansett Bay quahog populations. This is in strong contrast with the softshell clam (*Mya arenaria*), which is susceptible to hematopoetic neoplasia throughout its range. Incidences of neoplasia in soft clams have reached high levels in portions of Narragansett Bay. Cooper (1979) reported incidences as high as 40% in Allen Harbor with high mortality. This condition has features which suggest that it is caused by a virus with incidence and severity possibly modified by environmental factors (Oprandy et al. 1981; Brousseau 1987; Leavitt et al. 1990).

Table 1. Histopathology of quahogs collected in Narragansett Bay in 1985-1986. Percent prevalence of lesions and range of prevalences within samples for different portions of the Bay. Numbers of clams per sample are assumed to be 30 where no information is supplied (calculated from Kern 1986).

Location	Providence River	Greenwich Bay	Mount View	Mount Hope Bay
Samples	10	2	3	8
Stations	5	1	2	4
Ceriod pigment	68.7 (28-96)	4.0 (0-8)	55.0 (45-64)	88.9 (63-100)
Metaplasia diverticula	5.1 (0-12)	14.5 (14-15)	3.7 (0-7)	3.8 (0-17)
Edema	2.5 (0-10)	0.0	0.0	1.0 (0-10)
Sloughing	1.0 (0-6)	1.0 (0-2)	0.0	1.3 (0-4)
Inclusion	0.4 (0-4)	1.5 (0-3)	0.0	1.9 (0-8)
Inflammation	2.0 (0-10)	0.0	1.7 (0-3)	0.4 (0-4)
Necrosis	1.0 (0-8)	2.5 (0-5)	0.7 (0.2)	0.8 (0-5)
Neoplasia	0.4 (0-2)	0.0	0.0	0.5 (0-3)
Sarcoma	0.0	0.0	0.0	0.5 (0-3)
Chlamydia	25.7 (16-34)	21.0 (18-24)	24.3 (10-33)	36.0 (30-43)

Table 2. Histopathology of quahogs collected in Narragansett Bay in 1977-1978. Percent prevalence of lesions for selected tissues. Prevalence data on whole individuals is not available (calculated from Diamond 1981).

Station	**Sabin Pt.**	**Quonset Pt**	**Saunderstown**	**Dutch Island Harbor**
number of clams	205	32	43	197
Lipofuscin (gonad)	38.0	25.0	13.9	12.7
Lipofuscin (mantle)	17.6	16.6	7.0	4.1
Hemocytosis (mantle)	3.4	9.4	7.0	4.1
Kidney concretions	17.6	9.4	4.6	5.1
Hypoplasia (gill)	8.3	6.3	2.3	2.5
Necrosis (mantle)	2.4	3.1	0.0	0.0
Ulceration (stomach)	0.5	0.0	0.0	0.0
Neoplasia (gonad)	0.0	0.0	7.0	7.6
Chlamydia/Rickettsia (digestive gland)	14.1	9.4	2.3	4.6

Kidney Concretions - Kidney function is very different in bivalve mollusks than in higher vertebrates. In bivalves, nitrogen excretion is not important (ammonia is lost through the gill and mantle) and the kidney functions to resorb water and excrete metals and particulate wastes carried by lysosomes and phagocytic amebocytes (Andrews 1988). In many species of bivalves, some of the material collected by the kidneys can form concretions (usually less than 0.5 mm in diameter).

A number of authors have suggested that kidney concretion can be used as an index of environmental pollution. Jeffries (1972) found that quahogs collected at Sabin Point in 1969 had large masses of sticky black material filling their renal sacs. Black particles were also found in the mantle tissues, suggesting that pollutants or tissue debris had been sequestered by amebocytes. More recent studies have found increased incidences of individuals with high numbers of concretions from the Providence River compared to the lower Narragansett Bay, but did not find the gross pathological conditions that existed in 1969 (Rheinberger et al 1979; Diamond 1981). Cullen (1984) found concretion weights to be highly variable within quahogs from the same station and not significantly higher in the Providence River in comparison to other sites around Narragansett Bay. Additionally, quahogs collected in 1984 and 1985 failed to show any gross abnormalities relative to the rest of Narragansett Bay (Pratt, unpublished data). At this time, kidney concretions are not an obvious indicator of stress in Providence River quahogs. Additional information is need on the excretion process of bivalves in order to understand the relationships between contaminants in food, water and tissues and the time course of depuration.

3.3.4 Dissolved oxygen

3.3.4.1 Physiological and behavioral adaptations to low oxygen Quahogs are well adapted to survive short periods of oxygen depletion. Like other bivalve mollusks, they are able to utilize anaerobic pathways to provide energy for cellular metabolism. Additional physiological and behavioral adaptations make quahogs more resistant to low oxygen then many other species.

Anaerobic metabolism in bivalves is very different from that found in vertebrates, where buildup of lactic acid muscles inhibits further reactions. In bivalves, anaerobic metabolism provides sustained energy (ATP) by a complex process with a variety of end products (deZwaan and Wijsman 1976). Among the various metabolic end products are succinic and lactic acids, which build up during valve closure. The mechanism for neutralization of these acid products is through shell dissolution (Crenshaw and Neff 1969). In bivalves, the various products of anaerobic metabolism may help to detoxify ammonia by reacting with it so that it does not inhibit other important metabolic pathways (deZwaan 1977). Even though oxygen may be present and quahogs actively pumping water, there is evidence that anaerobic respiration may be occurring in tandem with aerobic respiration (Hammen 1980; Fields and Storey 1987).

Loss of burrowing activity and siphon extension appear to be behavioral responses of bivalves to lowered oxygen levels (hypoxia). Savage (1974, 1976) observed the rate of reburrowing of several species of bivalves in experiments carried out in Rhode Island. Of the species tested, quahogs had the best developed ability to burrow at low oxygen levels. This ability was not impaired by several weeks of exposure to oxygen concentrations as low as 1 mg/L at 21°C and 1.8 mg/L at 21-24°C. At low oxygen concentrations and high temperatures, <u>Pitar morrhuanus</u> greatly extended their siphons, which has been interpreted as a "gasping" response. Quahogs were much less reactive at similar low oxygen levels. All these physiological and behavioral studies suggest that quahogs are very well adapted to areas with transient hypoxia.

3.3.4.2 Dissolved oxygen levels in R.I. waters Oxygen is consumed by organisms and by reduced chemical compounds within both the water column and sediments. Oxygen reaches the bottom in shallow areas by two basic processes: a) diffusion from the air and downward mixing; and b) production within the water by phytoplankton via photosynthesis. Photosynthesis can only occur during the day, and only in the upper water column where there is sufficient sunlight. During the spring and summer, freshwater input and surface warming contribute to stratification and reduced downward mixing. Under these conditions, horizontal flow of oxygen from areas with higher concentration may be the only supply. A combination of stratification, sedimentation, and eventual oxidation of organic matter may consume all oxygen present in near-bottom waters.

Although quahogs are physiologically and behaviorally adapted to survive periods of low oxygen, there may be portions of Narragansett Bay where low oxygen levels could be persistent enough to affect quahog survival or growth. The most likely locations for low oxygen to affect quahogs are the Providence River and a number of small coves around the perimeter of the Bay. Desbonnet and Lee (1991a, 1991b) review changes in water quality in Narragansett Bay over time. In their data, there is a general pattern of decreasing levels of dissolved oxygen in the Seekonk and Providence Rivers through the early part of this century and recovery during the last 20 to 30 years. These data show that prior to 1955, average summer oxygen levels in channel bottom waters of the upper Providence River were near zero and 3-4 mg/L in the middle and lower portions of the river. In 1982-83 (Nixon et al. unpublished data cited in Desbonnet and Lee 1991a), bottom oxygen levels were slightly higher than 1955 levels in the lower river but had increased by about 3 mg/L above Field's Point. Doering et al (1990) suggest that quahogs living at depths below 3-5 meters (10-16 ft) in the middle and lower Providence River would be exposed to oxygen levels of 3-5 mg/L during the warm months. These levels of dissolved oxygen are high enough for larval and adult quahog survival, but larval growth may be affected. Morrison (1971) found that quahog larvae can survive at oxygen levels above 0.5 mg/L. Growth can occur at dissolved oxygen levels above 2.4 mg/L, but is slowed at levels below 4.2 mg/L. In most coves and harbors, tidal circulation probably keeps oxygen from reaching very low levels or allows low levels to persist for very long. In coves where dense beds of the green algae Ulva (sea lettuce) grow as the result of excess nutrients, anoxic conditions may be found beneath the algae, reducing the growth rate and the condition of quahogs there.

3.3.5 **Temperature** Temperature is one of the most important variables in quahog growth and reproduction. Quahogs are adapted to temperate waters, and many of their physiological functions reach maxima at summer temperatures of 25-30°C and decrease to very low levels in the winter.

A number of studies have focussed on the effects of temperature on reproduction and larval biology of the quahog. Spawning has been reported to require a minimum temperature of 18-22°C (Loosanoff 1937). Davis (1969) and Davis and Calabrese (1964) found optimum larval development to be between at 17.5-30°C in high salinity water. Carriker (1961) found a larval temperature tolerance range of 13-30°C. Lough (1975) found highest larval survival between 14 and 29.5°C and maximum growth rate at 22.5-36.5°C. Davis and Calabrese (1964) showed that digestion of algal food by larvae is slowed considerably at low temperatures (12.5°C), and concluded that this may be a limiting factor of growth at the low temperatures. In Narragansett Bay, some larvae are present at temperatures as low as 13°C (Landers 1954), but in July, when most of the quahog spawning is occurring, larvae would be exposed to temperatures of 20-23°C (Hicks 1959), well within optimum limits. Temperature affects the time it takes for larvae to settle and metamorphose (Figure 6).

Temperature can also affect the survival and growth of adult quahogs. Adult quahogs can tolerate temperatures from below freezing to over 30°C. Williams (1970) found that adults could survive to -6°C, but died when 64% of tissue water froze. Freezing appears to be a cause of mortality during especially cold winters in shallow subtidal areas such as Wickford Harbor (R. Sisson, personal communication). Ansell (1968) reviewed quahog growth in a number of locations and concluded that the optimum temperatures for shell growth was about 20°C and that shell growth ceased below 9°C or above 31°C. In Narragansett Bay, Pratt and Campbell (1956) found growth

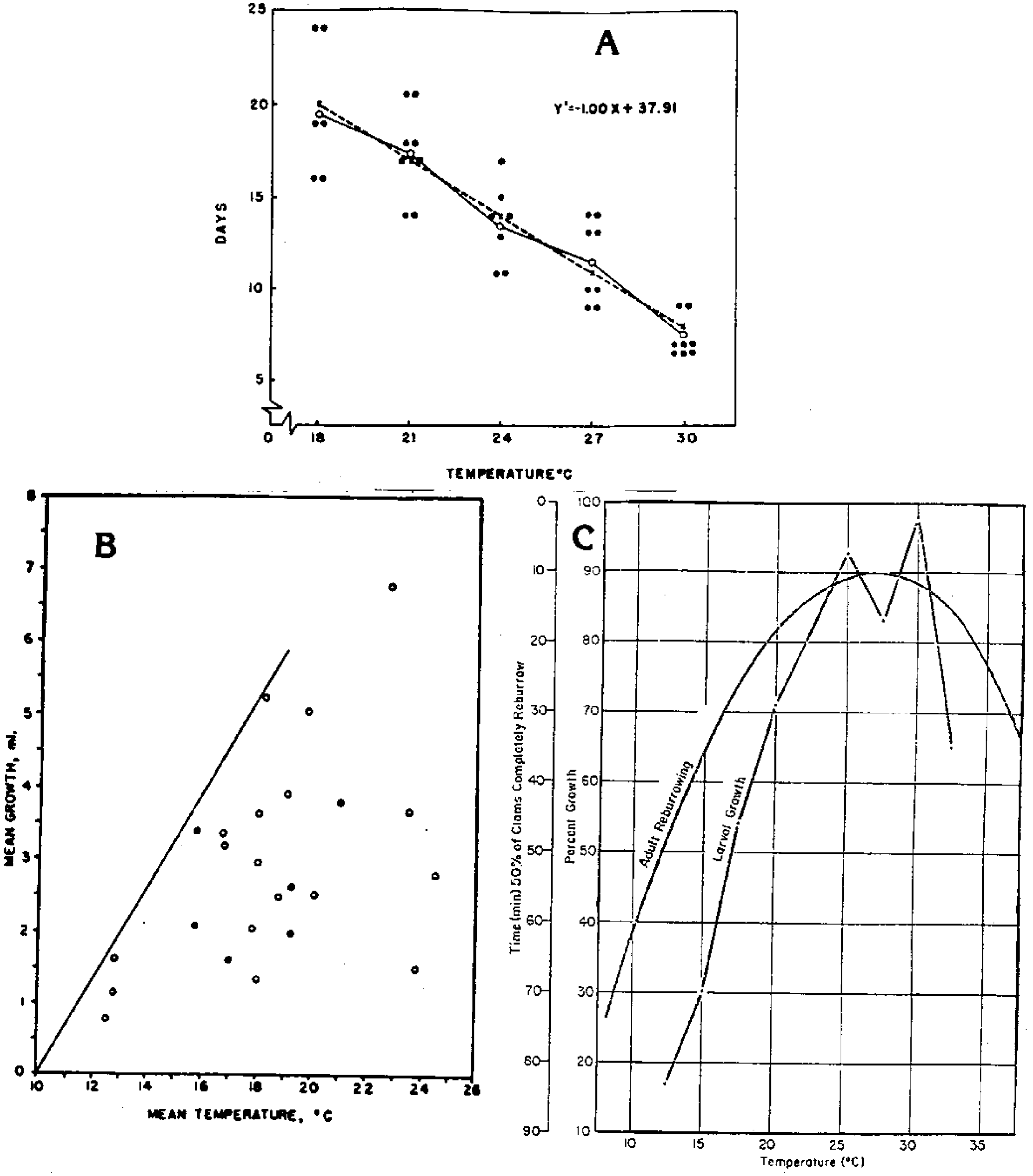


Figure 6. Effects of temperature on quahogs. A. Time to setting of larvae in culture (Loosanoff 1959). B. Mean growth of adults in six-week intervals in Narragansett Bay (Pratt 1956). C. Reburrowing of Narragansett Bay Quahogs and growth rate of larvae in culture (Davis 1969; Savage 1974).

rate to be variable at given temperatures, but decreased to low levels below 10°C (Figure 6). They estimated an optimum growth temperature of about 23°C.

Water temperature must be considered when planning quahog management strategies such as transplant or relay, because low winter temperatures substantially lower the metabolic rate of quahogs. Below 6°C, quahogs do not pump a large enough volume of water to filter feed (Hamwi 1968). In addition to limiting food supply to the animal, this low metabolic rate would result in a slow rate of depuration of bacteria and viruses in transplanted stock. Savage (1974, 1976), working with Narragansett Bay stock, found that the time for 50% of individuals to reburrow at summer temperatures was 10-20 minutes (Figure 6). At 10°C, typical of mid-November and early May, quahogs took an hour or more to reburrow. Reburrowing nearly ceased at temperatures below 9°C. This means that between mid-November and early May, quahogs left on the surface by rakes or transplantation would be subject to attack by predators.

3.3.6 Salinity The salinity within estuaries is a major determinant of quahog distribution. The salinity range in which adults are found in the field is quite similar to the range that embryos and larvae need to survive, about 20-32 ppt. Once larvae have metamorphosed into juveniles, becoming bottom dwelling, lower salinities can be tolerated. In a laboratory study, juveniles survived in freshwater for 22 days and in 10 ppt water for 28 days (Chanley 1958). In the field, adults survived in near-freshwater for 14 days (Burrell 1977). Salinity tolerance decreases when other factors are suboptimum (Stanley and DeWitt 1983). Findings on the effects of salinity on quahogs are summarized in Table 3. Hicks (1959) mapped salinity in Narragansett Bay. In Greenwich Bay, Providence River, upper Bay, and Mount Hope Bay, salinity was between 23 and 30 ppt, the range of optimum survival and growth of quahogs. In the deep parts of the mid-Bay and in the lower Bay, salinities were between 28 and 32 ppt, greater than the range of optimum growth of embryos and larvae, but within the range necessary for survival. The maximum salinities in which adults are found (Table 3) are the highest that occur in the regions surveyed, and do not indicate that seaward distribution is limited by salinity. Factors such as depth, temperature, substrate, and food supply probably exclude quahogs from the lower Bay, rather than high salinity.

Low salinities have a more obvious effect on quahog distribution than high salinities. Quahogs are excluded from otherwise suitable areas in which salinities fall below 15-20 ppt for prolonged periods. In many cases the transition from an environment in which quahogs are found to one supporting brackish-water species such as oysters is obscured by the presence of dams, dredged channels, and polluted water. Shells along the east shore of the Providence River indicate that the natural distribution of quahogs was to the mouth of the Seekonk River. Low salinity limits quahogs from large areas in Hundred Acre Cove and the Palmer River and in coastal ponds without breachways. Following heavy rainstorms, the salinity of Providence River surface waters falls to levels that inhibit development of larvae and feeding of adult quahogs. Effects on quahogs are minimized by the tendency for freshwater to be confined to the immediate surface (S. Grainger, unpublished data) and the ability of juveniles and adults to survive reduced salinities for many days.

Table 3. Salinity effects on quahogs

Salinity Range o/oo	**Effect**	**Location**	**Reference**
23-32	adult range	Massachusetts	(1)
20-34	adult range	Wellfleet, Mass.	(2)
15-35	adult range	Long Island Sound	(3)
20-32	embryo development	Long Island Sound	(4)
27.5	optimum embryo development	Virginia	(5)
27	optimum for veliger survival	Long Island Sound	(6)
20-27	optimum for veliger growth	Delaware	(7)
15	minimum for larval survival	Virginia	(5)
17.5-20	minimum for metamorphosis	Virginia	(5)
15-40	range, adult water pumping	New Jersey	(8)
23-27	maximum water pumping rates	New Jersey	(8)
24-32	optimum for siphon extension	Long Island Sound	(6)

References: (1) Belding (1931); (2) Curley et al. (1972); (3) MacKenzie (1979); (4) Davis (1958); (5) Castagna and Chanley (1973); (6) Davis and Calabrese (1964); (7) Carriker (1961); (8) Hamwi (1968).

3.3.7 Substrate In their species profile, Stanley and DeWitt (1983) state that "numerous studies have shown that hard clams are associated with a sandy bottom rather than a mud bottom." They also make the point that since sandy sediments are found in habitats with high current energy, it is difficult to determine whether distribution is a result of bottom type or current regime. In experiments in Narragansett Bay, Pratt (1953) found that sediments containing shell and rock had the highest recruitment rates of seed quahogs. He postulated that this was due to both induction of setting and protection of spat from predators. Wells (1957b) and Grizzle (1990) confirmed the positive effect of shell fragments on quahog recruitment in coastal Virginia and Florida. In a more detailed experiment, Keck et al (1974) showed that coarse-medium sand (0.5mm diameter grain size) induced three times as many larvae to set as coarse silt (0.05 mm). All sediment sizes between fine and coarse sand were more attractive than the silt.

Increased recruitment into sandier sediments results in greater adult populations. Pratt et al. (1987) conducted a dredge survey of the portions of Narragansett Bay closed to shellfishing and calculated the mean density of quahogs for sediment grain size strata mapped by McMaster (1960). In the Providence River, the mean number of quahogs per tow for each stratum was: clay/silt, 32; sand/silt, 102; sand/silt/clay, 461; and silt/sand, 860. The means of the first two categories were significantly lower than the remaining means. There were only two sediment strata within Mount Hope Bay. These had very similar low catches of 12.1 and 14.6 quahogs in clay/silt and sand/silt/clay with no significant difference between them. O'Conner (1972) found a strong effect of substrate on standing crop in Moriches Bay, Long Island (sand without vegetation, 34 g/m^2; sand with vegetation, 11.3 g/m^2; and sand with clay and silt, 1.6 g/m^2).

Sediment type has been found to be related to growth rate. Pratt (1953) found a 24% increase in growth in sand versus sandy silt in experimental boxes placed in Wickford Harbor. Additional experiments carried out throughout the Bay (Pratt and Campbell 1956) corroborate this finding. More recent studies have used multifactoral analyses to compare the relative effects of current speed, seston concentration, and sediment type on the growth of quahogs (Grizzle and Lutz 1989; Grizzle and Morin 1989). The product of seston concentration and current speed (horizontal seston flux) was determined to be the major determinant of quahog growth. The increased growth associated with sandier sediments in the earlier studies was interpreted to be a secondary result of sandier sediments being associated with higher current regimes.

4. The Rhode Island Fishery

4.1 Commercial Fishery

4.1.1 Descriptive Statistics

4.1.1.1 Landings In fisheries statistics published by the National Marine Fisheries Service (NMFS), the quahog catch is given in pounds of meat. This is obtained by multiplying the catch in bushels by an estimate of the pounds of meat per average bushel (12 pounds previous to 1985 and 10 pounds since). Only the catch sold to dealers appears in NMFS statistics.

Before 1928, annual Rhode Island commercial landings of quahogs were less than one million pounds of meat. The oyster industry was still important during this period, and much of the Upper Bay was under lease. Quahogs were of secondary importance, both in terms of food and management. Commercial catches increased from 1928 to 1955 with some fluctuation. The greatest increase in landings took place between 1951 and 1953 when they more than doubled to five million pounds (Figure 7). After remaining high for two years, landings decreased rapidly, then more slowly to a low of less than one million pounds in 1974. A second major increase took place between 1974 and 1983. Landings fluctuated around the four million pound level between 1982 and 1985, and then decreased steadily to 2.5 million pounds in 1990.

4.1.1.2 Value The annual value of Rhode Island quahog landings is shown in Figure 8. The low point in the 1950s reflects a peak in catch with little increase in consumer demand. The high peak in the 1970s and 1980s is the result of increases in catches and price increases due to inflation. When annual values are adjusted to constant 1967 dollars, the peak is lower but there is still an increase in the value of the product. This increase is a function of the larger proportion of valuable small clams in the catch and increased prices in all size categories.

The annual average price of quahogs (as pounds of meat) in actual and adjusted dollars is shown in Figure 9. The adjusted price increased gradually from 1951 to 1970, doubled from 1970 to 1980, decreased in 1982 and 1983, and then increased again in the late 1980s. The 1982 to 1983 dip was caused by a combination of sanitary quality problems in New York (COSMA 1985) and an abundance of supply from Rhode Island and other states. Prices rose steadily from 1983 to 1989, when they reached an all time high in actual dollars. In 1990, prices began to drop because of lowered consumer demand and abundant supply.

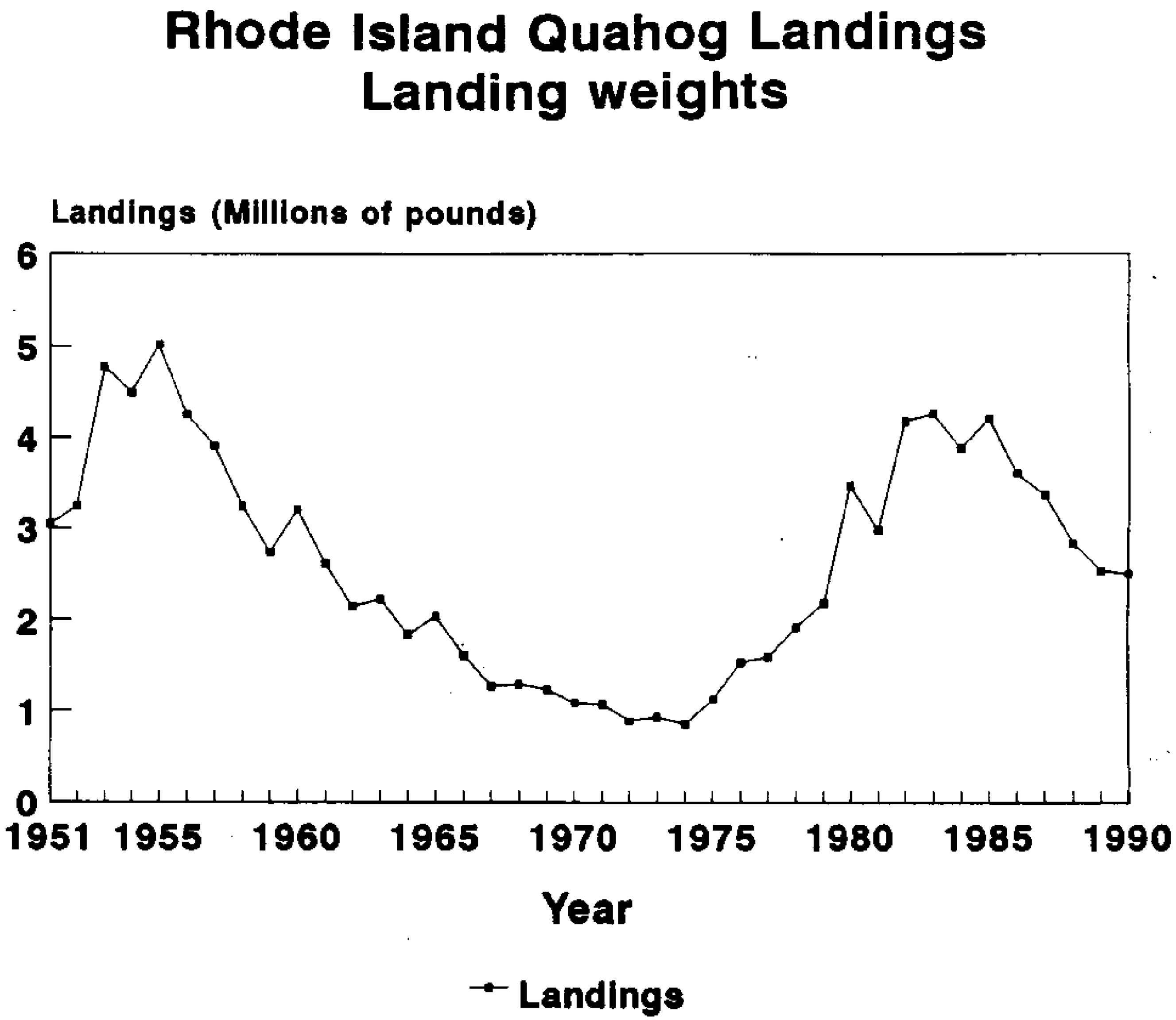


Figure 7. Landings of quahogs in Rhode Island. Source: NMFS statistics.

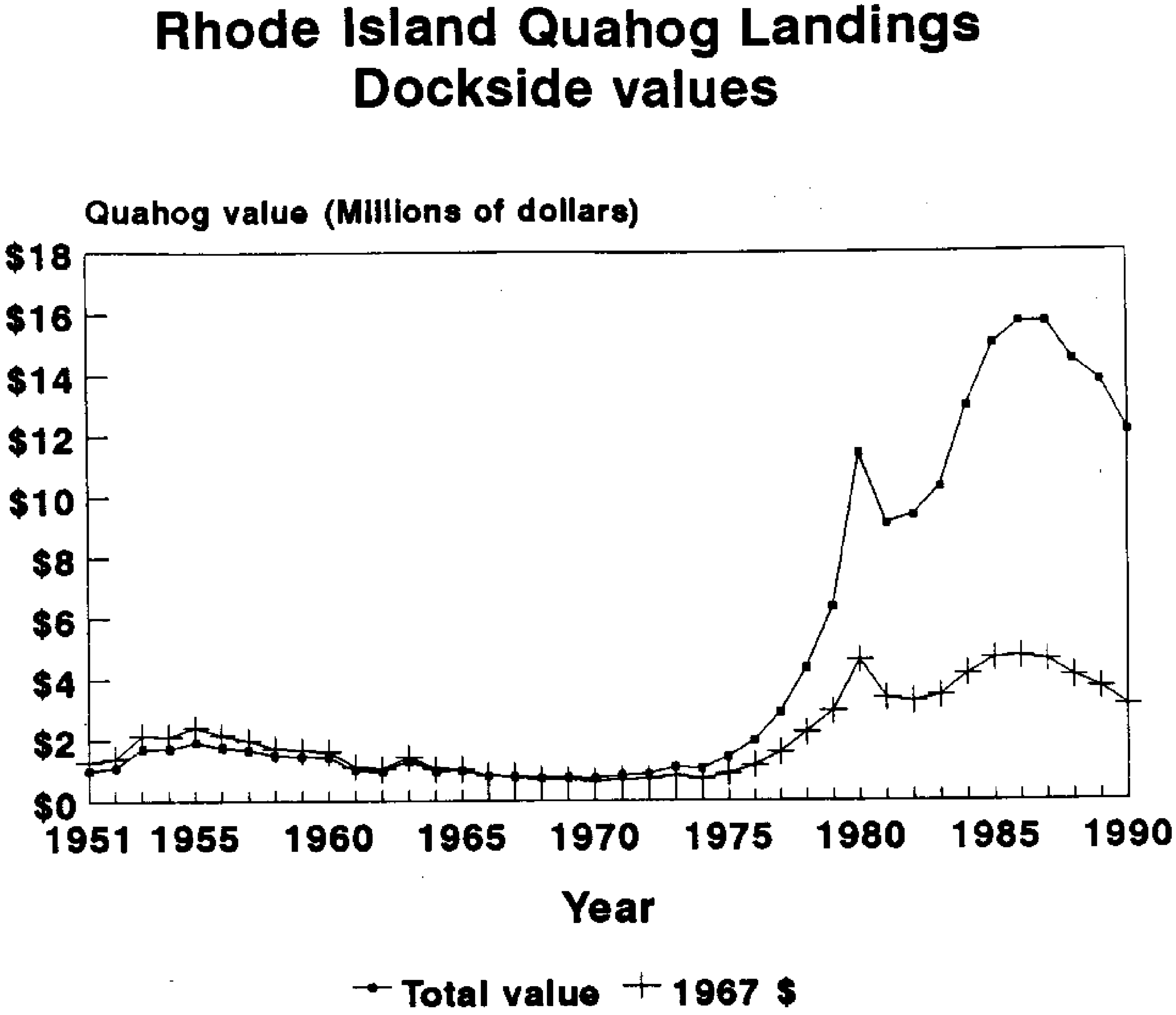


Figure 8. Value of quahogs landed in Rhode Island in actual dollars and in constant 1967 dollars. Source: NMFS statistics.

