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FINAL REPORT

for

DETERMINATION OF FLUSHING RATES AND HYDROGRAPHIC FEATURES OF SELECTED BUZZARDS BAY EMBAYMENTS

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Executive Summary

Flushing times were calculated for 27 embayments bordering Buzzards Bay. The flushing times are useful for estimating susceptibility to nutrient loading. However, prior to identifying heavily loaded embayments, the loading rate must be determined. For management purposes, the flushing rate combines with the nutrient-input rate to determine the susceptibility to nutrient loading.

To determine flushing rates, available bathymetry data were collected from existing sources. No new data were acquired. Since existing bathymetry data are sparse and old, the analysis is naturally limited in accuracy. Three methods were used to estimate flushing rates. Two of these methods are analytical approximations commonly used for flushing-rate estimation. The third method is a computer model based on the fundamental equations of flow. This latter model was applied to only four selected embayments. Although all results are based on limited data, they illustrate well the relative flushing of the various embayments.

Results from the two analytical models differ for some embayments but are nearly identical for others. The disagreements are related to the limited physics in the analytical models. In general, the box model (analytical model #1) underestimates the residence time compared to the more accurate spatial model (analytical model #2). The tendency for underestimation is accentuated for long embayments, where the box model is particularly weak. However, for short, equi-dimensional embayments, the two analytical methods agree well.

For all embayments except Aucoot Cove, the numerical computer model estimates of residence time are consistent with analytical model #2, but generally higher than model #1. The numerical model solution is the most robust. Results from the computer model provide better estimates than the broader analytical approaches. However, the estimates for Aucoot Cove appear too high in the numerical model analysis, and somewhat low for the analytical cases. Because Aucoot Cove is so equidimensional, the numerical model, which is one-dimensional, may not represent the physics well.

All estimates assume that tidal dispersion alone controls the residence time. In fact, residence time can be decreased by wind, freshwater inflow, and complex topography. Residence time also can be increased by density stratification. The present estimates of residence time are consistent and are representative of relative flushing times, and thus should be defensible for management purposes. However, all of these estimates could be improved by more complete bathymetry data, better knowledge of tidal characteristics, and better estimates of local dispersion coefficients.

1.0 Introduction

The Buzzards Bay Project (BBP) is responsible for characterizing and assessing pollution sources in Buzzards Bay and for making management recommendations to protect coastal water quality and the health of living resources within the Bay. As development in highly populated areas of Buzzards Bay continues, the maintenance of good water quality and ecosystem health is a high priority. One of the most serious issues threatening Buzzards Bay is the addition of nitrogen to coastal waters from human activities. Two primary sources of nitrogen are sewage effluent from septic systems, and lawn fertilizers. Additional sources of water pollution include storm-water runoff from roads and parking areas, pesticides, chemical contamination from improper disposal of hazardous wastes, oil and gasoline spills from boats and marinas, and animal wastes. Water-quality degradation from these sources is especially critical in shallow, poorly flushed harbors and embayments surrounded by development. The reduction of water quality in these harbors may adversely affect the productivity of shellfisheries and finfisheries, and may also lessen the esthetic and recreational appeal of these areas.

Since some effects of pollution and nitrogen loading are localized to the shallow embayments along the coast of Buzzards Bay, the BBP has identified some potentially "nitrogen-sensitive embayments." These are embayments with reduced flushing that have a large ratio of land-drainage area to water volume, and would suffer from nitrogen loading if future developments were managed incorrectly. The BBP uses several parameters to identify nitrogen-sensitive embayments: embayment volume, flushing time, water depth, and existing and future potential nitrogen inputs from the surrounding drainage basin (Buzzards Bay Project, 1991). These embayments will be negatively affected by increased nitrogen loading as their drainage basins become more developed.

