# A Study of Tidal Flushing for Use in a Nitrogen Sensitivity Index in Massachusetts

by

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B.S., Ocean Engineering (1995)
Massachusetts Institute of Technology

Submitted to the Department of Ocean Engineering
in Partial Fulfillment of the Requirements for the Degree of
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ABSTRACT

A study of the tidal flushing capabilities of the Massachusetts coast was done as part of a larger study of the nutrient assimilative capacity of the coastal embayments. The study was conducted in three parts: a review of tidal flushing, the calculation of residence times, and a proposal of how to incorporate that data into a nitrogen sensitivity index.

This work is part of a preliminary study being conducted by the Massachusetts Coastal Zone Management Office in conjunction with the Massachusetts Bays Program in order to assess the nitrogen sensitivity of embayments. The preliminary work is to be used for the purposes of ranking the embayments in order to focus resources and attention to where management of nutrient loading is most necessary.

Thesis Advisor: Henry S. Marcus
Title: Professor of Marine Systems

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## Acknowledgements

I would like to express my gratitude to Jan Smith of the Massachusetts Coastal Zone Management Office and Marie Studer of the Massachusetts Bays Program. Without their guidance and support, this project would never have been accomplished. I would also like to thank Professor Marcus agreeing to be my thesis advisor so late in the game.

*For my father.*

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# Chapter 1: Introduction

Embayments are critical habitats due to the unique conditions found in these intermediate waters between the land and sea, which include availability of nutrients, a range of salinity and water depths and protected, diverse and productive habitats. This broad range of conditions supports spawning and nursery grounds for a variety of sport and commercial fisheries and habitat for other wildlife. In addition to ecological functions, embayments also provide other benefits including recreation, flood control and marine transportation. However, due to their location, embayments are often greatly impacted by anthropogenic activities and receive domestic and industrial wastes that are discharged to upstream rivers and the estuary itself. In addition, nonpoint source pollution such as contaminated groundwater from septic system effluents or stormwater runoff frequently adversely impact estuarine waters and its living resources including shellfish and submerged aquatic vegetation. Coastal zone managers face the daunting task of creating policies to protect these special habitats while still allowing for the extensive human uses to which they are subject.

The pollution that reaches embayments can be divided into two rough categories: point source and nonpoint source pollution. Point source pollution is any type of pollution that can be traced to one, single place of origin. For example, a pipe emitting a toxic substance into the environment can be considered point source pollution. Regulation of point source pollution consists of identifying the particular "pipe" from which the regulated substance is coming and determining ways in which to reduce or eliminate emissions from that source. Obviously, this is much easier said than done. Much of the environmental legislation of the past twenty-five years has dealt with point source pollution.

As its name suggests, nonpoint source (NPS) pollution consists of pollution that cannot be traced to one, single place of origin. For example, runoff from city streets that contains everything from oil residues to rubber worn from tires is considered NPS pollution. Regulation of NPS pollution is much more difficult than point source pollution. This is one reason that much of the legislation is aimed at regulating point source pollution, even though NPS pollution is a significant contributor to the pollution problem (Rosenbaum 1995). NPS pollution will be discussed further in Chapter 2.

The research for this thesis was done in conjunction with the Massachusetts Coastal Zone Management Office and the Massachusetts Bays Program in order to develop a method for ranking embayments according to their risk of damage by nutrient loading, a form of NPS pollution. Nutrient loading can cause several problems within an embayment, including:

- degradation of water quality
- loss of eelgrass beds
- loss of shellfish habitat
- excessive growth of algae
- fish kills

The consequences of nutrient loading are discussed further in Chapter 2. Nitrogen is the nutrient of choice for management purposes, as nitrogen is often the limiting nutrient in aquatic ecosystems.

In order to understand which embayments are most at risk from nutrient loading, four characteristics must be determined:

1. watershed delineation
2. embayment flushing
3. land use
4. nutrient load/critical load

The nutrient load for an embayment is established from the land use characteristics within the defined watershed. The critical load is determined by the assimilative capacity of the embayment. The flushing capabilities of the embayment play a critical role in determining the assimilative capacity. These concepts are discussed further in Chapter 2.

The Massachusetts Coastal Zone Management Office (MCZM) has much of the responsibility for regulating many of the human activities that affect embayment water quality. (A brief history of the Coastal Zone Management program is given in Appendix A). In particular, Section 6217 of the Coastal Zone Act Reauthorization Amendments of 1990 mandates that those states with federally approved coastal zone management programs under the Coastal Zone Management Act of 1972 must develop Coastal Nonpoint Pollution Control Programs (EPA 1993). The study here is concerned only with the tidal flushing rates. The study consists of three major pieces:

1. A review of tidal flushing, including methods of calculation and influencing factors (Chapter 4).
2. The calculation of residence times based on tidal flushing for selected Massachusetts embayments (Chapter 5).
3. The development of a tidal flushing index for priority ranking purposes (Chapter 6).

The problem specifically tackled here is that of the flushing capabilities of the embayment. Water is transported through the embayment system via three major sources:

- river discharge (if a river is present)
- tidal exchange
- density-driven flows

In order to effectively balance competing uses of estuaries it is necessary to understand water transport mechanisms affecting the distribution and fate of contaminants entering the coastal zone and the time scales associated with these processes. These concepts are discussed in detail in Chapter 4.

# Chapter 2: Background

## *Embayments*

### *Definition*

Throughout this study, the term "embayment" is used. Specifically, the term "estuary" has been avoided. This is done to avoid the typical association with river-driven systems, which would not apply to many of the areas under consideration.

"Estuary" has actually been defined in two ways. Pritchard defines "estuary" as: "...a semi-enclosed coastal body of water which has a free connection with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage" (Pritchard 1964). No mentions of rivers is made, and this definition would be generally applicable to the coastal features in study.

However, another definition of "estuary" is given by Ketchum. "An estuary may be defined as a body of water in which the river water mixes with and measurably dilutes sea water" (Ketchum 1951). The most accepted definitions of "estuary" generally deal with those coastal features where river mouths meet tidal seas.

In order to avoid confusion, the use of the term "estuary" is generally avoided. The term "embayment" is preferred. For the purposes of this study, an embayment is considered to somewhat follow Pritchard's definition: a semi-enclosed body of water with open connection to the sea that is impacted by water drained from land. Included in this definition are river mouths, bays, lagoons and coves.

*The Ecosystems*

The embayment occupies a critical ecological zone between the open ocean and the land with its freshwater systems. Both the freshwater and marine systems are considered to be more stable than the ecosystems found in the embayment itself (Kinne 1964). These ecosystems are characterized physiologically as stress habitats and zones of reduced competition. Because of the lack of competition from biota, the factors that determine biological viability are almost entirely physical. These factors include:

- salinity
- the salinity gradient
- water movement
- temperature
- availability and type of nutrients
- turbidity
- availability of sunlight
- dissolved gases
- substrate

Because of the unstable nature of these habitats, even slight perturbations of the characteristics listed above can have large consequences on the organisms in the embayment.

*Human Uses*

Because of their close proximity to land, embayments are used extensively by human society. The National Oceanic and Atmospheric Administration (NOAA) produced the following list of uses for embayments:

- Commercial shipping
- Shoreline development for residences
- Shoreline development for industry
- Shoreline development for recreation
- Recreational boating
- Swimming and Surfing
- Hunting
- Recreational fishing
- Aesthetic enjoyment
- Mining of aggregates
- Electricity generation
- Water extraction
- Military purposes
- Research and education
- Climate control

- Biological harvest
- Preservation
- Waste placement

Embayments can be used for any combination of these purposes. Because of these varied uses, embayments are considered to have greater human value per unit area than any other part of the sea (NOAA 1979).

### *Nitrogen in Embayments*

Nitrogen is an essential nutrient found in embayments. Nitrogen occurs in both elemental and chemically combined forms. The nitrogen is supplied to the embayment in many ways. Some of these are:

- leached from rocks
- solution from the atmosphere
- runoff from agricultural land where nitrogenous fertilizers are used
- municipal sewage
- oceanic input
- biological recycling through ammonium and urea
- release from accumulated sediments

Nitrogen is removed from the system in several ways as well. Plants and animals use nitrogen in their biological processes. Nitrogen is washed out of the embayment with the tides and other currents. Because nitrogen is a nutrient, and, therefore used by the local biota, the cycle of nitrogen through the embayment system is very complex. Figure 1 is a diagram of the cycle (Aston 1980).

Because the cycle depends on so many different factors, the ability of an embayment to deal with the nitrogen is case specific. The amount of nitrogen good for one system might well destroy another.

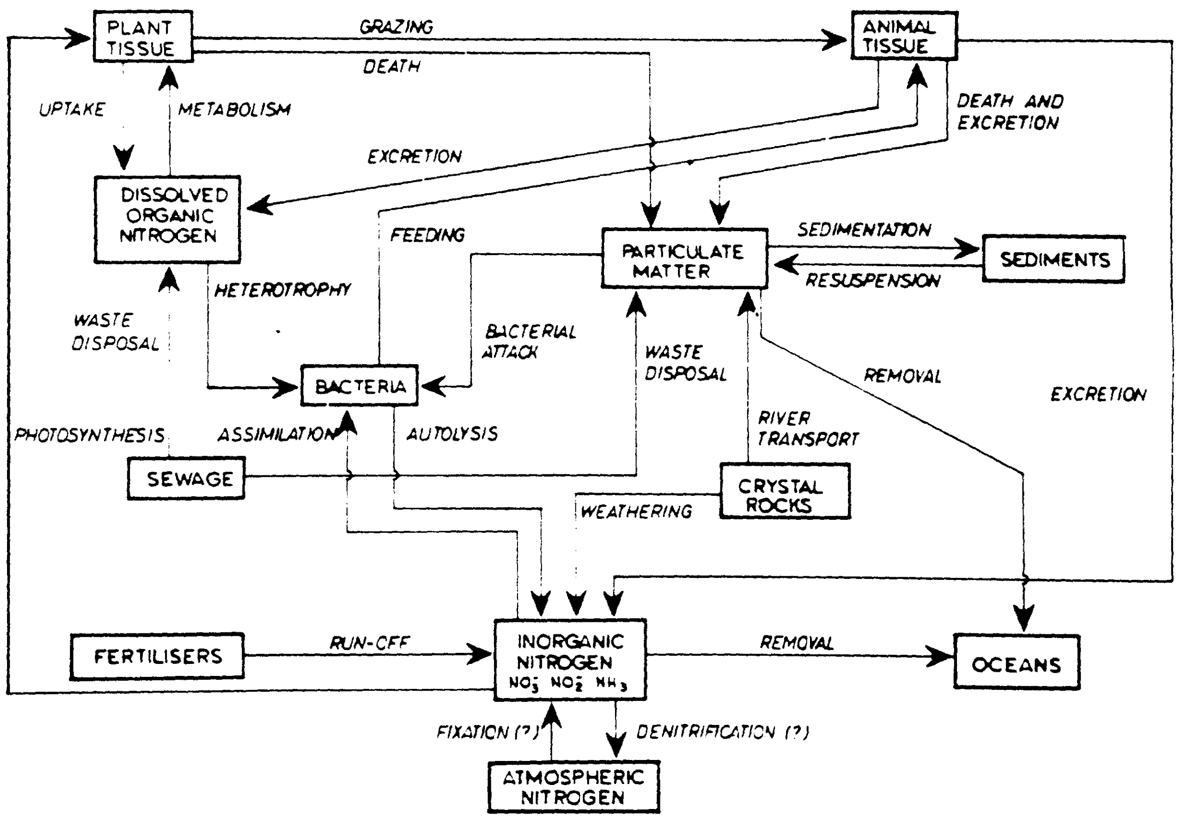


Figure 1: The Nitrogen Cycle in Embayments (Aston 1980)

### *Nonpoint Source Pollution*

As defined in Chapter 1, nonpoint source (NPS) pollution is the type of contamination that is not generated by any one contributor. NPS pollution is thought to contribute 65% of the pollution to surface waters (Rosenbaum 1995). The results of water pollution in coastal waters are beach closures, prohibitions on harvesting shellfish, and the loss of biological productivity. Some of the major sources of NPS pollution to coastal waters are:

- agriculture
- forestry
- urban areas
- marinas and recreational boating
- hydromodification

#### *Agriculture*

The major NPS pollutants from agricultural sources are (EPA 1993):

- nutrients (particularly nitrogen and phosphorous)
- sediment
- animal wastes
- pesticides
- salts

Current farming practices result in the increased erosion of farmland, and these sediments drain into coastal waters. The increased turbidity caused by this soil results in less sunlight penetrating to the embayment ecosystem. Nutrients end up in the water because of the use of chemical fertilizers and the production of animal wastes. These nutrients contribute to the eutrophication of coastal waters. Pesticides used for pest control can retain their toxicity for long periods of time, causing a threat to the organisms in the coastal waters they enter. These contaminants can enter the aquatic environment either by direct runoff or by seepage into ground water that will eventually end up in surface waters.

*Forestry*

Silviculture contributes sediment, nutrients, pesticides to coastal NPS pollution. The pathways to and the effects in the coastal environment are the same as those from agricultural sources.

*Urban Areas*

The pollutants found in urban runoff include:

- sediment
- nutrients
- oxygen-demanding substances
- road salts
- heavy metals

- petroleum hydrocarbons
- pathogenic bacteria
- viruses

Suspended sediments are the most prevalent pollutant found in urban runoff. Construction is the major source of these sediments. These sediments will increase the turbidity of coastal waters, with the result of the loss of sunlight to the system.

*Marinas and Recreational Boating*

Because marina activities occur directly at the water's edge, there is generally no buffering area between the pollution generated there and the ecosystems that will be damaged by the pollution. Discharge from boats, runoff from parking lots, and hull maintenance are the major sources of pollution from marinas.

*Hydromodification*

Hydromodification activities include:

- channelization and channel modification
- dams
- streambank and shoreline erosion

These activities not only cause the destruction of ecosystems by physically altering the habitat, but they can also increase the amount of NPS pollution received by the system. For example, channel modification can result in the hardening of banks that allow more pollution from the watershed to enter coastal waters.

*Managing NPS Pollution*

Several management measures can be taken in order to prevent or minimize the impact of NPS pollution from these sources, depending on the originating activity. For example, agricultural practices that reduce erosion can be encouraged. Marinas can be designed to minimize their impact on the surrounding waters.

## *Assimilative Capacity*

Assimilative capacity has been defined by the United States National Oceanic and Atmospheric Administration (NOAA) as "...the amount of a substance that the [embayment] can receive without damage to desired natural characteristics or uses..." (NOAA 1979). In assessing assimilative capacity, two very important characteristics for the system must be established:

- the rate of input of the substance into the system
- the rate of extraction of the substance from the system

As long as these two rates remain in balance, no nutrients will build up in the ecosystem, and life in the embayment can proceed as normal. However, as soon as the rate of input into the system exceeds the rate of extraction, the substance will begin to accumulate in the embayment, with the potential to alter a sensitive ecosystem.

Assimilative capacity can be thought of as the point at which the two rates come into balance. Below this point, the rate of input can still be increased, and the system will still be able to deal with the substance. After that point, the embayment cannot accept the input of any more of the substance without accumulation and the detrimental effects associated with the accumulation of the substance.