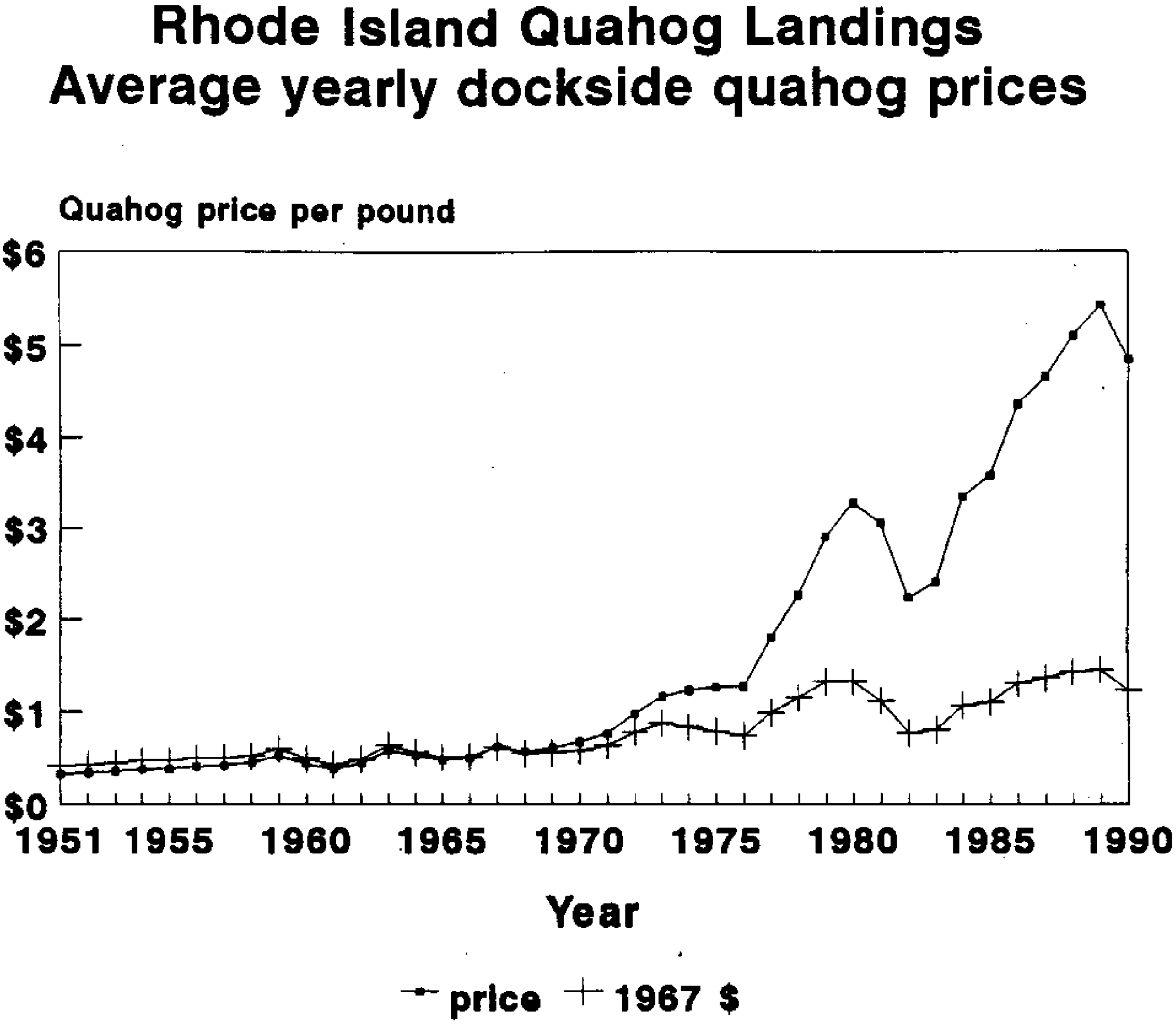


Figure 9. Average yearly prices per pound of quahogs landed in Rhode Island in actual dollars per pound and in constant 1967 dollars. Source: NMFS statistics.

4.1.1.3 Number of fishermen The National Marine Fisheries Service estimates of full-time quahoggers in Rhode Island from 1951-1990 are shown in Figure 10. The numbers of full-time fishermen reached a peak in 1956 during a period of high landings. Numbers decreased steadily as catches declined in the 1960s, and increased as landings and prices improved. The number of fishermen nearly doubled between 1978 and 1979, and has remained at a high level since then (between 1,000 and 1,300 fishermen).

At present, the number of full-time fishermen is estimated by adding the numbers of holders of regular shellfish licenses for harvest from a boat, and 20% of the multipurpose licenses. Holders of shellfish licenses who are under 19 years of age (juniors) and over 65 years old (seniors), or who do not fish from a boat, and 40% of multipurpose license holders are assumed to be part-timers. In 1990, there were 1178 regular licensees with boats; 927 junior, senior, and non-boat licenses; and 807 multipurpose licenses. Thus the estimated number of full-timers was 1,339, and the estimated number of part-timers was 1,250. This estimate is higher that the working estimate of 700-800 full-time shellfishermen currently used by the Department of Environmental Management.

There is considerable uncertainty about the number of multipurpose license holders in the quahog fishery since there is no requirement to identify the primary fishery. This license option was introduced in 1981.

To manage the fishery, it is more important to know the levels of fishing effort in addition to the numbers of fishermen. The division of fishermen into full and part-time categories is difficult because there is a gradual transition from the highest to the lowest levels of effort. One of the main characteristics of the Rhode Island quahog fishery is the relative ease of increasing or decreasing effort as conditions change within the fishery or the general economy. Holmsen (1966) and Holmsen and Horsley (1981) conducted mail surveys of all shellfish license holders and made the following estimates of number of those deriving different proportion of their income from quahogging.

Table 4 (Holmsen and Horsley 1981)

Proportion of Income years	**number** 1962-1963	%	**number** 1978-1979	%
none	139	17	113	11
less than 20%	359	44	297	29
about 25%	81	10	114	11
about 50%	65	8	135	13
about 75%	33	4	31	3
over 90%	138	17	338	33
total	815		1,028	

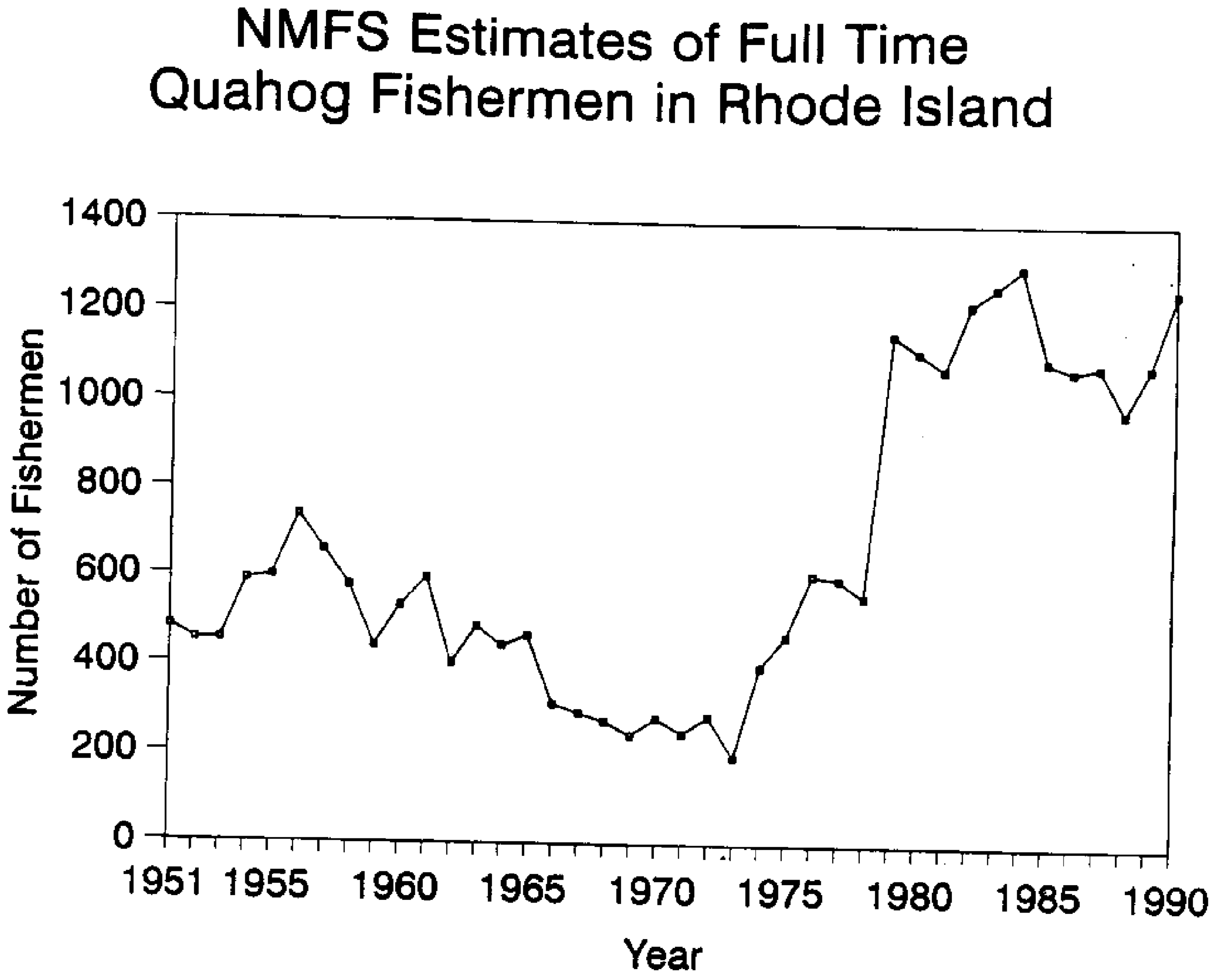


Figure 10. Estimated numbers of full-time quahog fishermen in Rhode Island. Source: NMFS statistics.

The proportion of fishermen obtaining at least 75% of their income from quahogging increased from 21% to 36% in the two surveys. Holmsen (1966) also found an increase in full-timers from the 1950s to 1961, indicating a trend of professionalization during periods of both decline and increase of landings. National Marine Fisheries Service estimates of full-time fishermen are high relative to the numbers reported by Holmsen and Horsley (1981). The NMFS totals would include fishermen obtaining less than 25% (1962) or 50% (1978) of their income from quahogging. No direct survey information is available on the number of fishermen deriving a high proportion of income from the quahog fishery in the period after 1979 when the absolute numbers of license holders have been at high levels.

4.1.2 Fishing methods and location of effort At present, there are three basic methods of commercial quahog fishing used in Rhode Island waters. These include tongs, bullrakes and commercial diving. Commercial diving for quahogs has increased in importance since the 1981 study of Holmsen and Horsley, so there is very little information available as to their numbers. Boyd (1991) provides an excellent description of the history of tonging and bullraking in Narragansett Bay. There has been a gradual shifting from a predominance of tongers in the quahog fishery to a predominance of bullrakers. The National Marine Fisheries Service is required to make an estimate of the numbers of tongers and rakers in the fishery. From 1951 to 1970, a figure of 20-25% bullrakes was used, increased to 80% from 1971 to 1980, and to 95% afterward.

Location of Fishing Effort -- The location of tong and bullrake fishing effort was mapped intermittently by the state of Rhode Island between June 1955 and August 1960. The initial object was to obtain area-specific data on catch, catch/effort, and size distribution of clams for research in the productivity of the bottom (Campbell and Dalpe 1960a). After a brief hiatus, the fleet plotting project was reactivated to be able to establish dredge boat harvest areas where they would not be in conflict with hand collectors (Campbell 1961). The locations of bullrake and tong fishermen were recorded on 40 days between September 1959 and August 1960 (Figure 11). Campbell provides maps of bullrake and tong locations for all observations and also provides separate maps for winter and summer. The areas of productive fishing have changed very little in 28 years. Wickford, the upper West Passage, Greenwich Bay, the upper Bay, and Bristol were all concentrated boat locations. Bullrakers were able to fish in areas of intermediate depth in upper West Passage and the upper Bay that were denied to tongers. Although the plotting operation was supposed to take into account "all the known areas ... frequented by fishermen," no locations are shown in the Sakonnet River. It appears that that area was not surveyed, possibly because much of it was assigned to dredge boats at that time.

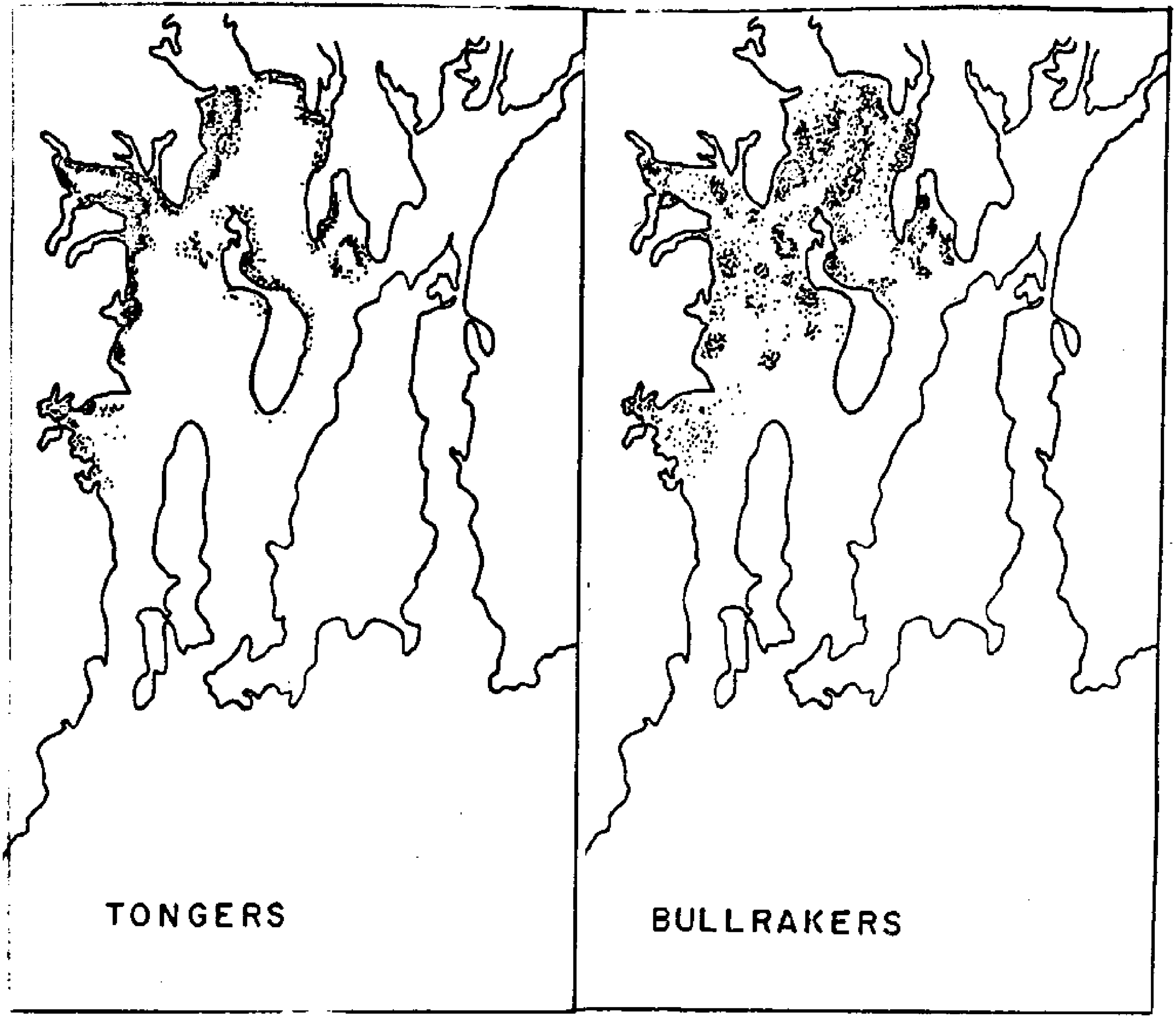


Figure 11. Location of tong and bullrake fishermen in Narragansett Bay recorded between September 1959 and August 1960. Source: Campbell (1961).

4.2 Recreational Fishery Recreational harvesting of quahogs and other shellfish is a popular activity among many Rhode Island residents as well as many out of state visitors. One recent estimate is that 50,000 people are engaged in the recreational shellfisheries of Rhode Island (Borden 1992). Because of so many participants in the recreational shellfishery, there are many problems for resource managers and enforcement officers. Over fishing of popular recreational areas is a common problem.

Most Rhode Island residents consider recreational shellfishing one of the few freedoms that they have left. The ability to go out and "dig a few clams" is a treasured right. All Rhode Island residents are allowed to harvest shellfish from certified waters of the state without a license, but are limited by daily catch limits of one half bushel per person per day of quahogs, soft shell clams, and oysters as long as they are not offered for sale. These resources are considered "free and common" to all by the Rhode Island state constitution.

Rhode Island is one of the few states that permits out of state residents to participate in the recreational shellfishery. The debate over the issue of banning participation of out of state people in recreational shellfishing has continued over the years, but legislative efforts to enact bans have been blocked by interests of the tourism industry. Currently, non-residents may purchase a recreational shellfishing license from authorized agents throughout the state. These licensed individuals are limited to a daily catch of one peck (1/4 bushel) each of oysters, clams, and quahogs; which may not be sold. Daily catch limits are more stringent in shellfish management areas.

Recreational shellfishing takes place throughout the state where people can access the resource. The most popular shellfishing areas are usually those with adequate parking. Some of the most popular are Conimicut Point, Longmeadow, Oakland Beach, Nausauket, and Goddard Park in Warwick; Mount View, Wickford, and Bissel Cove in North Kingstown; Barrington Beach and Colt Park in the East Bay; and Seapowet, Fogland Point, and Jack's Island along the Sakonnet River. All of the Washington County salt ponds are heavily fished by recreational diggers.

4.3 Quahog Population Characteristics

4.3.1 Distribution There have only been a few surveys in which the the distribution of quahogs in Rhode Island coastal waters is mapped. The first Narragansett Bay wide mapping of quahog distribution was based on a 1956 to 1957 dredge survey undertaken in response to proposals for mid-Narragansett Bay hurricane barriers. Data collected at that time indicated the areas in which quahogs were present and also provided estimates of the standing crop population densities (Stringer 1959). A total of nearly 2,800 samples was taken on a 900-foot grid. The map generated from

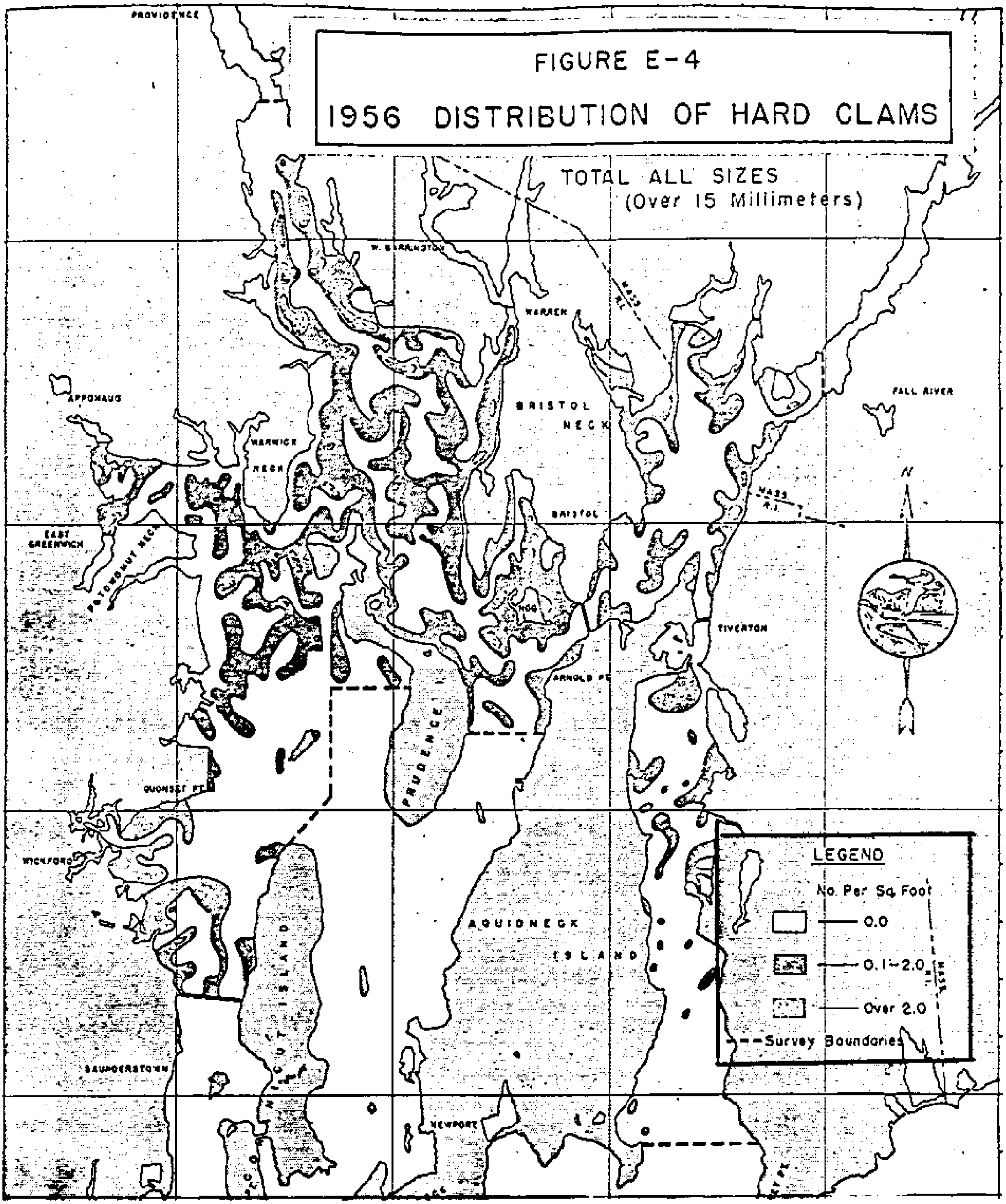


Figure 12. Distribution of quahogs in Narragansett Bay from a quantitative survey 1955-1956. From Stringer (1959).

these data shows three density classes of quahogs and that the areas of high abundance were very similar to areas of high abundance found today (Figure 12). The major reasons why more extensive surveys have not been made are expense, difficulty in resolving problems of spatial heterogeneity, and the constant changes that take place due to fishing pressure and growth of the quahogs. If a bottom grab is used, it must be large enough to recover more than a few quahogs per station, and stations must be close enough together to define areas with different abundances and numerous enough to provide good estimates of standing crop. Taking large numbers of grabs is slow and expensive. Dredges have the advantage of sampling large bottom areas and integrating small scale patchiness, and do not require sieving aboard the boat. The major faults of dredge samples are variation of efficiency due to bottom type and vessel operation, and failure to recover small quahogs.

Since the late 1940s, a number of surveys have been carried out in sub-areas of Narragansett Bay as part of studies of populations, responses to pollution, and to fisheries management. When these surveys are examined together, they show the general distribution of quahogs and changes which have taken place over time. The areas studied and the techniques used are summarized below.

In 1949-1950, a dredge survey of Narragansett Bay (123 stations) was made to determine the distribution patterns of quahogs in relation to sediment type (Pratt 1953). The data were not mapped.

Quahog population studies were conducted in Greenwich Bay from 1951-1957 by the U.S. Fish and Wildlife Service and the Rhode Island Division of Fish and Game using a construction bucket that took a large (0.46m^2) sample. Shallow areas were sampled by tongs. All clams at least 15 mm (0.6 inches) long were counted. Quahog distribution in Greenwich Bay in 1952 was mapped in Stickney and Stringer (1957)(Figure 13). Density was low on muddy bottom in the center of the Bay. The areas of high density on mixed bottom at the mouth of the Greenwich Bay, off Marys Creek, and at the mouth of Greenwich Cove continue to be productive today. For comparison, Rice et al (1989) provide recent data about population densities of quahogs at the mouth of Greenwich Cove (averaging 190/m^2 in closed areas and 78/m^2 in actively fished areas).

Quantitative surveys of quahogs have been carried out on three occasions using the same grab sampling and tong sampling techniques in Upper Narragansett Bay areas closed to shellfishing. In 1956, the Providence River and Mount Hope Bay were surveyed along with much of the Upper Narragansett Bay (Stringer 1959; Campbell n.d.). The Providence River was again surveyed in 1957 (Stringer 1959) and in 1965 (Canario and Kovach 1965b; Saila et al. 1967). In each survey, stations were located on a 274m (900-foot) grid: 120 in the Providence River from 700m north of Sabin Point to Conimicut Point, 188 in the Rhode Island portion of Mount Hope Bay, and an unknown number in the

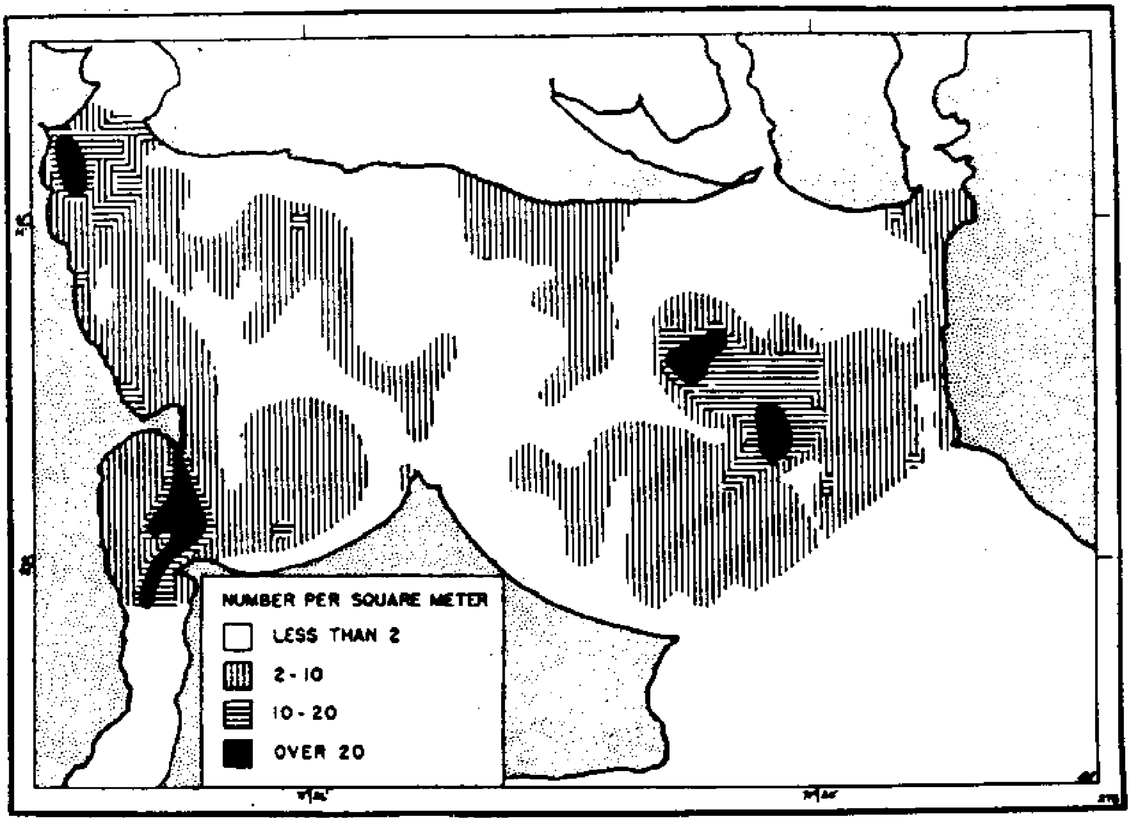


Figure 13. Distribution of quahogs over 25mm long in Greenwich Bay during 1952. Data were gathered from 226 stations using a $0.46m^2$ grab sampler and a 12mm sieve. From Stickney and Stringer (1957).

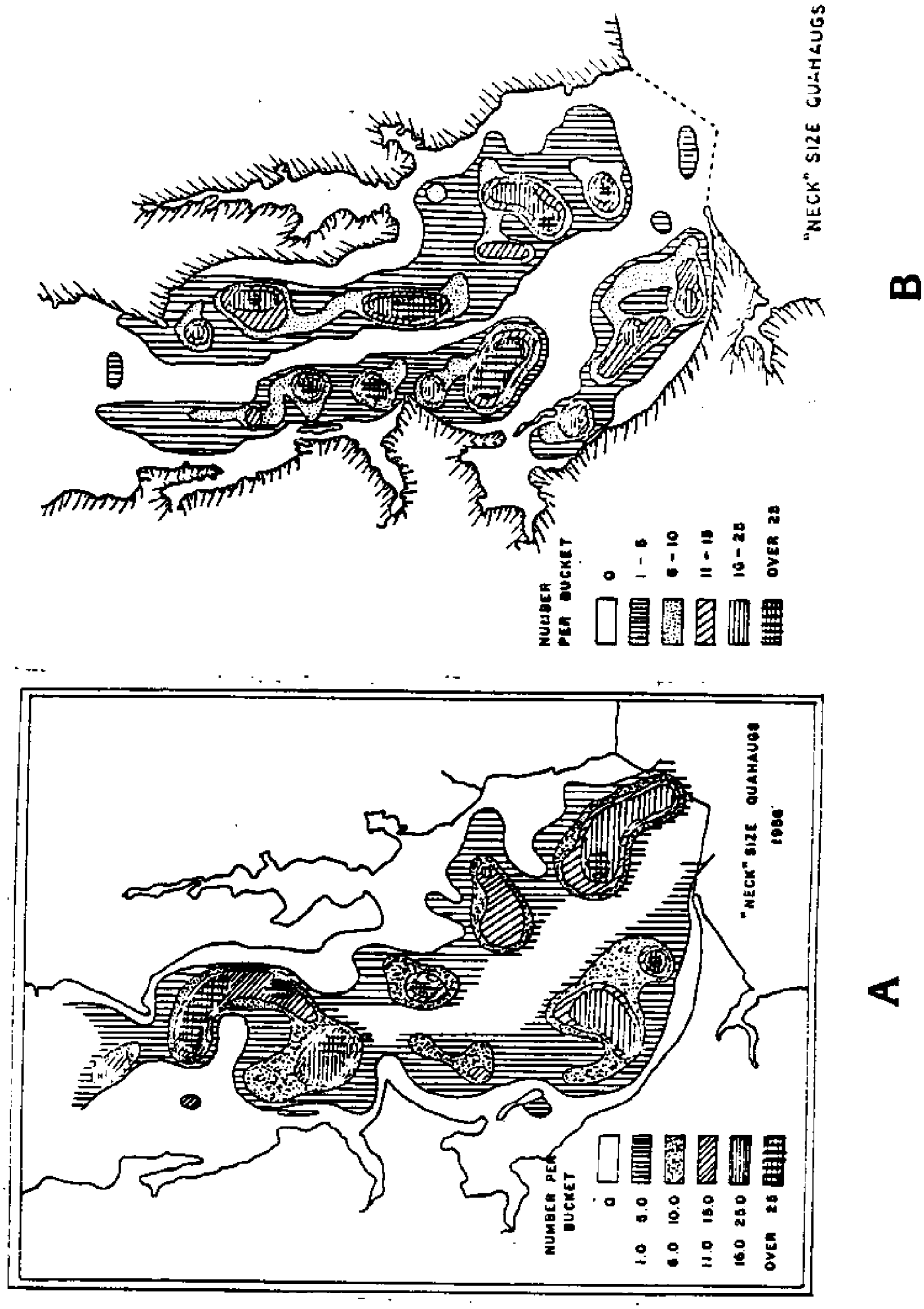


Figure 14. Contoured catch per sample (0.46m^2 grab) in the Providence River in (A) 1956 and (B) 1965. Figures from Canario and Kovach (1965).