One of the most important parameters identifying nitrogen-sensitive embayments is the flushing time, or residence time. The ecology of tidal embayments depends on freshwater and saltwater flushing between the inlet/embayment system and the open ocean. The distributions of salinity and dissolved oxygen are controlled in part by tidal flushing. In addition, the distribution of planktonic organisms, eggs spawned within the estuary, and pollutants introduced by nearby sources are dependent on the exchange of freshwater and saltwater. The distribution of any material that is either dissolved or suspended in the water column is affected by the circulation of freshwater and saltwater, and by the exchange of water between various parts of the embayment.

2.0 OBJECTIVES AND SCOPE OF WORK

The objective of this study was to estimate the flushing rates within potentially "nitrogen-sensitive embayments" located in Buzzards Bay. Flushing rates were approximated as residence times for each embayment. The physical parameters required for calculation of residence time were obtained from existing data sources. These parameters included bathymetric and tidal elevation data, as well as information on the geometry of the embayments. In addition, mean low water (MLW) volume, hypsographic curves, average water depth, and tidal prism volume were calculated for each of the embayments.

First-order estimates of residence time were determined for each embayment assuming complete mixing of water from Buzzards Bay with less-saline water from the embayment. Freshwater inflow was estimated for those embayments where significant fluvial discharge takes place. Results of the first-order estimation of residence times were used to identify four embayments for further analysis. At these selected embayments, refined residence times were calculated using a one-dimensional (1-D) numerical hydrodynamic model developed for shallow, tidal embayments. The refined times were calculated directly from the numerical model simulations of tidal prism and water volume exchange in sub-sections of each selected embayment.

3.0 DATA COLLECTION

The BBP identified 27 Buzzards Bay embayments for this study. These are potentially "nitrogen-sensitive embayments" for which residence times and hydrographic parameters were not previously known. During this study, several hydrographic parameters were measured and calculated for each embayment: surface area contained within 1-m contour intervals, embayment width and length, MLW volume, average water depth, tidal range, and tidal prism volume. The methods used to develop these parameters are discussed in the following section.

3.1 METHODOLOGY

The 27 embayments extend around the shores of Buzzards Bay from the town of Falmouth in the southeast to the town of Westport in the northwest (Table 1). The embayments vary greatly in size,

shape, and physical characteristics, with some being fed by freshwater discharge from rivers and others simply by groundwater discharge. Boundaries of the embayments were selected by the BBP (Figure 1). Several of the larger embayments were divided into an upper and lower section (Table 1). In most cases, the seaward boundary was chosen where the embayment opened significantly to Buzzards Bay. The landward boundary was chosen at the inland extent of tidal marsh or the MLW shoreline.

Table 1. Buzzards Bay Embayments Selected for Analysis of Flushing Rates and Hydrographic Features

Embayment Name	Embayment Name
1. Acushnet River*	15. Quissett Harbor
2. Allens Pond	16. Red Brook Harbor
3. Apponagansett Bay*	17. Sippican Harbor*
4. Aucoot Cove	18. Slocums River
5. Brant Island Cove	19. Squeteague Harbor
6. Buttermilk Bay	20. Wareham River
7. Clarks Cove	21. West Falmouth Harbor
8. Hens Cove	22. Westport River, East Branch
9. Marks Cove	23. Westport River, West Branch
10. Mattapoisett Harbor*	24. Weweantic River
11. Nasketucket Bay	25. Widows Cove
12. Onset Bay	26. Wild Harbor
13. Phinneys Harbor	27. Wings Cove
14. Pocasset River	

* embayments divided into upper and lower sections

3.1.1 Bathymetric Maps and Contour Development

Bathymetric data for most of the embayments were taken from the National Oceanic and Atmospheric Administration (NOAA) nautical chart #13229, *South Coast of Cape Cod and Buzzards Bay,* dated June 1990. For the Westport River and Allens Pond, bathymetric data were taken from NOAA nautical chart #13228, *Westport River and Approaches,* dated September 1988. Scales of these maps range from 1:20,000 to 1:40,000. Soundings are in feet below MLW; the shoreline is also referenced