### *Damage Caused by Nutrient Loading*

Wastes dumped into a system such as an embayment can virtually wreak havoc on the ecology of the system. NOAA compiled a list of all the possible damages that can be done to an embayment when waste inputs are allowed to exceed the amount extraction. A partial list that deals with nitrogen in particular is given below:

- Reduction of solar energy received (due to suspended solids)
- Overstimulation of growth of undesired species
- Reduction of the availability of nutrients to desired species
- Creation of intolerable or unfavorable physical environments for some organisms
- Killing or reducing the reproductive success of individual organisms

- Elimination of species locally by making an essential element or compound unavailable
- Reduction of the stability of the ecosystem
- Decrease in species diversity
- Destruction of commercially valuable fish, shellfish or algae
- Replacement of desired species by less useful forms
- Reduction of predator populations, permitting destructive runaway production of prey species
- Introduction of human pathogens and parasites
- Introduction of pathogens of desired aquatic organisms
- Production of aesthetically unattractive conditions

Of particular importance is the threat of eutrophication. Eutrophication starts when a surplus of nutrients begins to accumulate in the water. This causes certain types of undesirable algae to thrive. This algae consumes not only the nutrients, but also reduces the amount of oxygen available to the other forms of life in the water. These algal blooms cause the other forms of life die off because of the lack of nutrients and oxygen. Eventually, even the algal blooms are unable to sustain themselves, and the entire ecosystem becomes a dead area. While eutrophication is a natural process for aquatic systems, the loading of the system with nutrients such as nitrogen and phosphorous enhances the rapidity at which the system goes through this cycle, resulting in the premature death of a valuable area.

# Chapter 3: The Coastal Zone of Massachusetts

The marine environment is one of Massachusetts' most valuable natural and economic resources. The natural ecosystems include:

- salt marsh complexes
- shallow coastal embayments
- estuaries
- salt ponds
- tidal flats

These ecosystems support many types of wildlife. Wildlife depend on these ecosystems for food, as spawning and nursing grounds, and nesting areas.

Economically, Massachusetts has depended on the marine environment since the founding of the colony. Some of the economic aspects of the coastal zone include:

- commercial fishing
- shipping
- recreation
- energy use

All of these uses will be discussed further later in this chapter. These human uses are all dependent upon a clean, productive environment. This means that one of the other major uses of the coastal zone, waste disposal, poses a potentially devastating threat not only to the natural ecosystems of Massachusetts, but also the economic stability of the state.

### *Definition of the Coastal Zone*

The Massachusetts Coastal Zone is defined by the Massachusetts Coastal Zone Management Office as the land and water contained in the area defined by the seaward limit of the state's territorial sea (three miles), from the Massachusetts-New Hampshire border to the Massachusetts-Rhode Island Border, and inland to the manmade boundary that most closely matched natural systems delineation (MCZM 1978). The coastal zone also includes:

- all of Cape Cod
- all of Martha's Vineyard
- all of Nantucket
- all islands
- transitional and intertidal areas
- coastal wetlands
- beaches
- tidal rivers and adjacent uplands to the extent of vegetation affected by saltwater
- anadromous fish runs to the freshwater breeding grounds

The manmade boundaries used to define the coastal zone include:

- major roads
- rail lines
- other visible rights-of-way

The natural systems used to define the coastal zone include:

- coastal watersheds
- coastal floodplains
- the fifty-foot topographic elevation
- coastal ecosystems
- coastal "viewsheds"

The delineation of the coastal zone as set by the natural systems is generally within one-half mile of coastal water or salt marshes, except in the case of watersheds, which can extend quite far inland.

All land owned or controlled by the federal government is excluded from the coastal zone by law.

## *Uses of the Coastal Zone*

### *Wildlife Habitat*

As stated above, the coastal zone of Massachusetts is a valuable environmental resource for wildlife. Salt marshes, estuaries, salt ponds and shallow coastal embayments provide many of the nutrients necessary for marine life. These areas are considered areas of high "primary productivity", where the conversion of solar energy to chemical energy takes place, and they also provide valuable spawning and nursery areas for finfish, shellfish and crustaceans. Migratory birds use the salt marshes, tidal flats and waters of Massachusetts for breeding and nesting. Some of the critical systems are shown in Figure 2.

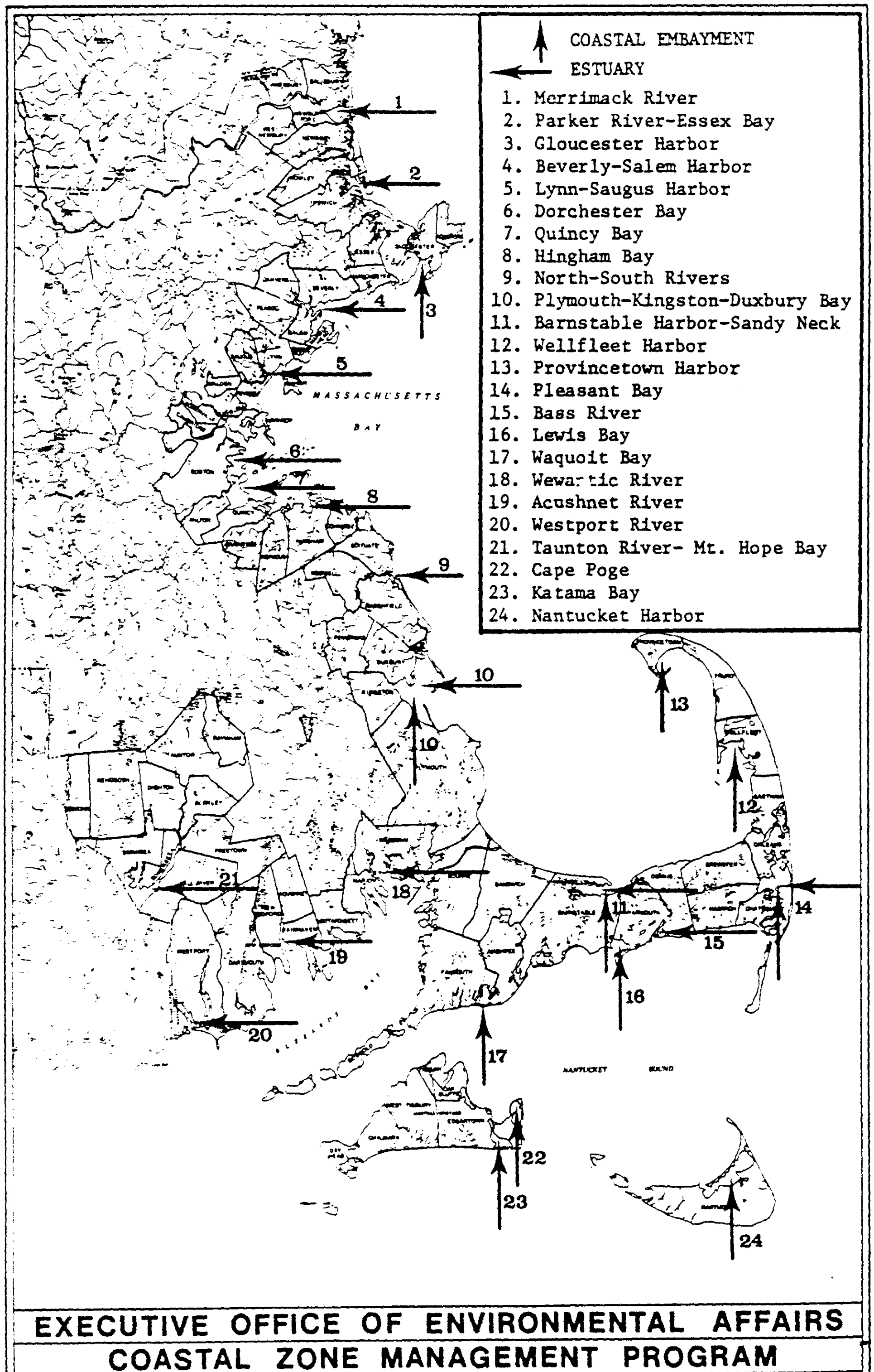


Figure 2: Some Important Ecosystems (MCZM 1978)

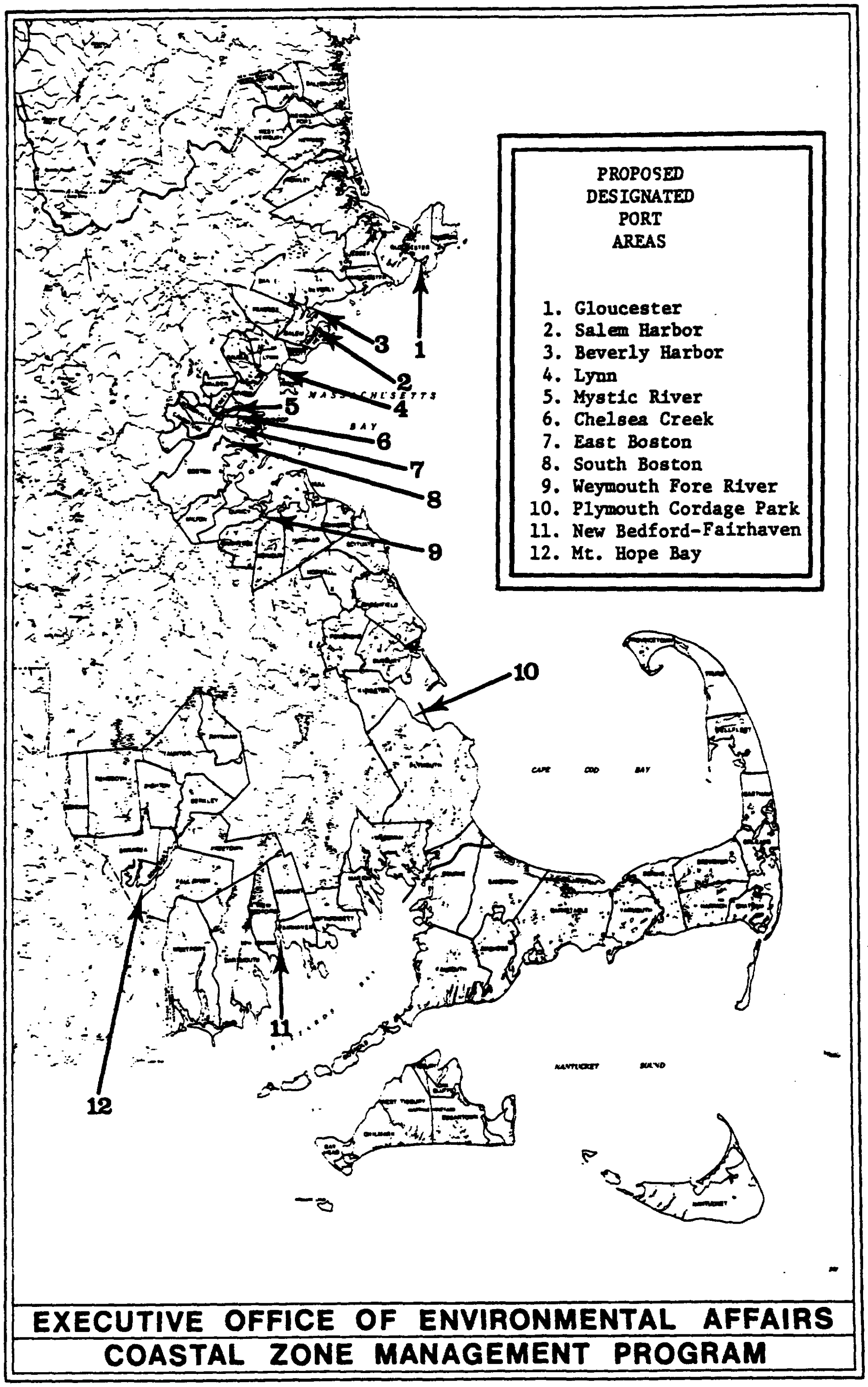


Figure 3: Ports (MCZM 1978)

The damage of ecosystems due to nitrogen loading will have a tremendous impact on the health and survival of the species that use the Massachusetts coast. The protection of the coastal zone is critical for the continued use of these areas by wildlife.

*Commercial Fishing*

Commercial fishing in Massachusetts has traditionally been of great economic importance to the state. In addition to actually fishing for finfish in the waters of Massachusetts, processing of the fish also provides many jobs in the Commonwealth. Shellfish are also harvested in the many embayments and estuaries along the coastline.

The New England fishing industry has been greatly impacted by deleterious environmental effects. Shellfish beds have been closed due to contamination by both toxic substances and human waste. Overfishing has caused the closing of fishing grounds. Successful management of the coastal zone can revitalize the fishing industry in Massachusetts.

*Ports and Harbors*

The protected bays and river mouths of the Massachusetts coastline have traditionally been used to provide stable waterfront for piers, wharves and warehouses. The ports and harbors are generally used for the following activities:

- container shipping

- ferry services
- boating
- commercial fishing

The maintenance of harbors and ports requires activities such as dredging. Dredging not only disturbs the local wildlife, but the dredged materials must be dumped somewhere. Management of the coastal zone must take these issues into account. The major ports in Massachusetts are shown in Figure 3.

*Recreation*

Recreational activities draw more people to the Massachusetts coastline than any other use. The tourist industry in Massachusetts associated with the recreational use of coastal waters and beaches exceeds one billion dollars annually, and the demand for these activities continues to grow (MCZM 1978). Some of the recreational uses of the coast are:

- boating
- fishing
- swimming
- beach outings
- camping

In addition to direct uses of the ocean and beaches, the recreational uses of the coast are considered gateway enterprises, because other businesses depend on the coast to draw visitors to the region. These visitors support restaurants, hotels and other tourist facilities.

The recreational use of the coast is threatened by coastal pollution. Beaches sometimes have to be closed because of bacteria levels in the water. Tourists looking for a pleasant vacation at the seaside will not come to an area that has a reputation for being contaminated. The overstimulation of algae growth also produces an unpleasant odor that will not attract visitors to a beach. Ironically, marinas themselves are a major contributor to nonpoint source pollution.

*Energy Use*

Nearly 80% of the Commonwealth's energy facilities are located in the coastal zone. These facilities are located there for three reasons:

- accessibility of water for cooling purposes
- proximity to fuel supply
- accessibility to market areas

Massachusetts, like most places in the U.S., is heavily dependent on imported oil. The majority of this oil is brought in through marine ports. The cooling towers for nuclear generation plants use water from the ocean for cooling.

Figure 4 shows the location of some of the energy facilities in the coastal zone.