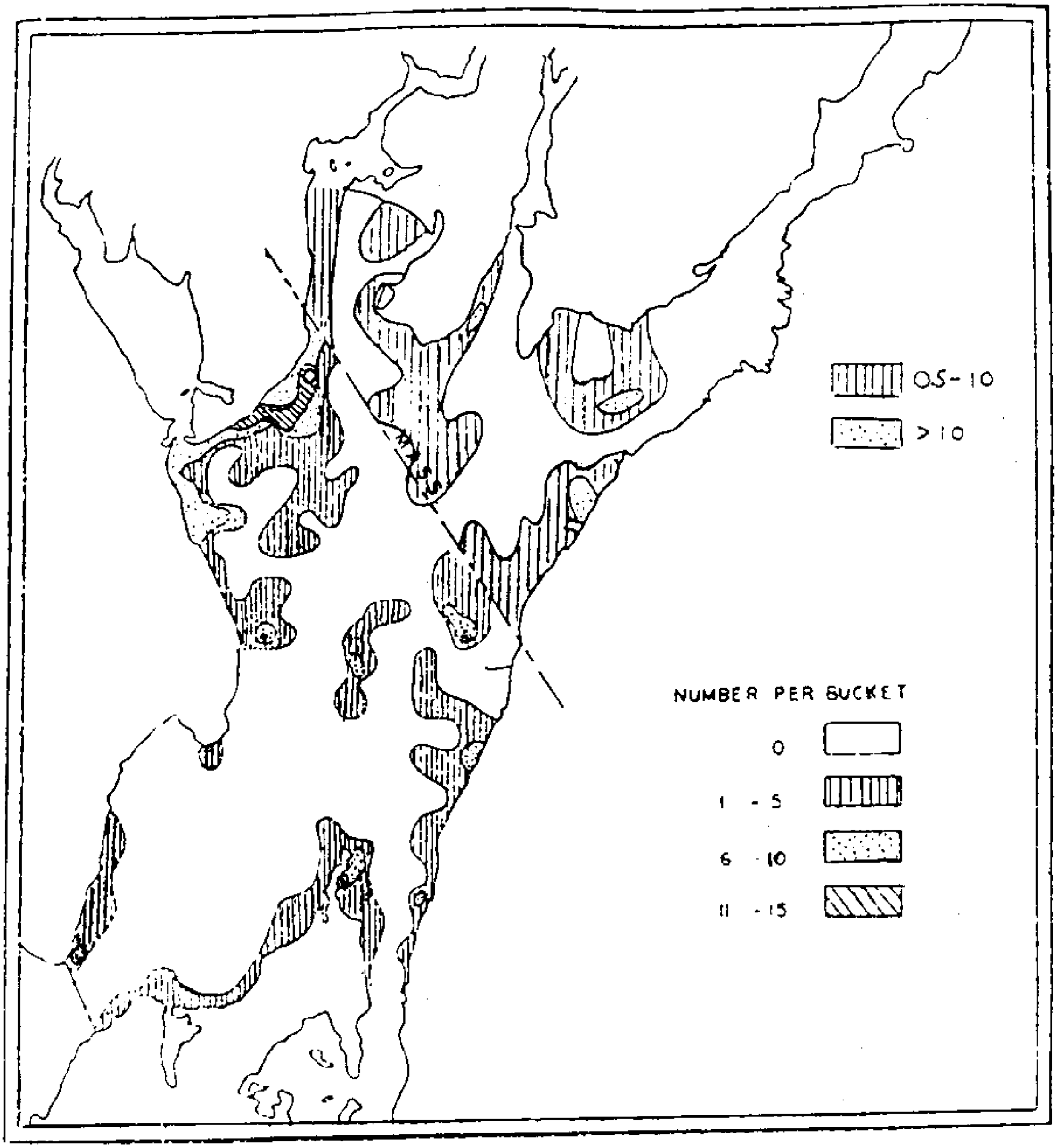


Figure 15. Contoured catch per sample from stations in Mount Hope Bay in 1956. Numbers are individuals over 15mm long collected in a 0.46m^2 grab sampler. Distribution in Rhode Island from Campbell (n.d.) and distribution in Massachusetts from Stringer (1959). Note differences in density scales for each state.

Massachusetts portion of Mount Hope Bay. At each station a single $0.46m^2$ sample was taken with a construction bucket. In the Providence River, shallow stations were sampled with tongs. Samples collected in 1956 and 1957 were washed on a 12.7mm screen and quahogs larger than 15mm in width were recorded. A 6.35mm screen was used in 1965. Clam density is given in four size classes for 1956 and 1957 data (Stringer 1959) and contoured in three commercial size categories for 1956 and 1965 data (Campbell, n.d.; Canario and Kovach 1965b). The high sample density and the systematic coverage of each area (at depths of less than about 6 meters) made it possible to map in detail the quahog distribution in the Providence River and Mount Hope Bay (Figures 14 and 15).

A study carried out by the Rhode Island Department of Environmental Management (Russell 1972) demonstrated that acceptable estimates of population size can be made with dredge data for single substrate types. Use of a dredge is justified by savings in time and by its ability to integrate small scale patchiness. The lower Providence River and the upper Bay were surveyed in 1976 by the Division of Fish and Wildlife (Sisson 1977) using a dredge for which efficiency values had been determined in five sediment types. Results are given as potential yield to dredging of three size classes in each sediment type, rather than as mapped densities.

The Providence River and Mount Hope Bay were surveyed by dredge in 1985 as part of the Narragansett Bay Project (Pratt et al 1987). The sample areas were: (1) Providence River north of the closure line from Conimicut Point, Conimicut light house, Nayatt Point, and south of a line from Pawtuxet Neck to Sabin Point; and (2) Mount Hope Bay between Mount Hope Bridge, Braga Bridge, and Tiverton Bridge, but excluding the Kickamuit River. The stratified random sampling plan used in that survey improved estimates of standing crop and identified effects of different substrates on quahog condition. Maps of quahog densities in the Providence River and Mount Hope Bay were generated (Figures 16, 17). In 1983, the Massachusetts Division of Marine Fisheries surveyed the northern portion of Mount Hope Bay with a dredge for which efficiency had been determined by diver sampling (Hickey 1983). The maps of quahog abundance in the Massachusetts portion of Mount Hope Bay produced by Hickey (Figure 18) and the map produced by Pratt et al (Figure 17) show high quahog densities in shallower waters and very low densities in the deeper areas.

Surveys of quahogs have been carried out by DEM personnel in various other portions of Narragansett Bay including East Passage (Canario and Kovach 1965a) and West Passage (Gray 1969; Russell 1972). The Sakonnet River was surveyed in 1968 (Division of Conservation 1968). The area of Quonset Point closed to shellfishing was surveyed by bucket sampler in 1967 (31 stations)(Kovach and Canario 1968). The entire Quonset-Davisville area was surveyed in

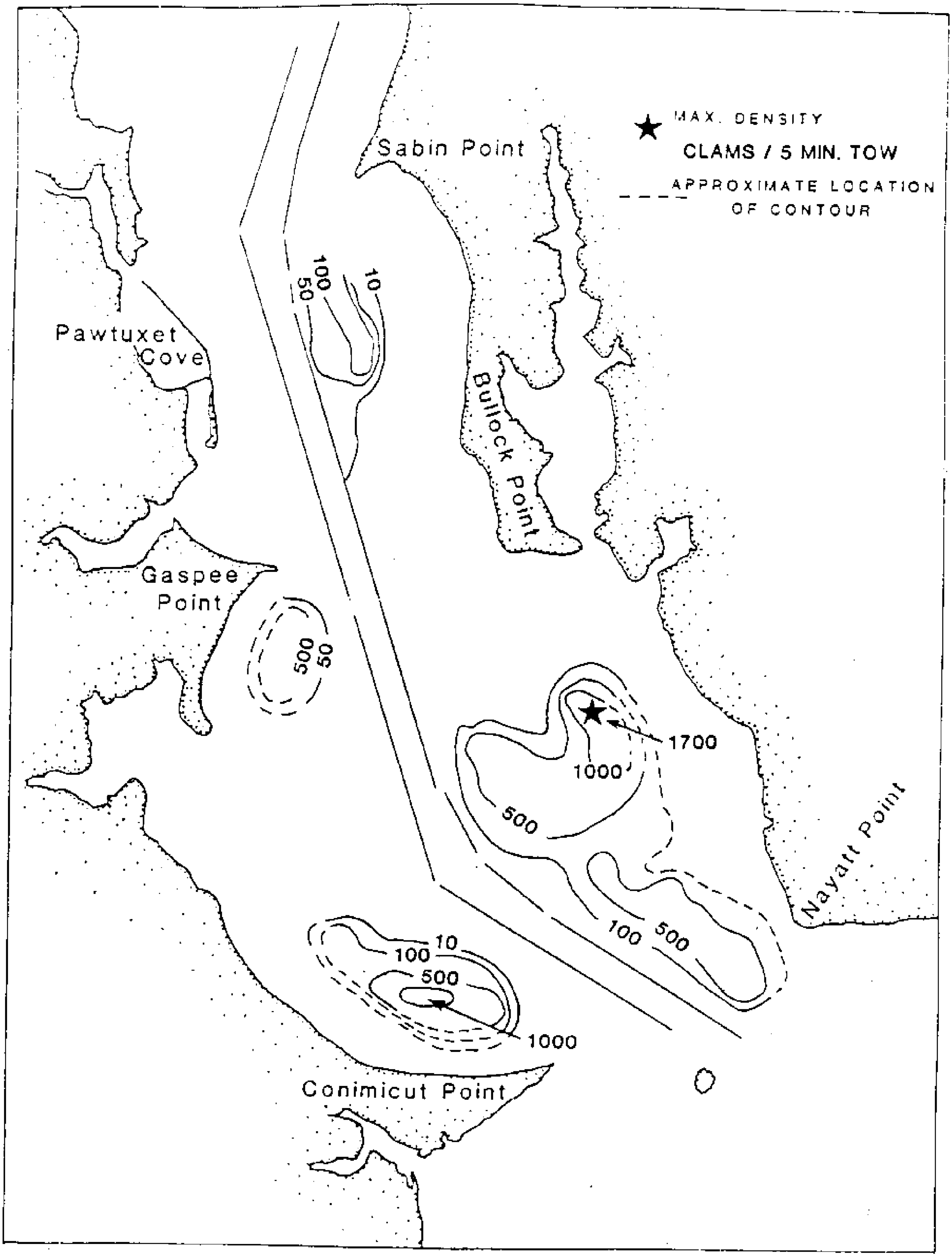


Figure 16. Contoured catch per tow in the Providence River, November to December 1985. From Pratt et al (1987).

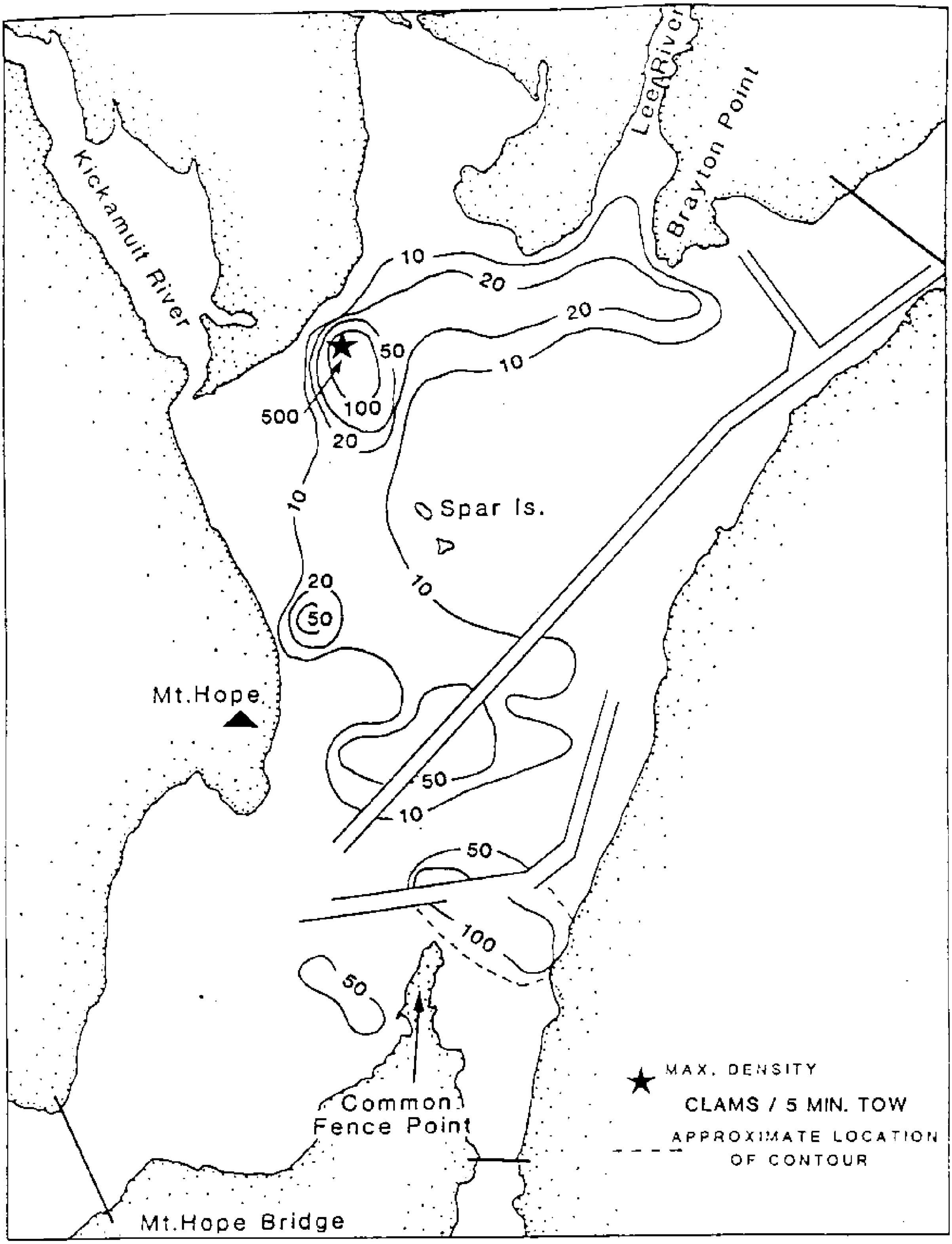


Figure 17. Contoured catch per tow in Mount Hope Bay, November to December, 1985. From Pratt et al (1987).

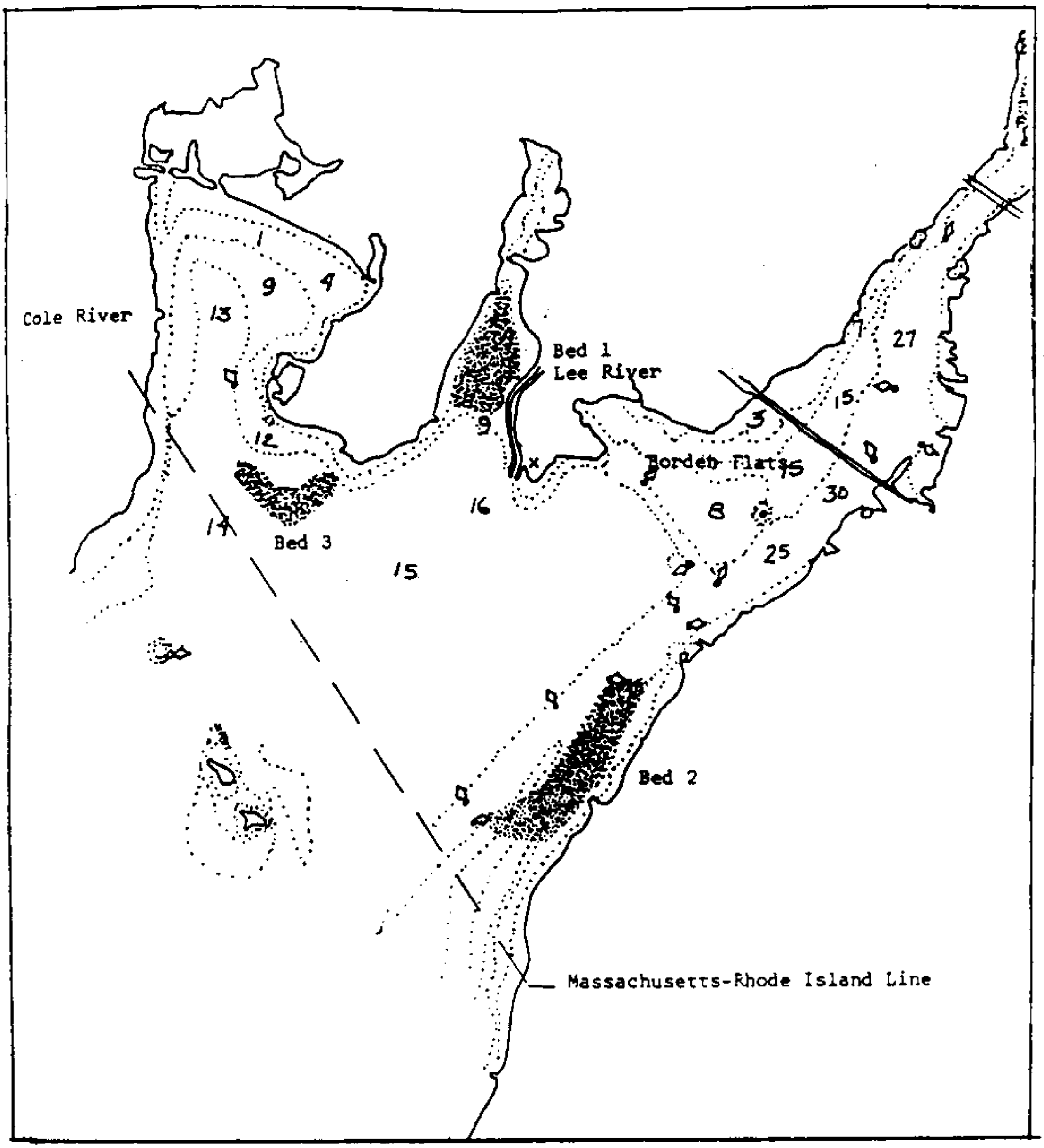


Figure 18. Areas of high quahog densities in the Massachusetts portion of Mount Hope Bay in 1980. From Hickey (1984).

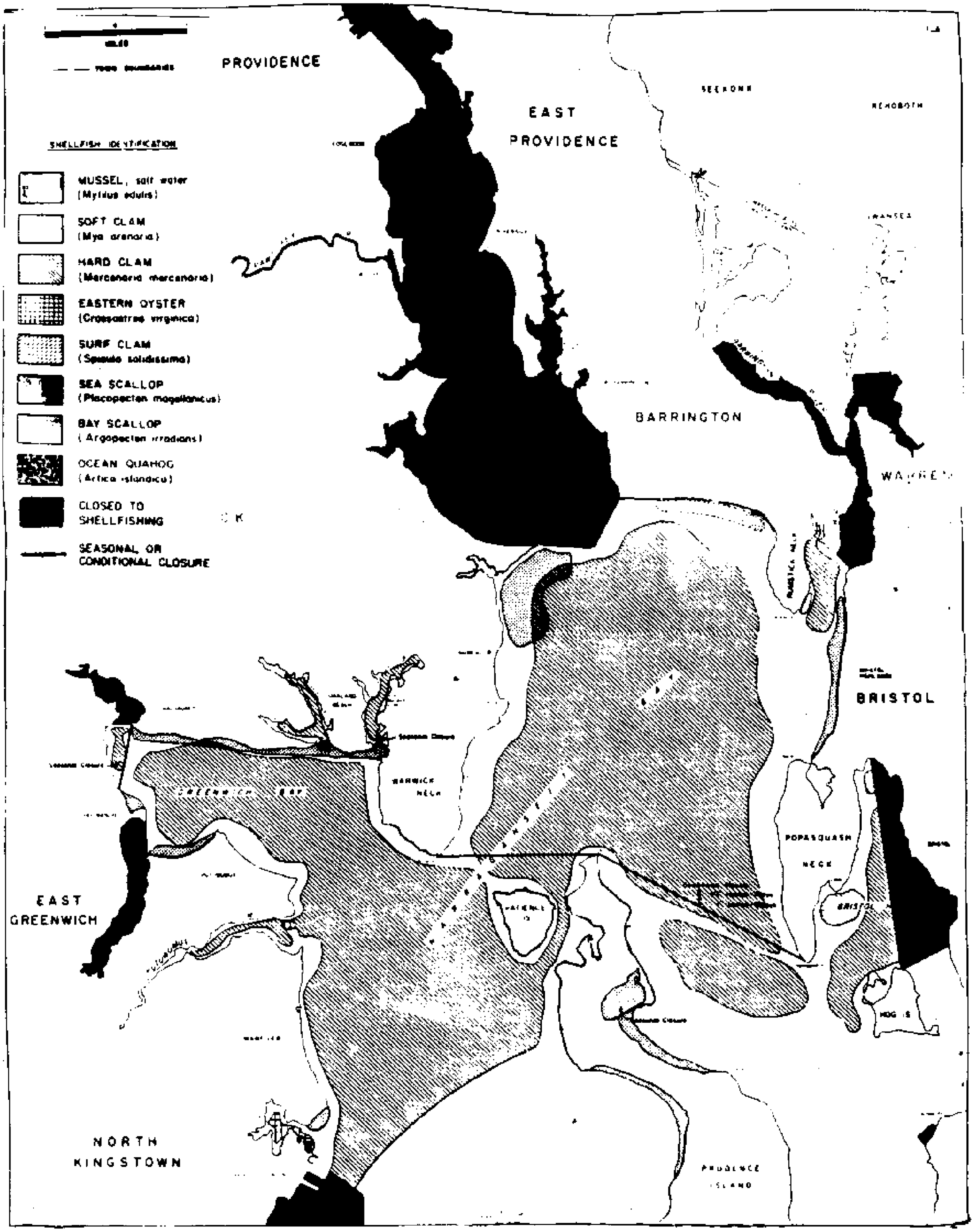


Figure 19. Shellfish map showing the Providence River, Upper Narragansett Bay, and Greenwich Bay. Source: U.S. EPA and Div. of Fish and Wildlife (1974).

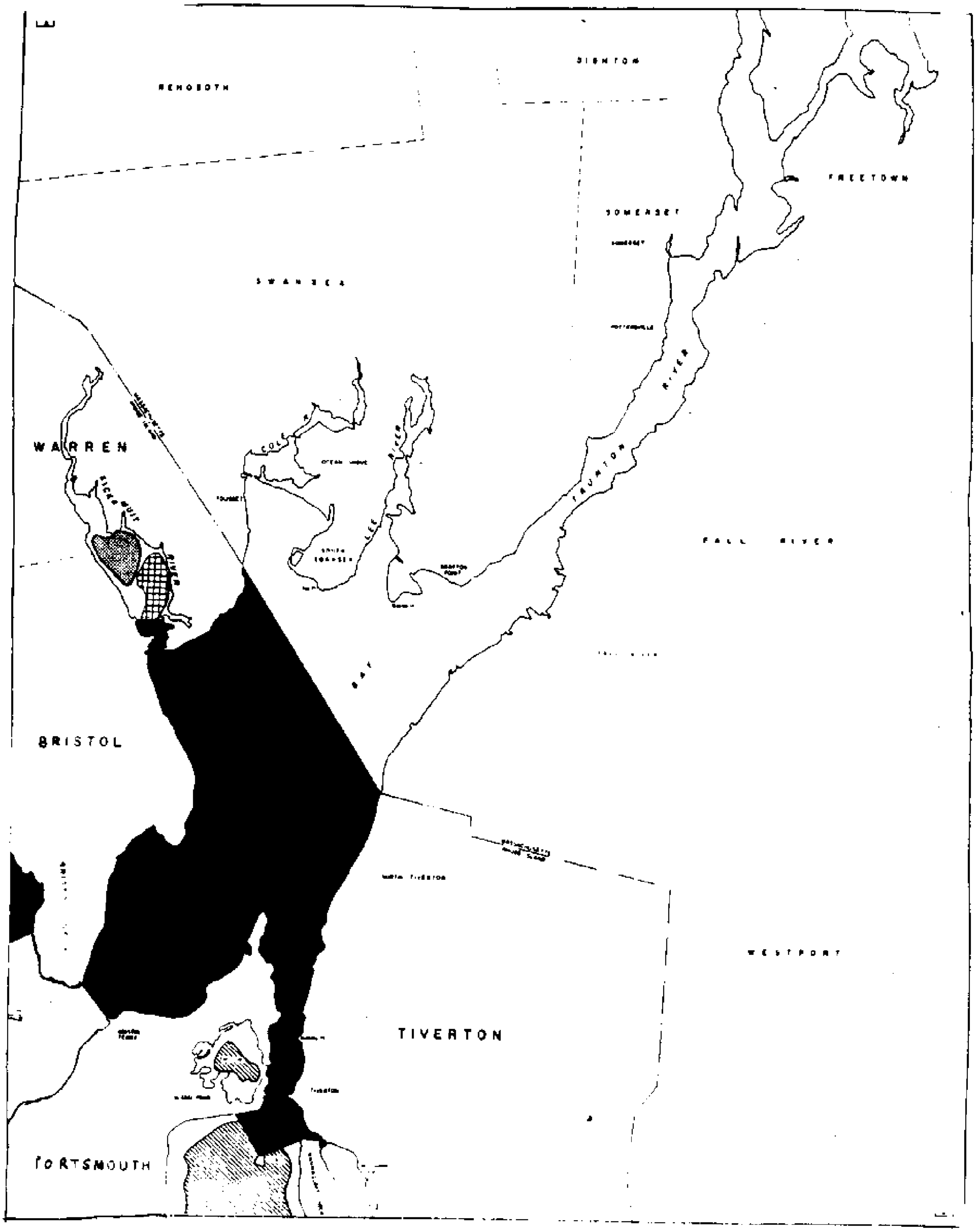


Figure 20. Shellfish map showing the pollution closure area in the Rhode Island portion of Mount Hope Bay. Map symbols are in legend of Figure 19. Source: U.S. EPA and Div. of Fish and Wildlife (1974).

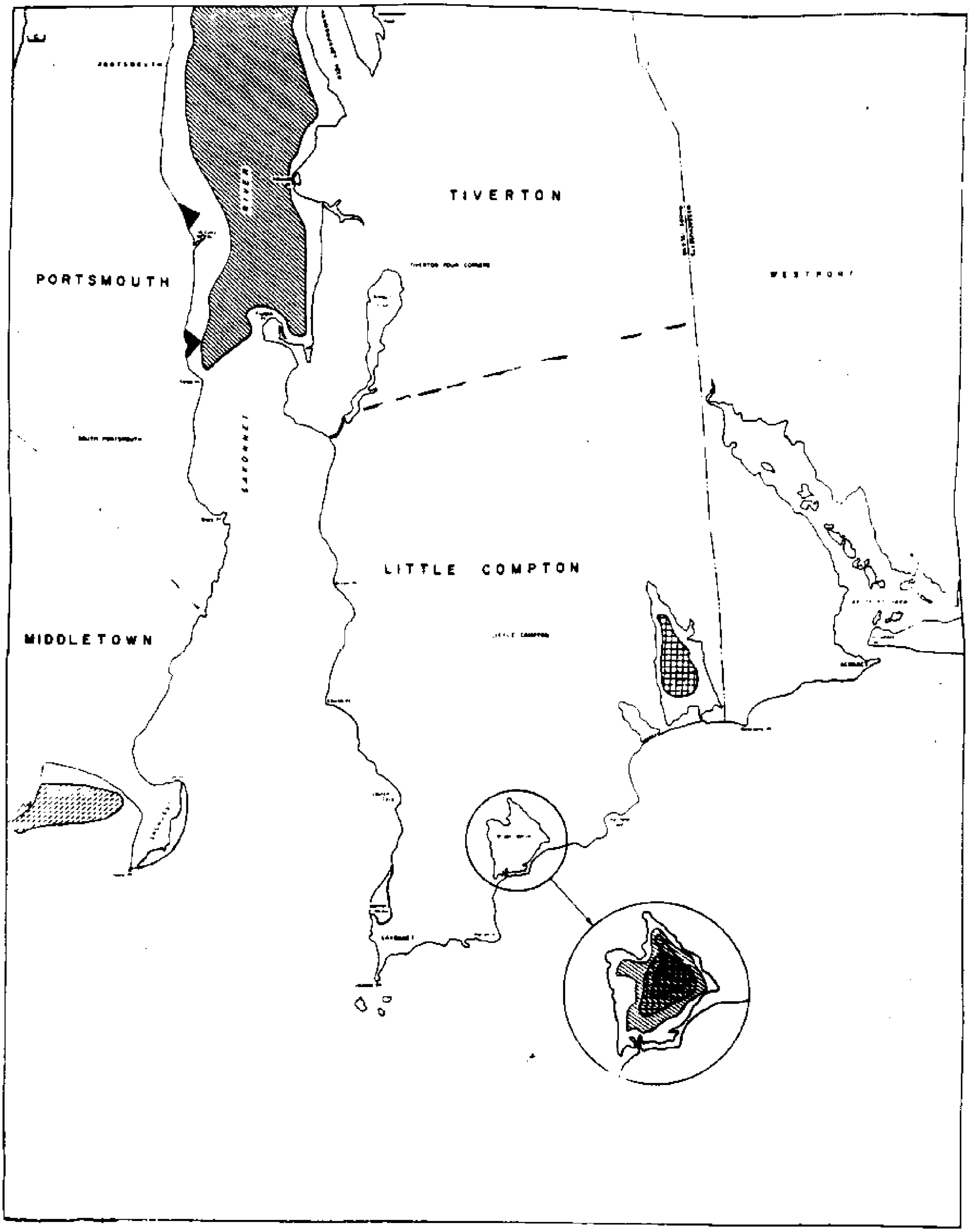


Figure 21. Map of shellfish areas in the Sakonnet River area of eastern Rhode Island. Map symbols are in legend of Figure 19. Source: U.S. EPA and Div. of Fish and Wildlife (1974).

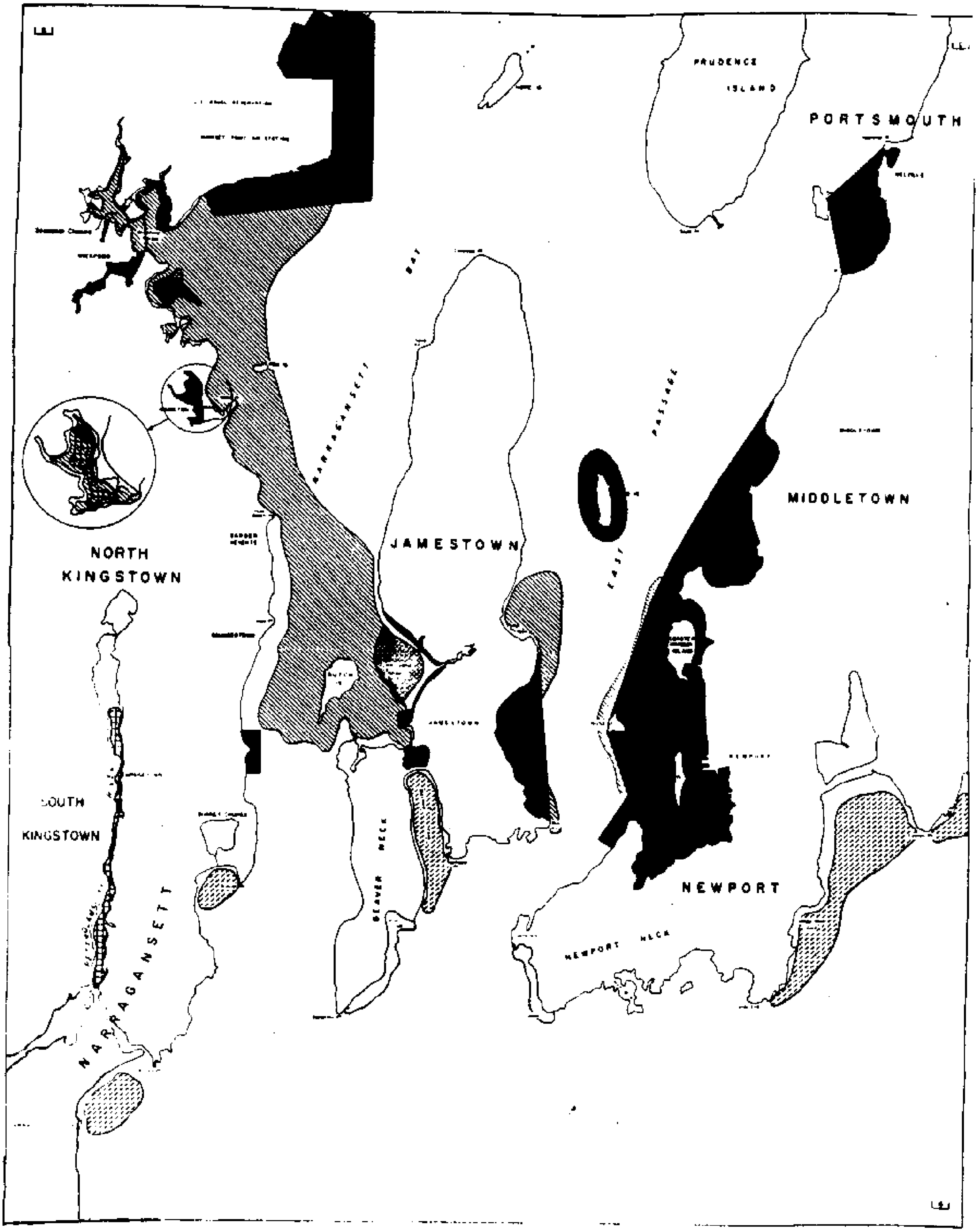


Figure 22. Shellfish areas of West Passage and East Passage in Narragansett Bay. Map symbols are in legend of Figure 19. Source: U.S. EPA and Div. of Fish and Wildlife (1974).