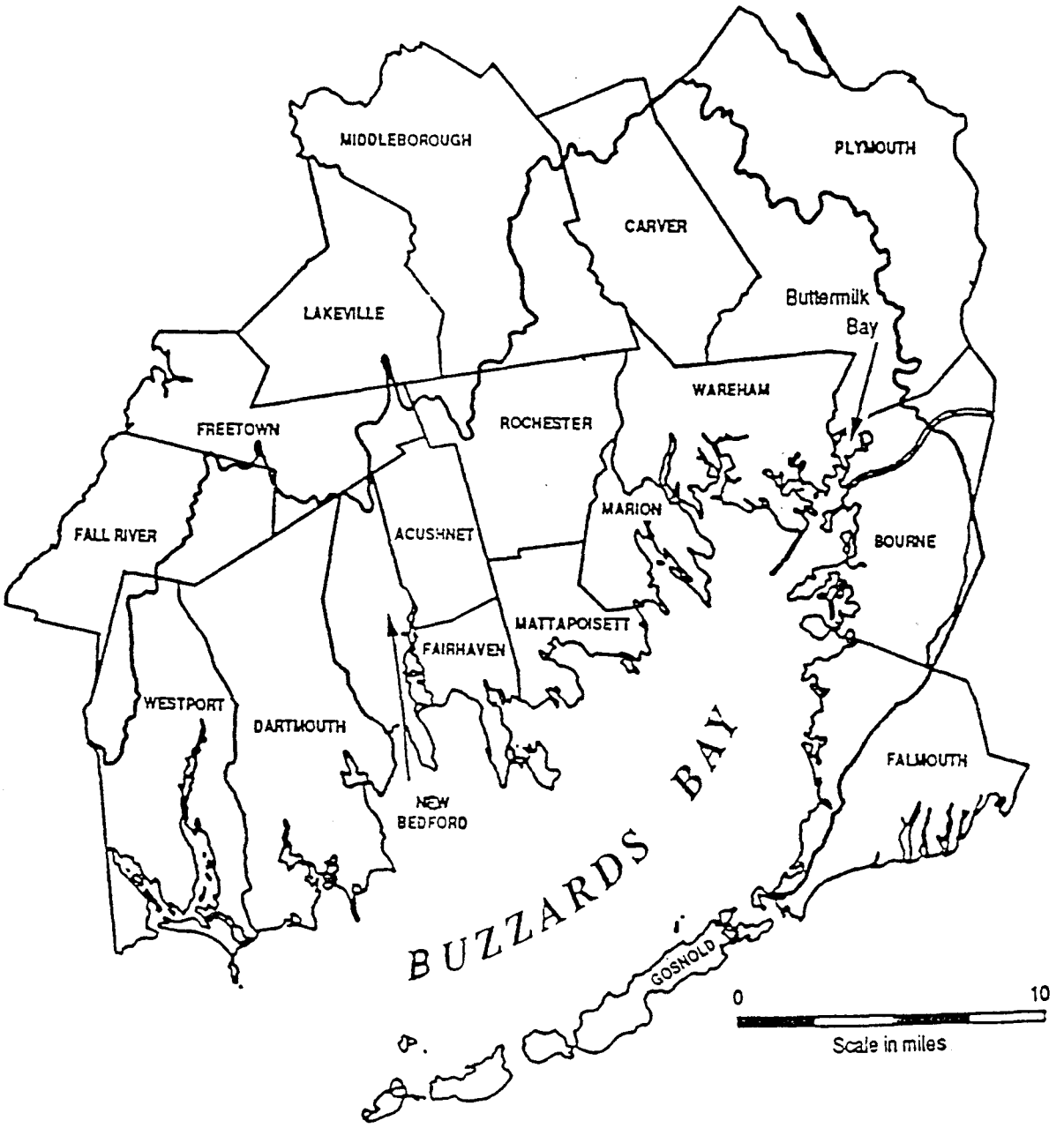

Figure 1. Boundaries of 27 Buzzards Bay Embayments Chosen for Study of Flushing Characteristics

to MLW. Contour maps for each embayment were produced from the soundings on the NOAA charts. The soundings were converted to meters and hand-contoured using a 1-m contour interval. Since most soundings from these charts are old, and since spatial coverage is poor, significant inaccuracies may exist for some embayments. Unfortunately, better data for these areas are lacking.