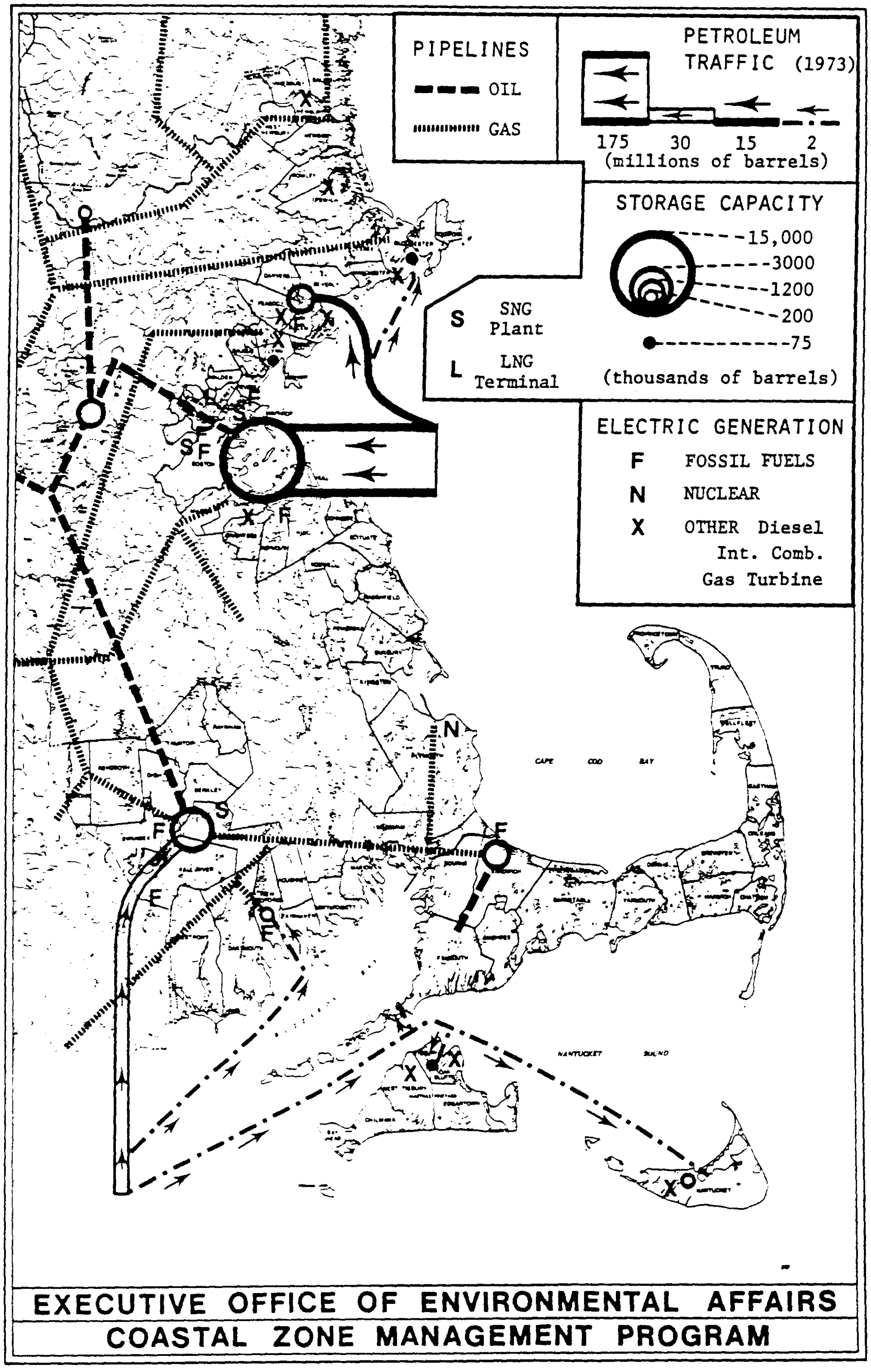


Figure 4: Energy Facilities (MCZM 1978)

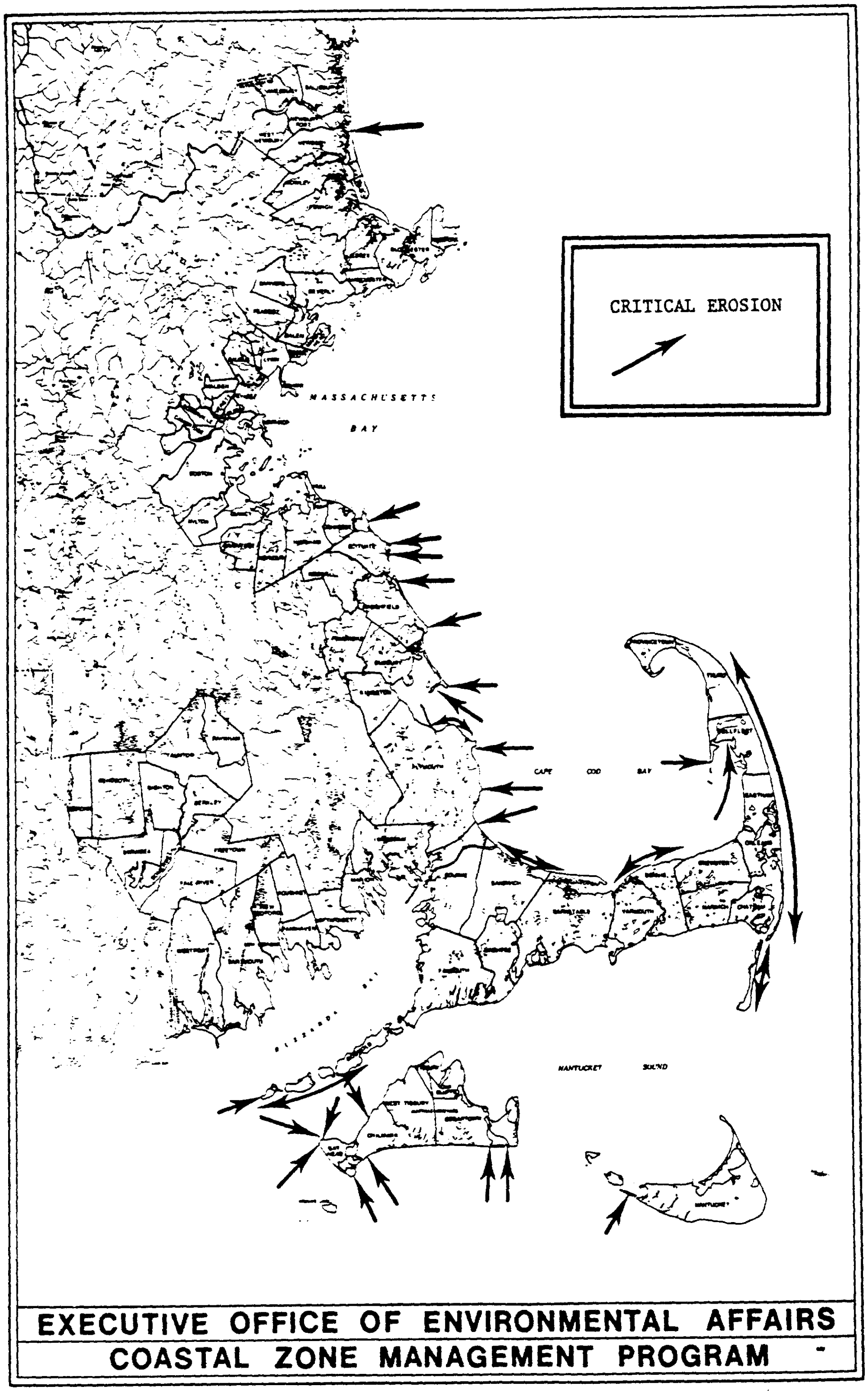


Figure 5: Critical Erosion Areas (MCZM 1978)

Residual heat from the cooling process causes some damage to marine ecosystems, but the citizens of Massachusetts still need the power generated by these plants. Nonpoint source pollution should not significantly impact this coastal use.

*Other*

The Massachusetts coastline is used for other purposes. Many sites along the coast are of historical or aesthetic significance. Maintaining the integrity of the coastline for the appreciation of these areas is important.

Massachusetts also uses its coastline extensively for research and educational purposes. In addition to Woods Hole Oceanographic Institute, Waquoit Bay is one of the National Estuarine Research Reserves. Several local universities use the coastlines for research.

Finally, certain landforms in the coastal zone provide a buffer zone from coastal hazards. Barrier beaches, dunes, beaches and salt marshes provide protection from storms, flooding and erosion. For example, beaches and marshes dissipate the energy of destructive storm waves. Also, manmade structures do not perform the function as well as the natural ones. Groins constructed to prevent beach erosion can actually cause the beach on their downdrift side to erode faster. Figure 5 shows areas where the prevention of erosion is critical.

## *Areas Included in the Study*

The Massachusetts Coastal Zone Management Office identified the following embayments for inclusions in the study. These embayments were only chosen by virtue of their relative size on the 1:80,000 scale NOAA nautical chart of the Massachusetts coastline. 122 embayments were identified.

Cape Ann:

1. Merrimack River
2. Newburyport Harbor
3. Parker River
4. Rowley River
5. Eagle Hill River
6. Ipswich River
7. Plum Island Sound
8. Essex Bay
9. Ipswich Bay
10. Annisquam River
11. Sandy Bay
12. Gloucester Harbor

Massachusetts Bay

1. Magnolia Harbor
2. Manchester Harbor
3. Bass River
4. Danvers River
5. Beverly River
6. Salem Harbor
7. Marblehead Harbor
8. Nahant Bay
9. Lynn Harbor
10. Saugus River
11. Pines River
12. Broad Sound
13. Cohassett Harbor
14. Scituate Harbor
15. North River
16. South River

Boston Harbor:

1. Boston Harbor

2. Charles River

3. Dorchester Bay

4. Neponset River

5. Quincy Bay

6. Weymouth Fore River

7. Weymouth Back River

8. Hingham Harbor

9. Weir River

10. Hingham Bay

11. Hull Bay

Cape Cod Bay

1. Green Harbor River

2. Duxbury Bay

3. Kingston Bay

4. Plymouth Harbor

5. Plymouth Bay

6. Ellisville Harbor

7. Sandwich Harbor

8. Scorton Harbor

9. Barnstable Harbor

10. Sesuit Harbor

11. Rock Harbor

12. Herring River

13. Wellfleet Harbor

14. Pamet River

15. Provincetown Harbor

Nantucket and Vineyard Sound

1. Nauset Bay

2. Pleasant Bay

3. Chatham Harbor

4. Stage Harbor

5. Sasquatucket Harbor

6. Allens Harbor

7. Herring River

8. Swan Pond River

9. Bass River

10. Parker River

11. Lewis Bay

12. Centerville Harbor

13. West Bay

14. Cotuit Bay

15. Pomponessett Bay

16. Waquoit Bay

17. Eel Pond

18. Bournes Pond

19. Green Pond

20. Great Pond

21. Falmouth Inner Harbor

22. Woods Hole Great Harbor

23. Nantucket Harbor

24. Polpis Harbor

25. Madaket Harbor

26. Katama Bay

27. Cape Poge

28. Egartown Harbor

29. Sengekontucket Pond

30. Oak Bluffs Harbor

31. Lagoon Pond

32. Vineyard Haven Harbor

33. Lake Tashmoo

34. Menemsha Pond

Buzzards Bay

1. Quissett Harbor

2. West Falmouth Harbor

3. Wild Harbor

4. Megansett Harbor

5. Squeteaque Harbor

6. Red Brook Harbor

7. Hen Cove

8. Pocassett Harbor

9. Pocassett River

10. Phinneys Harbor

11. Buttermilk Bay

12. Onset Bay

13. The Widows Cove

14. Little Harbor

15. Wareham River

16. Marks Cove

17. Weweantic River

18. Wings Cove

19. Sippican Harbor

20. Aucoot Cove

21. Mattapoisett Harbor

22. Brant Island Cove

23. Nasketucket Bay

24. New Bedford Harbor

25. Acushnet River

26. Clarks Cove

27. Apponagansett Bay

28. Slocums River

29. Allens Pond

30. Westport River East Branch

31. Westport River West Branch

Mount Hope Bay:

1. Cole River

2. Lee River

3. Taunton River

In the end, several embayments were excluded from the above list. For some, the data required for even the simplest calculation were not available. Also, the Cape Cod Commission is conducting its own study of the assimilative capacity of its coastal waters. In order not to repeat work, Cape Cod was, in general, not included in the final list.

# Chapter 4: Tidal Flushing Review

The first step in defining estuarine or embayment water transport mechanisms is the characterization of how long a parcel of water remains in an estuary. Time scales of water movement can be described either by residence times or flushing rates. Residence times are the average length of time that a parcel of water or a contaminant remains in an embayment. Tidal flushing rates are a measure of the amount of contaminant that leaves an embayment in a given period of time. Flushing rates provide the basis for determining the time scale of contaminant removal from a defined area. The residence time helps to determine the potential for impacts on estuarine resources. Furthermore, flushing rate information is critical for all aspects of coastal and harbor development planning. The natural characteristics of an embayment, including the rate at which water is exchanged with the open ocean, will determine, in part, the activities (e.g. aquaculture operations) that can be supported in the harbor while maintaining environmental quality. Once flushing rates are determined, estuaries or embayments can be ranked in terms of potential or relative risk of eutrophication or contamination for management purposes. In addition, flushing studies are critical for evaluating siting plans for wastewater treatment facilities or other discharges. To fully characterize an estuary in terms of risk, additional data are needed, such as loading estimates of contaminants and habitat and natural resource information. Much of this information can be obtained from existing sources, but what is lacking are flushing studies for many Massachusetts estuaries in order to characterize contaminant transport and fate within the systems.

### *Importance of Tidal Flushing*

Embayment flushing rates are needed to make informed decisions for many aspects of marine environmental management, including coastal facilities siting and waste disposal options, protection of ecological integrity extending from wetland areas to marine waters, as well as to develop adequate study designs for marine monitoring programs. For example, flushing rate estimates assist state environmental agencies in the identification of nitrogen sensitive embayments where the threat of eutrophication is high and assist with the development of water quality standards for nutrients and other constituents (ie, heavy metals and organic contaminants) in marine waters.

Tidal flushing is a dominant factor defining the characteristics of embayment ecosystems. Fresh water enters the embayment from the land side. Mixing of freshwater entering an embayment from the land-side with higher salinity waters from offshore defines the salinity gradient present in an embayment, which determines the character of the embayment's ecosystem. A well-mixed, well-flushed embayment is going to support different types of life than a highly stratified, more stagnant embayment.

As a cleansing process, tidal flushing works in two different ways. When salt water that has lower contaminant concentrations enters an embayment and mixes with fresher water elevated in contaminants, the pollution in an embayment is diluted, thereby decreasing the potential stress on the ecosystem. When the tide goes out, the flushing of the mixed water out of the embayment lowers the total level of contaminants in the embayment. This constant flushing of the embayments protects habitats from impacts due to contaminant build-up. However, if the influx of contaminants is greater than the flushing rate of water in the embayment, concentrations of contaminants can increase and cause detrimental impacts.

Aside from determining the biological characteristics of the embayment, the rate of tidal flushing is instrumental in determining the capability of the embayment to provide a stable habitat for the existing community. Much in the same way that alkalinity buffers a lake from excessive shifts in pH, tidal flushing buffers an embayment from rapid changes in chemical content. Tidal flushing prevents the rapid build up of nutrients and contaminants in an embayment, protecting the ecosystem from rapid changes in the content of the run off from land. Of course, the ability of tidal flushing to protect the embayment in this manner has its limitations. If the amount of pollution coming from land exceeds the capability of the tidal flushing rate to dilute the contaminant, the contaminants will accumulate in the embayment. This may lead to environmental degradation, such as eutrophication resulting in low dissolved oxygen concentrations. Thus, tidal flushing is one of the factors that determines the capacity of the embayment to tolerate pollution.

### Influences on Tidal Flushing

Several factors influence the amount of tidal flushing each embayment will experience, including the strength of the tides in a region and physical characteristics. A strong tide is more capable of mixing the ocean water with the water in the embayment and will more thoroughly flush an embayment. More complete mixing allows a greater amount of the pollution in the embayment to be flushed with each tidal cycle. The mixing due to a strong tide will also occur further in the embayment. This means that the pollution will not have to drift as close to the mouth of the embayment before it can be flushed to the open ocean. This reduces the amount of time that the contamination stays in the embayment.

In Massachusetts, tides are semidiurnal, with two high tides and two low tides each day (roughly a 12.4 hour cycle). Tidal range is a key factor influencing tidal flushing rate. For Massachusetts, tidal ranges north of Cape Cod average about 3 meters (9 feet), while for areas south of the Cape, including Buzzards Bay and Nantucket Sound, the range averages about 1.5 meters (4.6 feet).

Physical parameters of the embayment will also determine the amount of tidal flushing. The size of the mouth of the embayment, the bathymetry, distance from the mouth to the shoreline, and the bottom topography primarily influence the ability of the incoming ocean water to mix with the embayment water. Greater mixing leads to more rapid flushing. Other factors that can affect tidal flushing are freshwater inflow, winds, tidal range, Coriolis effect, and longshore currents at the mouth of the embayment (Fischer 1979).