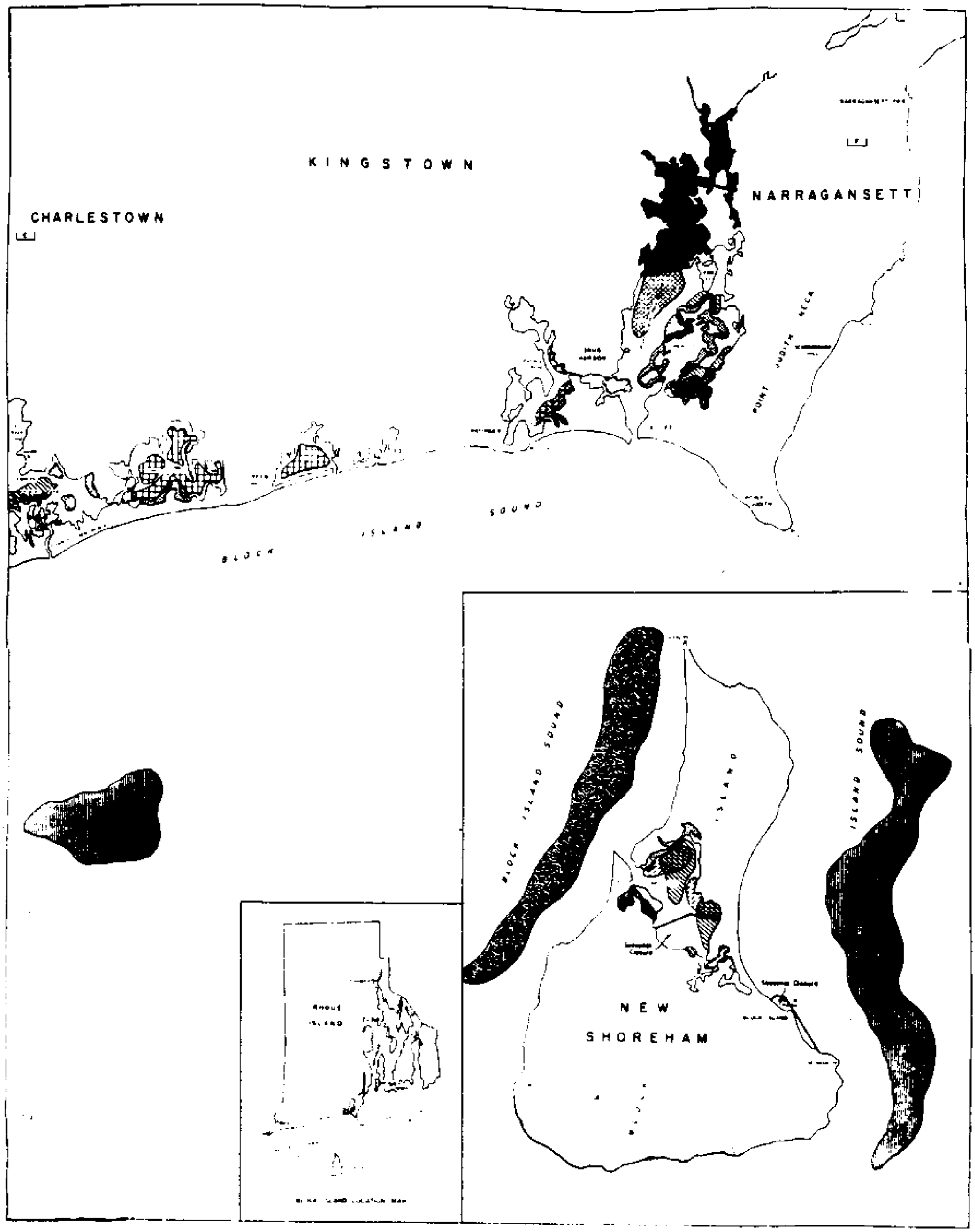


Figure 23. Shellfish areas of Point Judith Pond, Block Island Sound and Block Island. Map symbols are in legend of Figure 19. Source: U.S. EPA and Div. of Fish and Wildlife (1974).

Figure 24. Shellfish areas in coastal Rhode Island and Block Island Sound from Charlestown to the Connecticut state line. Map symbols are in legend of Figure 19. Source: U.S. EPA and Div. of Fish and Wildlife (1974).

1978 (Ganz and Sisson 1977), in which shellfish were sampled intertidally, in shallow water by bullrakes, and in deep water by dredge (32 stations).

The following coves and harbors have also been surveyed: Nausauket-Buttonwoods 1955-1958-1959 (Campbell 1959a); Potowomut River (Campbell 1959b); Kickamuit River (Campbell 1959c; Canario 1963a); Warren River (Canario and Kovach 1966); and Wickford Harbor (Kovach 1969).

An atlas describing the location of various species of economically important bivalve mollusks in relation to pollution closure lines was produced jointly by the United States Environmental Protection Agency and the Rhode Island Division of Fish and Wildlife (1974). Figures 19, 20, 21, 22, 23, and 24 are taken from this atlas. The shellfish atlas for Rhode Island is currently under revision by Division of Fish and Wildlife personnel.

4.3.2 Growth rate Growth rates of quahogs are an important factor to consider in management of the fishery, and estimating the production of quahog biomass in a given time (secondary productivity). Growth rates of quahogs in Narragansett Bay have been estimated by measuring changes in the length-frequency distributions of experimental populations over time (Pratt 1953) and by successive measurement of marked individuals at stations throughout the Bay (Pratt and Campbell 1956). It had not been possible to recognize quahog year classes in Narragansett Bay because spawning takes place throughout the summer, and individuals growth rates are variable. More recently, the techniques of sclerochronology (the assessment of age by quantification of periodic increments in hard anatomical structures) have been applied to the shells of quahogs (Rhoads and Panella 1970; Kennish 1980; Kennish et al 1980). See section 3.1.2.2 in this report for a discussion of periodic growth lines in quahog shells. Exterior growth checks can provide a rough estimate of age, while shell sectioning provides a more accurate count of annual bands, especially in older individuals.

4.3.2.1 von Bertalanffy growth function Most studies of quahog growth record the highest rates during the first year and decreasing rates in successive years until annual growth increments are very minute. This type of growth pattern is best described by a negative-exponential equation. Jones et al (1989) showed that the von Bertalanffy growth equation best describes quahog growth. These mathematical models can be fitted to size-at-age data to provide a basis of growth comparisons between populations and for measures of variability of growth within populations. In most studies of growth rate in field populations, the size at time of collection is plotted against number of annual growth rings. Rice et al. (1989) used this procedure in an analysis of Greenwich Cove and West Passage populations. Their data and fitted growth curves for shell length are shown in Figure 25. Jones et al. (1989) made a detailed study of selected larger quahogs

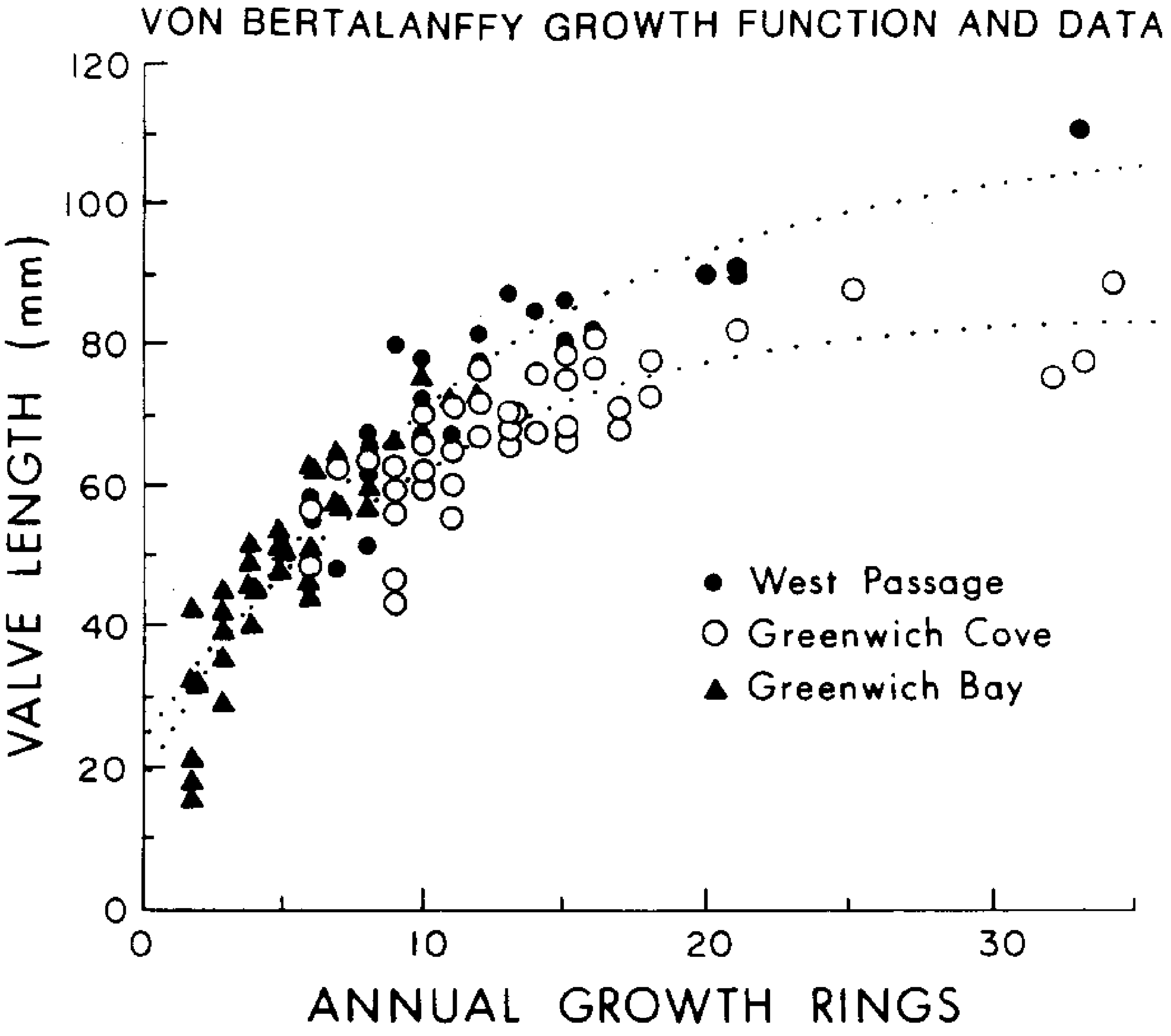


Figure 25. The valve length of quahogs from three study sites in Narragansett Bay are plotted as a function of estimated age. Von Bertalanffy growth curves were fit to Greenwich Cove and West Passage data. The von Bertalanffy parameters were L_∞=110mm and k = 0.087/yr for West Passage quahogs, and L_∞=86mm and k = 0.10/yr for Greenwich Cove quahogs. From Rice et al (1989).

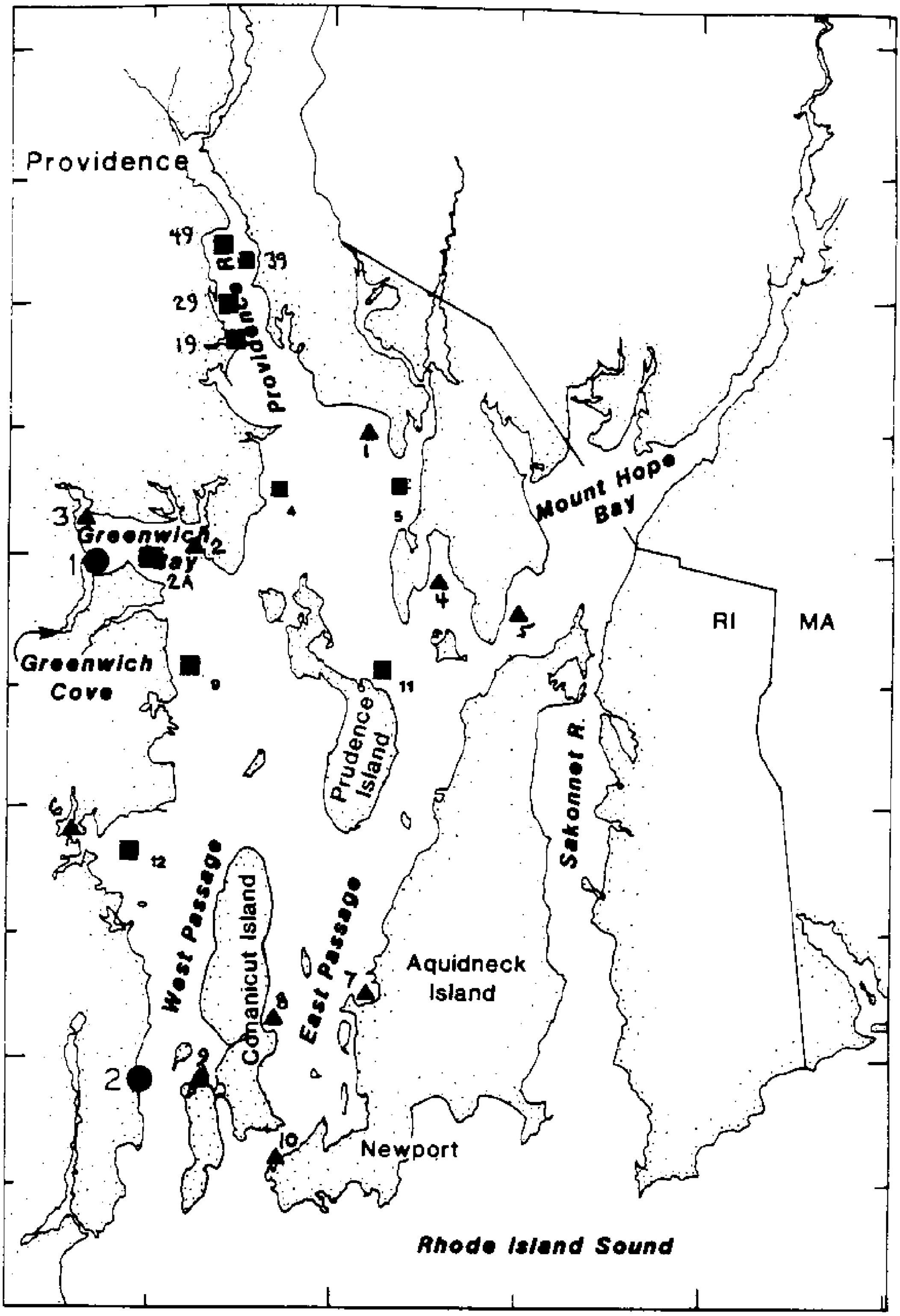


Figure 26. Locations of stations in Narragansett Bay from which quahogs were sampled for studies of growth rate. Triangles: Pratt and Campbell (1956); Squares: Jones et al (1989); Circles: Rice et al (1989).

from 10 stations through the Bay (locations: Figure 26). On sectioned shells they measured shell sizes at each annual ring and calculated von Bertalanffy function parameters for each individual.

Once the von Bertalanffy growth parameters L_∞ and K_t have been determined for any population of quahogs, it is possible to make predictions as to how long an individual quahog or the population of quahogs will take to reach marketable (or any desired) size. This procedure uses the von Bertalanffy equation:

$$L_t = L_\infty(1-e^{-k(t-t_o)}) \qquad (1)$$

when,

L_t is valve length at time (t) in years
L_∞ is the maximum theoretical valve length
t_o is the theoretical time of zero length,
and k is an empirically derived growth constant.

To determine the time it takes a quahog to reach the marketable size of 48mm valve length, you must first rearrange the equation to solve for t:

$$L_t = L_\infty(1-e^{-k(t-t_o)}) \qquad (1)$$

$$L_t/L_\infty = 1 - e^{-k(t-t_o)} \qquad (2)$$

$$1 - L_t/L_\infty = e^{-k(t-t_o)} \qquad (3)$$

$$-k(t-t_o) = \log_e(1 - (L_t/L_\infty)) \qquad (4)$$

assuming $t_o = 0$,

$$t = \log_e(1-(L_t/L_\infty))/-k \qquad (5)$$

For an example, assume there is a population of quahogs in West Passage which have an average valve length of 25 mm and we wanted to know how long it would take them to reach legally harvestable size. The von Bertalanffy growth parameters are L_∞ = 110mm; k = 0.087/yr; t_o = 0 (data from Rice et al 1989). The age of the average 25mm quahog would be:

$$t = \log_e(1-(25\text{mm}/110\text{mm}))/-0.087/\text{yr}$$

$$= 2.96 \text{ yrs}$$

The age of legally harvestable quahogs averaging 48mm valve length would be:

$$t = \log_e(1-(48\text{mm}/110\text{mm}))/-0.087/\text{yr}$$

$$= 6.59 \text{ yrs}$$

The difference between these values, approximately 3.6 years, would be the additional time required for this population to reach legally harvestable size.

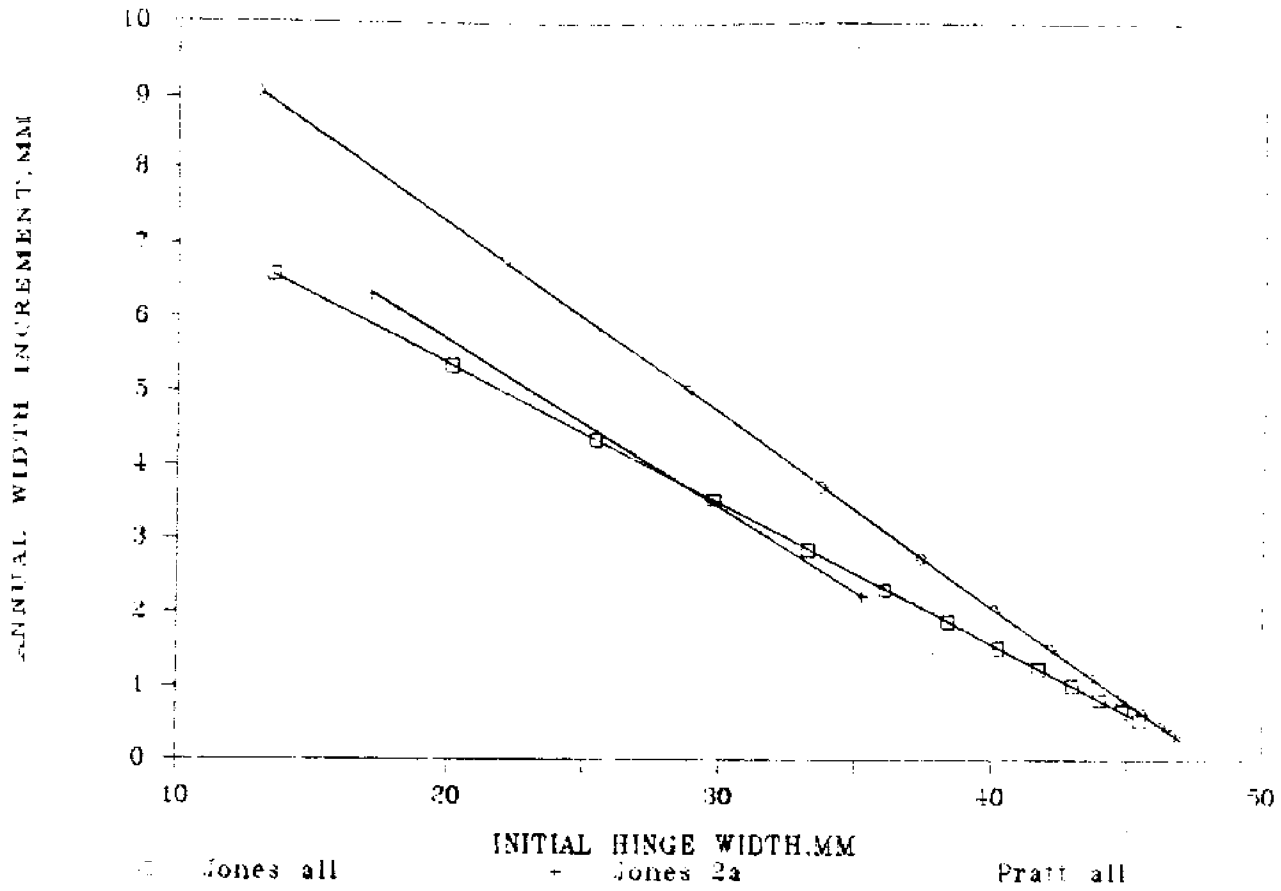


Figure 27. Size-specific annual growth in width of Narragansett Bay quahogs. "Jones all," "Jones 2a" annual growth increments were calculated from von Bertalanffy parameters for valve height and converted to width (data from Jones et al 1989). "Pratt all" average annual growth increments based on eight size intervals were converted from valve length (data from Pratt and Campbell 1956).

The von Bertalanffy growth function can be used to analyze the growth of various quahog sub-populations in Narragansett Bay. Data from Pratt and Campbell (1956) and from the von Bertalanffy analysis of Jones et al. (1989) are graphed together to provide a basis for comparison (Figure 27). The relationship of annual growth with initial size is very similar, although different methods were used, and the studies were more than 30 years apart. The Jones et al. (1989) data include size at age, as well as annual growth increments. Average annual growth rates decreased from 6.5mm in width in first year individuals to 1 mm in 10-year old animals. Sub-populations of quahogs from different areas around Narragansett Bay can be variable as to initial growth rate as well as maximum attained size. Figure 25 present data from Rice et al (1989) showing von Bertalanffy growth parameters of quahogs from Greenwich Cove and South Ferry, West Passage. The Greenwich Cove quahogs are stunted in relation to the South Ferry quahogs, which may have been to their extremely dense numbers (averaging $190/m^2$) and concomitant food limitations. The average Narragansett Bay quahog (Jones et al. 1989) reaches minimum legal size (25.4mm, 1 inch wide) by the end of the third year and remains in the littleneck size category for four years (25.4 - 38mm wide). The average von Bertalanffy growth parameters determined by Jones et al. (1989) from the 10 stations in Narragansett Bay were:

$$SH_\infty = 73.32\text{mm (valve height)},$$

$$k = 0.21,$$

$$\text{and } t_o = -0.57.$$

4.3.3 Size distribution There are many areas within Narragansett Bay that are open to shellfishing, and others that are closed to shellfishing because of varying levels of pollution. The presence of these areas in Narragansett Bay provides an opportunity to assess the effects of fishing pressure, natural variables and pollution on the population structure of the quahogs. The size of individual quahogs in a population is one frequently studied characteristic. Size distribution data has been routinely obtained in surveys of quahogs conducted by the Rhode Island Division of Environmental Management in order to estimate the potential yield of different market sizes.

Areas open to fishing - In the portions of Narragansett Bay open to commercial quahog fishing, fishing pressure is the dominant influence on population structure (Rice et al. 1989; Walker 1989). In exploited quahog populations, smaller and younger quahogs predominate. Figure 28 are size-frequency comparisons of quahogs from three locations in Narragansett Bay: Greenwich Cove, Greenwich Bay, and South Ferry, West Passage. Both the

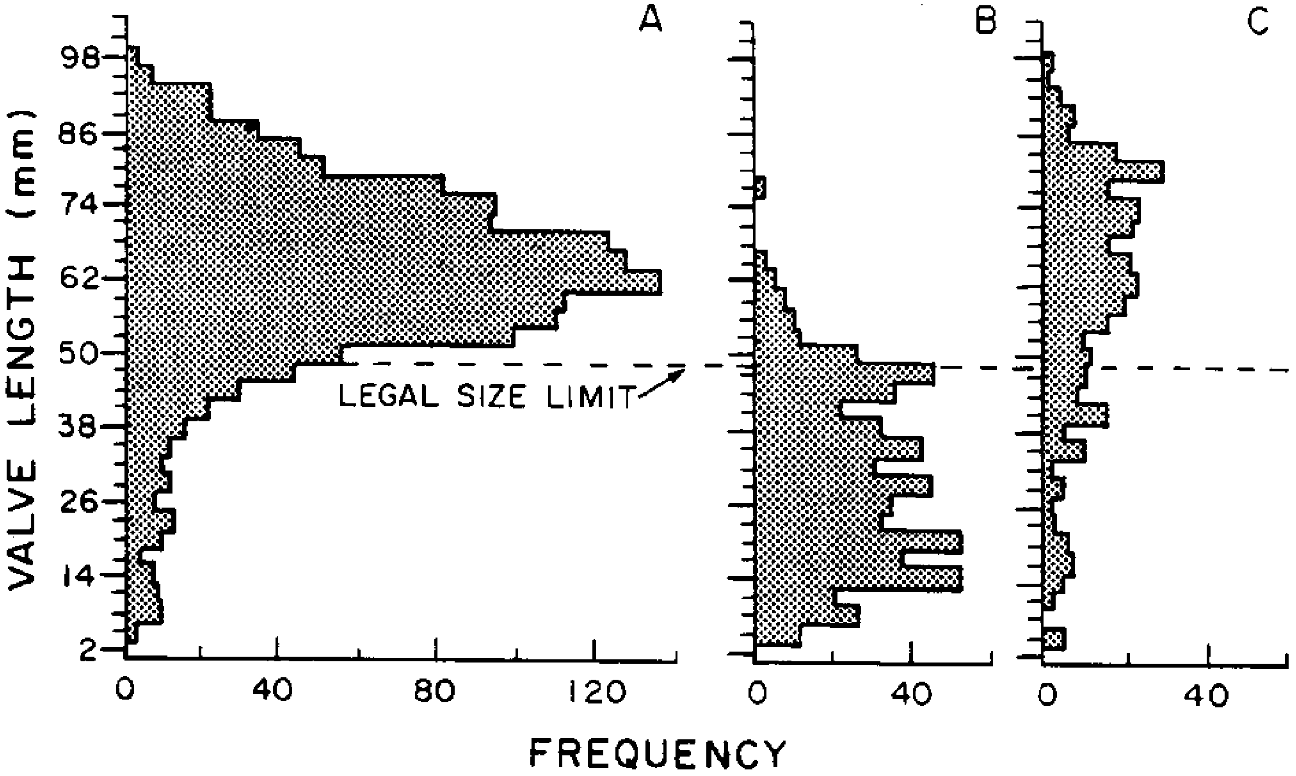


Figure 28. Quahogs were collected by divers from 30 quadrats (0.25m^2) in each of three sotes in Narragansett Bay. The sites are: (A) Greenwich Cove, (B) Greenwich Bay, and (C) South Ferry, West Passage. Histograms represent total numbers of quahogs in size classes of 3mm increments. The indicated valve lengths are size class midpoints. The dashed line represents the Rhode Island legal size limit for quahogs that is a one-inch hinge width, which corresponds to a 48mm valve length.

South Ferry and the Greenwich Cove locations are closed to shellfishing. The Greenwich Bay location is less than 100 m from the Greenwich Cove location, but in waters open to shellfishing. The absolute number of quahogs in the 5 to 48mm size classes are higher in the fished area. This is evidence that removal of large adults or other modification of the bottom by shellfishing may enhance the set of juveniles.

Closed areas , There have been a number of studies in Narragansett Bay that have described the quahog populations in areas closed to shellfishing. Diamond (1981) provides the size distribution of clams from south of Sabin Point and Dutch Island Harbor on three dates in 1977-1978 (Figure 29). McDonald and Grimm (1984) give size distributions of clams from four stations in the Providence River and Mount View sampled in June 1984 (Figure 30). The length-frequency distribution of all measured clams from the 1985 study of Pratt et al. (1987) of the Providence River and Mount Hope Bay are shown in Figure 31.

Most of these surveys utilized handrakes or dredges to make it possible to sample from relatively large areas. The drawback of most mechanically aided means of harvesting is that they cannot accurately sample smaller quahogs. In the study of Rice et al (1989), quahogs were collected from relatively small areas of Greenwich Cove and West Passage by divers using 0.25m^2 quadrats and carefully removing all quahogs with valve lengths down to 5mm. In the Greenwich Cove and West Passage areas (Figure 28), both closed to shellfishing, there were very few quahogs <48mm in valve length. This suggests that in closed areas, surveys utilizing mechanically aided sampling methods may be giving a reasonable estimate of actual size-frequencies.

The quahog populations in areas closed to fishing are largely composed of large mature individuals. Many finfish populations show a gradual decrease in density with size and age because mortality rates are similar for all ages. A different pattern is found in species such as the quahog in which individuals are better able to resist the attack of predators as they become larger. Thus, under natural conditions and in a stable environment, quahog populations become dominated by large individuals. Size-frequency distributions of quahogs in areas closed to shellfishing is typically unimodal (with one peak). The size distribution of Providence River clams from 10 station groups in different sediment strata and in different segments of the sampled area are shown in Figure 31. In the nine upstream groups, size distributions were unimodal with a slight increase in modal length downstream. The Nayatt-South samples had length modes at 46, 68, and 80mm.

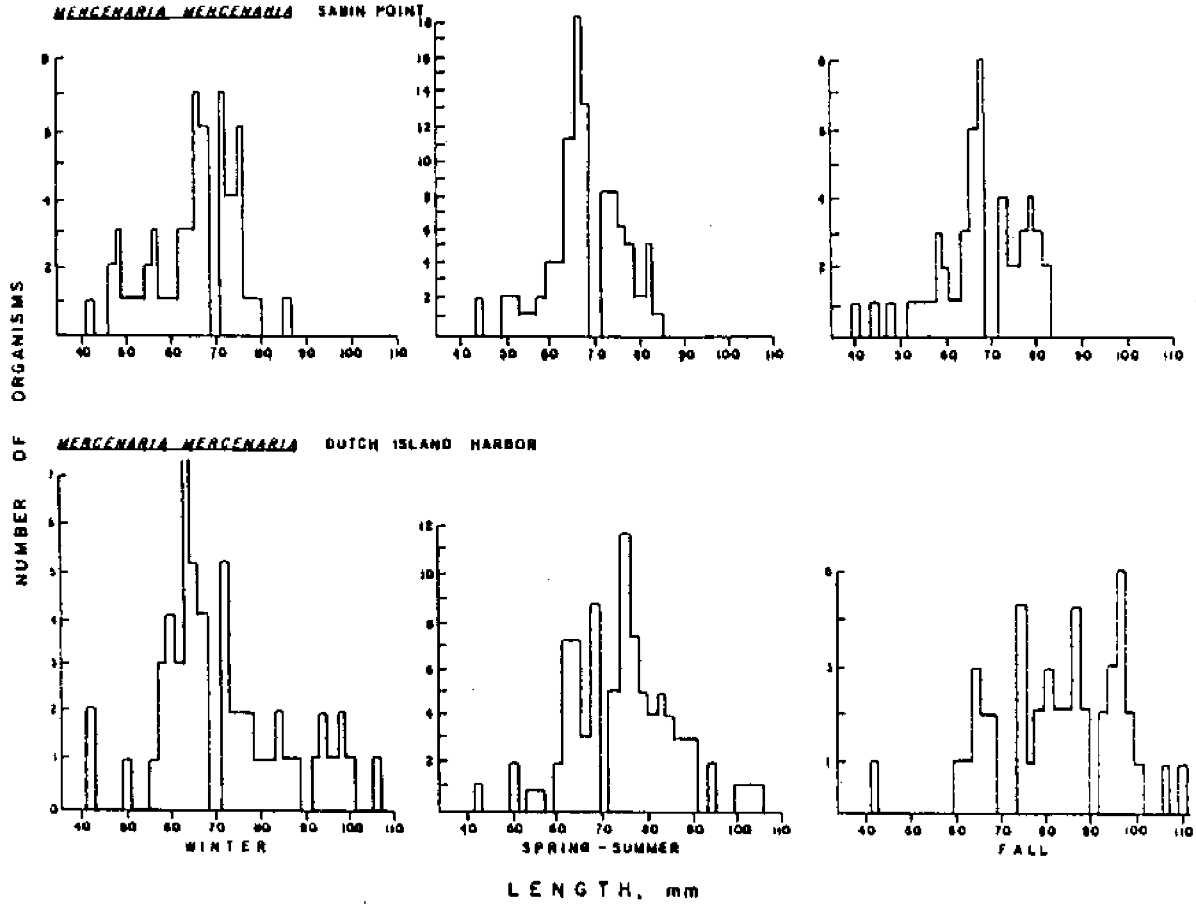


Figure 29. Seasonal length-frequency distributions of quahogs from Sabin Point and Dutch Island Harbor, 1977 to 1978. From Diamond (1981).