### Measuring Tidal Flushing

Tidal flushing can be interpreted in two ways: as a residence time or as a tidal flushing rate. The residence time is defined as the average length of time that a parcel of water or a particle will stay in an embayment, and are usually given in hours or days. The tidal flushing rate is the volume of water that is washed out of an embayment in a given length of time, usually the length of one tidal period.

Residence times and tidal flushing rates are simply different ways of interpreting the same thing. The question being asked about an embayment will determine whether the answer should be expressed as a residence time or a tidal flushing rate. For instance, if a toxicant is being discharged into an embayment, a biologist might want to know how the toxicant will affect the indigenous life. In this case, the length of exposure is important, therefore the convenient number to consider is the residence time. On the other hand, if a substance is added to an embayment at a steady rate, the important characteristic to know is the rate at which the substance is being flushed out of the embayment, allowing for comparison of the incoming and outgoing rates. Both residence times and tidal flushing rates can be used to determine the level of accumulation of a substance in an embayment. However, residence times provide somewhat limited knowledge in that the time is averaged over an entire embayment. Thus, the effects of any subembayments will not be shown, and a separate calculation will have to be performed in order to determine the residence time of a subembayment.

Many different methods are used to determine both residence times and tidal flushing rates. These methods range in complexity from simple analytical methods to sophisticated numerical models. In general, the more complex the method used to determine the residence time or flushing rate, the more accurate the answer. Because the methods vary in complexity, accuracy and expense, it is important to know the intended use of the flushing rates and the availability and accuracy of the data needed for the calculation

*.Box Model*

This method is based on the tidal prism (P), which is the difference in embayment volume between mean high water (MHW) and mean low water (MLW). The tidal prism, or the exchange volume, is the amount of water exchanged or replaced during each tidal period, diluting the water in the embayment with water from offshore. The box model assumes complete mixing of the flood tide waters with the water in the embayment and that all water leaving the embayment during a tidal ebb tide does not reenter with the flood. Any freshwater inflow can be added to the tidal prism. The average length of time that a parcel of water or a particle will stay in the embayment is given by:

$$t = (P+V)T/P \qquad (1)$$

where t is the residence time in hours, P is the tidal prism, T is the tidal period, and V is the low tide embayment volume.

This residence time is averaged along the entire length of the embayment. This makes the box method a poor estimate for elongated embayments, where the mouth is relatively far from shore, because the water at the mouth of the embayment mixes much better than the water near shore. The actual accuracy will depend on particular embayments. Also, the water near the mouth is exchanged with ocean water more rapidly than the water near shore. This makes the box model the lower bound estimate of the residence time, as the worst case is not considered.

Nonetheless, this type of method is particularly useful when comparing large numbers of embayments. The calculations can be made from existing information and the calculations can be done quickly. The accuracy of this method is the lowest of the methods described here.

*Dronkers and Zimmerman*

This method is an enhancement of the box model. The same assumptions are used, except this method only assumes complete vertical mixing rather than complete total mixing of ocean and embayment water. The assumption of incomplete horizontal mixing is a correction of the box model. Therefore, this method will give a range of residence times, depending upon the location of the particle in the embayment. A particle near the mouth will have a lower residence time than one near the shore, which provides a more physically accurate picture of the flushing of an embayment. The residence time is calculated using the following equation:

$$t(x) = (L^2 - x^2)/2D \qquad (2)$$

where t is the residence time in hours, L is the length of the embayment, x is the horizontal position in the embayment (x=0 at the head of the embayment), and D is the longitudinal dispersion coefficient.

Although this method is more accurate, the determination of the dispersion coefficient makes the method more complicated. The dispersion coefficient is given by

$$D = 0.1\, u^2\, T[(1/T')f(T')] \qquad (3)$$

where u is the mean tidal velocity, T is the tidal period, and T' is the dimensionless time scale for cross-sectional mixing (Dronkers 1982). Determining the longitudinal dispersion coefficient requires special experimentation, but this has already been done for many embayments. A more detailed discussion of this method can be found in Dronkers and Zimmerman's original paper (Dronkers 1982). This method has been used in the calculation of residence times for Buzzards Bay (Aubrey 1991).

The methods generally used for calculating tidal flushing rates are: the use of a tracer, the tidal prism method, and the modified tidal prism method. The tracer method requires specialized knowledge of an embayment, such as the salinity profile and the freshwater inflow. The tidal prism method is analogous to the box model, described above, for the type of information necessary and the accuracy of the calculation. As the name suggests, the modified tidal prism method is an enhancement of the tidal prism method, providing flushing information for discrete segments of an embayment, similar to the Dronkers and Zimmerman (1982) methodology.

*Tracer (Dyer 1973)*

Common tracers used to calculate flushing rates include freshwater entering an embayment as well as dyes (e.g. rhodamine) that can be added to an embayment. The use of a tracer works best when the embayment is well-mixed. The easiest tracer to use is freshwater, assuming that the volume of freshwater entering an embayment is known and is entering as a point source, such as a river. Salinity profiles of an embayment provide the necessary information for the calculation of the tidal flushing rate. Calculating the local freshness ($f_x$)as

$$f_x = (S_o - S_x)/S_o \qquad (4)$$

where $S_o$ is the ocean salinity, and $S_x$ is the local salinity. The rate at which the freshwater is flushed from the embayment is given by

$$Q = Q_f / f_x \qquad (5)$$

where Q is the rate at which freshwater is flushed from the estuary, and $Q_f$ is the rate at which freshwater is added to the embayment.

This method is particularly useful for the purposes of determining the transport and fate of point sources of pollution in an estuary. This method traces the actual dispersal of freshwater or a dye. This method provides a medium level of accuracy (more accurate than a one dimensional model, but less than a 3 dimensional).

*Tidal Prism Method (Dyer 1973)*

The tidal prism method is a simple method for calculating the tidal flushing rate. The information necessary to use this method (tidal range and period, physical dimensions of the embayment) is generally available. This method assumes that oceanic water mixes uniformly with water in the embayment, and the salinity distribution in the embayment is at steady state. Also, the assumption is made that none of the water leaving the embayment during ebb tide returns with the next flood tide. Following these assumptions, the tidal flushing rate is given by

$$Q = P/T \tag{6}$$

where P is the tidal prism and T is the tidal period. This simple method provides an upper bound estimate of the tidal flushing rate, as less water is actually flushed from the embayment than is predicted using this method.

Because this is the upper bound estimate for tidal flushing rates, this method is better for comparison of flushing rates, or as a first-order approximation for the embayment.

*Modified Tidal Prism Method (Ketchum 1951)*

As stated earlier, this method for quantifying tidal flushing is an enhancement of the tidal prism method. The modified tidal prism method, however, does not assume that the entire tidal prism is flushed from the embayment during ebb tide. This method also does not assume complete mixing. This method does assume that the freshwater flux is at steady state.

To use the modified tidal prism method, the embayment must be partitioned into segments. The length of the segments is defined by the average excursion of a particle on the flood tide. This exchange ratio for a segment is the proportion of water introduced from land (e.g. rivers) that escapes during ebb tide. The exchange ratio for segment n is given by

$$r_n = P_n/(P_n + V_n) \qquad (7)$$

where $P_n$ is the tidal prism for the segment and $V_n$ is the low water volume of the segment. Following the steady state assumption, the amount of water that moves seaward through the segment is given by R, the amount of water from land being added to the system. Thus, the amount of water from land that is being flushed from each section in one tidal cycle is given by

$$Q = r_n R. \qquad (8)$$

This implies a net accumulation of land water in the segment, as

$$Q = (1-r_n)R \qquad (9)$$

remains. After many tidal cycles, the amount of land water that has accumulated in any segment is given by

$$Q_n = R/ r_n \qquad (10)$$

This shows the steady state nature of the modified tidal prism method, as the amount of water that is moving seaward is equal to the amount of water from land introduced to the embayment during one tidal cycle. The amount of fresh water that is flushed from the embayment in one tidal cycle is equal to the amount introduced during the tidal cycle. Thus the tidal flushing rate for a specific tidal cycle is given by

$$Q = R/T \qquad (11)$$

where T is the tidal period and R is the volume of fresh water introduced during that tidal cycle. Since the volume of fresh water that is flushed is the volume contained in the final segment, the water is a mixture of fresh water introduced to the embayment at different times.

The number of segments defines a residence time of sorts, as the fresh water moves seaward by one segment during each tidal cycle. Therefore, the number of segments equals the number of tidal cycles necessary for water to be flushed from the head of the embayment out to sea. This method provides very good results for river-driven systems.

*Numerical Methods*

Numerical methods rely on computer simulations of the flow in an embayment. These simulations begin by having extremely accurate bathymetric data for the area in question. This volume is then divided into smaller segments for use by the computer program. In general, the greater the number of segments the embayment is divided into for the simulation, the better the accuracy of the result. Once the embayment is segmented, the flow in each segment is calculated. Finally, the solutions for all of the segments are aggregated into a final solution for the entire embayment.

One of the benefits of numerical methods are that three dimensional solutions can be obtained. This provides greater accuracy in the result. The major drawback associated with numerical methods is that they are very data intensive. If the data does not exist, then the method cannot be done without going to great expense to gather the information.

None of the methods described here provides a perfect solution. However, for the purposes of ranking the embayments, the simpler methods with their undemanding data requirements provide resolution sufficient for the task without utilizing limited resources for data gathering. The more data intense methods should be reserved for those embayments most at risk from nitrogen loading. Table 1 provides a summary of the calculation methods.

| Table 1: Summary of Flushing Calculation Methods | | |
|---|---|---|
| | | |
| Method | Data Requirements | Accuracy |
| Box Method | Nautical Charts | Low |
| Dronkers and | Nautical Charts and | Moderate |
| Zimmerman | Dispersion Testing | |
| Tracer | Nautical Charts and | Moderate |
| | Tracer Input Information | |
| Tidal Prism | Nautical Charts | Low |
| Modified Tidal Prism | Nautical Charts and | Moderate |
| | Segmentation Information | |
| Numerical Model | Intense Bathymetry and | High |
| | Surface Area Data | |

# Chapter 5: Calculating Flushing Rates in Massachusetts

Coastal water nitrogen loading is an area of concern for those interested in managing the use of coastal waters. Several factors influence the nitrogen loading of embayments, including the amount of nitrogen entering the embayment and the ability of the embayment to flush the nitrogen to the open ocean. The evaluation of all the factors allows the manager to rate the embayment's risk of eutrophication from nitrogen loading. With this in mind, the Massachusetts Bays Program has initiated a study of the nitrogen loading of embayments in Massachusetts. This study will look into the many factors which govern nitrogen loading, a primary factor influencing the risk of eutrophication. As a part of this study, the calculation of tidal flushing rates for as many estuaries and embayments as current data allows has been done. The goal of the project is to document existing flushing information and methodologies used to calculate the values. In addition, flushing rate determinations were done for as many embayments as possible.

The first step in the calculation of flushing rates was the choosing of a method for calculation. Of the methods discussed above, the original choice was the Modified Tidal Prism Method (Ketchum 1951). However, as this method lends itself mainly to the calculation of river-driven systems, which are the exception in Massachusetts, the simpler Box Model was chosen instead for uniformity. In addition, this method was chosen for the preliminary work because of the goal of having a calculated residence time for as many embayments as possible. The data requirements of the Box Model were a major consideration. Also, box models provide "...reasonable, first order approximations" (Officer 1979).

The necessary physical parameters of an embayment are the mean high water (MHW) and mean low water (MLW) volumes of the embayment and the tidal period. For very few of the embayments in question are the MHW and MLW volumes calculated. National Oceanic and Atmospheric Administration (NOAA) charts of the Massachusetts coastline provided the necessary depth and width measurements for many of the embayments in question. Also, whenever available, the tidal exchange was used in the calculation. The tidal exchange divided by the tidal period gives an analogous result of the same level of accuracy as the Box Model. The tidal exchange information was found mainly in the Division of Marine Fisheries Monograph Series 1-17. Whenever possible, existing calculations of residence times were used. In particular, a flushing study of Buzzards Bay by Aubrey Consulting, Inc. proved very useful (Aubrey 1991).

### *Description and Example of Calculations*

Mean High Water (MHW) and Mean Low Water (MLW) volumes were calculated as follows. A NOAA chart of 1:40,000 scale or less of an embayment was obtained. The NOAA chart is sectioned off into one-quarter inch boxes, starting at the head of the embayment. The mouth of the embayment is defined as a straight line from the tip of one arm of the embayment to the tip of the other.

The quarter inch boxes are further subdivided by the depth readings. The cross-sectional area of these smaller boxes is calculated for MHW and MLW conditions. The volume of the boxes is calculated by multiplying the scaled one-quarter inch width by the cross-sectional area. The summation of all of the smaller boxes yields the total MHW and MLW volumes of the embayments. The resolution of this method is very low.

Once the MHW and MLW volumes have been calculated, the calculation of the residence time is relatively simple, and follows the description of the Box Model above. Using Sandy Bay in Rockport on the North Shore as an example:

MHW = 9.3x10^7 m^3

MLW = 8.1x10^7 m^3

Tidal Prism = MHW-MLW = 1.1x10^7 m^3

Tidal Period = 12.5 hours

Residence Time = (Prism + MLW) * Tidal Period / Prism = 99.9 hours

Residence times for Massachusetts embayments are compiled in Table 2. Data were either collected from existing reports or were calculated for the remaining embayments.

The residence times reveal some important trends. The residence time depends on several different physical characteristics of the embayments. In general, the wider the mouth of the embayment to the open ocean, the shorter the residence time. However, as is the case with Sandy Bay, an embayment that is wide open with a large residence time, the ratio of the tidal range to the overall depth of the embayment also is also important in determining the flushing characteristic. Sandy Bay is very deep, and the tidal influence is thus, relatively small. The residence times provided are an average for the entire embayment. The effects of subembayments are not included.

As discussed in Chapter 4, the Box Model is one of the lowest resolution methods. The residence time produced is an average time, so the time will be shorter at the mouth and longer at the head. Also, the method assumes complete mixing of incoming tidal water with the embayment water and that no water leaving the embayment returns. These assumptions reduce the accuracy of the method. The low accuracy is further compounded by the method in which the MHW and MLW volumes were calculated. These residence times will be good for comparing the different embayments, but other uses might require a higher degree of accuracy than is given by these values.

| Table 2: Massachusetts Embayment Flushing Information | | |
|---|---|---|
| | | |
| Embayment | Tidal Exchange (%) | Residence Time (hrs) |
| Acushnet River* | .16 | 51 |
| Allens Pond | .53 | 18 |
| Annisquam River** | .31 | 40 |
| Apponagansett Bay* | .24 | 32 |
| Aucoot Cove* | .22 | 34 |
| Bass River** | .8 | 15 |
| Beverly Harbor** | .29 | 43.5 |
| Boston Harbor+ | | 31 |
| Brant Island Cove* | .87 | 21 |
| Broad Sound | .23 | 53 |
| Buttermilk Bay* | .31 | 26 |
| Cape Poge** | .55 | 22 |
| Charles River | | 22 |
| Clarks Cove | .14 | 53 |
| Cohassett Harbor | .57 | 22 |
| Danvers River | .7 | 18 |
| Dorchester Bay** | .47 | 23 |
| Duxbury Bay** | .66 | 19 |
| Edgartown Harbor** | .6 | 20 |
| Eel Pond** | .3 | 42.5 |
| Essex Bay** | .74 | 17 |
| Gloucester Harbor** | .31 | 38 |
| Hens Cove* | .42 | 21 |
| Hingham Bay** | .5 | 25 |
| Ipswich Bay | .23 | 54 |
| Ipswich River++ | | 8 |
| Katama Bay** | .46 | 26 |
| Kingston Bay** | .66 | 19 |
| Lynn Harbor** | .42 | 30 |
| Madaket Harbor** | .71 | 17 |
| Magnolia Harbor | .49 | 25.5 |
| Manchester Harbor** | .8 | 15 |
| Marblehead Harbor | .33 | 38 |
| Marks Cove* | .42 | 21 |
| Mattapoisett Harbor* | .14 | 53 |
| Merrimack River** | .56 | 22 |
| Nahant Bay | .14 | 48 |
| Nantucket Harbor | .27 | 45 |
| Nasketucket Bay* | .26 | 30 |
| Neponset River | .5 | 25 |
| Onset Bay* | .29 | 28 |
| Parker River** | .72 | 17 |

| | | |
|---|---|---|
| Phinneys Harbor* | .23 | 33 |
| Pines River** | .41 | 30 |
| Pleasant Bay** | .32 | 32 |
| Plum Island Sound++ | | 46 |
| Plymouth Bay** | .66 | 19 |
| Plymouth Harbor+++ | | 12 |
| Pocasset River* | .31 | 26 |
| Pomponessett Bay* | | 20 |
| Quincy Bay+ | | 33 |
| Quissett Harbor* | .28 | 29 |
| Red Brook Harbor* | .26 | 30 |
| Rowley River++ | | 88 |
| Salem Harbor** | .29 | 43 |
| Sandy Bay | .12 | 100 |
| Saugus River** | .42 | 30 |
| Scituate Harbor | .56 | 22 |
| Sippican Harbor* | .19 | 38 |
| Slocums River* | .43 | 21 |
| Squeteaque Harbor* | .43 | 21 |
| The Widows Cove* | .39 | 22 |
| Vineyard Haven Harbor** | .6 | 20 |
| Waquoit Bay** | .29 | 43 |
| Wareham River* | .39 | 22 |
| Wellfleet Harbor** | .63 | 20 |
| West Falmouth Harbor* | .5 | 19 |
| Westport River East Branch* | .24 | 32 |
| Westport River West Branch* | .34 | 24 |
| Weweantic River* | .17 | ~42 |
| Wild Harbor* | .34 | 25 |
| Wings Cove* | .3 | 27 |
| | | |
| *From Aubrey, 1991 note: Aubrey uses Half-Tide Water instead of MHW | | |
| **From DMF Series | | |
| +From Adams,1995 | | - |
| ++From Plum Island Sound Minibays Project | | |
| +++From CDM minutes, 1995 | | |

# Chapter 6: Tidal Flushing in a Nitrogen Sensitivity Index

## *Nitrogen Sensitivity Index*

When determining the nitrogen sensitivity of an embayment, several factors need to be taken into account. These factors include:

- the size of the watershed that drains into the embayment
- the land use characteristics of the watershed
- biota (nitrogen input from ammonium and urea as well as biological extraction)
- current water quality
- flushing capabilities

All of these factors must be combined in order to reflect the abilities of the embayment to deal with the nitrogen levels that it faces. Characterizing flushing is an important part of this process.

## *Flushing in the Index*

Once the raw data has been accumulated, the tidal flushing needs to be characterized in a quantitative manner. Nominally, "rapid" flushing is "good", while "slow" flushing is "bad". This type of characterization does not, however, provide managers with any helpful tools for regulating the coastal zone. "Rapid" requires definition, as does "slow". The following methodology provides the means of defining these terms for the purposes of developing a ranking scheme for embayments.

*Choice of Parameter*

The characterization of flushing that best fits this problem is tidal exchange. The embayments of Massachusetts are very diverse. Attempting to compare them can prove problematical if the physical characteristics of the embayment (volume, tidal period, etc.) are left in the quantity used for comparison. Tidal exchange provides a nondimensional quantity that characterizes only the flushing capabilities of the system. The residence time itself incorporates the tidal period, which could vary from place to place. The tidal prism reflects the actual size of the embayment. Tidal exchange is the best quantity for comparison of these diverse systems. The tidal exchanges for the embayments are included in Table 2 (Chapter 5).

The study that the Cape Cod Commission has done on nitrogen sensitivity does not use tidal exchange as the characterization of flushing. Rather, they used the "Area of Embayment vs. Ocean Inlet Width", under the assumption that if the surface area of the embayment is large and the opening to the ocean is restrictive, the residence time of particles in the embayment is likely to be long, making the embayment more susceptible to damage from nitrogen inputs (CCC 1995). However, this assumption will not hold if the embayment is extremely deep relative to the tidal range. Referring back to the example in Chapter 5, Sandy Bay in Rockport has a very wide opening to the ocean. This would lead to the assumption that the bay is well-flushed. Yet the residence time for the bay is nearly 100 hours; well above the average residence time in Massachusetts. This is because Sandy Bay is very deep.

Tidal exchange provides a better characterization of the flushing capabilities of the embayments. Inherent in the calculation of tidal exchange is the ability of ocean water to intrude into, and, therefore, cleanse the embayment system.

*Weighting for Incorporation into the Index*

In order to define what is meant by rapid flushing for the state of Massachusetts, an average characterization of the rate of flushing needs to be found (the weighting of the values should be based on fractions of the average tidal exchange). This index is aimed at identifying those embayments in Massachusetts that are most at risk of deleterious effects from nutrient loading. The actual assimilative capacity of an embayment is yet to be determined, and this index is supposed to show where best to concentrate the study of assimilative capacity. Until further study of the assimilative capacity of the embayments is initiated, any quantity used as the baseline for comparison will not be rigorous with respect to assimilative capacity. Because of this, comparison to the average rate in Massachusetts will at least show which embayments are better at flushing than the others. How that fits into the assimilative capacity would have to be determined with further study. These weighted values would then be incorporated into a nitrogen sensitivity index.

# Chapter 7: Conclusion

Ranking the embayments of Massachusetts according to nitrogen sensitivity characteristics provides useful knowledge for the coastal zone manager. In addition to knowing where to focus resources for further study of nitrogen sensitivity in those embayments most at risk, coastal managers can more effectively make choices for the types of managerial solutions needed to control the problem.

Throughout this project, progress was hampered by the lack of available data. This study would have been benefited by greater accuracy in volume calculations, but the relevant bathymetric data simply does not exist. The method used to calculate volumes here was simply not applicable for many of the smaller embayments because of the low resolution coupled with a relative lack of data. Better data is needed for the smaller embayments if this method is to be extended to them. For many of the larger embayments, the information needed to calculate the residence time was difficult, if not impossible, to obtain during the scope of this project. Even when information such as the tidal exchange was available, the volumes were not. The basic physical information, such as volume calculations and tidal information, needs to be gathered into one database. Such a database would greatly facilitate projects such as these. Appendix C summarizes the information gathered in the course of this project, but the many gaps in the table show the necessity for a more complete database.

Once the basic information is in hand, the choice of method could be changed. A more accurate method, as described above, would obviously give better numbers. With more time, and access to better information, the residence times of the embayments in Massachusetts can be determined with greater accuracy.

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# Appendix A: A Brief History of the Coastal Zone Management Program

In Massachusetts, the task of regulating embayment usage falls to the Coastal Zone Management Office (MCZM). Created under the federal Coastal Zone Management Act of 1972 (P.L. 92-583), the objectives of MCZM were originally (Godschalk 1992);

- to identify the boundaries of the coastal zone
- to define permissible land and water use within that zone
- to designate areas of concern
- to propose means for exerting state control over land and water uses in the zone
- to set guidelines on the priority of uses
- to propose an organizational structure to implement the management choices

The Coastal Zone Management Act required that participating states submit plans regarding the achievement of the goals listed above. By 1979, the Massachusetts Coastal Zone Management Office had federal approval.

From the beginning, the importance of estuarine environments was recognized. The Coastal Zone Management Act contained provisions for the creation of the National Estuarine Sanctuary Program. The purpose of this program was to preserve certain estuarine environments at pristine conditions in order to maintain a representative sample of these ecosystems. Under this program, the secretary of commerce was given the ability to acquire, develop and operate these sanctuaries as natural field laboratories. By 1995, 21 National

Estuarine Research Reserve sites had been created, including the Waquoit Bay National Estuarine Research Reserve (WBNERR) in southern Massachusetts.

Under the Coastal Zone Management Improvement Act of 1980 (P.L.96-464), the loosely defined goals listed above were solidified into a program that reflected federal policy in the following nine areas (Godschalk 1992):

- natural resource protection
- hazards management
- major facility siting
- public access for recreation
- redevelopment of urban waterfronts and ports
- simplification of decision procedures
- coordination of affected federal agencies
- public participation
- living marine resource conservation

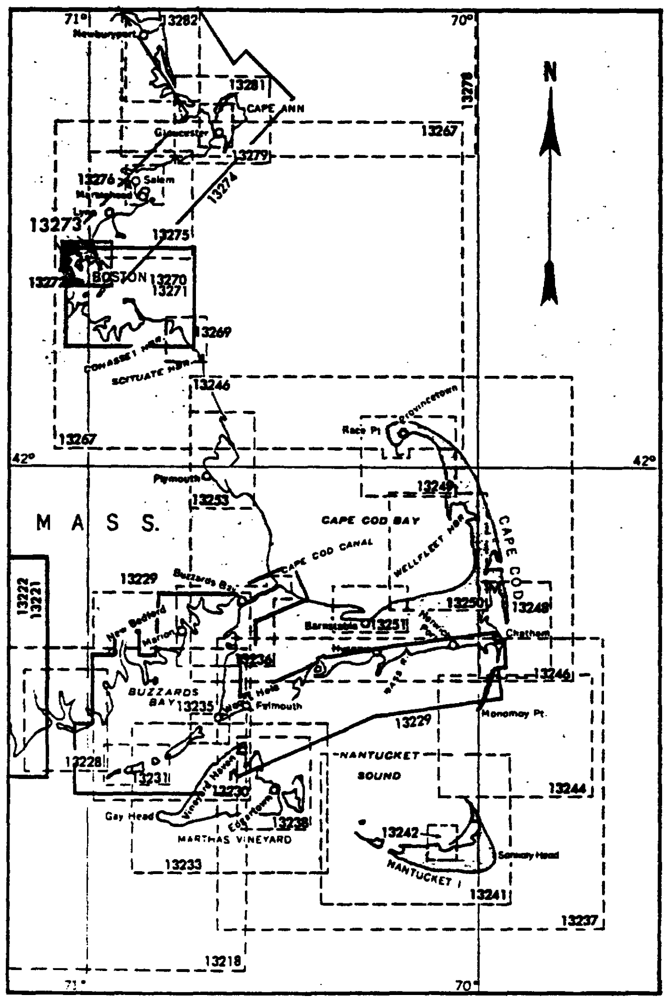
As part of the 1990 reauthorization of the Coastal Zone Management Act, the policy goals of the federal government were again amended. The issues given priority were (Godschalk 1992):

- coastal environmental protection
- coastal pollution
- wetlands management and protection
- natural hazards management
- public access
- cumulative and secondary impacts
- coastal energy development
- federal consistency with state CZM programs

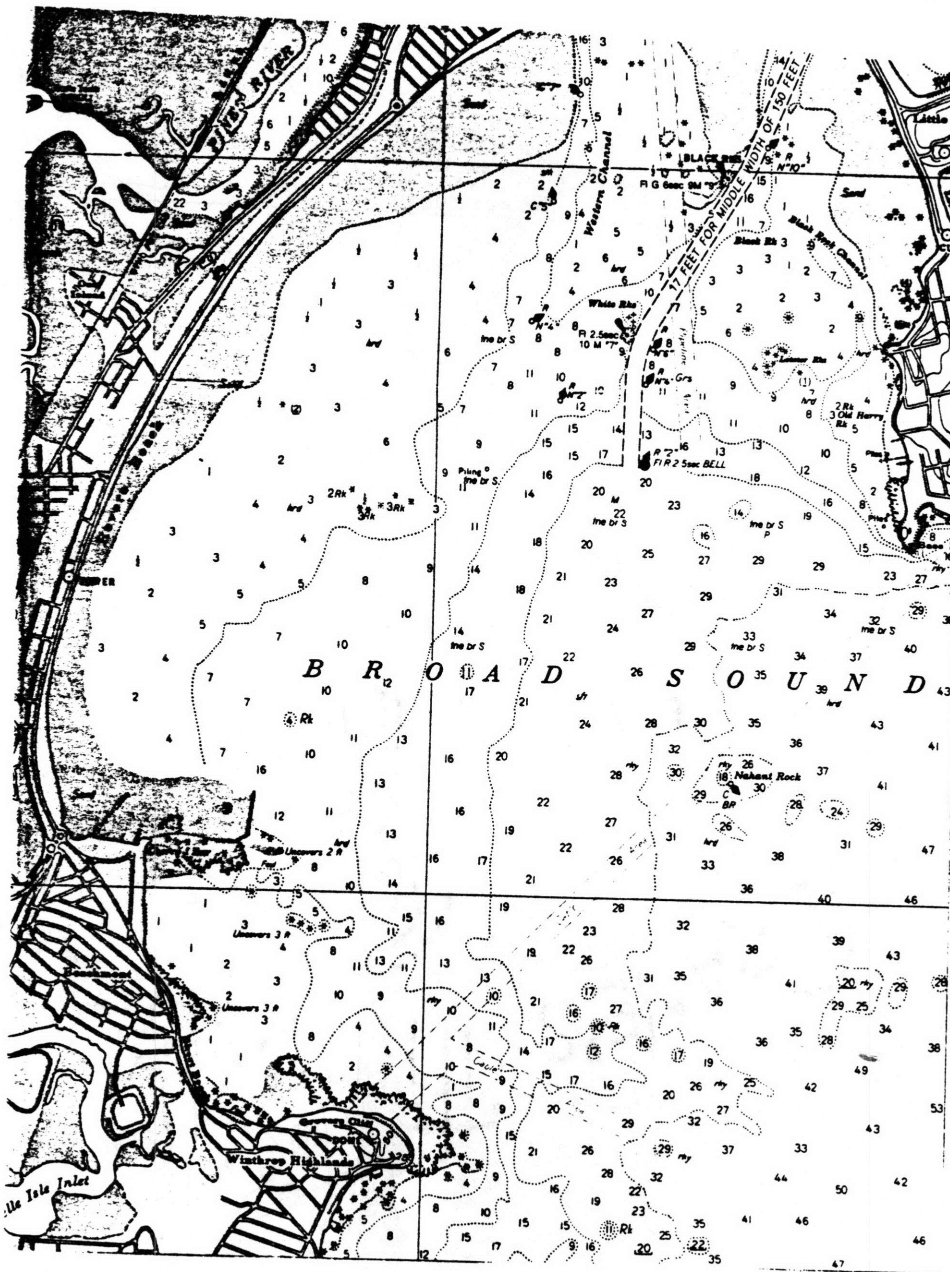
In accordance with these goals, the Act established the Coastal Nonpoint Pollution Control Program. Each state CZM is required to submit to the U.S. Environmental Protection Agency (EPA) for approval a plan for dealing with nonpoint source pollution. This study was done as part of the Massachusetts Coastal Zone Management Office's plan for dealing with nonpoint source nutrient loading of coastal embayments.