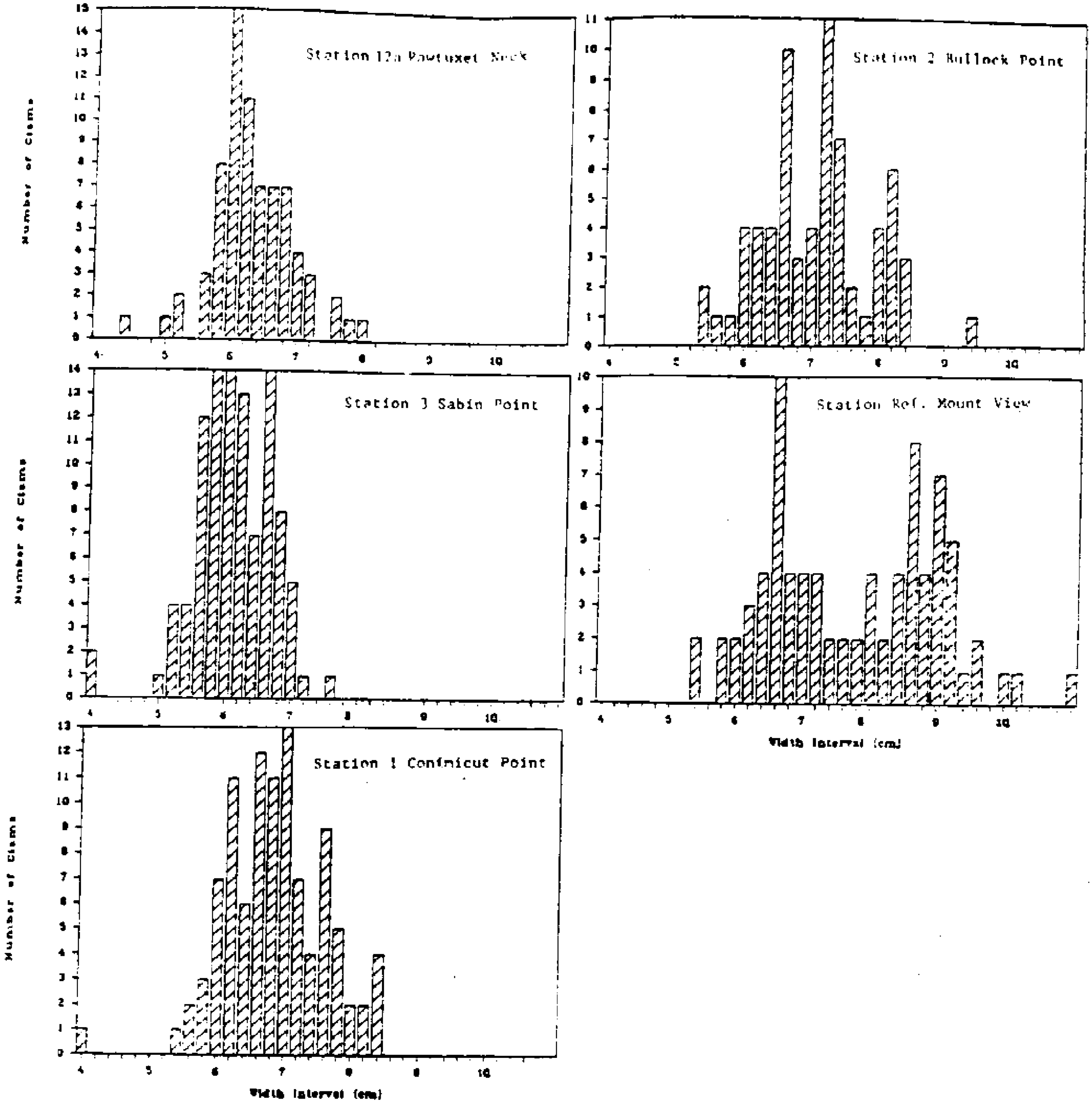


Figure 30. Height-frequency distribution of quahogs from the Providence River and West Passage collected July 1984. From McDonald and Grimm (1984). Sizes must be multiplied by 12 to be comparable with data in Figures 29 and 31.

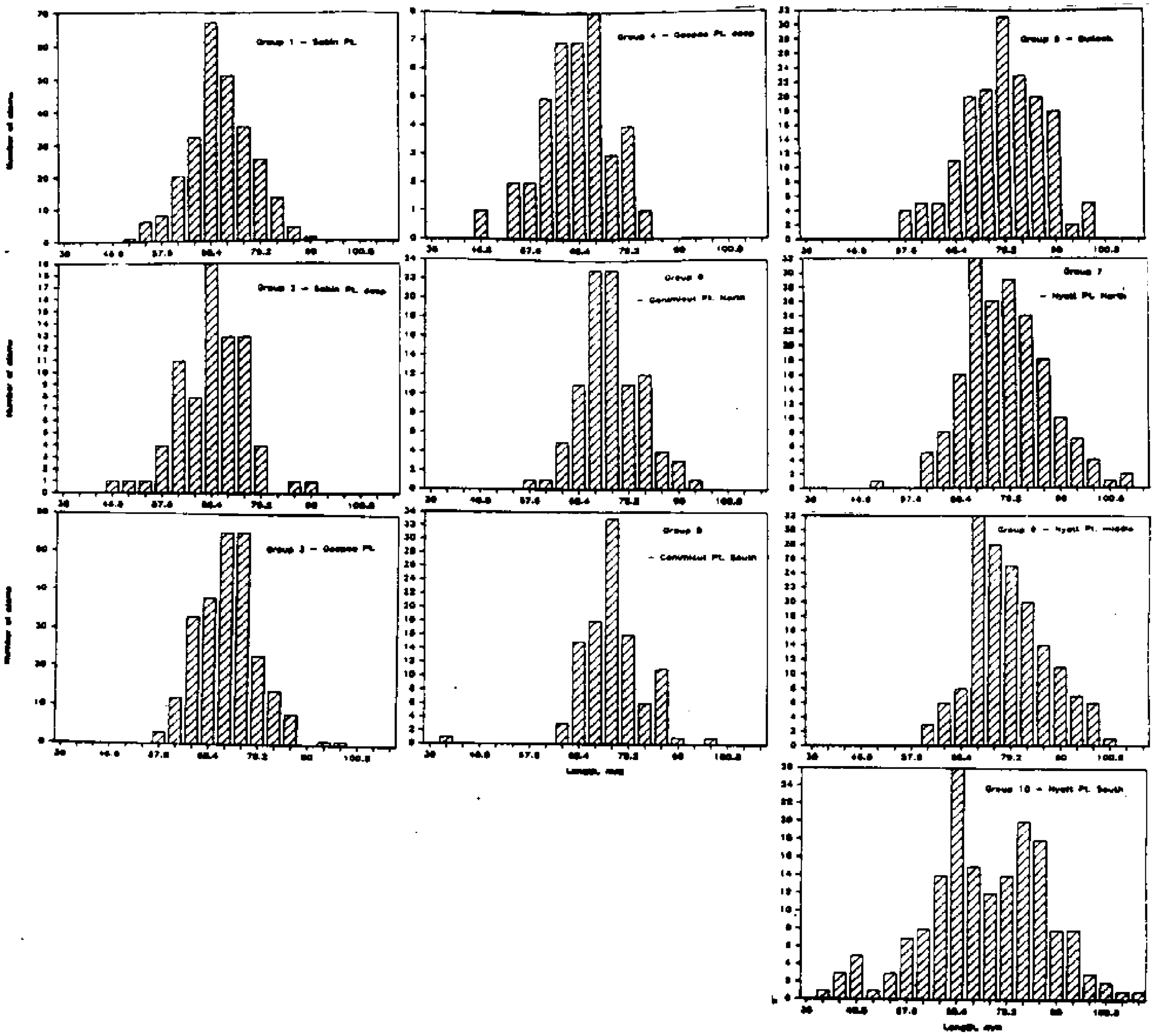


Figure 31. Length-frequency distributions of quahogs in 10 station groups in the Providence River collected November 1985. From Pratt et al 1987.

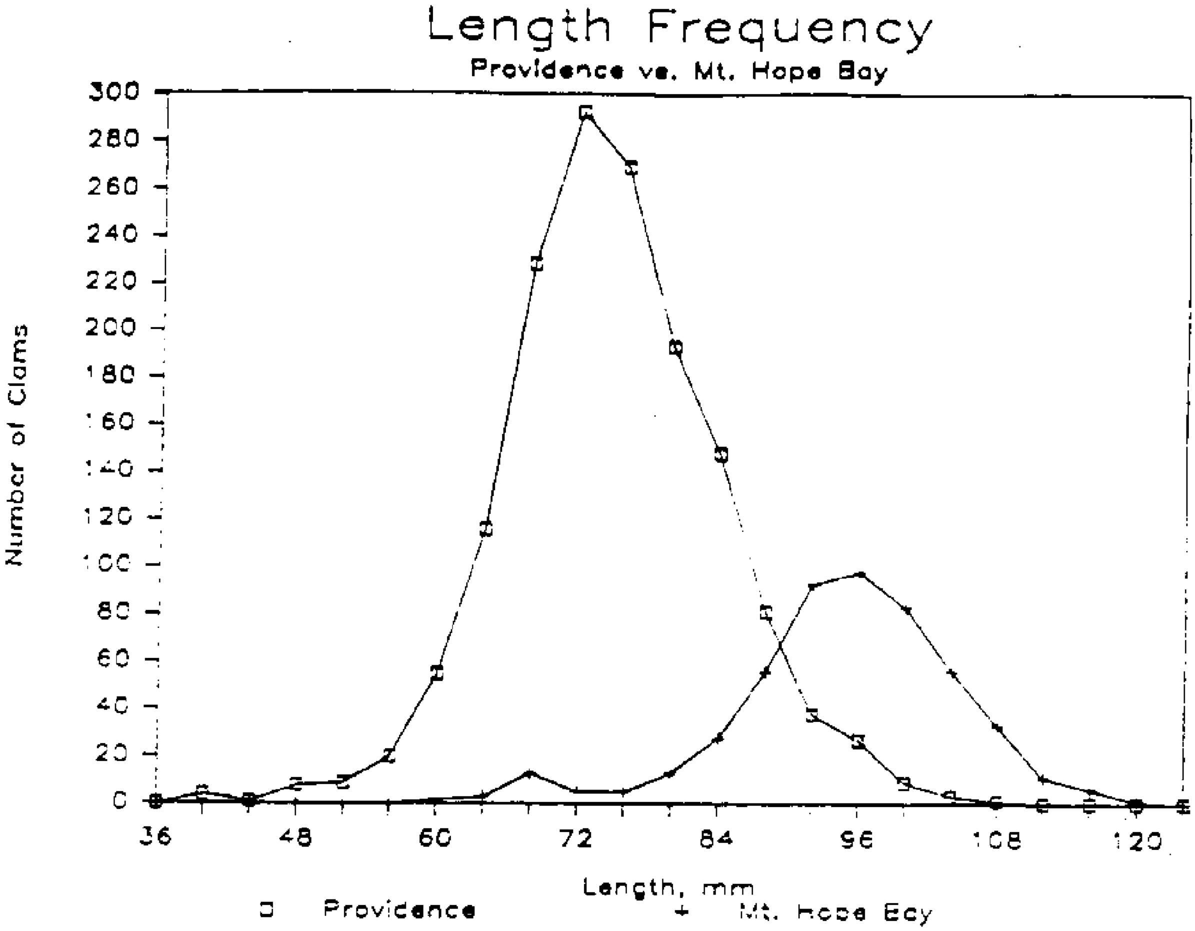


Figure 32. Overall length-frequency distribution of quahogs in Providence River and Mount Hope Bay. Both areas are closed to shellfishing. Quahogs collected November 1985. From Pratt et al (1987).

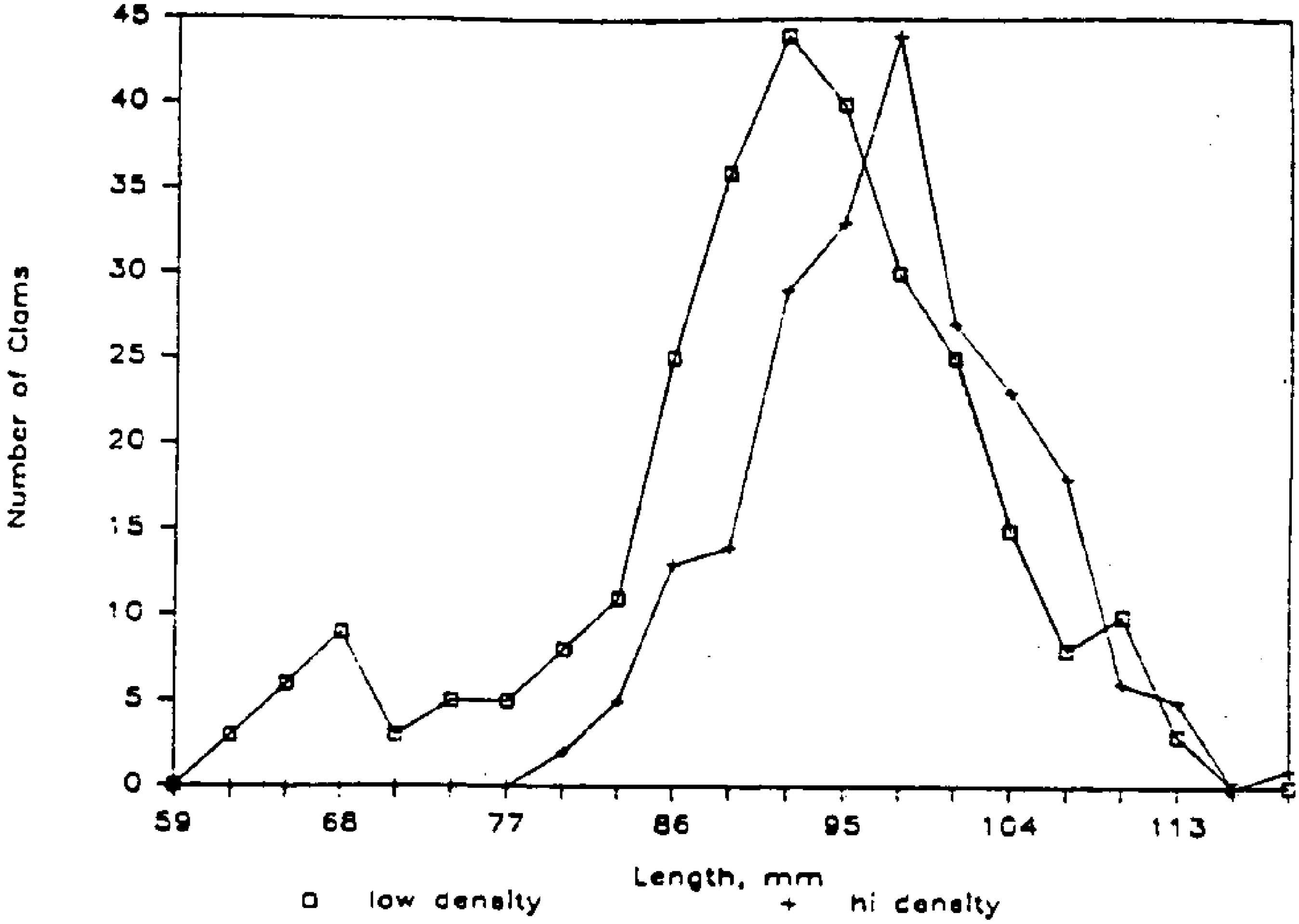


Figure 33. Length-frequency distribution of quahogs in high- and low-density samples from Mount Hope Bay collected November to December 1985. High-density areas were defined as those that yielded >50 quahogs/tow. From Pratt et al (1987).

Conimicut-South samples had a narrow range of size and few individuals smaller than 68mm. The overall valve length-frequency distribution of all quahogs collected in the Providence River had a modal length of 72mm and a maximum length of 108mm (Figure 31). Likewise, quahogs from Greenwich Bay and South Ferry exhibit similar length-frequency distributions (Figure 28).

The only exception to the general pattern of unimodal size-frequency distributions appears to be in Mount Hope Bay, in which the length-frequency distribution is bimodal with peaks at 68 and 96mm (Figure 32), and with the largest quahogs 118mm long. An explanation for this exception may be that there are sub-areas that have lower densities of quahogs and smaller individuals. In the Mount Hope Bay study (Pratt et al 1987), a high-density group included nine stations that yielded over 50 quahogs/tow, and a low-density group that included 20 stations in which at least one quahog was caught. The size distributions within these groups were very different. At high-density stations length was distributed unimodally with a peak at 97mm (Figure 33), and no clam less than 77mm long was recovered. The low-density stations had a bimodal size distribution with a large peak at 92mm and a small peak at 68mm. All of the small quahogs seen in the Mount Hope Bay catch came from the low-density group. The bimodality of some of these length-frequency distributions in Mount Hope Bay suggests that there was an extended period in which there was reduced larval recruitment. The reasons for this lowered recruitment and its subsequent recovery are unclear.

4.3.4 Morphometric Relationships

Shell Proportions -- A listing of approximate shell dimension conversion factors have been provided earlier in this review (Section 3.1.2.1). These approximations become less accurate if quahogs are collected from populations with differing shell proportions from the "normal." For example, in Narragansett Bay quahogs are found with a range of length/width proportions. The extreme cases are termed "sharps" and "blunts." Sharp clams have shells that come together at a small angle and add new material along the distal border. The edges of blunt clams come together at a large angle and shell growth takes place along facing inner bands. There is a tendency for sharp clams to be found in good water quality areas and to be actively growing. Blunt clams appear to be older and more abundant in crowded or stressed conditions. Although there is this tendency for blunt quahogs to be found in more stressed areas, they co-exist with sharp quahogs throughout Narragansett Bay; examples of sharp and blunt individuals can be found in most areas (Pratt et al. 1987).

It is often useful to compare external valve measurements to the weight of the soft tissues. This can

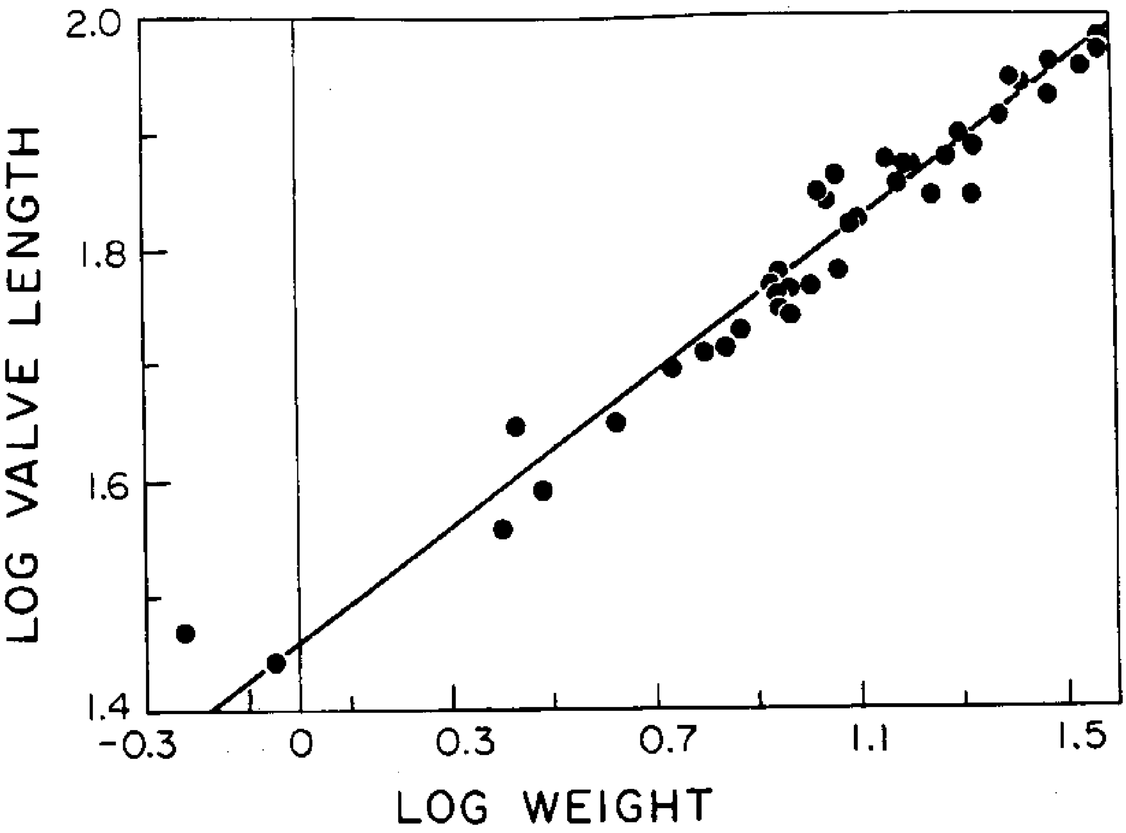


Figure 34. The valve length and the shell-free tissue weight of quahogs can be correlated by using a linear transformation of the allometric equation. Quahogs were collected at South Ferry, West Passage and ranged from 26 to 95mm in valve length. Allometric coefficients were determined to be $a = 9.51 \times 10^{-5}$ and $b = 2.81$. From Rice et al (1989).

be useful for estimating potential biomass of quahog meats available in fishery stocks when you have average quahog densities and their average size. The relationship between valve length of quahogs and meat weight is presented in Figure 34. The meat weight of quahogs can be expressed by the allometric equation:

$$W = a\ L^{b} \qquad (6)$$

when,

W is the meat weight in grams,
L is the shell length in millimeters,
a is empirical constant = 9.51×10^{-5},
and b is another constant = 2.81.

For example, the meat weight of a 100mm long quahog would be:

$$W = (9.51 \times 10^{5})\ 100^{2.81}$$

$$= 39.6\ g$$

Use of this allometric equation allows estimation of average meat weight based upon a valve length measurement, but meat weight will change with reproductive or nutritional state. Measurement of condition index can indicate differences in meat weight during the annual growth cycle.

4.3.5 Condition Index The ratio of tissue volume to internal shell volume is a traditionally used measure of condition or "fatness" of bivalves. This index provides a method of tracking development of gonads and time of spawning. To determine internal shell volume, a water displacement technique is used. First, the displacement volume of an unshucked quahog is weighed. The quahog is then shucked and the meat removed, and afterwards the displacement volume of the two shucked valves is weighed. The internal shell volume is equal to the difference in the two displacement volumes. The volume of the meat is simply proportional to its weight. Simply divide the blotted meat weight by the internal shell volume to get the condition index value.

Only two studies report condition indices of quahogs from Rhode Island waters. Green (1966) recorded an index based on displacement volume for: (1) quahogs from East Greenwich Cove, (2) Cove quahogs that had been transplanted to Greenwich Bay, (3) quahogs from Bullock Point, (4) Bullock Point quahogs transplanted to the East Passage (Melville), and (5) quahogs from Longmeadow. Observations were made from July to December 1965. Green found that, in general, populations had high index values in spring and early fall and low values in late summer (after spawning) and in winter (with reduced feeding activity). The natural

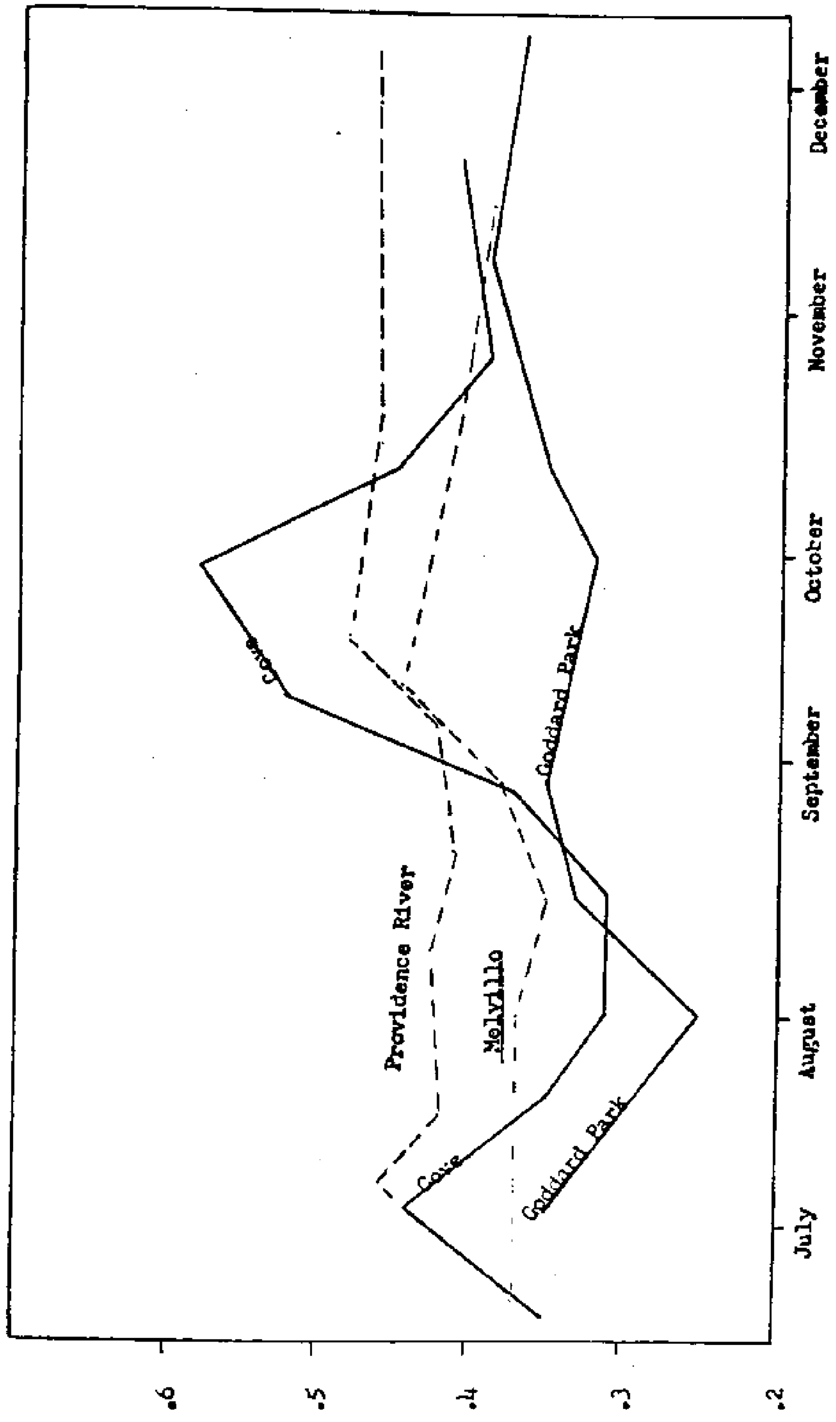


Figure 35. Ratio of tissue volume to internal shell volume of quahogs from natural populations (Greenwich Cove, Bullock Point/Providence River) and transplanted populations (Goddard Park and East Passage/Melville). From Green (1966).

Greenwich Cove population had the highest range of values (0.3-0.6) and transplants had lower values than source populations (Figure 35).

It has been suggested that condition index can be used as an indicator of stress due to pollution. Condition index was not a good indication of pollution level in Green's study. Additionally, Cooper et al. (1964) reached this same conclusion in a study of quahogs from polluted and clean areas of Point Judith Pond. But the issue of whether condition indices can be used as an indicator of pollution stress remains unresolved. Diamond (1981) calculated condition indices by other means. She calculated one condition index from the ratio of tissue weight to shell length, and another index by comparing tissue weight to the product of shell length, width, and height. Quahogs from Sabin Point (presumably polluted) and Dutch Island Harbor (presumably clean) were sampled monthly for over a year, and by using both condition indices, statistically significant differences were found between the two populations.

4.4 Public Health Issues Since quahogs are confined to coastal estuaries and are filter feeders, they are capable of filtering from the water the various pollutants and waste products of our modern industrial society. Of concern to public health are microbiological pathogens associated with sewage and runoff from lands adjacent to the estuaries, as well as industrial and agricultural chemical wastes. Additionally, toxins from naturally occurring phytoplankton accumulating in shellfish can be a threat to public health during the warmer parts of the year.

4.4.1 Microbiological contamination Kadri (1991) outlines the key sources of sewage input into Narragansett Bay. During periods of heavy precipitation, combined sewage flow and storm runoff water is diverted into Narragansett Bay to prevent overloading sewage treatment plants. As a result, an estimated 4 billion gallons of untreated sewage enter Narragansett Bay annually.

4.4.1.1 Diseases Vaughn and Landry (1984) and Piedrahita and Tchobanoglous (1987) provide information as to the types of pathogenic organisms that can be carried in human excreta (Table 5). It must be emphasized that most of the listed pathogens are not viable in seawater or are not common outside of the tropics, and therefore do not pose a threat to public health. Historically, bacterial diseases such as cholera and typhoid fever associated with consumption of shellfish was a problem in Rhode Island (Frost 1925). Matyas (1991) provides some information as to the the types of diseases that are currently a problem in Rhode Island and the United States as a whole. Most of the recent health problems associated with shellfish in the

Table 5. Pathogens found in human excreta (modified after Vaughn and Landry 1984; Piedrahita and Tchobanoglous 1987)

Biological group	**Organism**	**Disease**
Viruses	Adenovirus	respiratory infections & gastroenteritis
	Coxasackievirus	various
	Echovirus	various
	Hepatitis A virus	infectious hepatitis
	Norwalk virus	gastroenteritis
	Parvovirus-like	gastroenteritis
	Poliovirus	poliomyelitis
	Reovirus	various
	Rotavirus	gastroenteritis
Bacteria	*Camphylobacter*	gastroenteritis
	Pathogenic *Escherichia coli*	gastroenteritis
	Pathogenic *Klebsiella* sp.	respiratory infections
	Salmonella typhi	typhoid fever
	other Salmonellae	food poisoning
	Shigella spp.	bacillary dysentery
	Vibrio cholerae	cholera
	Vibrio vulnificus	septicemias
	other vibrios	diarrhea
	Yersinia spp.	yersiniasis
Protozoa	*Balantidium coli*	diarrhea
	Entamoeba histolytica	amoebasis
	Giardia lamblia	giardiasis
	Isospora spp.	intestinal parasitism
Helminthic parasites	*Ascaris lumbricoides*	ascariasis
	Clonorchis sinensis	clonorchiasis
	Diphyllobothrium latum	diphyllobothriasis
	Fasciolopsis buski	fasciolopsiasis
	Schistosoma spp.	schistosomiasis
	Paragonimus westermani	paragonimiasis

United States have been mainly of viral etiology. The key exception to this general statement is that there have been outbreaks of shellfish-associated disease due to Vibrio bacteria, but these outbreaks have been mainly confined to the warm subtropical waters of the Gulf of Mexico coast (Kilgen et al. 1988). The main viral diseases have been gastroenteritis due to the Norwalk virus and hepatitis-a (Verber 1984; Richards 1985). According to U.S. Public Health records, cases of gastroenteritis (probably Norwalk virus) have been attributed to Rhode Island quahogs in 1966, 1977, 1982, 1983, and 1984. Additionally, cases of hepatitis-a in 1964, 1971, and 1982 have been attributed to Rhode Island quahogs. Since the mid-1980s, Rhode Island Department of Health records do not show any cases of shellfish-associated hepatitis-a (Matyas 1991).