# Appendix B: Selected Maps Used in Calculation of Residence Times

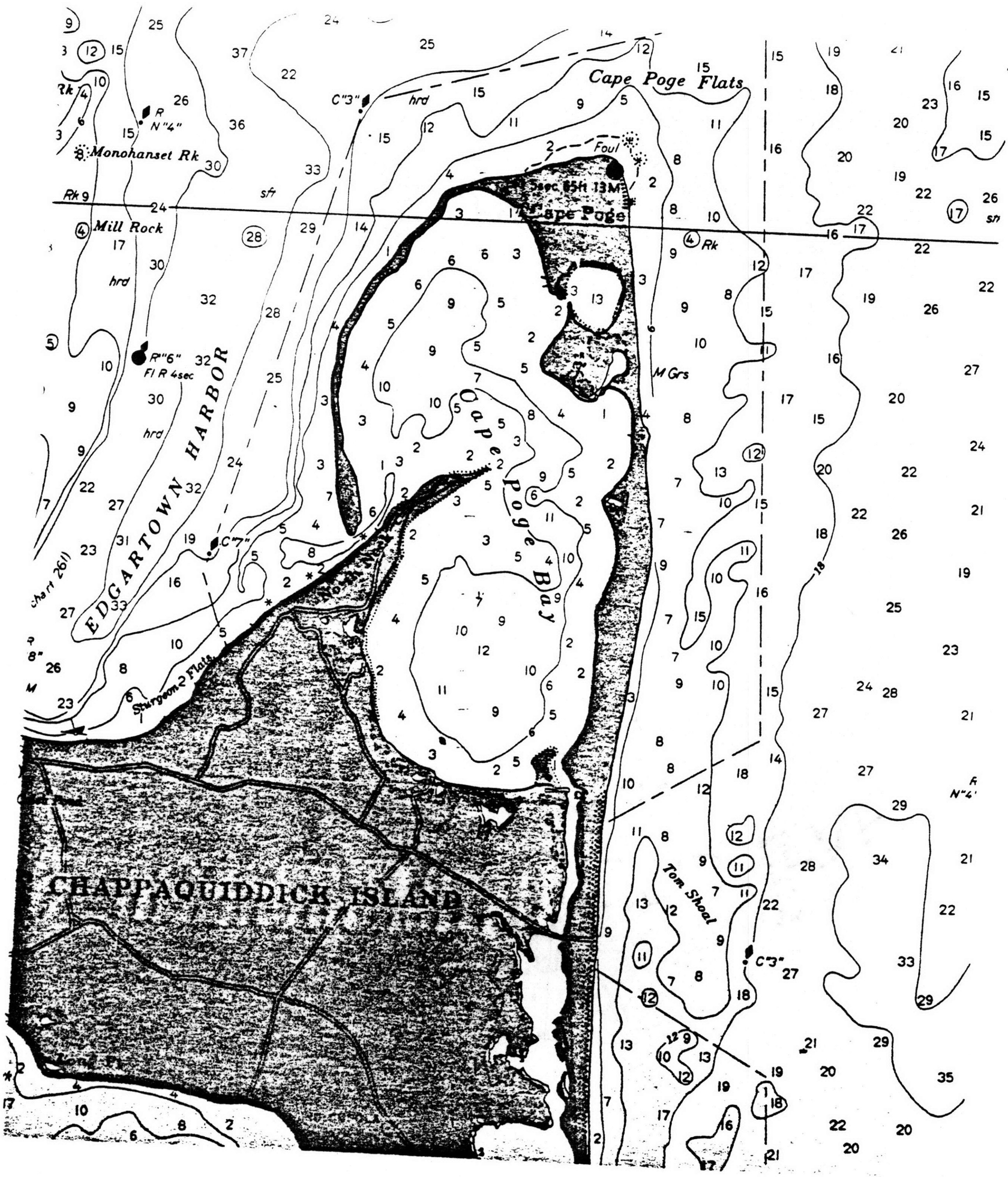
The maps used in the calculations for this study were all National Oceanic and Atmospheric Administration nautical charts. Below is a map of the coastline with the NOAA chart numbers for Massachusetts.



Broad Sound. NOAA Chart 13275, scale: 1:25,000

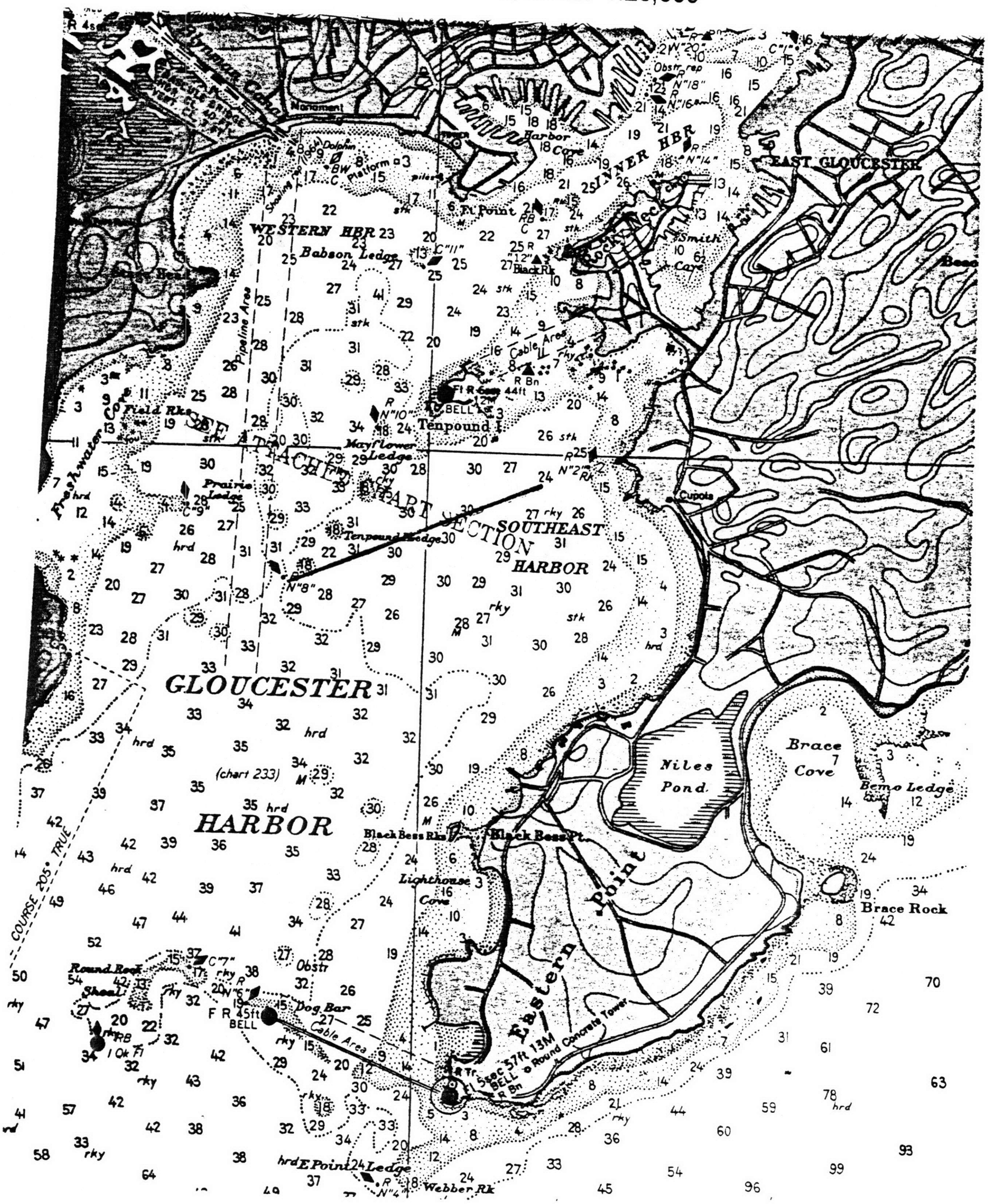


Cape Poge Bay. NOAA Chart 13233, scale: 1:40,000

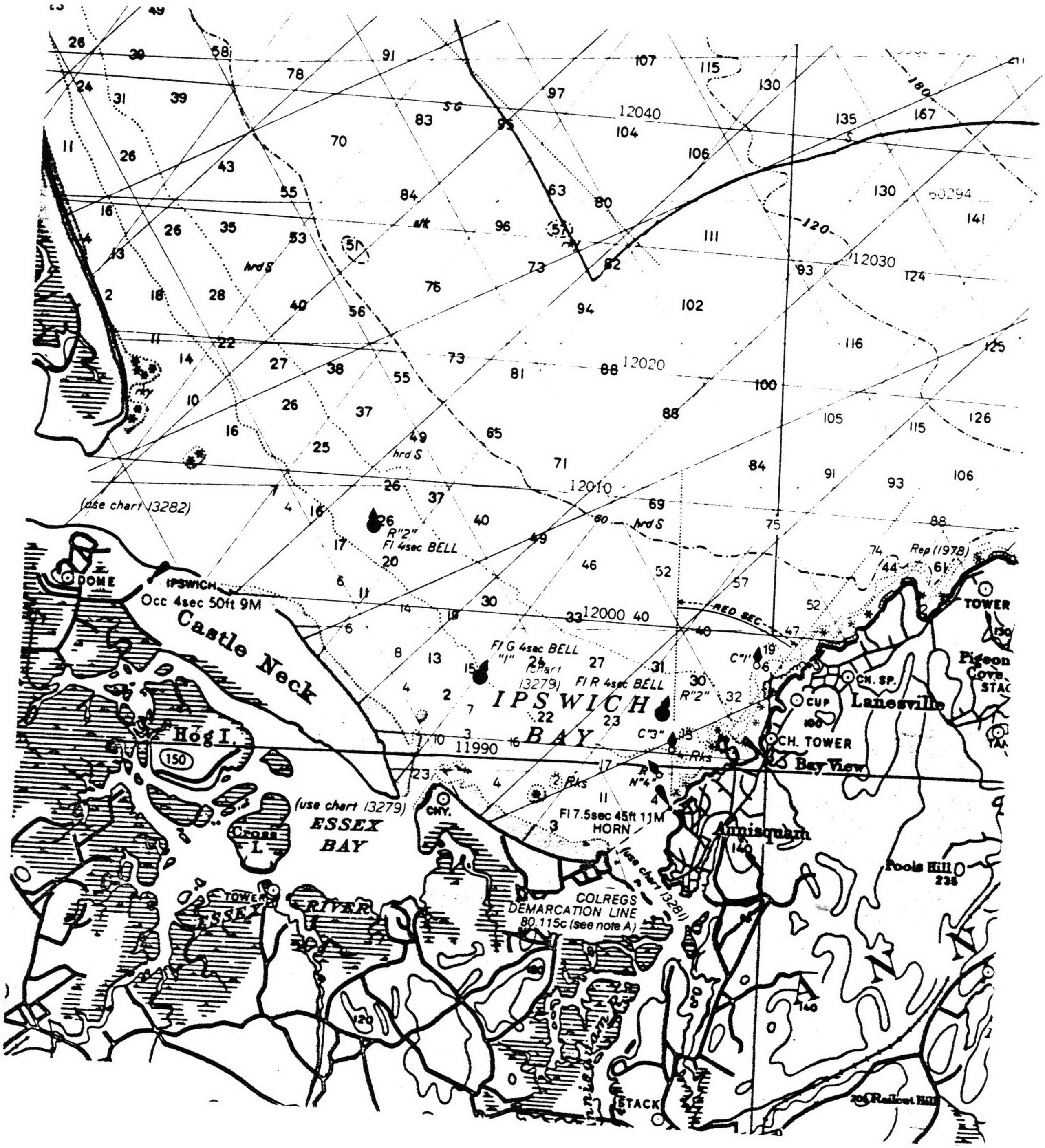


Cohasset Harbor. NOAA Chart 13269, scale: 1:10,000

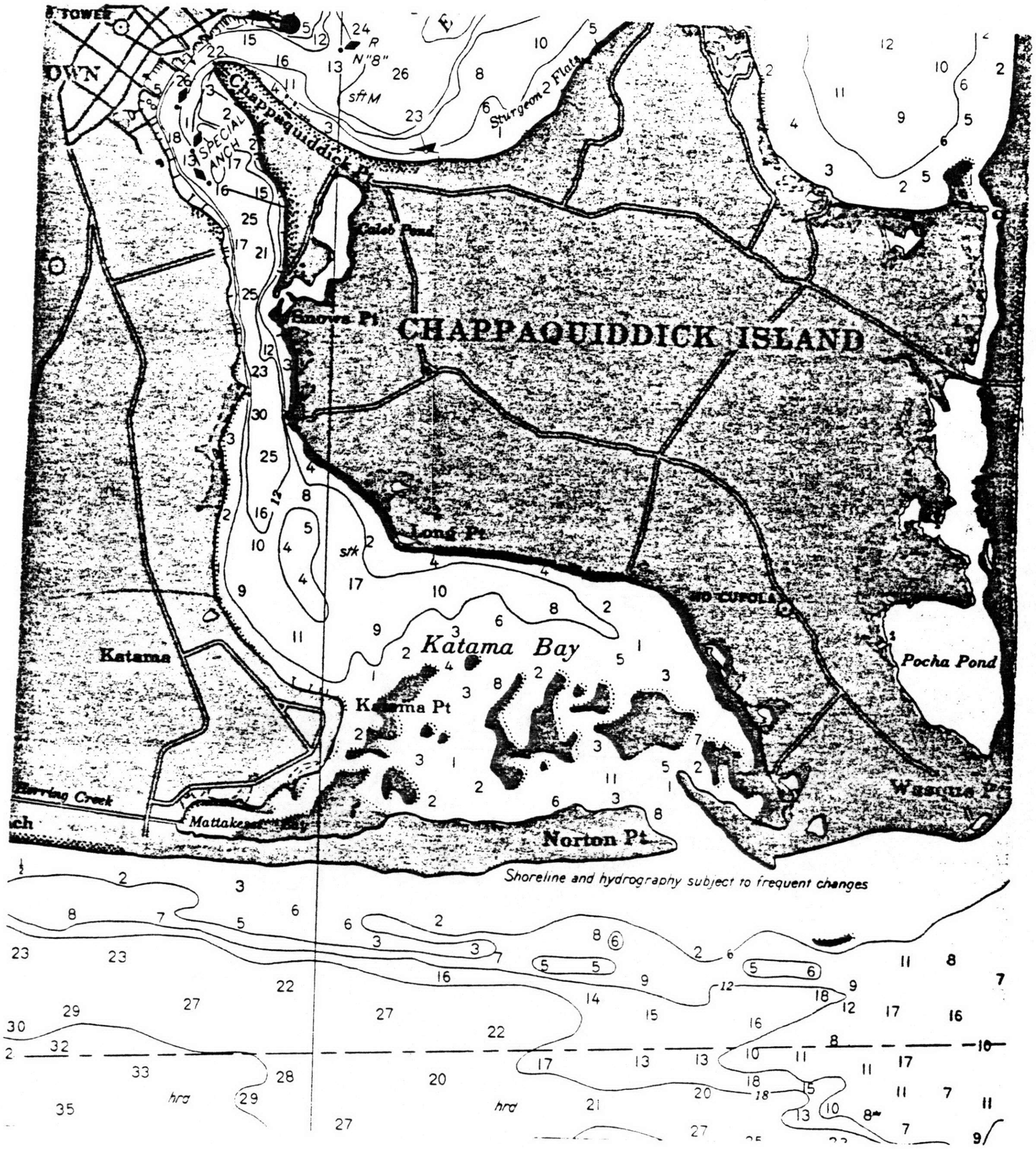
Gloucester Harbor. NOAA Chart 13279, scale: 1:20,000



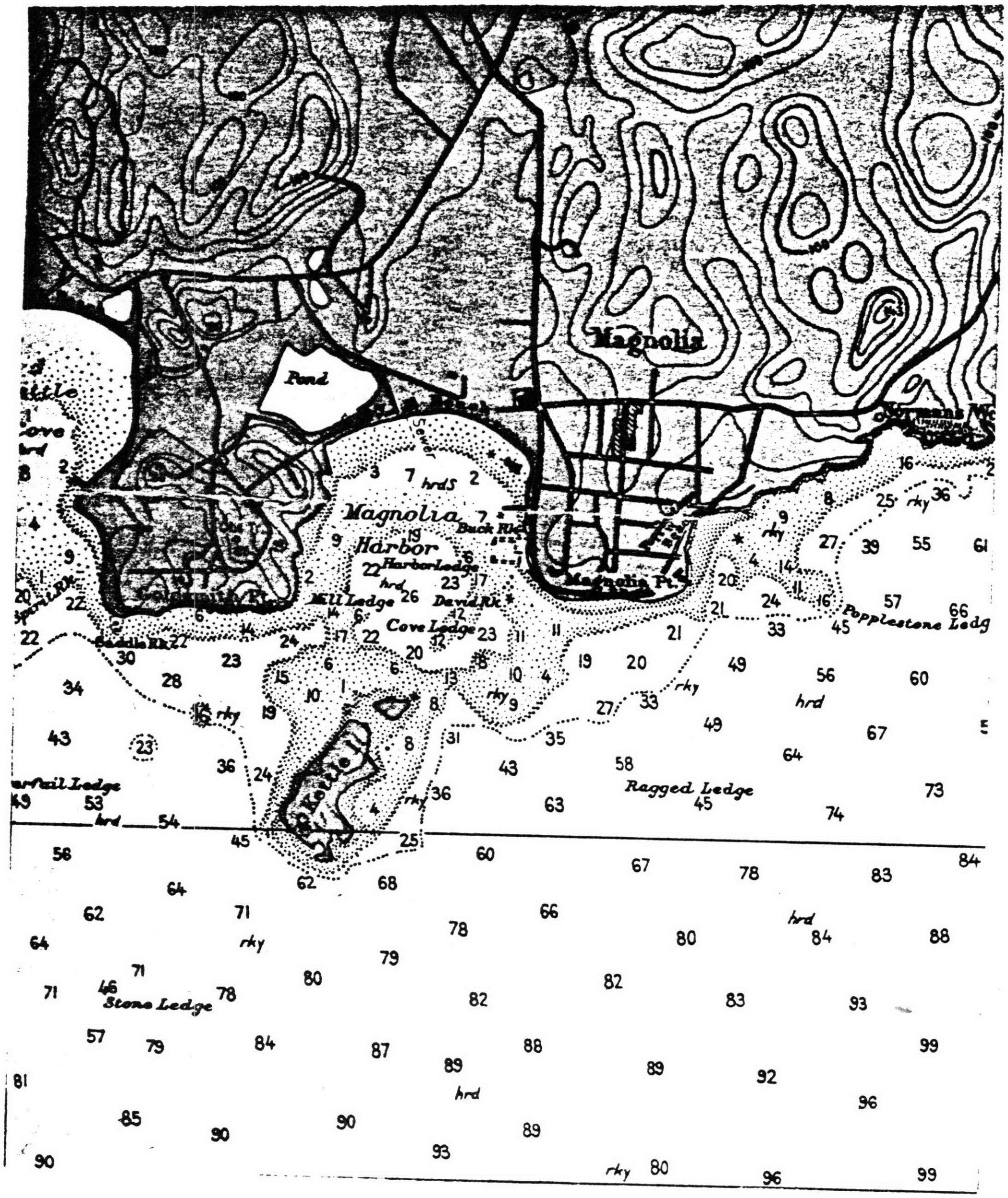
Ipswich Bay. NOAA Chart 13278, scale 1:80,000



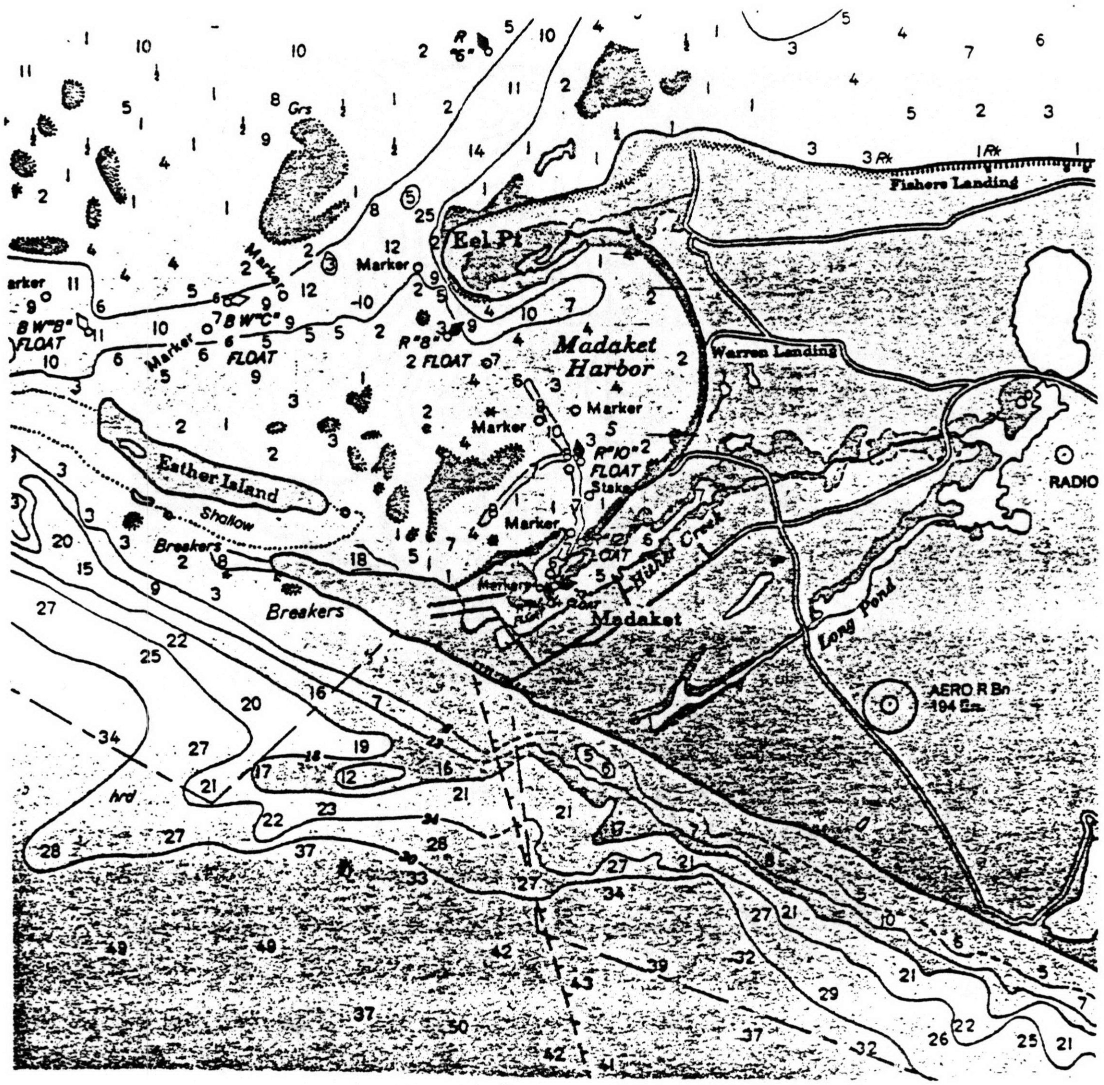
Katama Bay. NOAA Chart 13233, scale 1:40,000