4.4.1.2 Shellfish Sanitation Requirements After the major outbreaks of typhoid and cholera of the 1910s and 1920s, the first federal guidelines for shellfish sanitation were developed (Frost 1925). The agency responsible for the implementation of federal shellfish sanitation guidelines is the Rhode Island Department of Health (Matyas 1991). The current shellfish sanitation guidelines are set forth by the Interstate Shellfish Sanitation Conference (ISSC 1989b). The guidelines cover shellfish meat quality in harvest, processing, and marketing, as well as requirements for proper facilities and equipment to maintain sanitary quality. If any state does not comply with ISSC guidelines, the federal Food and Drug Administration is empowered to halt any interstate shipments of shellfish from the offending state.

4.4.1.3 Source Water Sanitation Requirements An important facet of the National Shellfish Sanitation Program is the maintenence of water quality in shellfish growing waters (ISSC 1989a). Migliore (1991) outlines the Rhode Island program for monitoring bacterial water quality in Rhode Island coastal waters. Shellfish growing areas in Rhode Island are classified according to a number of criteria, including total coliform bacteria, fecal coliform bacteria, dissolved oxygen levels, and the presence of refuse, floating solids, or odors in the water. Table 6 shows the various water quality criteria and the water quality classifications in shellfish growing areas. According to Rhode Island water quality standards, shellfish for direct consumption or sale may be taken only from class SA waters. Figure 36 shows the areas of Narragansett Bay that are closed or conditionally closed to shellfishing due to water quality. If state programs to assure water quality in shellfish growing waters do not adequately comply with ISSC guidelines, the Federal Food and Drug Administration can halt interstate shipments of shellfish from the offending state.

Table 7. Rhode Island Department of Environmental Management Division of Water Resources' class-specific criteria for sea waters. Shellfish for direct consumption or sale may be harvested only in class SA waters. From Migliore (1991).

Criterion	Class SA	Class SB	Class SC
Dissolved oxygen	≥ 6mg/L except as naturally occurs	≥ 5 mg/L except as naturally occurs	≥ 5 mg/L during at least 16 hours of any 24-h period and ≥ 4 mg/L at any place or time except as naturally occurs
Sludge deposits, solid refuse, floating solids oils, grease, scum	none allowed	none allowed	none except that amount that may result from discharge from an appropriately operating waste treatment facility
Total Coliform bacteria/ 100mL	not to exceed a median MPN of 70 and not >10% of the samples shall ordinarily exceed 330 MPN in a 3-tube decimal dilution	not to exceed a median MPN of 700 and not >10% of the samples shall ordinarily exceed 2,300 MPN	none in such concentrations that would impair any usages specifically assigned to this class
Fecal Coliform bacteria/ 100mL	not to exceed a median MPN of 15 and not >10% of the samples shall ordinarily exceed 50 MPN	not to exceed a median MPN of 50 and not >10% of the samples shall ordinarily exceed 500 MPN	none in such concentrations that would impair any usages specifically assigned to this class
Taste and Odor	none allowed	none in such concentrations that would impair any assigned uses to this class and none that would cause taste and odor in the edible parts of the shellfish	none in such concentrations that would impair any usages specifically assigned to this class and none that would cause taste and odor in the edible parts of the shellfish

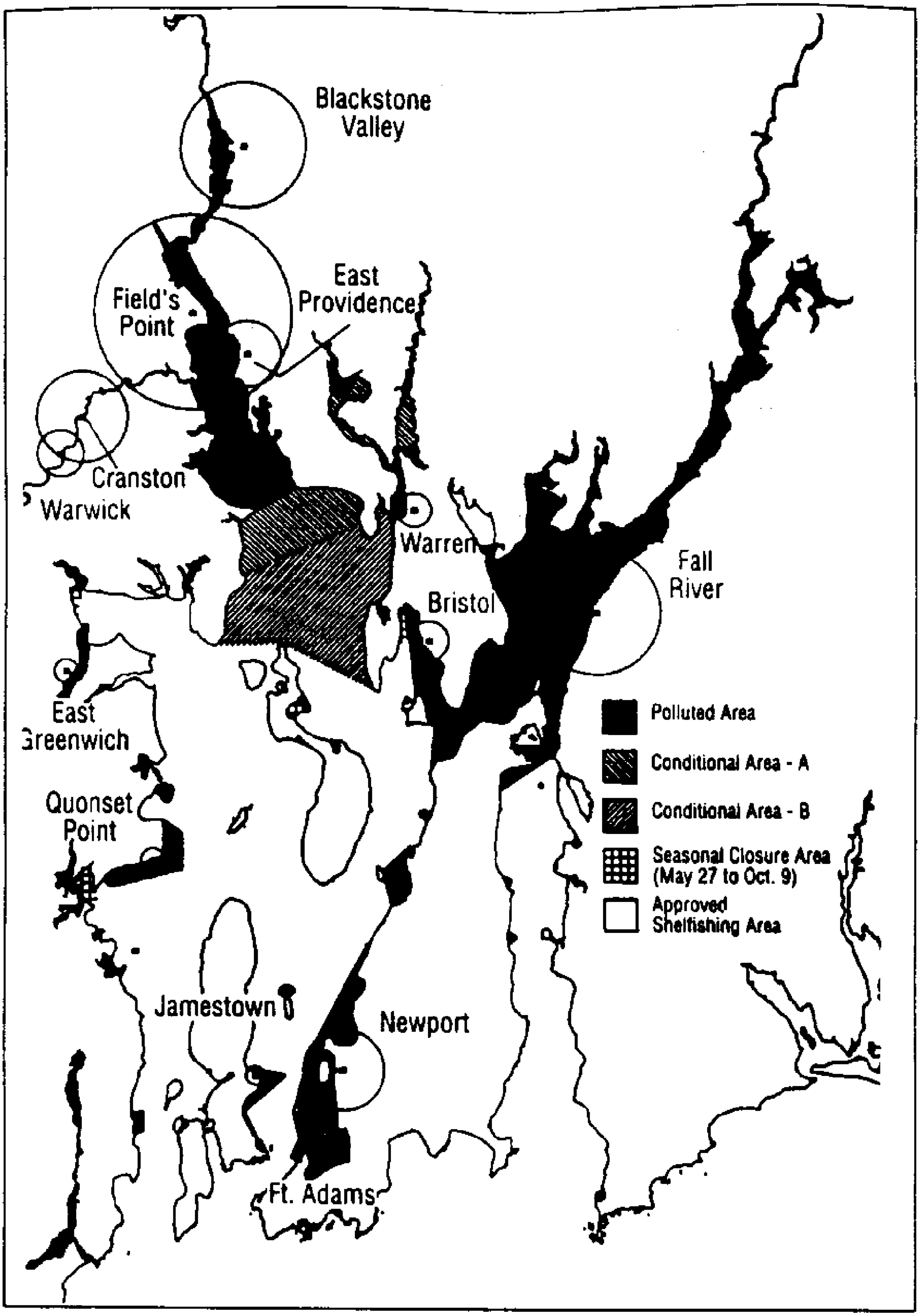


Figure 36. Shellfishery pollution closure areas in Narragansett Bay 1992. Source: Rhode Island Department of Environmental Management, Division of Water Resources.

4.4.2 Paralytic shellfish poisoning Toxins associated with some species of phytoplankton are a potential health threat to the shellfish-consuming public. This is because filter-feeding allows for accumulation of toxins in bivalve soft tissues. Shumway (1990) provides a recent review of the impacts of toxic algal blooms on shellfisheries and aquaculture. The dinoflagellate Alexandrium fundyense (formerly Protogonyaulax tamarensis), responsible for "red tides," produces the toxin responsible for paralytic shellfish poisoning (PSP). During one major red tide event in Massachusetts, various species of bivalves were shown to be very toxic, including mussels, Mytilus edulis; soft-shelled clams, Mya arenaria; and scallops, Argopecten irradians, but quahogs remained completely free of the toxins. Laboratory studies have shown that quahogs will retract their siphons and completely close their shells if there are bloom concentrations of Alexandrium fundyense in the water (Shumway and Cucci 1987). However, another laboratory study suggests that quahogs can accumulate algal toxins if dinoflagellates are in mixtures with other phytoplankton, as is likely in the natural aquatic environment (Bricelj et al. 1991). Quahogs might accumulate some of the toxins if there is a red tide event; however, they will tend to release the toxins in a few days (Bricelj et al. 1991). The exact conditions for the initiation of an Alexandrium bloom are not well understood, but they are much more common during the warm summer months.

Toxins associated with the phytoplankton Dinophysis are responsible for diarrhetic shellfish poisoning (DSP). DSP is manifested as mild to moderate gastroenteritis, and there have been no known fatalities. Quahogs can accumulate the DSP toxin. Like PSP, the incidence of DSP is higher during the warm-water summer months (Freudenthal and Jijina 1988).

States such as Maine, with major shellfish industries, have programs to closely monitor the appearance of red tides (Shumway et al. 1988). In Rhode Island, the monitoring of toxic algal blooms is a joint responsibility of the Department of Health and the Division of Water Resources. During sanitary surveys by the Division of Water Resources, "odd" colored water samples are sent to the phycology laboratory at the URI's Graduate School of Oceanography for phytoplankton species identification. The Department of Health collects mussel meats from a series of primary stations in Narragansett Bay. If there is an elevation of any type of biotoxin, secondary stations are activated so that confirmatory data can be collected prior to issuance of health advisories and action to close the shellfisheries (Migliore 1991). There have been no closures of quahog beds in Rhode Island due to red tide blooms to date.

4.4.3 Chemical contaminants

4.4.3.1 Heavy metals Heavy metals are toxic to organisms at levels that vary with the element, its chemical form, and the sensitivity of the organism. It has been shown that larval and juvenile quahogs are much more sensitive to the toxic effects of metals than are the adults (Calabrese et al. 1977). Metal pollutants in the aquatic environment may be a factor in reducing recruitment by way of reducing larval numbers or larval fitness. Some species of marine organisms accumulate metals to very high concentrations in tissue relative to surrounding water and sediment (copper and zinc in oysters are examples) (Cunningham 1979). Even at levels sub-lethal to marine organisms, some forms of metals (such as methyl mercury and cadmium) have a high potential for bioaccumulation and have been the cause of very serious public health problems.

Heavy metals are present above natural levels in the waters and sediments of urbanized estuaries, entering from industrial sources, domestic waste, and fuel emissions. In the NOAA National Status and Trends Program seven trace metals are monitored in sediments and blue mussels to determine levels of contamination from human activity. Because of the presence of metal-working industries, as well as other sources in the Narragansett Bay area, metals have been monitored and studied in some detail. The Rhode Island Department of Health (RI DOH) has monitored metals in quahogs since 1971 collected from areas of the Bay both open and closed to harvest. Research at the US EPA Laboratory (Narragansett) and the URI Graduate School of Oceanography has focused on the distribution of metals in the sediments and water of the Bay and the transfer of metals between environmental pools.

The research that is most useful in describing metal levels in quahogs are: (1) RI DOH monthly samples at 14 stations from 1971 to the present; (2) Cullen (1984) nine stations sampled September 1977; (3) Thibault/Bubly (1989) 12 stations sampled November 1985 and 13 stations sampled June 1986, (4) Cullen and King (1990) one station sampled November 1985 and seven stations sampled fall 1987, and (5) Munns et al. (1991) five stations sampled in 1988. Locations of these studies are given in Figure 37. Data on separate metals is graphed along a general north-south gradient in Figures 40-45. A summary of the key findings follows.

(1) **Age effect** - If quahogs continued to accumulate contaminants over long periods of time, older (larger) individuals would have the highest concentrations. If very young or very old individuals had diminished ability to regulate contaminants, their loads could increase. Thibault/Bubly (1989) classified all individuals analyzed into commercial size classes. Inspection of their data indicates an absence of size-specific metal concentrations with the possible exception of small increases in chromium and mercury in the largest individuals at some stations. In

the case of chromium, large variations in season and location suggest that the apparent size effect could be an artifact.

(2) **Season effect** - Seasonal change in feeding rate, gonod maturation, or release of sex products could affect uptake and retention of metals. In RI DOH and Thibault/Bubly (1989) data, most metals did not vary from summer to winter. IN RI DOH mid-Bay samples, chromium was usually higher and more variable in summer than winter (Figure 45). In Thibault/Bubly (1989) data, variability obscures any relationship. Low levels found by Cullen and King (1990) in November agree with RI DOH results. A possible cause of summer chromium increase is retention of chromium body burden with loss of biomass from spawning. Behrens and Duedall (1981) found a chromium increase of about 30 percent from this cause. Apparent summer uptake could also be related to sediment-bound metal in the guts of undepurated specimens.

(3) **Pollution gradient** - Tissue concentrations of pollutants in quahogs will be correlated with environmental levels if physiological regulatory mechanisms are absent, or if the mechanisms are overwhelmed by very high exposures. Potential sources of contaminants are water, suspended particles, pore water, and sediments. There is a general decrease of most metals in all three potential sources from the Providence River to the lower Bay. Lead, nickel, and zinc show a small down-Bay decrease in quahog tissues (about 50 percent). Copper decreases from the Providence River to the upper Bay in RI DOH data and from Sabin Point to the lower Providence River in Thibault/Bubly (1989) data. In samples obtained in 1987, Cullen (unpublished data) found similar levels of copper at all stations. In all investigations tissue levels of cadmium showed no down-Bay gradient. Seasonal factors and other sources of variation obscure the down-Bay gradient of chromium. Rhode Island Department of Health winter data and Cullen and King fall data show a small down-Bay decrease in chromium. RI DOH summer data show a mid-Bay increase, while Thibault/Bubly (1989) data is highly variable in both fall and summer samples.

(4) **Sources** - Cullen (1984) found that copper and nickel in quahog tissues were more closely correlated with concentrations dissolved in the water column than to concentrations in suspended particulate matter. Cullen and King (1990) found a strong correlation between copper in quahog tissues and the flux of copper in particulate settling traps. They found weaker correlations between levels of tissue cadmium, chromium, and lead and particulate flux. Cullen and King (1990) found a strong relationship between copper in tissues and in sediments in which quahogs were living, a weak relationship between sediment and tissue cadmium, and no relationship between sediment and tissue nickel, chromium, and lead.

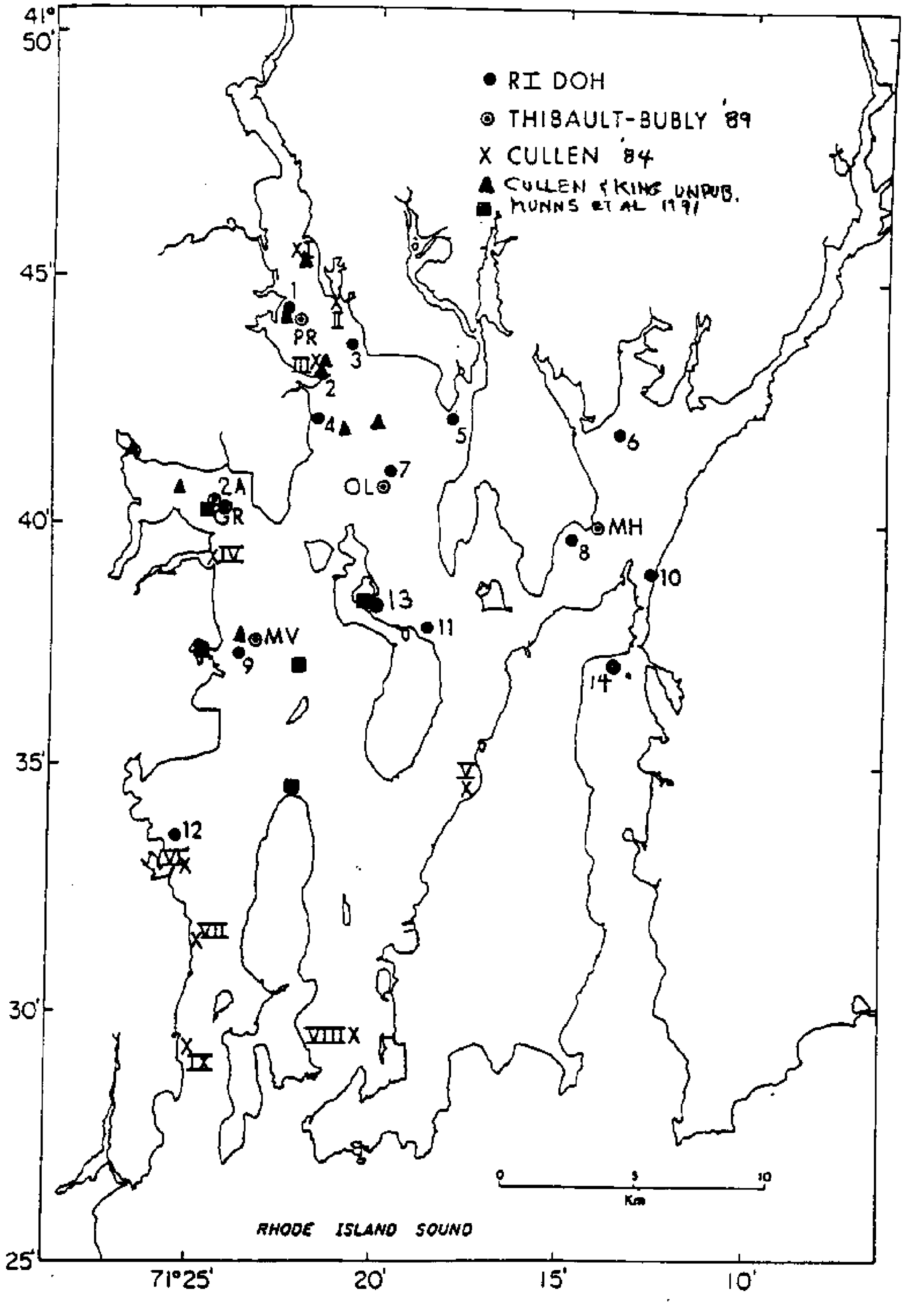


Figure 37. Narragansett Bay sampling stations for metals in quahog tissues.

In Apponaug Cove, sediments contain high levels of chromium and lead deposited by former industries, while present water quality is relatively high. The low levels of tissue contaminants in quahogs obtained from this location by Cullen and King (1990) provide strong evidence of a low potential of uptake from sediments and suggest that areas with moderate metal contamination of sediments could be used to harvest quahogs if contaminants were absent from the water column

Mercury levels are low in quahogs from all parts of Narragansett Bay. However, average concentrations in Mount Hope Bay are higher than the rest of the Bay, possibly indicating historical sources in the Taunton River. The highest mercury levels were found in the largest, oldest individuals, possibly reflecting the ability of mercury to accumulate with time.

There had been concern that historic disposal of industrial waste in the area surrounding Allen Harbor (Davisville) could have affected shellfish quality. Data on tissue contaminants in quahogs from the Allen Harbor area show all metals measured at or below typical mid-Narragansett Bay levels (Munns et al. 1991).

(5) **Long-term trends** - The variability of the data makes it difficult to detect a long-term pattern in RI DOH records. At all stations copper appears to have been elevated during the period from 1975 to 1980, decreased by a factor of four from 1981 to 1984, and slowly increased afterwards. Although high copper levels were found in quahogs from Sabin Point in 1969 (Myers and Phelps 1977) and 1977 (Cullen 1984), copper decreased rapidly to physiologically-controlled levels in stations further south. This suggests that the pattern in RI DOH data is an artifact. The decrease from the level of 95 ppm dry weight obtained by Myers and Phelps (1977) and Cullen (1984) at Sabin Point to recently obtained concentrations of 30-47 ppm (Thibault/Bubly 1989; Cullen and King, unpublished) may be a real effect of improved water quality.

The generally low and temporally stable (chromium is an exception) levels of metals in Bay quahogs led Taylor et al. (1991) to suggest that RI DOH monitoring could be reduced in frequency. Kipp (1991a; 1991b) noted that metal concentrations of Bay quahogs were not significantly different from those reported from 11 other states. Kipp concluded that there was no risk from non-pathogen contamination of quahogs from approved harvest areas of Narragansett Bay or the deeper portions of Mount Hope Bay.

4.3.3.2 Organic contaminants Organic contaminants such as petroleum hydrocarbons (PHCs), polycyclic aromatic hydrocarbons (PAHs), chlorinated hydrocarbon pesticides, including chlordane and DDT, and polychlorinated biphenyls (PCBs) could affect the marketability or safety for consumption of quahogs. Questions about sources, distribution, and accumulation in organisms are similar to those discussed in the previous section on heavy metal contamination. Organic contaminants differ from metals in the existence of a large number of compounds and in greater difficulty of analysis.

Few studies have been made of organic contamination of quahogs in Narragansett Bay. The most detailed is the recent study of Pruell et al (1988) for the Narragansett Bay Project. The quahogs analyzed in that study were collected at the same stations and times as those in studies by Thibault/Bubly (1989) on metals (Figure 39). Pruell et al. analyzed 50 samples consisting of four quahogs of similar size homogenized together. The quahogs came from 12 stations sampled November 1985 and 13 stations sampled June 1986. Fifty compounds were quantified within the categories of PAHs, pesticides, PCBs, and benzotriazoles (synthetic chemicals produced by Cieba-Giegy between 1963 and 1986). Munns et al (1991) measured a similar suite of compounds in quahogs collected from five stations in Allen's Harbor and Narragansett Bay during November 1988. Quinn et al (1989) analyzed both quahogs and sediments at nine stations (collected in 1987). They present data on two PCB compounds two PAHs, two benzotriazoles, PHCs, and coprostanol (a natural compound present in sewage effluent). Data from Quinn et al (1989) and Pruell et al (1988) are summarized in Table 7 (non-PHCs) and Table 8 (PHCs).

Pruell et al. (1988) examined the relationship between size and contaminant load by testing for differences between three size classes of the most precisely determined compound in each class of contaminant. No significant differences were found. The absence of a size effect agrees with an earlier study of quahogs from retail stores (Pruell et al. 1984).

In the same study, Pruell et al. (1988) found levels of DDTs, chlordanes, PAHs, and benzotriazoles significantly higher in Providence River quahogs than from all other areas. PCBs were significantly higher in the Providence River than other areas with the exception of Ohio Ledge, which had generally higher contaminant loads than Greenwich Bay, Mount View, or Mount Hope Bay. Quahogs from Mount Hope Bay had the lowest levels of all contaminant classes except PAHs. Average concentrations of PCBs in quahogs in harvestable areas varied from 155-285 ppb dry weight. The highest single value (from the Providence River) was 630 ppb dry weight or about 95 ppb wet weight, well below the FDA action level of 2,000 ppb wet weight. From examination of National Status and Trends Program data, Latimer (1989) concluded that Narragansett Bay had low PCB concentrations relative to other sites in southern New England. High concentrations of benzotriazoles were found in quahogs from the Providence River near a single source, the Pawtuxet River. Concentration of benzotriazoles decreased rapidly with distance down Narragansett Bay. The levels of several chlorinated pesticides was near or below detectable

Table 7. Organic contaminants in quahog tissues in Narragansett Bay.

Top: Data from Pruell et al. (1988) giving sums of concentrations of all compounds quantified within chemical groups as means of all samples taken within areas. Units are ppb (ng/g) wet weight

Bottom: Data from Quinn et al (1989), concentrations are given for two PCBs (CB101, CB138); two benzotriazoles (CL-BZT, C10-BZT); two PAHs (Fluoranthene, Pyrene); and coprostanol (cop). Units are ppb (ng/g) wet weight. PHCs are given in Table 8.

Pruell et al. (1988)

	PCBs	BZTs	PAHs	DDTs	Chlordanes
Providence River	358	1630	427	15.30	11.40
Ohio Ledge	285	749	225	12.60	6.28
Greenwich Bay	160	445	147	10.60	6.49
Mount View	238	367	279	8.48	5.13
Mount Hope Bay	155	103	274	7.50	4.20

Quinn et al (1989)

	CB101	CB138	CLBZT	C10-BZT	FLR	PYR	COP
Sabin Point	22.8	16.1	112.0	659.0	125.0	155.0	3860
Gaspee Point	19.5	16.4	121.0	634.0	93.6	83.2	3180
Conimicut Pt	5.9	4.8	56.4	282.0	118.0	97.0	1010
Rocky Point	2.0	1.8	1.0	4.5	55.0	48.3	1590
Ohio Ledge	12.1	12.4	48.1	229.0	56.8	57.5	490
Apponaug Cove	6.6	5.4	2.4	7.3	50.4	64.5	640
Sally Rock	3.7	3.2	2.1	13.1	44.0	39.5	210
Mount View	7.3	7.1	21.4	107.0	91.7	126.0	750
Wickford Cove	3.4	3.7	0.5	2.7	56.1	37.4	850

Table 8. Hydrocarbon concentrations in quahogs from Narragansett Bay (ppm wet weight) modified from Quinn (1989). The ppm (mg/kg) dry weight values were divided by 6.7 to obtain approximate ppm wet weight.

Date collected	Providence River	Wickford Cove	Dutch Island/ West Passage	**Reference**
1970-71	14-16	4.1-10	2.9	(1)
1973	90	9.6	---	(2)
1976	42	---	5.3-7.1	(3)
	Retail markets		Dutch Island	
1979	36.5-10.7		8-12	(4)
1987	Sabin Point	53.8		(5)
	Gaspee Point	37.6		
	Conimicut Point	31.7		
	Rocky Point	15.7		
	Ohio Ledge	10.6		
	Apponaug Cove	6.6		
	Greenwich Bay	5.8		
	Mount View	9.2		
	Wickford Cove	8.9		

References: (1) Farrington & Quinn (1973); (2) Farrington & Medeiros (1975); (3) Boehm & Quinn (1978); (4) Pruell et al. (1984); (5) Quinn (1989) limits. Two chlorane compounds and two DDT breakdown products were detectable. These were highest in the Providence River and decreased by a factor of about two in mid-Bay. Providence River chlordane levels were 0.4% of the FDA action level and the most abundant DDT compound in the Providence River (DDE) was about 0.03% of the FDA action level.

All of the compounds analyzed by Quinn et al (1989) follow the same general pattern found by Pruell et al. (1988) of decrease from Sabin Point south. Benzotriazoles decreased by the greatest amount along the survey transect (about 98%), PCBs, PHC, and coprostanol decreased by about 80%, and PAHs by only 50%. The similarity of PAH concentrations thoughout Narragansett Bay is a result of import from combustion products as well as point and non-point inputs of petroleum (R. Pruell, pers. comm.). It was also found that three classes of compounds in quahog tissues and sediments were correlated: benzotriazoles, PCBs, and PHCs. It was suggested that quahog source areas in Narragansett Bay could be identified by analysing these three classes of compounds in quahogs. Quinn (1989) reviewed the distributions of PHCs in organisms in Narragansett Bay. Data from that review and from Quinn et al (1989) (Table 8) illustrate the regular decrease of hydrocarbon contamination with distance toward the mouth of Narragansett Bay. Because of relatively few analyses and highly variable results (e.g. in the Providence River low levels in 1970-71 and high levels in 1973), it is not possible to detect any change in PHC concentrations over time.

Kipp (1991a; 1991b) found that, in general, health risks from organic chemicals in quahogs from Narragansett Bay are quite low. There was a slightly higher risk of cancer induction among consumers of the largest quantities of quahogs by exposure to PAHs and PCBs. The increased concentration of these contaminants in Providence River quahogs increased risk by less than a factor of two relative to consumption of quahogs from the open parts of Narragansett Bay. There were no difference in risks associated with organic chemicals in quahogs from Mount Hope Bay and from presently harvested areas.

4.5 Management Activities A number of different agencies participate in management of shellfish resources in coastal waters of Rhode Island that are open to shellfishing. The Rhode Island Marine Fisheries Council is an appointed board that is charged with regulating the quahog fishery. Regulations enacted by the Fisheries Council are usually recommended by the Department of Environmental Management Division of Fish and Wildlife, which plays strictly an advisory role. The DEM Division of Enforcement acts to enforce fisheries laws and regulations. An important aspect of the Rhode Island shellfisheries is that they are considered "free and common," held by the state in the public trust for the benefit of all. The key aim of management officials in Rhode Island is to assure that a "tragedy of the commons" does not occur with respect to shellfish resources (Hardin, 1968).

4.5.1 Quahog Fishery Laws and Regulations The laws relating to the quahog fishery in Rhode Island are relatively straightforward since most are applicable to public fisheries throughout the state and represent a consensus of managers and fishing interests. Laws within different categories are summarized below. Requirements and penalties contained inseparate statutes are combined here.

Marine Fisheries Council -- Although many state laws provide specific requirements for shellfish management, the requirements are under the control of, and can be changed by, the Marine Fisheries Council.

20-3-1 Composition -- The council is made up of the director of DEM or his or her designee as chairman, and eight private citizens appointed by the governor with the advice and consent of the senate. At least two represent the commercial fishing industry and two represent sports fishing. The chairman of the Coastal Resources Management Council and the chiefs of the DEM Divisions of Enforcement and Fish and Wildlife serve in an advisory capacity. Terms are four years and members may succeed themselves

20-3-2 Powers and Duties -- The council has regulatory jurisdiction over all marine animals within state territory. It is authorized, after the holding of a public hearing, to adopt regulations governing the following activities in taking fish, lobsters, and shellfish: fishing method, legal size limits, number and quantities, seasons and hours, and opening and closing of areas.

20-3-4 Shellfish and Marine Life Management Areas -- The council may,in cooperation with the director of DEM,designate land covered by tidewater or portions of the free and common fisheries of the state as management areas to enhance the cultivation and growth of marine species, manage the harvest of marine species, facilitate the conduct by the department of experiments in planting, cultivation, propagation, and managing all kinds of marine life. Designation fishing may be restricted or regulated as required to carry out the goals of the program.

Licenses -- All licenses are for one year; commercial licenses expire on December 31. The following licenses can be obtained for quahog fishing:

	Category	**Fee**	**Limit**	**Penalty for exceeding**
20-2-22	non-commercial resident	none	1/2 bu/day	no more than $50 or 30 days-1/2 bu excess
	non-resident	$15.50 annual $5.50 14 days	1/4 bu/day	$100/bu or no more than 30 days
20-2-20	commercial, >65	$1	12 bu/day	" "
20-2-20	commercial	$100	12 bu/day	" "
20-2-20	multipurpose commercial marine	$150	12 bu/day	" "
20-2-23	shellfish buyer	$50		
20-6-4	boat registration (commercial)	$2		
20-6-12	shellfish dredging	$100	30 bu/day	no more than $100 or 30 days

20-2-28 Deposit of Chapter 2 Fees -- Monies generated from license fees over $200,000 shall be appropriated to the Department of Environmental Management and can only be used for: (1) protection and propagation of marine fish, lobsters, and shellfish, (2) enforcement of marine fishery regulations, and (3) transplantation of shellfish from closed areas.

20-6-25 Disposition of Chapter 6 Fees -- These are deposited with the general treasurer and appropriated by the general assembly to DEM.

20-2-8 & 20-2-10 License holders must give truthful information on application, endorse the license, and not transfer or loan the license. The penalty is a fine of up to $50 and the loss of the license for one year.

20-2-9 Licenses must be in possession when engaged in shellfishing and presented to enforcement officers on request. If this is not done, the individual will be considered to be fishing without a license.

20-6-22 Minimum size of quahogs -- For many years, the minimum size allowed was 1 1/2 inches across the smallest diameter (shell height). This was determined by attempting to pass the clam through a ring. Effective July 1, 1986, the minimum was changed to 1 inch between the highest parts of the shell perpendicular to the plane of closure or "thickness." This measure was changed to comply with a directive of the Atlantic States Marine Fisheries Commission for standardization to facilitate both onboard culling and commercial grading by machine. The penalty for harvesting undersize is $10-$50/quart.

20-6-26 Transfer of shellfish from uncertified waters -- The director of DEM is authorized and directed to transfer shellfish to approved areas with necessary safeguards. He or she may make rules and regulations governing the reharvest to the best economical benefit of the state.

20-6-28 Cost of transfer -- The director is authorized to hire dredge boats or handrakers. Any transferred shellfish may be sold and the proceeds retained to be used for additional transfers.

20-6-7 Use of dredges -- Under normal circumstances, any taking of oysters, soft-shell clams, or quahogs by dredges, rakes, or other apparatus operated by mechanical power is prohibited. No such device can be in use while fishing for the above species. If quahogs are caught during mussel dredging, they must be returned to the Bay. Recently, use of winches to return diver-caught quahogs to the surface was banned. Use of small winches to recover bullrakes from deep water was also banned.

Opening areas for dredging -- Although there have been no openings since 1969, dredging could be allowed under the following statute:

20-6-8 Opening areas for quahog dredging -- Pursuant to good conservation practices, the Marine Fisheries Council shall be authorized to open areas of public waters of the state for taking quahogs under license by a registered boat, by dredges, rakes or other apparatus operated by mechanical power or hauled by power boats and shall be authorized to close such areas at any time there is a danger of depletion of quahogs or when flagrant violations of this chapter occur.

20-6-13 Dredging violations -- The penalties for dredging without a license or violating other provisions of the shellfish laws, for which a penalty is not otherwise provided, include a fine of $250 and the option of impoundment at the owners expense of the dredge boat and equipment for between 30 and 60 days. For subsequent violations, the penalty is imprisonment for 30 days and the option of impoundment for between 90 and 120 days.

20-149 Enforcement in waters between states -- When adjoining states have similar fisheries laws, persons of either state who are authorized to make arrests shall have authority on any part of such waters between such states or the shores thereof and to take any person or persons so arrested for trial to the state in which the violation was committed and to prosecute according to the laws of that state.

The following laws provide the enforcement power to deter commercial harvest in areas closed because of pollution or for management purposes:

20-6-29 Transferred shellfish -- Taking shellfish in closed transfer areas can be punished by a fine of less than $500 or less than 30 days imprisonment.

20-6-23 Shellfishing at night -- Taking shellfish between sundown and sunrise is punishable by a fine of less than $1,000 or less than three years imprisonment, and forfeiture of boat, motor, and equipment.

20-8.1-5 to 20-8.1-11 Shellfish from polluted areas -- Taking or selling shellfish taken from polluted waters and possession of shellfish while in a vessel upon polluted waters from two hours after sunrise until sunrise is punishable on the first offense by a fine less than $500 and for less than 1 year imprisonment and on subsequent offenses by a fine less than $2,000 and/or less than four years. Any boat, motor, and equipment employed in the illegal fishing can be seized.

20-1-10 Obligation to heave-to -- Refusal to heave-to on command from a marine patrol boat operated by DEM or disposal of anything overboard when requested to heave-to is punishable by a fine of between $25 and $500.

4.5.2 Division of Fish and Wildlife programs A synopsis of DEM Division of Fish and Wildlife shellfish management projects is given by Ganz (1991). Programs for quahog fishery enhancement in Rhode Island have included: (1) restoration by simply closing an area to fishing and letting natural recruitment occur undisturbed; (2) transplanting stocks into a depleted area; (3) planting juveniles (seeding areas); and (4) operating "spawner sanctuaries."

The quahog transplant programs have been one of the most successful management strategies. Ganz (1987) listed the following potential benefits of transplants:

1) reduction of stocks that might be harvested illegally
2) enhancement of settlement and growth in the source area
3) increase of stocks in certified waters
4) enhanced reproduction in certified waters
5) reduction of effort in overfished portions of certified waters.

Early Transplant Programs in Rhode Island -- Between 1954 and 1975, approximately 480,000 bushels of quahogs were transplanted from source waters in the Providence River and Mount Hope Bay. Transplants were carried out mainly by state-owned or hired dredge boats. Information on the amounts of quahogs transplanted and their source is presented in Table 9. Much of the information on these early programs is reviewed in annual reports of the DEM Division of Fish and Game and in Holmsen (1966).

The committment to transplant large quantities of shellfish from the closed areas in Providence River and Mount Hope Bay ended in 1968 due to lack of funding, but quahog stocks in these areas remain high and can be a viable source of transplant stock (Pratt et al. 1987). While both of these areas could be sources of stock for transplants, it is not present stocks that are of most economic interest. There is the potential for production of valuable "littleneck" quahogs. It is likely that the lower Providence River has this potential since it is adjacent to the productive upper Narragansett Bay, and

Table 9. Quahog transplants in Narragansett Bay in bushels. These figures from Division of Fish and Game annual reports are subject to some error because sources are not always identified, and it is not always clear whether the fiscal (June-June) or calendar year is referred to. After 1978, the major transplant area was from closed coves adjacent to Greenwich Bay and reported by DEM in pounds. A conversion factor of 80 pounds per bushel was used for these data.

	Method of Harvest			**Source**	
Fiscal Year	State Vessels	Hired Dredge Boats	Handrakers	Prov River	Mt Hope Bay
1954	---	32,805	---	?	---
1955	---	26,690	---	?	---
1956	29,335	9,802	---	?	---
1957	28,398	---	---	28,398	---
1958	24,853	15,723	---	40,576	---
1959	26,674	---	---	26,674	15,723
1960	17,757	---	1,500	19,257	---
1961	16,661	---	563	10,777	15,522
1962	22,881	4,660	3,804	8,318	15,658
1963	6,643	---	2,304	6,643	---
1964	---	39,867	---	39,876	---
1965	---	42,538	9,950	40,128	---
1966	---	43,764	9,950	43,764	---
1967	---	36,434	?	36,934	---
1968	---	16,569	2,733	10,756	---
1969	---	---	---	---	---
1970	---	---	---	---	---
1971	1,868	---	---	1,868	---
1972	?	---	---	?	---
1973	"small"	---	---	"small"	---
1974	"small"	---	---	"small"	---
1975	---	---	---	---	---
1976	---	---	---	---	---
1977	---	---	---	Coves off Greenwich Bay	
1978	---	---	1844	1844	
1979	---	---	2362	2362	
1980	---	---	1978	1978	
1981	---	---	1942	1942	
1982	---	---	2250	2250	
1983	---	---	1376	1376	
1984	---	---	2594	2594	
1985	---	---	1649	1649	
1986	---	---	2850	2850	
1987	---	---	2438	2438	
1988	---	---	2888	2888	
1989	---	---	2126	2126	
1990	---	---	7850	7850	
1991	---	---	213	213	

juvenile clams are found in the latter area. Between 1954 and 1962, an average of 25,825 bushels/year were transplanted from the river, while at the same time standing stocks of legal size clams increased from 588,000 to 1,257,000 bushels (data of Stickney and Stringer 1957; and Saila et al. 1965). This indicates that the transplant harvests were cropping very slow-growing adults from the population and having a positive effect on recruitment and growth.

Transplant programs since 1978 -- In the past, transplantation of quahogs from closed to open waters was an important part of the state shellfish management program in Narragansett Bay. Recognizing this, the transplant programs were reintroduced in 1978 after a brief hiatus beginning in 1974. In 1978, the state legislature appropriated $20,000 per year for operation of the program, which involved the payment of 10 cents per pound to shellfishermen for transfering quahogs from designated uncertified areas. The transplant operation was done in compliance with all of the federal shellfish sanitation requirements (ISSC 1989a; 1989b). This program was originally conceived as a "put and take" operation in which shellfish were planted in the late summer or fall, to be cleansed and harvested during the rough winter fishing season. In 1981, the program was restructured so that the bulk of the transplants were to be carried out during the spring. This was done in the belief that late spring or early summer spawning by the transplanted stock can provide a lasting benefit to the transplant receiving areas. These recent transplants have been much smaller in volume than the early (1950s and 1960s) Providence River and Mount Hope Bay transplants, and have mainly targetted smaller coves such as Greenwich Cove, Apponaug Cove, Bristol Harbor, and Spectacle Cove as source areas for quahogs. A total of approximately 200,000 pounds (2,500 bushels) are transplanted each year.

Shellfish management areas -- Nineteen waterways within the state have been designated as shellfish management areas by the Rhode Island Marine Fisheries Council (RIMFC). Shellfish management areas are established in locations that have been demonstated by field research by Division of Fish and Wildlife personnel to be overfished. Resource recovery strategies in proposed management areas include reduced daily catch limits, gear restrictions, or even temporary shellfishing closures. In areas in which natural recruitment is unable to restore shellfish populations, additional adult broodstock may be transplanted into the area (spawner sanctuaries established). RIMFC holds public hearings prior to final designation of shellfish management areas and establishment of concomitant regulations.

Most of the management areas are small coves, estuaries, and coastal salt ponds that are accessible to great numbers of recreational harvesters. Periodic closures and reduced daily catch limits usually allows recovery of shellfish resources in these areas.

The largest of the shellfish management areas is the Greenwich Bay management area. Greenwich Bay, prior to the late 1970s, was one of the most productive quahog fishing grounds in the state, but it was overfished to the point that there was no longer an economically viable fishery. In 1981, Greenwich Bay was closed to shellfishing and designated as a management area. Transplant of 400,000 pounds of quahogs from adjacent pollution closure areas was carried out that year to augment the natural productivity. In 1982, the management area was reopened with a number of restrictions. Greenwich Bay was open for harvest only 12 hours per week during the winter, and with reduced catch limits. The Greenwich Bay management area continues to operate in this manner. The area is closed in the spring, transplants occur prior to spawning, and the area is reopened each December. The annual harvest from Greenwich Bay now ranges from 700,000 to 1 million pounds. The Greenwich Bay management plan has wide support by the shellfishing industry.

4.5.3 Division of Enforcement -- The Enforcement Division of the Department of Environmental Management monitors the harvest of quahogs in the coastal waters of Rhode Island. Without close monitoring of the harvest methods, quantities, and locations, Rhode Island would be jeopardized in the interstate market and would face depletion of a productive resource.

The 27 conservation officers of the Division of Enforcement devote approximately 75% of their time to shellfish law enforcement. In addition, they are charged with enforcement of other marine fisheries laws, lobstering, boating, hunting, freshwater fishing, camping, littering, wood cutting, dumping of hazardous and solid wastes, and the illegal filling of wetlands and coastal areas. The state is divided into three enforcement areas: 1) Newport and Bristol Counties; 2) Providence and the northern half of Kent Counties; and 3) Washington County, including Block Island, the lower half of Kent County, and Jamestown. Each area has a field lieutenant and sergeant. In the Providence office are a chief and deputy chief. Numerous vacancies exist at the present time (April, 1992): a field sergeant, a records and communications sergeant, an administrative aide, an administrative lieutenant, as well as several conservation officers.

In addition to its education and enforcement activities, the Division of Enforcement assists the shellfish industry by participating in the ongoing transplant programs (see section 4.5.2). Each May and June, paid and voluntary transplants of shellfish are made from closed areas into Greenwich Bay, Bristol, and Grinnell's Beach Management Areas for harvest during the winter.

Starting in 1988, the Division of Enforcement instituted expanded enforcement actions against shellfish dealers. Working with agents of the National Marine Fisheries Service (NMFS), officers conducted a four phased approach for monitoring shellfish after it reached the dealer level. Working with NMFS agents allows Rhode Island officers to conduct checks of product in areas where they do not have the authority to enter on their own. The enforcement activities included: 1) unannounced checks of area markets; 2) commercial vehicle checkpoints in cooperation with the RI State Police Truck Squad, RI Dept of Health agents, and NMFS agents; 3) inspections of freight at the major airports (Logan, Kennedy, Bradley, and T.F. Greene); and 4) and the acvtual targetting of shipments and following them to their destinations. The commercial vehicle checkpoints were especially successful, with numerous dealer's shipments being checked in one time period. Many cases were made against dealers and shippers for possessing undersized shellfish, and shipping untagged product. A number of unlicensed dealers were arrested and the Health Department made several seizures of unfit product.

The Rhode Island Judicial system continued to support enforcement efforts to prevent shellfish harvested in closed areas from reaching the public. Forfeiture of gear, heavy fines, and prison terms for repeat offenders has caused a general slowing down of activity in polluted waters. Total monies generated in fines from shellfish violations between 1986 and 1990 are as follows: 1986 - $27085; 1987 - $19130; 1988 - $24694; 1989 - $21034; 1990 - 18685. Table 10 provides a summary of enforcement activities during those years.

Table 10. Shellfish citations* charged by the Rhode Island DEM Division of Enforcement 1986-1990.

Violation	**Number Charged**				
	1986	1987	1988	1989	1990
Night shellfishing	20	10	19	4	19
Conspiracy to commit night shellfishing	3			1	
Implement in pollution	21	18	28	49	20
Implement in pollution (second offense)	7		2	3	1
Taking shellfish from pollution	114	76	101	104	158
Taking shellfish from pollution (2nd)	10	4	2	9	
Possession of noncomplying shellfish	1	1	8	3	6
Psssession of undersized shellfish	45	19	69	61	100
Use of illegal implement	4	7		6	9
Selling shellfish without a license	4	13	3	10	5
Buying shellfish without a license		1	3	1	
Nonresident shellfishing w/o license	15	16	8	16	28
Nonresident exceeding daily limit		3			1
Resident exceeding daily limit	10	17		19	10
Exceeding commercial daily limit	3	3			
Selling shellfish for unlicensed person		1			
Buying illegal shellfish			2		
Shellfishing in closed management area	18	10	3	2	6
Shellfishing w/ illegal means in mg't area	3	3			
Exceeding daily limit in management area		24	42	23	30
Taking shellfish out of season			2		
Shucking oysters on water		1			
Shipping untagged shellfish			4	4	4
Failure to produce shellfish license					1
Fraudulent purchase of shellfish license	1	1		1	
TOTALS:	279	228	296	316	398
Total Felonies:	40	14	23	17	20

*Multiple charges may be levied on the same individual

4.6 Aquaculture

4.6.1 History of shellfish aquaculture From the 1880s to the 1930s, oyster aquaculture was by far the most important fishery in Narragansett Bay. Approximately 20,000 acres of estuary bottom in Narragansett Bay were leased from the state by aquaculture concerns. Almost all of these leased areas were in areas where quahogs are presently harvested. Hundreds of fixed fish traps (weirs) along the shoreline were an additional restriction on public use of Narragansett Bay waters. The quahog fishery was of minor importance, and in some cases payments were made to oyster lease holders for the right to fish for these secondary species in the leased areas.

As the oyster industry declined between the 1930s to the 1950s, the quahog fishery increased in areas harvested and in yield. Both hand collecting (by tongs, rakes, or diving) and mechanical dredging by boats were utilized as methods for harvesting natural stocks of quahogs in Narragansett Bay until the 1950s. Since then, hand collecting (tongs, rakes, and diving) of quahogs has been carried out in all certified waters without restriction from leases or competition from dredgers.

Overfishing of natural stocks of quahogs in certified waters, nationwide increases in demand and prices for shellfish, and advances in culture techniques caused a renewed interest in marine aquaculture throughout the United States in the 1970s. In Rhode Island, the concept of aquaculture came into direct conflict with the free and open fishery of hand collectors. The following description of the resolution of this conflict has been condensed from Nixon (1981).

When the state began its coastal management program in the mid-1970s, control over aquaculture was given to the newly created Coastal Resources Management Council. Two permits were granted under their authority, despite a lack of implementing regulations: the Blount Oyster Farm on Prudence Island and the Blue-Gold Sea Farms of Middletown. Blue-Gold received a permit to culture mussels using an off-bottom system in over sixty acres in the East Passage. Fishermen objected to this proposal because the regulatory program was not yet in place. They feared that this would be the beginning of a series of projects that would once again monopolize Narragansett Bay's most productive shellfishing areas.

In an effort to clarify the regulatory program, the General Assembly passed a new aquaculture law in its 1980 session (G.L.R.I. 20-10-1) that repealed the oyster leasing laws of the 19th century and recognized the potential for conflict between Bay fishing and aquacultural interests. Regulations implementing the new law were not in place by the fall of 1980 when the Narragansett Mussel Company submitted an application for a site in the West Passage of the Bay in an area utilized by a variety of fishing and recreational interests. In October 1980, the Rhode Island Shellfishermen's Association requested a meeting with Governor J. Joseph Garrahy to seek his intervention in what was perceived to be a serious threat to the future of fishing in Narragansett Bay. The Governor responded by declaring a moratorium on new aquaculture permits and appointed a task force representing fishing, aquaculture, environment, regulatory, and scientific interests. The task force was to develop recommendations by June 1, 1981 to resolve the dispute.

The task force began its deliberations in January 1981 with friction between aquaculture and fishing interests high. Research, hearings, and studies were conducted for seven months in an effort to find a common ground for the parties to agree upon. At the outset, the parties were diametrically opposed; fishermen maintained that aquaculture should not be allowed within Narragansett Bay, while aquaculturists argued that they should be allowed to operate wherever environmental conditions allowed, since their use was the most intensive and beneficial use of the water column. By July 14, 1981, consensus was achieved on a number of significant points: (1) fishermen softened their position that aquaculture should not be allowed in Narragansett Bay at all and recognized that limited efforts of a relatively small size would not necessarily be harmful to their operations; (2) aquaculturists acknowledged that they should seek locations that are not actively exploited by commercial fishing operations; (3) the State Division of Fish & Wildlife developed a draft Aquaculture Management Plan that mapped the location of existing fishing areas with the aim of identification of high conflict areas for exclusion of aquaculture; and (4) the Coastal Resources Management Council announced that regulations implementing the aquaculture law would require set fees for aquaculture leases and bonding requirements.

4.6.2 Aquaculture Regulations The Coastal Resource Management Council's program on aquaculture is described in a 1983 report (Olsen and Seavey 1983). Policies are that: (1) aquaculture is a viable means for supplementing the yields of marine fish and shellfish food products and will be supported where it can be accommodated among other users; and (2) applicants will be granted exclusive use of submerged lands and water column when such use is necessary, otherwise the public will be allowed use of the area for traditional water activities.

The aquaculture permitting process includes a number of preliminary steps designed to inform other potential user groups. The Council will ask the director of the Department of Environmental Management to determine that the proposed activity will not adversely affect marine life outside of the proposed area and the continued vitality of indigenous fisheries. The chairman of the Marine Fisheries Council will be asked to determine that the activity is consistent with competing uses of marine fisheries. Permits must be obtained from the director of DEM for possession, importation, and transportation of species used in aquaculture. Applicants for aquaculture permits and leases must:

1) describe the location;
2) identify the species managed;
3) describe methods used and whether they are experimental, commercial, or for personal use; and
4) provide information required to determine:
    a) compatibility w/ existing and potential uses;
    b) degree of exclusivity required;
    c) safety and marking of the lease area;
    d) projected yield per unit area;
    e) cumulative impact on the area;
    f) capability of the applicant; and
    g) impact on scenic qualities.

Once the applications are approved, permittees are charged an annual fee ($75 for 1/2 acre or less; $150 for 1/2 to 1 acre, and $100 for each additional acre) and are required to submit an annual report to receive a renewal. Leases can be renewed annually for 10 years by this simple process of submitting an annual report. After 10 years, the permittee must reapply through the CRMC.

4.6.3 Practice of Shellfish Aquaculture Commercial aquaculture of quahogs has been slow to develop in the United States, but in the last 10 years it has grown considerably. Cultivation of quahogs is now being practiced in all coastal states from Massachusetts to Florida. In the areas in which quahogs are being cultured there are a variety of culture methods. For example in the southeast, hatchery reared quahogs can reach marketable size in two years, but a high level of predator control by way of exclusion screening is necessary. In Connecticut, some operators have leased beds that are prepared by removal of old individuals and some predators to allow for seeding by natural set.

Much quahog aquaculture is devoted to production of seed, which is in demand by towns to plant for recreational use. In Massachusetts, seed is provided by hatchery/nursery operations varying from large commercial enterprises to small, town operated facilities. A problem in the production of seed clams is that although it is easy to produce large numbers of very small clams (1-2mm), larger seed (>8mm) is the most desirable for field planting because of its predator resistance. Littlefield (1991) outlines the methods used by the Town of New Shoreham for the production of seed quahogs for Block Island's Great Salt Pond.

The potential for privately operated quahog aquaculture operations in Rhode Island waters can be best illustrated by the experiences of aquaculturists in nearby Massachusetts and New York. Since 1974, a system of intensive quahog aquaculture has been developed in Wellfleet, Massachusetts (Chapman 1987). In 1987, 50 persons had grants on 80 acres of tidal flats. Most operators stock 4 feet x 8 feet net boxes with 10,000 or more seed from a local hatchery ($12-$16/1,000), allow them to grow to 19-24mm, and then transfer them to narrow net-covered plots for grow out at a density of $1000/m^2$. Clams are harvested at a length of 51-63mm (2-2.5 inches). Individuals have reported gross sales of $30,000/acre in recent years (J. Fox, personal communication to R. Rheault, URI). Wellfleet grant holders are quick to stress the potential contribution of their operations to the spawning stock (Chapman 1987). Malinowski (1986) has prepared an illustrated manual on "small-scale farming of the quahog on Long Island, New York." His concept is of leases of less than five acres worked with light equipment by a few individuals. Most of the quahogs produced would be sold as seed, but some would be kept until they were of harvest size. The suggestion is made that since overfishing and environmental deterioration have severely reduced quahog harvests on Long Island, quahog farming would be a way that baymen could continue using their skills to make a living on the water. Interference with the remaining open fishery would be reduced by only utilizing areas where clams do not naturally occur.

Practice of shellfish aquaculture in Rhode Island -- Annual reports from aquaculture permittees are regularly summarized in a report by the DEM Fish and Wildlife Division. The most recently available report (Ganz 1987) states that: Aquaculture continued to decline in 1987. Only three operations marketed their cultured products; this amounted to 116 bushels of oysters. The other operations were active in producing shellfish, but did not sell product. There does not appear to be any desire by operators to expand their projects.

Specific projects that were active in 1987 include four oyster culture operations in salt ponds, the Blue Gold mussel farm in East Passage, and a quahog "clam box" experiment in Charlestown Pond. No mussel harvest or new planting was reported for 1987 by Blue-Gold, which presently spends most of its effort marketing product from other sources. The "clam box" operation, an attempt to attract quahog settlement in various configurations of boxes, has apparently not succeeded in producing or concentrating seed. One oyster operation has made plans to start grow out of hatcheries-reared softshell clams during 1988.

Although the potential for profit from private aquaculture is probable, the reasons for the low level of activity in Rhode Island are legal and political obstacles erected for protection of the open fishery. However, the commitment to the maintenence of an open fishery does not necessarily preclude the use of techniques developed by aquaculture. The techniques of induction of set, transplantation, and predator control should be examined for enhancment of the public fishery. The existence of shellfish management areas and the availability of license fee (804) monies for shellfish propagation would make such projects possible.

REFERENCES

Abbott, R.T. 1974. American Seashells. Van Nostrand Reinhold, New York. 663 pp.

Aldrich, J.C. 1976. The spider crab Libinia emarginata and the starfish, an unsuitable predator but a cooperative prey. Crustaceana 31:152-156.

Allard, D.J. 1988. Stable isotopic analyses of selected Narragansett Bay molluscs. Masters thesis, Graduate School of Oceanography, University of Rhode Island, Narragansett.

Andrews, E.B. 1988. Excretory system of molluscs. Pp. 381-448. In: E.R. Trueman and M.R. Clarke (eds.), The Mollusca Vol. 11. Academic Press, New York.

Ansell, A.D. 1967. Egg production of Mercenaria mercenaria. Limnology and Oceanography 12:172-176.

Ansell, A.D. 1968. The rate of growth of the hard clam Mercenaria mercenaria throughout the geographical range. J. Cons. Int. Explor. Mer. 31:364-409.

Arnold, W.S. 1984. The effects of prey size, predator size, and sediment composition on the rate of predation of the blue crab, Callinectes sapidus Rathbun, on the hard clam, Mercenaria mercenaria (Linne). J. Exp. Mar. Biol. Ecol. 80:207-219.

Barnes, R.D. 1974. Invertebrate Zoology (3rd edition). W.B. Saunders Company, Philadelphia. 870pp.

Barry, M.M. and P.P. Yevich. 1972. Incidence of gonadal cancer in the quahaug (Mercenaria mercenaria). Oncology 26:87-96.

Bass, A. E. 1983. Growth of hard clams, Mercenaria mercenaria, feeding on chlorophyte and cyanobacterial picoplankton. M.S. Thesis, SUNY, Stony Brook. 55 pp.

Behrens, W.J., and I.W. Duedall. 1981. The behavior of heavy metals in transplanted hard clams Mercenaria mercenaria. J. Cons. Int. Explor. Mer. 39:223-230.

Belding, D.L. 1931. The quahaug fishery of Massachusetts. Mass. Dept. of Conservation, Div. of Fish and Game, Marine Fisheries Service Bulletin no. 2. 41pp.

Bisagni, J.J. 1976. The origin and development of turbidity structure in the lower Providence River and upper Narragansett Bay, Rhode Island. M.S. Thesis, Univ. of Rhode Island, Kingston, Rhode Island.

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

Borden, D.V.D. 1992. Rhode Island marine fisheries management program future requirements. Pp. 33-39. In: C.A. Penniman and C.A. Karp (eds.), Science and the Narragansett Bay Comprehensive Conservation and Management Plan, Symposium Proceedings, 17 Feb 1992. Narragansett Bay Project, Providence.

Boyd, J.R. 1991. The Narragansett Bay shellfish industry: a historical perspective and an overview of problems of the 1990s. Pp. 2-10. In: M.A. Rice, M. Grady and M.L. Schwartz (eds.), Proceedings of the First Rhode Island Shellfisheries Conference. Rhode Island Sea Grant, University of Rhode Island, Narragansett.

Bricelj, V.M. 1979. Fecundity and related aspects of the hard clam, *Mercenaria mercenaria*, reproduction in the Great South Bay, New York. M.S. Thesis, State University of New York, Stony Brook. 98pp.

Bricelj, V.M., and R.E. Malouf. 1980. Aspects of reproduction of hard clams in Great South Bay, New York. Proceed. National Shellfisheries Assoc. 70:216-229.

Bricelj, V.M., and R.E. Malouf. 1984. Influence of algal and suspended sediment concentrations on the feeding physiology of the hard clam *Mercenaria mercenaria*. Marine Biology 84:155-165.

Bricelj, V.M., R.E. Malouf, and C. deQuillfeldt. 1984. Growth of juvenile *Mercenaria mercenaria* and the effect of resuspended bottom sediments. Marine Biology 84:167-173.

Bricelj, V.M., J.H. Lee, and A.D. Cembella. 1991. Influence of dinoflagellate cell toxicity on uptake and loss of paralytic shellfish toxins in the northern quahog, *Mercenaria mercenaria*. Mar. Ecol. Prog. Ser. 74:33-46.

Brousseau, D.J. 1987. Seasonal aspects of sarcomatous neoplasia in *Mya arenaria* from Long Island Sound. J. Invertebr. Pathol. 50:269-276.

Brown, R.S. 1977. Histopathological findings in *Mya arenaria* and *Mercenaria mercenaria*, sampled from Quonset Point/Davisville, Rhode Island. In: The Redevelopment of Quonset/Davisville: An Environmental Assessment. Tech. Appendix 4, Coastal Resources Center, Univ. of Rhode Island, Kingston, Rhode Island. 9 pp.

Burbanck, W.D., M.E. Pierce, and G.C. Whiteley, Jr. 1956. A study of the bottom fauna of Rand's Harbor, Massachusetts: An application of the ecotone concept. Ecological Monographs 26:213-243.

Burkenroad, M.D. 1946. General discussion of problems involved in starfish utilization. Bull. Bingham Oceanogr. Coll. 9(3):44-58.

Burrell, V.G. 1977. Mortalities of oysters and hard clams associated with heavy runoff in the Santee River system, South Carolina in the spring of 1975. Proc. Nat. Shellfish. Assn. 67:35-43.

Butman, C.A. 1987. Larval settlement of soft-sediment invertebrates: the spatial scales of pattern explained by active habitat selection and the emerging role of hydrodynamical processes. Oceanography and Marine Biology Annual Reviews 25:113-165.

Calabrese, A., J. Macinnes, D.A. Nelson , and J.E. Miller. 1977. Survival and growth of bivalve larvae under heavy metal stress. Marine Biology 41:179-184.

Campbell, R. No date. An inventory of the quahog population of the Providence River and Mount Hope Bay. RI Div. of Fish and Game. Un-numbered leaflet.

Campbell, R. 1959a. Quahog investigations - Nausauket - Buttonwoods, 1955-1958-1959. RI Div. Fish and Wildlife. Leaflet No 1.

Campbell, R. 1959b. Quahog investigations - Potowomut River. RI Div. of Fish and Game. Leaflet No. 2.

Campbell, R. 1959c. Quahog investigations - Kickamuit River. RI Div. of Fish and Game. Leaflet No. 3.

Campbell, R. 1961. A summary report on the fleet plotting program in Narragansett Bay. RI Div. of Fish and Game. Leaflet No. 7.

Campbell, R., and P. Dalpe. 1960a. A preliminary report on the fleet plotting program in Narragansett Bay. RI Div. of Fish and Game. Leaflet No. 4.

Campbell, R. and P. Dalpe. 1960b. A report on the 1960 starfish census in Narragansett Bay. RI Div. of Fish and Game. Leaflet No. 8.

Canario, M.T. 1963a. Shellfish survey of the Kickamuit River. RI Div. of Fish and Game Leaflet No. 12.

Canario, M.T. 1963b. Starfish survey 1962. RI Div. of Fish and Wildlife. Leaflet No. 13.

Canario, M.T., and K.A.M. Kovach. 1965a. A shellfish survey of East Passage Channel. RI Div. of Fish and Game Leaflet No. 16.

Canario, M.T., and K.A.M. Kovach. 1965b. Shellfish survey of the Providence River. RI Div. of Conservation Leaflet No. 17.

Canario, M.T., and K.A.M. Kovach. 1966. Shellfish survey of the Warren River. RI Div. of Conservation Leaflet No. 22.

Carriker, M.R. 1951. Observations on the penetration of tightly closing bivalves by Busycon and other predators. Ecology 32:73-83.

Carriker, M.R. 1952. Some recent investigations on native bivalve larvae in New Jersey estuaries. Proc. Nat. Shellfisheries Assn. 1950:79-74.

Carriker, M.R. 1961. Interrelation of functional morphology, behavior, and autecology in early stages of the bivalve (Mercenaria mercenaria). J. Elisha Mitchell Soc. 77:162-241.

Castagna, M. and P. Chanley. 1973. Salinity tolerance of some marine bivalves from inshore and estuarine environments in Virginia waters on the western mid-Atlantic coast. Malacologia 12:47-96.

Chanley, P.E. 1958. Survival of some juvenile bivalves in water of low salinity. Proc. Nat. Shellfish. Assn. 48:52-65.