Magnolia Harbor. NOAA Chart 13279, scale: 1:20,000

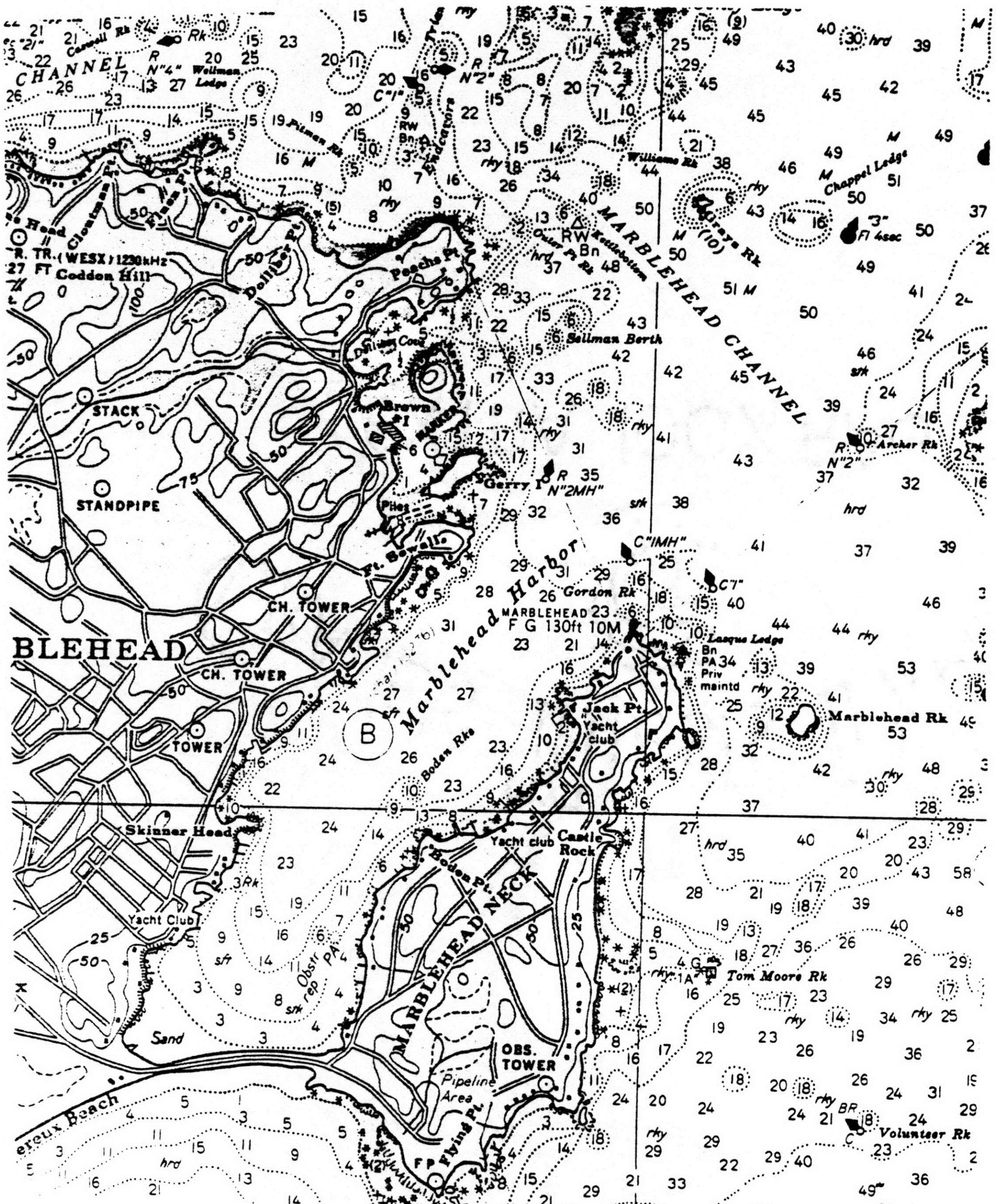


Madaket Harbor. .NOAA Chart 13241, scale: 1:40,000

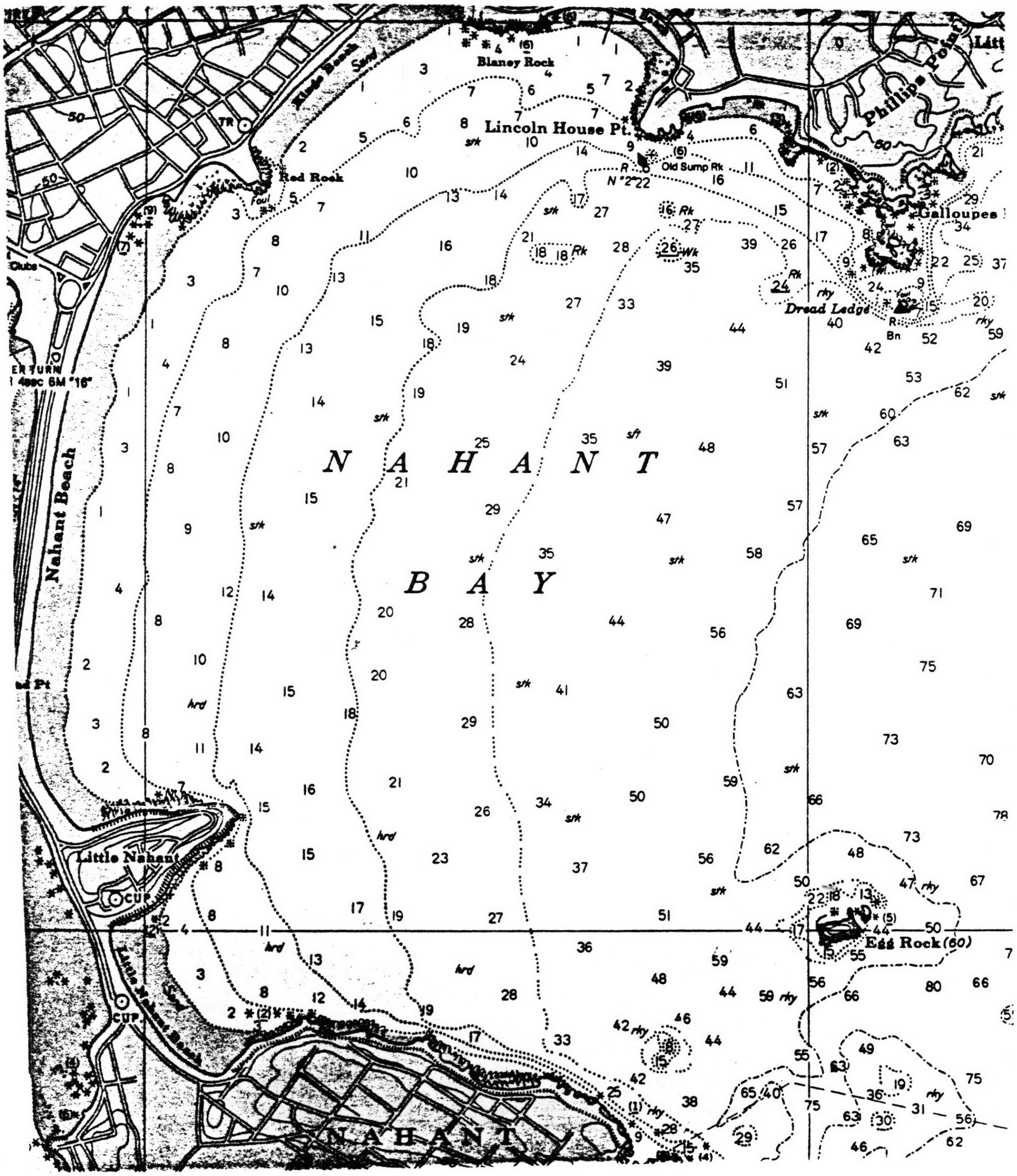


Manchester Harbor. NOAA Chart 13275 (insert), scale: 1:10,000

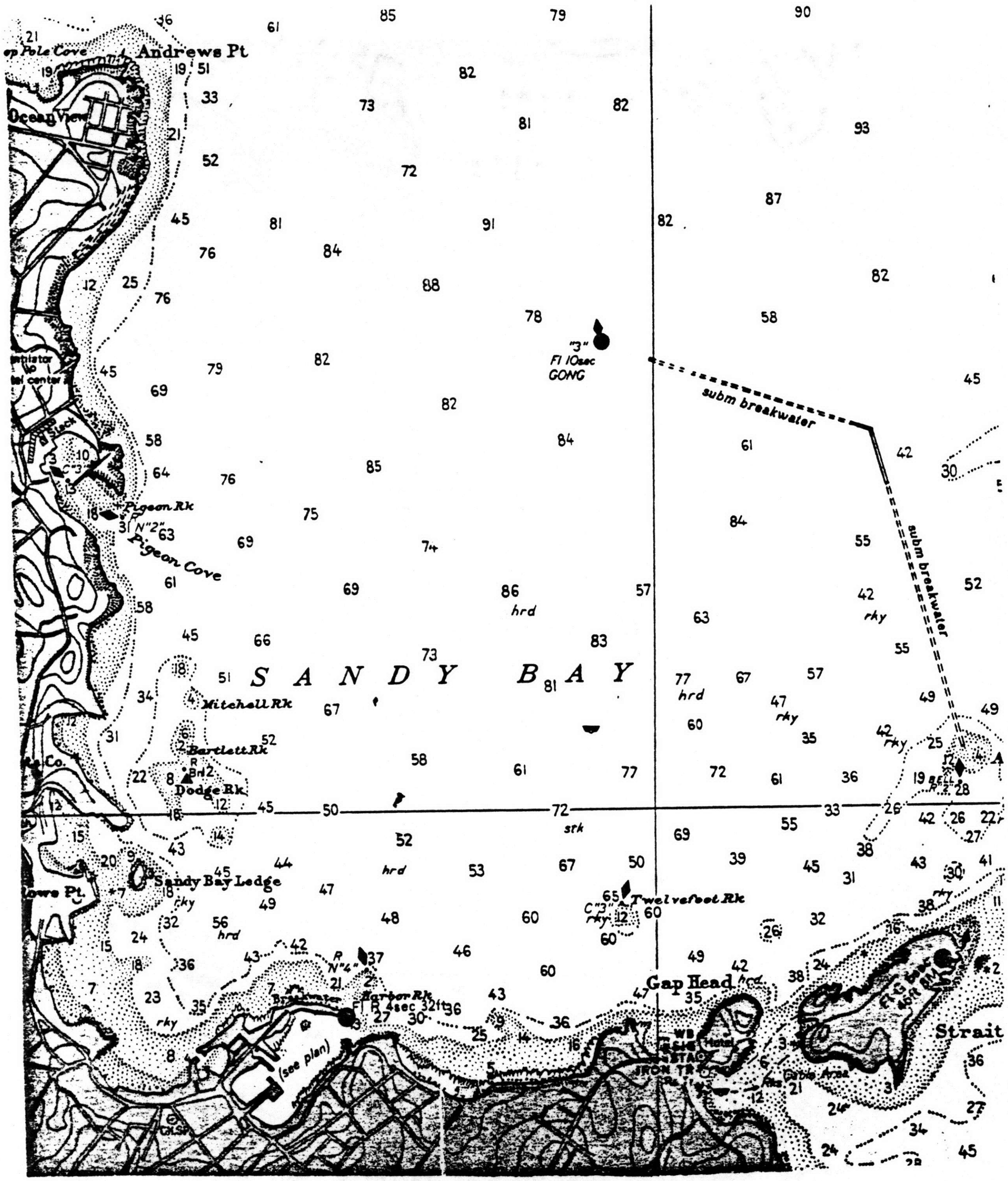
Marblehead Harbor. NOAA Chart 13275, scale: 1:25,000



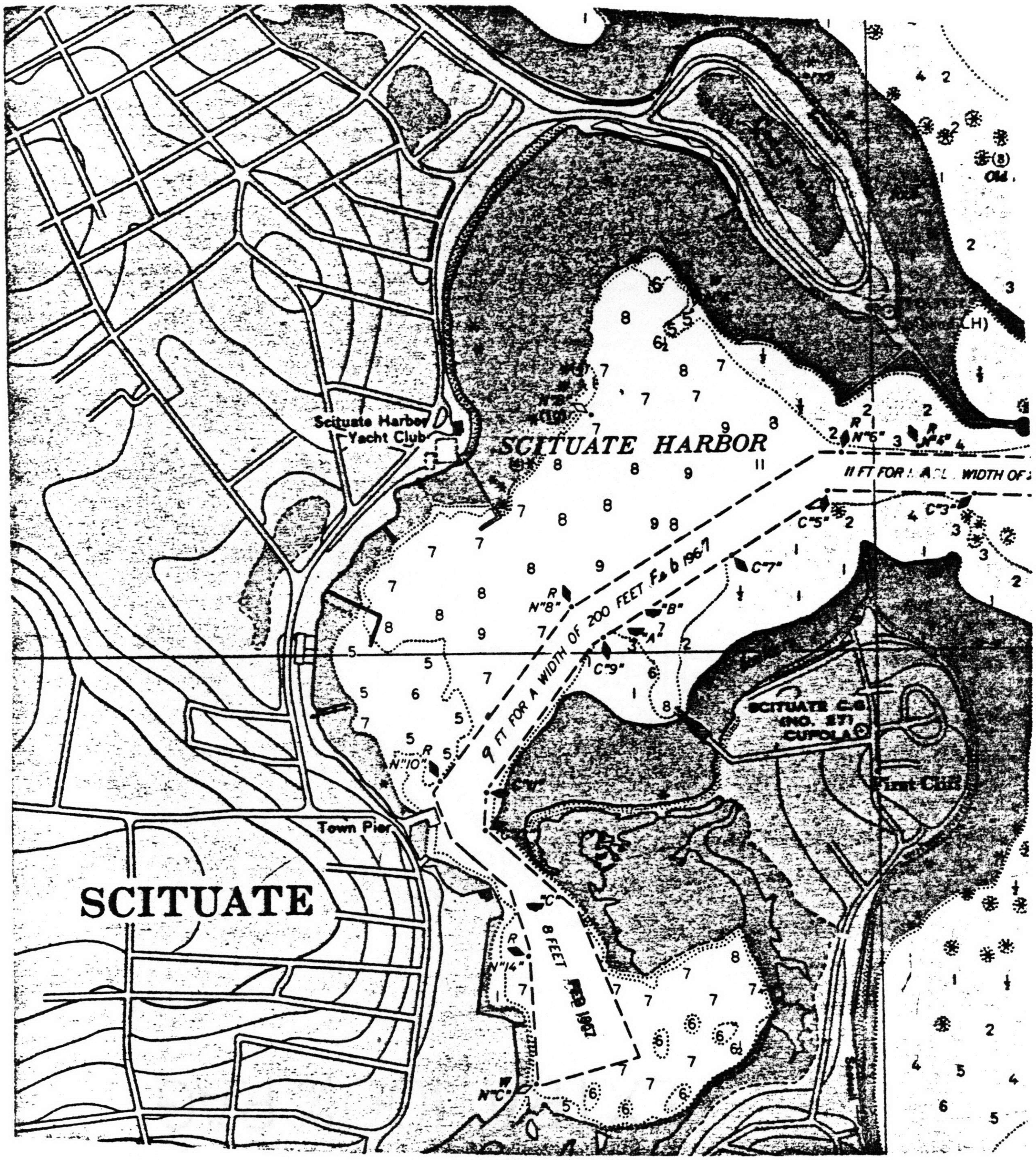
Nahant Bay. NOAA Chart 13275, scale: 1:25,000



Sandy Bay. NOAA Chart 13279, scale: 1:20,000



Scituate Harbor. ·NOAA Chart 13269, scale: 1:10,000



Vineyard Haven Harbor. NOAA Chart 13233, scale: 1:40,000

# Appendix C: Data Collected

| Embayment | MHW Volume (M^3) | MLW Volume (M^3) | Tidal Exchange (%) | Tidal Range (M) | Residence Time (hrs) |
|---|---|---|---|---|---|
| Acushnet River* | 1.61E+07 | 1.36E+07 | .16 | 1.2 | 51 |
| Allens Harbor | | | | | NA |
| Allens Pond | 8.20E+05 | 3.85E+05 | .53 | 1.1 | 18 |
| Annisquam River** | 7.61E+07 | 5.24E+07 | .31 | | 40 |
| Apponagansett Bay* | 6.75E+06 | 5.10E+06 | .24 | 1.1 | 32 |
| Aucoot Cove* | 3.68E+06 | 2.86E+06 | .22 | 1.3 | 34 |
| Barnstable Harbor | | | | | NA |
| Bass River** | | | .8 | | 15 |
| Beverly Harbor** | 3.28E+08 | 2.35E+08 | .29 | | 43.5 |
| Boston Harbor+ | | | | | 31 |
| Bournes Pond | | | | | NA |
| Brant Island Cove* | 3.68E+06 | 4.68E+05 | .87 | 1.1 | 21 |
| Broad Sound | | | .23 | | 53 |
| Buttermilk Bay* | 3.71E+06 | 2.55E+06 | .31 | 1.1 | 26 |
| Cape Poge** | | | .55 | | 22 |
| Centerville Harbor | | | | | NA |
| Charles River+ | | | | | 22 |
| Chatham Harbor | | | | | NA |
| Clarks Cove | 1.18E+07 | 1.02E+07 | .14 | 1.1 | 53 |
| Cohassett Harbor | 6.86E+06 | 2.98E+06 | .57 | 2.684 | 22 |
| Cotuit Bay | | | | | NA |
| Danvers River | | | .7 | | 18 |
| Dorchester Bay** | 1.24E+08 | 6.58E+07 | .47 | | 23 |
| Duxbury Bay** | | | .66 | | 19 |
| Edgartown Harbor** | | | .6 | | 20 |
| Eel Pond** | | | .3 | | 42.5 |
| Ellisville Harbor | | | | | NA |
| Essex Bay** | 1.70E+07 | 4.39E+06 | .74 | | 17 |
| Falmouth Inner Harbor | | | | | NA |
| Gloucester Harbor** | | | .31 | | 38 |
| Great Pond | | | | | NA |
| Green Harbor River | | | | | NA |
| Green Pond | | | | | NA |
| Hens Cove* | 3.74E+05 | 2.17E+05 | .42 | 1.2 | 21 |
| Herring River | | | | | NA |
| Hingham Bay** | 1.68E+08 | 8.45E+07 | .5 | | 25 |
| Hingham Harbor | | | | | NA |
| Hull Bay | | | | | NA |
| Ipswich Bay | 3.73E+08 | 2.87E+08 | .23 | | 54 |
| Ipswich River++ | | | | | 8 |
| Katama Bay** | | | .46 | | 26 |
| Kingston Bay** | | | .66 | | 19 |
| Lewis Bay | | | | | NA |
| Lynn Harbor** | 1.69E+08 | 9.79E+07 | .42 | | 30 |
| Madaket Harbor** | | | .71 | | 17 |
| Magnolia Harbor | 1.54E+06 | 7.92E+05 | .49 | 2.684 | 25.5 |
| Manchester Harbor** | | | .8 | | 15 |
| Marblehead Harbor | 1.20E+07 | 8.06E+06 | .33 | 2.7755 | 38 |
| Marks Cove* | 6.20E+05 | 3.61E+05 | .42 | 1.2 | 21 |
| Mattapoisett Harbor* | 1.91E+07 | 1.65E+07 | .14 | 1.2 | 53 |
| Merrimack River** | 5.28E+07 | 2.34E+07 | .56 | | 22 |
| Nahant Bay | 1.51E+10 | 1.29E+10 | .14 | 2.745 | 48 |
| Nantucket Harbor | | | .27 | | 45 |
| Nasketucket Bay* | 4.40E+06 | 3.25E+06 | .26 | 1.1 | 30 |
| Nauset Bay | | | | | NA |
| Neponset River | 3.40E+09 | 1.69E+09 | .5 | | 25 |
| Onset Bay* | 4.33E+06 | 3.09E+06 | .29 | 1 | 28 |
| Pamet River | | | | | NA |
| Parker River** | | | .72 | | 17 |
| Phinneys Harbor* | 5.67E+06 | 4.35E+06 | .23 | 1.2 | 33 |
| Pines River** | | | .41 | | 30 |
| Pleasant Bay** | | | .32 | | 32 |
| Plum Island Sound++ | | | | | 46 |
| Plymouth Bay** | | | .66 | | 19 |
| Plymouth Harbor+++ | | | | | 12 |

| | | | | | |
|---|---|---|---|---|---|
| Pocasset River* | 1.08E+06 | 7.42E+05 | .31 | 1.2 | 26 |
| Pomponessett Bay* | | | | | 20 |
| Provincetown Harbor | | | | | NA |
| Quincy Bay+ | | | | | 33 |
| Quissett Harbor* | 1.02E+06 | 7.38E+05 | .28 | 1.2 | 29 |
| Red Brook Harbor* | 1.43E+06 | 1.06E+06 | .26 | 1.2 | 30 |
| Rock Harbor | | | | | NA |
| Rowley River++ | | | | | 88 |
| Salem Harbor** | 3.28E+08 | 2.35E+08 | .29 | | 43 |
| Sandwich Harbor | | | | | NA |
| Sandy Bay | 9.26E+07 | 8.11E+07 | .12 | 2.684 | 100 |
| Sequatucket Harbor | | | | | NA |
| Saugus River** | | | .42 | | 30 |
| Scituate Harbor | 2.46E+06 | 1.07E+06 | .56 | 2.684 | 22 |
| Scorton Harbor | | | | | NA |
| Sesuit Harbor | | | | | NA |
| Sippican Harbor* | 2.32E+07 | 1.87E+07 | .19 | 1.2 | 38 |
| Slocums River* | 2.54E+06 | 1.45E+06 | .43 | 1.1 | 21 |
| Squeteaque Harbor* | 4.24E+05 | 2.43E+05 | .43 | 1.2 | 21 |
| Stage Harbor | | | | | NA |
| Swan Pond River | | | | | NA |
| The Widows Cove* | 8.30E+05 | 5.07E+05 | .39 | 1.2 | 22 |
| Vineyard Haven Harbor** | | | .6 | | 20 |
| Waquoit Bay** | 4.53E+06 | 3.21E+06 | .29 | | 43 |
| Wareham River* | 3.92E+06 | 2.40E+06 | .39 | 1.2 | 22 |
| Weir River | | | | | NA |
| Wellfleet Harbor** | 4.79E+07 | 1.76E+07 | .63 | | 20 |
| West Bay | | | | | NA |
| West Falmouth Harbor* | 9.32E+05 | 4.66E+05 | .5 | 1.2 | 19 |
| Westport River East Branch* | 8.17E+06 | 6.21E+06 | .24 | 0.5 | 32 |
| Westport River West Branch* | 6.36E+06 | 4.17E+06 | .34 | 0.8 | 24 |
| Weweantic River* | 3.29E+06 | 2.72E+06 | .17 | 1.2 | 42 |
| Weymouth Back River | | | | | NA |
| Weymouth Fore River | | | | | NA |
| Wild Harbor* | 8.66E+05 | 5.73E+05 | .34 | 1.2 | 25 |
| Wings Cove* | 1.75E+06 | 1.22E+06 | .3 | 1.2 | 27 |
| Woods Hole Great Harbor | | | | | NA |

*From Aubrey, 1991 note: Aubrey uses Half-Tide Water (HTL) instead of MHW

**From DMF Series

+From Adams, 1995

++From Plum Island Sound Minibays Project

+++From CDM minutes, 1995