Chanley, P.E. 1961. Inheritance of shell markings and growth in the hard clam, Venus mercenaria. Proceedings of the National Shellfisheries Association 5:163-169.

Chapman, W. 1987. Quahog propagation in Wellfleet. videotape (30 minutes). Wellfleet Public Library Productions. Wellfleet, Massachusetts.

Chestnut, A.F. 1951. The oyster and other mollusks in North Carolina. pp. 141-190. In: H.F. Taylor (ed) Survey of Marine Fisheries of North Carolina. Univ. of North Carolina Press, Chapel Hill.

Cooper, K.K. 1979. Hematopoietic neoplasm in a commercially important bivalve mollusk, Mya arenaria (Linne). PhD Dissertation, University of Rhode Island, Kingston.

Cooper, R.A., S.B. Chenometh, and N. Marshall. 1964. Condition of the quahog, Mercenaria mercenaria, from polluted and unpolluted waters. Chesapeake Sci. 5:155-160.

COSMA. 1985. Suffolk County's hard clam industry: an overview and an analysis of management alternatives. A report by the Coastal Ocean Science and Management Alternatives Program. Ref. 85-19, Marine Sciences Research Center, SUNY, Stony Brook, NY.

Craig, M.A. and T.J. Bright. 1986. Abundance, age distributions and growth of the Texas hard clam, Mercenaria mercenaria texana, in Texas bays. Contributions in Marine Science 29:59-72.

Crenshaw, M.A. and J.M. Neff. 1969. Decalcification at the mantle-shell interface in mollusks. American Zoologist 9:881-885.

Cullen, J.D., Jr. 1984. Copper and nickel in Mercenaria mercenaria, relative to concentrations in the water column in a New England Estuary. M.S. Thesis, Univ. of RI, Kingston, RI. 141 pp.

Cullen, J.D., Jr. and J. King. 1990. Relationships between Cu, Ni, Cd, Cr and Pb levels in soft tissues of Narragansett Bay Mercenaria and sediments. DRAFT Report to the Narragansett Bay Project.

Cunningham, P.A. 1979. The use of bivalve mollusks in heavy metal pollution research. Pp. 183-221. In: W.B. Vernberg, F.P. Thurberg, A. Calabrese, and F.J. Vernberg (eds.), Marine Pollution: Functional Responses. Academic Press, New York.

Curley, J.R., R.P. Lawton, D.K. Whittaker, and J.M. Hickey. 1972. A study of the marine resources of Wellfleet Harbor. Mass. Dept. Nat. Resources, Div. Mar. Fish., Monograph 12, 37pp.

Davis, H.C. 1958. Survival and growth of clam and oyster larvae at different salinities. Biol. Bull. 114:296-307.

Davis, H.C. 1969. Shell fisheries: present and future. Trans. Amer. Fish. Soc. 98:743-750.

Davis, H.C., and A. Calabrese. 1964. Combined efforts of temperature and salinity on development of eggs and growth of larvae of M. mercenaria and C. virginica. Fish. Bull. 63:643-655.

Desbonnet, A. and V. Lee. 1991a. Historical trends in water quality and fisheries resources in Narragansett Bay, Rhode Island. NOAA, National Ocean Pollution Program Office, Washington, DC. 223pp.

Desbonnet, A. and V. Lee. 1991b. Links between water quality and shellfisheries in Narragansett Bay, Rhode Island. pp. 11-18. In: M.A. Rice, M. Grady and M.L. Schwartz (eds.) Proceedings of the First Rhode Island Shellfisheries Conference, Narragansett, RI, August 27, 1990. Rhode Island Sea Grant, Univ. of Rhode Island, Narragansett.

deZwaan, A. 1977. Anaerobic energy metabolism in bivalve molluscs. Oceanogr. Mar. Biol. 15:103-187.

deZwaan, A. and T.C.M. Wijsman. 1976. Anaerobic metabolism in bivalvia (Mollusca). Comp. Biochem. Physiol. 54B:313-324.

Diamond, H.A. 1981. Life history and environmental adaptation of bivalves as a function of feeding mode. M.S. Thesis. Univ. of Rhode Island, Kingston, Rhode Island. 151 pp.

Dillon, R.T. and J.J. Manzi. 1989. Genetics and shell morphology in a hybrid zone between the hard clams Mercenaria mercenaria and M. campechensis. Marine Biology 100:217-222.

Doering, P.H. 1976. A burrowing response of Mercenaria mercenaria (Linnaeus, 1758) elicited by Asterias forbesi (Desor, 1848). Veliger 19:167-175.

Doering, P.H. 1981. Observations on the behavior of Mercenaria mercenaria. Ophelia 20:169-177.

Doering, P.H. 1982. Reduction of sea star predation by the burrowing response of the hard clam, Mercenaria mercenaria. Estuaries 5:310-315.

Doering, P.H., C.A. Oviatt, and B.L. Welsh. 1990. Characterizing the late summer water quality in the Seekonk River, Providence River, and Upper Narragansett Bay. Report to Narragansett Bay Project, U.S. Environmental Protection Agency. 24pp.

Dow, R.L. and D.E. Wallace. 1955. Natural redistribution of a quahog population. Science 122:641-642.

Epifanio, C.E. 1979. Growth in bivalve molluscs: nutritional effects of two or more species of algae in diets fed to the American oyster, Crassostrea virginica and the hard clam, Mercenaria mercenaria. Aquaculture 18:1-12.

Farrington, J.W. and G. Medieros. 1975. Evaluation of some methods of analysis for petroleum hydrocarbons in marine organisms. Pp. 115-123, In: 1975 Conference on the Prevention and Control of Oil Pollution. American Petroleum Institute, Washington DC.

Farrington, J.W. and J.G. Quinn. 1973. Petroleum hydrocarbons in Narragansett Bay. I. Survey of hydrocarbons in sediments and clams (*Mercenaria mercenaria*). Estuar. Coastal Mar. Sci. 1:71-79.

Fields, J.H.A. and K.B. Storey. 1987. Tissue-specific alanopine dehydrogenase from the gill and strombine dehydrogenase from the foot muscle of the cherrystone clam, *Mercenaria mercenaria* (Linne). J. Exp. Mar. Biol. Ecol. 105:175-185.

Flagg, P.J., and R.E. Malouf. 1983. Experimental plantings of juveniles of the hard clam *Mercenaria mercenaria* in the waters of Long Island, New York. J. Shellfish Res. 3:19-27.

Freudenthal, A.R. and J.L. Jijina. 1988. Potential hazards of *Dinophysis* to consumers and shellfisheries. J. Shellfish Res. 7:695-701.

Frost, W.H. 1925. Report of the committee on sanitary control of the shellfish industry in the United States. Supplement 53, Public Health Reports. 17pp.

Galtsoff, P.S., and V.L. Loosanoff. 1939. Natural history and method of controlling the starfish (*Asterias forbesi*). U.S. Bureau of Fisheries, Fish. Bull. 49:75-132.

Ganz, A.R. 1987. Shellfish stock relocations: the Greenwich Bay experience. Narragansett Bay Symposium, April 22-25, 1987. p. 113.

Ganz, A.R. 1991. Shellfish management projects in Rhode Island. Pp. 65-67. In: M.A. Rice, M. Grady and M.L. Schwartz (eds.) Proceedings of the First Rhode Island Shellfisheries Conference, Narragansett, RI, August 27, 1990. Rhode Island Sea Grant, Univ. of Rhode Island, Narragansett.

Ganz, A.R., and R. Sisson. 1977. Inventory of the fisheries resources of the Quonset-Davisville area. RI Div. of Fish and Wildlife Leaflet No. 48.

Gibbons, M.C., and M. Castagna. 1985. Biological control of predation by crabs in bottom cultures of hard clams using a combination of crushed stone aggregate, toadfish, and cages. Aquaculture 47:101-104.

Glude, J.B. and W. S. Landers. 1953. Biological effects of bullraking vs. power dredging on a population of hard shell clams, *Venus mercenaria*. Nat. Shellfisheries Assn. Conv. Addresses 1951:47-69.

Gray, G.W., Jr. 1969. Shellfish survey of the West Passage of Narragansett Bay. RI Div. of Conservation Leaflet 26.

Green, R.A. 1966. Condition index of quahogs *Mercenaria mercenaria* from selected areas of Narragansett Bay - Progress Report. RI Div. of Fish and Game Leaflet No. 19.

Grizzle, R.E. 1990. Distribution and abundance of *Crassostrea virginica* (Gmelin, 1791) (eastern oyster) and *Mercenaria* spp. (quahogs) in a coastal lagoon. J. Shellfish Res. 9:347-358.

Grizzle, R.E. and R.A. Lutz. 1988. Descriptions of macroscopic banding patterns in sectioned polished shells of Mercenaria mercenaria from southern New Jersey. Journal of Shellfish Research 7:367-370.

Grizzle, R.E. and R.A. Lutz. 1989. A statistical model relating horizontal seston fluxes and bottom sediment characteristics to growth of Mercenaria mercenaria. Marine Biology 102:95-105.

Grizzle, R.E. and P.J. Morin. 1989. Effect of tidal currents, seston and bottom sediments on growth of Mercenaria mercenaria: results of a field experiment. Marine Biology 102:85-93.

Hammen, C.S. 1980. Total energy metabolism of marine bivalve mollusks in anaerobic and aerobic states. Comp. Biochem. Physiol. 67A:617-621.

Hamwi, A. 1968. Pumping rate of Mercenaria mercenaria as a function of salinity and temperature. Proc. Nat. Shellfisheries Assn. 58:4 (abstract).

Hardin, G. 1968. The tragedy of the commons. Science 162:1243-1248.

Hickey, J.M. 1983. Assessment of quahog stocks in contaminated waters of southeastern Massachusetts. Mass. Div. Marine Fisheries Pub. 13636-92-50-6-84-C.R. 31 pp.

Hicks, S.D. 1959. Physical oceanography of Narragansett; Bay. Limnol. and Oceanogr. 4:316-327.

Hinga, K.R., N.F. Lewis, R. Rice, K. Dodey, and A. Keller. 1989. A review of Narragansett Bay Phytoplankton data: status and trends. Narragansett Bay Project Report no. NBP-89-21. U.S. Environmental Protection Agency. 254pp.

Holmsen, A.A. 1966. The Rhode Island quahog industry - Some economic aspects. URI Agriculture Experiment Station Bulletin No. 386.

Holmsen, A.A., and S. Horsley. 1981. Characteristics of the labor force in quahog handraking. NOAA/Sea Grant/URI Marine Memorandum No. 66.

Humphrey, C.M. and R.L. Walker 1982. The occurrence of Mercenaria mercenaria form notata in Georgia and South Carolina: calculation of phenotypic and genotypic frequencies. Malacologia 23:75-79.

ISSC. 1989a. National Shellfish Sanitation Program Manual of Operations. Part I. Sanitation of Shellfish Growing Areas. Interstate Shellfish Sanitation Conference, U.S. Food and Drug Administration, Washington, DC.

ISSC. 1989b. National Shellfish Sanitation Program Manual of Operations. Part II. Sanitation of the Harvesting, Processing, and Distribution of Shellfish. Interstate Shellfish Sanitation Conference, U.S. Food and Drug Administration, Washington, DC.

Jeffries, H.P. 1972. A stress syndrome in the hard clam, Mercenaria mercenaria. J. Invert. Pathol. 20:242-251.

Jeffries, H.P., A. Keller, and S. Hale. 1986. Catch compilation: A weekly trawl program Narragansett Bay-Rhode Island Sound 1966-1985. Final Report to U.S. EPA, Region I, Water Management Division. 71 pp.

Jones, D.S., M.A. Arthur and D.J. Allard. 1989. Sclerochronological records of temperature and growth from shells of Mercenaria mercenaria from Narragansett Bay, Rhode Island. Marine Biology 102:225-234.

Kadri, J. 1991. A raw deal: combined sewer overflows in Narragansett Bay. Pp. 43-57. In: M.A. Rice, M. Grady, and M.L. Schwartz (eds.), Proceedings of the First Rhode Island Shellfisheries Conference. Rhode Island Sea Grant, University of Rhode Island, Narragansett.

Keck, R., D. Maurer, and R.E. Malouf. 1974. Factors influencing the setting behavior of larval hard clams, Mercenaria mercenaria. Proc. Nat. Shellfisheries Assn. 64:59-67.

Kennish, M.J. 1980. Shell microgrowth analysis: Mercenaria mercenaria as a type example for research in population dynamics. pp. 255-294. In: D.C. Rhoads and R.A. Lutz (eds.). Skeletal Growth of Aquatic Organisms. Plenum Press, New York.

Kennish, M.J., R.A. Lutz, and D.C. Rhoads. 1980. Preparation of acetate peels and fractured sections for observation of growth patterns within the bivalve shell. Part A, Appendix 1. pp. 597-601. In: D.C. Rhoads and R.A. Lutz (eds.). Skeletal Growth of Aquatic Organisms. Plenum Press, New York.

Kern, F.G. 1986. Narragansett Bay Project: quahog histopathology studies. Final Report to US EPA, Region I, Water Management Division. 25 pp.

Kerswill, C.J. 1941. Some environmental factors limiting growth and distribution of the quahog Venus mercenaria L. Ph.D. Dissertation, Univ. of Toronto, 104pp.

Kilgen, M.B., M.T. Cole, and C.R. Hackney. 1988. Shellfish sanitation studies in Lousiana. J. Shellfish Res. 7:527-530.

Kipp, K. 1991a. Health risk from chemically contaminated seafood. Briefing Paper and Proceedings from the Narragansett Bay Project Management Committee. Narragansett Bay Project Rept. NBP-91-62.

Kipp, K. 1991b. Shellfish safety: Human health implications of toxic contamination in Narragansett Bay, Rhode Island. Pp. 29-41. In: M.A. Rice, M. Grady and M.L. Schwartz (eds.) Proceedings of the First Rhode Island Shellfisheries Conference, Narragansett, RI, August 27, 1990. Rhode Island Sea Grant, Univ. of Rhode Island, Narragansett.

Kovach, K.A.M. 1969. Shellfish survey of Wickford Harbor. RI Div. of Conservation Leaflet No. 24.

Kovach, K.A.M., and M.T. Canario. 1968. Shellfish survey of Quonset Point area. RI Div. of Conservation Leaflet No. 25.

Kranz, P.M. 1974. The anastrophic burial of bivalves and its paleoecological significance. Journal of Geology 82:237-265.

Landers, W.J. 1954. Notes on the predation of the hard clam, *Venus mercenaria*, by the mud crab, *Neopanope texana*. Ecology 35:422.

Latimer, J.S. 1989. A review of the major research done in Rhode Island on polychlorinated biphenyls in water, atmosphere, sediment and biota. Report no. NBP-89-20, Narragansett Bay Project, U.S. Environmental Protection Agency. 151pp.

Leavitt, D.F. et al 1990. Hematopoietic neoplasia in *Mya arenaria*: prevalence and indices of physiological condition. Marine Biology 105:313-321.

Littlefield, C.N. 1991. Growth of seed quahogs (*Mercenaria mercenaria*) in Nursery Trays in Great Salt Pond, Block Island, Rhode Island. pp. 81-84 In: M.A. Rice, M. Grady, and M.L. Schwartz (eds.), Proceedings of the First Rhode Island Shellfisheries Conference. Rhode Island Sea Grant, University of Rhode Island, Narragansett.

Loosanoff, V.L. 1937. Spawning of *Venus mercenaria* L. Ecology 18:506-515.

Loosanoff, V.L. 1959. The size and shape of metamorphosing larvae of *Venus* (*Mercenaria*) *mercenaria* grown at different temperatures. Biol. Bull. 117:308-318.

Loosanoff, V.L. and H.C. Davis. 1950. Conditioning *Venus mercenaria* for spawning in winter and breeding its larvae in the laboratory. Biological Bulletin 98:60-65.

Loosanoff, V.L. and H.C. Davis. 1963. Rearing of bivalve mollusks. Advances in Marine Biology 1:1-136.

Loosanoff, V.L., W.S. Miller and P.B. Smith. 1951. Growth and setting of larvae of *Venus mercenaria* in relation to temperature. Journal of Marine Research 10:59-81.

Lough, R.G. 1975. A reevaluation of the combined effects of temperature and salinity on survival and growth of bivalve larvae using response surface techniques. Fish. Bull. U.S. Fish Wildlife Serv. 73:86-94.

MacKenzie, C.L., Jr. 1977. Predation on hard clam (*Mercenaria mercenaria*) populations. Trans. Am. Fish. Soc. 106:530-537.

MacKenzie. 1979. Management for increasing clam abundance. Mar. Fish. Rev. 41(10):10-22.

Malinowski, S. 1986. Small-scale farming of the hard clam on Long Island, New York. The New York State Urban Development Corp., Aquaculture Innovation Program 1515, Broadway, New York, New York. 60 pp.

Malinowski, S. and R.B. Whitlatch. 1988. A theoretical evaluation of shellfish resource management. Journal of Shellfish Research 7:95-100.

Matyas, B. 1991. Public health concerns regarding shellfish in Rhode Island. Pp. 19-27. In: M.A. Rice, M. Grady, and M.L. Schwartz (eds.), Proceedings of the First Rhode Island Shellfisheries Conference. Rhode Island Sea Grant, University of Rhode Island, Narragansett.

McDonald, K. and K. Grimm. 1984. Growth of *Mercenaria mercenaria* in upper Narragansett Bay. Abstract and data submitted to School for Field Studies course "Hazardous Waste Issue," Narragansett Bay, RI

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

Mead, A.D. 1901. The natural history of the starfish. US Fish Commission Bull. for 1899 19:203-224.

Migliore, J. 1991. Regulatory requirements of shellfish-growing areas. Pp. 59-63 In: M.A. Rice, M. Grady, and M.L. Schwartz (eds.), Proceedings of the First Rhode Island Shellfisheries Conference. Rhode Island Sea Grant, University of Rhode Island, Narragansett.

Mileikovski, S.A. 1973. Speed of active movement of pelagic larvae of marine bottom invertebrates and their ability to regulate their vertical position. Marine Biology 23:11-17.

Mitchell, R. 1974. Aspects of the ecology of the lamellibranch *Mercenaria mercenaria* in British waters. Hydrobiol. Bull. 8:124-138.

Mitchell-Innes, B.A. 1973. Ecology of the phytoplankton of Narragansett Bay and the uptake of silica by natural populations and the diatoms *Skeletonema costatum* and *Detonula confervacea*. Ph.D. Thesis, Univ. of Rhode Island, Kingston, Rhode Island. 112 pp.

Morrison, G. 1971. Dissolved oxygen requirements for embryonic and larval development of the hardshell clam, *Mercenaria mercenaria*. J. Fish. Res. Bd. Canada 28:379-381.

Morton, R.W. 1967. Spatial and temporal observations of suspended sediment: Narragansett Bay and Rhode Island Sound. Tech. Memo 396, Naval Underwaters Weapons Research and Engineering Station, Newport RI. 54pp.

Munns, W.R. Jr., C. Mueller, D.J. Cobb, T.R. Gleason, G.G. Pesch, and R.K. Johnston. 1991. Risk assessment pilot study, Phase I Naval Construction Battalion Center, Davisville, Rhode Island. ERLN Contribution 1124, EPA Environmental Research Laboratory, Narragansett RI. 161 pp + appendices.

Murphy, R.C. 1985. Factors affecting the introduced bivalve, *Mercenaria mercenaria*, in a California lagoon - the importance of bioturbation. Journal of Marine Research 43:673-692.

Myers, A.C. and D.K. Phelps. 1977. Criteria of benthic health: A transect study of Narragansett Bay, Rhode Island. Report to U.S. Environmental Protection Agency Environmental Laboratory, Narragansett, Rhode Island. 75pp.

Nelson, T.C. and H. H. Haskin. 1949. On the spawning behavior of oysters and of Venus mercenaria with special reference to to the effects of spermatic hormones. Anatomical Record 105:484-485.

New England Power Company (NEPC). 1976. Environmental Report. New England Power Company, Units I and II, Charlestown, Rhode Island Appendix B-1, 21pp.

Nixon, D.W. 1981. Multiple use conflicts in Narragansett Bay: Commercial fishing and aquaculture. Oceans '81 Conference Record, IEEE, Piscataway, New Jersey. pp. 635-638.

Nixon, S.W., C.A. Oviatt, and S.L. Northby. 1973. Ecology of small-boat marinas. Marine Technical Report No. 5, Rhode Island Sea Grant, University of Rhode Island, Narragansett. 20pp.

NMFS. 1987. Fisheries of the U.S.-1986 current fisheries statistics 8385, National Marine Fisheries Service, NOAA, U.S. Department of Commerce. 119 pp.

O'Connor, J.S. 1972. The benthic macrofauna of Moriches Bay, New York. Biol. Bull. 142:84-102.

Olsen, S. and G.L. Seavey. 1983. The State of Rhode Island Coastal Resources Management Program as amended. Coastal Resources Center, Univ. of Rhode Island. RI Sea Grant Pub. Office no. P963. 144 pp.

Oprandy, J.J., P.W. Chang, A.D. Provonost, K.R. Cooper, R.S. Brown and V.J. Yates. 1981. Isolation of a viral agent causing hematopoietic neoplasia in the soft-shell clam, Mya arenaria. J. Invert. Pathol. 38:45-51.

Pechenik, J.A. 1990. Delayed metamorphosis by larvae of benthic marine invertebrates: Does it occur? Is there a price to pay? Ophelia 32:63-74.

Pechenik, J.A. 1991. Biology of the Invertebrates (2nd edition). W.C. Brown Publishers, Dubuque, IA. 567 pp.

Peterson, C.H. 1982. Clam predation by whelks (Busycon spp.): Experimental tests of the importance of prey size, prey density, and seagrass cover. Marine Biology 66:159-170.

Peterson. 1983. A concept of quantitative reproductive senility: Application to the hard clam, Mercenaria mercenaria. Oecologia 58:164-168.

Peterson, C.H. 1986. Quantitative allometry of gamete production by Mercenaria mercenaria into old age. Mar. Ecol. Prog. Ser. 29:93-97.

Piedrahita, R. and G. Tchobanoglous. 1987. The use of human wastes and sewage in aquaculture. Pp. 336-352. In: D.J.W. Moriarty and R.S.V. Pullin (eds.), Detritus and microbial ecology in aquaculture, proceedings of the conference on detrital systems for aquaculture, Bellagio, Como, Italy. International Center for Living Aquatic Resources Management, Manila. 420pp.

Pratt, D.M. 1953. Abundance and growth of *Venus mercenaria* and *Callocardia morrhuana* in relation to the character of bottom sediments. J. Mar. Res. 12:60-74.

Pratt, D.M. 1965. The winter-spring diatom flowering in Narragansett Bay. Limnol. Oceanogr. 10:173-184.

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

Pratt, S.D. 1977. Benthic biology of areas adjacent to the Quonset/Davisville base. Appendix 2. The redevelopment of Quonset/Davisville; an environmental assessment. Marine Tech. Rept. 55, Coastal Resources Center, Univ. of Rhode Island, Narragansett.

Pratt, S.D. 1978. Impact of power plant construction on sediment erosion, transport and deposition. Appendix 4. In: An environmental study of a nuclear power plant, phase II. University of Rhode Island Marine Technical Report 64. 54pp.

Pratt, S.D. 1988. Status of the hard clam fishery in Narragansett Bay. Narragansett Bay Project Report NBP-88-13. 94pp.

Pratt, S.D., B.K. Martin, and S.B. Saila. 1987. Status of the hard clam (*Mercenaria mercenaria*) in the Providence River and Mount Hope Bay. Report no. NBP-88-08, Narragansett Bay Project, U.S. Environmental Protection Agency. 38pp.

Pruell, R.J., E.J. Hoffman, and J.C. Quinn. 1984. Total hydrocarbons, polycyclic aromatic hydrocarbons and synthetic organic compounds in the hard shell clam, *Mercenaria mercenaria*, purchased at commercial seafood stores. Mar. Envir. Res. 11:163-181.

Pruell, R.J., C.B. Norwood, R.D. Bowen, R.E. Palmquist, and S.J. Fluck. 1988. Organic contaminants in quahogs, *Mercenaria mercenaria*, collected from Narragansett Bay. Report no. NBP-88-05, Narragansett Bay Project, U.S. Environmental Protection Agency. 50pp.

Quinn, J.G. 1989. A review of the major research studies on petroleum hydrocarbons and polycyclic aromatic hydrocarbons in Narragansett Bay. Report no. NBP-89-19, Narragansett Bay Project, U.S. Environmental Protection Agency. 235pp.

Quinn, J.G., J.S. Latimer, L.A. LeBlanc, and J.T. Ellis. 1989. Assessment of organic contaminants in Narragansett Bay sediments and hard shell clams. Draft report to the Narragansett Bay Project.

Rheinberger, R., G.L. Hoffman, and P.P. Yevich. 1979. The kidney of the quahog (Mercenaria mercenaria) as a pollution indicator. Pp. 119-129. In: Animals as Monitors of Environmental Pollutants. National Academy of Sciences, Washington, DC.

Rhoads, D.C. and G. Panella. 1970. The use of molluscan shell growth patterns in ecology and paleoecology. Lethaia 3:143-161.

RI DNR. 1968. Management plan and shellfish survey of the West Passage and Sakonnet River of Narragansett Bay, RI. RI Div. of Conservation. Un-numbered leaflet. December 1968.

Rice, M.A. and G.C. Stephens. 1988. Influx, net flux and transepithelial flux of amino acids in the hardshell clam, Mercenaria mercenaria (Linne): influence of salinity. Comp. Biochem. Physiol. 89A:631-636.

Rice, M.A., C. Hickox, and I. Zehra. 1989. Effects of intensive fishing effort on the population structure of quahogs, Mercenaria mercenaria, in Narragansett Bay. Journal of Shellfish Research 8:345-354.

Richards, G.P. 1985. Outbreaks of shellfish-associated enteric virus illness in the United States: requisite for development of viral guidelines. J. Food Protection 48:815-823.

Russell, H.J., Jr. 1972. Use of a commercial dredge to estimate hard-shell clam population by stratified random sampling. J. Fish. Res. Bd. Canada 29:1731-1735.

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

Savage, N.B. 1974. Responses of selected bivalve mollusks to temperature and dissolved oxygen. Ph.D. Thesis. Univ. of Rhode Island, Kingston, Rhode Island. 129 pp.

Savage, N.B. 1976. Burrowing activity in Mercenaria mercenaria and Spisula solidissima as a function of temperature and dissolved oxygen. Mar. Behav. Physiol. 3:221-234.

Shuster, C.N. 1969. A three ply representation of the major organ systems of a quahaug. Supplement to Leaflet 14. National Shellfish Sanitation Program, U.S. Food and Drug Administration, Davisville, RI.

Shumway, S.E. 1990. A review of the effects of algal blooms on shellfish and aquaculture. J. World Aquaculture Soc. 21:65-104.

Shumway, S.E. and T.L. Cucci. 1987. The effects of the toxic dinoflagellate Protogonyaulax tamarensis on the feeding and behavior of the bivalve mollusks. Aquatic Toxicol. 10:9-27.

Shumway, S.E., S. Sherman-Caswell, and J.W. Hurst, Jr. 1988. Paralytic shellfish poisoning in Maine: monitoring a monster. J. Shellfish Res. 7:643-652.

Sisson, R.T. 1972. Biological and commercial fisheries related research on the channeled whelk, Busycon canaliculata, in Narragansett Bay, Rhode Island. M.S. Thesis, Univ. of Rhode Island, Kingston, Rhode Island. 68 pp.

Sisson, R.T. 1977. Hard clam resource assessment study in upper Narragansett Bay and the Providence River. RI Div. of Fish and Wildlife Leaflet No. 49.

Smayda, T.J. 1988. Environmental conditions ans plankton dynamics in Narragansett Bay during an annual cycle characterized by a brown tide. Narragansett Bay Project Report NBP-88-13.

Stanley, J.G. and R. DeWitt. 1983. Species profiles: Life histories and environmental requirements of coastal fishes and invertebrates -- hard clam. U.S. Fish Wildl. Serv. Biol. Rept. FWS/OBS-82/11.18 19pp.

Stanley, S.M. 1975. Why clams have the shape they have: an experimental analysis of burrowing. Paleobiology 1:48-58.

Stickney, A.P. and L.D. Stringer. 1957. A study of the invertebrate bottom fauna of Greenwich Bay, RI. Ecology 38:111-122.

Stringer, L.D. 1959. The population abundance and effect of sediment on the hard clam. In: Hurricane Damage Control, Narragansett Bay and Vicinity, Rhode Island, and Massachusetts. A detailed report on fishery resources. US Fish and Wildlife Service. Appendix E. 17 pp.

Taylor, D., C.A. Oviatt, and L. Beatty. 1991. Monitoring plan for Narragansett Bay. Draft Report to the Narragansett Bay Project, University of Rhode Island. 254pp.

Terceiro, M. 1985. Changes in the epibenthic macro-invertebrate and demersal fish assemblages in Narragansett Bay and Rhode Island Sound. Ph.D. Thesis, Univ. of Rhode Island, Kingston, Rhode Island. 122 pp.

Thibault/Bubley Associates. 1989. Trace metals in quahog clams from Narragansett Bay. Final Report to Narragansett Bay Project, U.S. EPA, Region I, Water Management Division. 20 pp.

Tracey, G.A., P.W. Johnson, R.W. Steele, P.E. Hargraves, and J. McN. Sieburth. 1988. A shift in photosynthetic picoplankton composition and its effects on bivalve mollusk nutrition: The 1985 "brown tide" in Narragansett Bay, Rhode Island. J. Shellfish Research 7:671-676.

Turner, E.J. and D.C. Miller. 1991. Behavior and growth of Mercenaria mercenaria during simulated storm events. Marine Biology 111:55-64.

US EPA and RI Div. of Fish and Wildlife. 1974. State of Rhode Island shellfish atlas. 6 figs. + key.

Vaughn, J.M. and E.F. Landry. 1984. Public health considerations associated with molluscan aquaculture systems: human viruses. Aquaculture 39:299-315.

Verber, J.L. 1984. Shellfish borne disease outbreaks. U.S. Public Health Service, Food and Drug Administration, Northeast Tecnichal Services Unit, Davisville, RI.

Walker, R.L. 1989. Exploited and unexploited hard clam *Mercenaria mercenaria* (L.) populations in in Georgia. Contributions in Marine Science 31:61-75.

Walne, P.R. 1970. Studies on food value of nineteen genera of algae to juvenile bivalves of the genera *Ostrea*, *Mercenaria*, and *Mytilus*. Fisheries Investigations of the Ministry of Agriculture Fisheries and Food, (Great Britain), Series II 25:1-62.

Walne, P.R. 1972. The influence of current speed, body size and water temperature on the filtration rate of five species of bivalves. J. Mar. Biol. Assn. U.K. 43:345-374.

Walne, P.R. and G.J. Dean. 1972. Experiments on predation by the shore crab, *Carcinus maenus* L. on *Mytilus* and *Mercenaria*. Journal of Conservation 34:190-199.

Wells, H.W. 1957a. Status of the name *Venus*. Ecology 38:160-161.

Wells, H.W. 1957b. Abundance of the hard clam, *Mercenaria mercenaria* in relation to environmental factors. Ecology 38:123-128.

Whetstone, J.M. and A.G. Eversole. 1978. Predation on hard clams, *Mercenaria mercenaria*, by mud crabs, *Panopeus herbstii*. Proceedings of the National Shellfisheries Association 68:42-48.

Williams, R.J. 1970. Freezing tolerance in *Mytilus edulis*. Comp. Biochem. Physiol. 35:145-161.

Yevich, P.P. 1985. Histopathologic examination of animals collected from Narragansett Bay. internal memorandum 8/2/85. EPA Environmental Research Laboratory, Narragansett, 2pp.