3.1.2. Embayment Surface Area

The distribution of depth within each embayment was determined by calculating the surface area contained within the contours. The surface areas were digitized with a Kurta 30- × 36-in. digitizing tablet having a resolution of 1000 parts per inch. Nautical charts were registered on the digitizer by keying in the distance between a minimum of four known points; scaling of the charts was performed automatically by the digitizer.

As each contour was digitized, the surface area contained within the contour was recorded. The surface area for 1-m depth increments was determined by subtracting the area contained within the next-deepest contour. For example, the surface area between the 2- and 3-m contours was determined by subtracting the area contained within the 3-m contour from the area contained within the 2-m contour. The total surface area of each embayment (Table 2) was the area contained within the MLW shoreline. The Acushnet River has the largest surface area, whereas Squeteague Harbor has the smallest surface area. The percentage of the embayment shallower than a given water depth (hypsometric curve) was also calculated using the cumulative surface areas within each contour (Appendix A).

3.1.3. Embayment Width and Length

The shape of each embayment was quantified by its length and width (Table 2), as digitized from the NOAA nautical charts. The lengths were measured along the long axis of the embayment extending from Buzzards Bay to the inland boundary of the embayment. The widths were calculated by taking the average of width measurements taken at equi-spaced intervals throughout the embayments.

The longest embayment is the Westport River, East Branch (14,630 m), whereas the shortest embayment is Wild Harbor (810 m). The average embayment length is approximately 4000 m.

Acushnet River is the widest embayment (2000 m), whereas Allens Pond is the narrowest embayment (180 m). The average embayment width is approximately 824 m.

3.2 ANALYSIS

The measurements of embayment surface area, length, and width were used to calculate a number of hydrographic parameters for each embayment: MLW volume, half tide level (HTL) water depth, and tidal prism volume. In addition, estimates of average tidal range at the center of each embayment were calculated. Finally, the surface-area data for the 1-m contour intervals were used to develop hypsometric curves.

3.2.1. MLW Volume

The volume of each embayment at MLW was calculated as:

$$V_{MLW}=\sum [(A_0-A_1)*0.5+(A_1-A_2)*1.5+(A_2-A_3)*2.5...] \quad (1)$$

where A_0 is the area contained by the shoreline, A_1 is the area contained by the 1-m contour, A_2 is the area contained by the 2-m contour, etc. HTL volumes (V_{HTL}) were calculated by adding one-half the tidal prism to the MLW volume (V_{MLW}; Table 3). The Acushnet River has the largest MLW volume, followed by Sippican Harbor, Mattapoisett Harbor, and Clarks Cove. The smallest MLW volume occurs in Hens Cove, followed by Squeteague Harbor, Brant Island Cove, and Marks Cove.

Table 2. Surface Area, Length, and Width Measurements for Buzzards Bay Embayments

Embayment	Surface Area (sq km)	Length (m)	Width (m)
Acushnet River, upper	4.3	9,120	1,000
Acushnet River, total	10.7	12,050	2,000
Allens Pond	0.8	3,740	180
Apponagansett Bay, upper	1.5	3,800	1,020
Apponagansett Bay, total	2.9	5,710	940
Aucoot Cove	1.3	1,280	1,020
Brant Island Cove	0.3	1,340	360
Buttermilk Bay	2.2	3,800	960
Clarks Cove	2.9	2,380	1,270
Hens Cove	0.3	2,650	410
Marks Cove	0.4	1,230	410
Mattapoisett Harbor, upper	1.6	3,860	1,470
Mattapoisett Harbor, total	4.3	5,690	1,880
Nasketucket Bay	2.1	2,640	1,320
Onset Bay	2.4	3,910	760
Phinneys Harbor	2.2	2,770	1,220
Pocasset River	0.8	1,520	510
Quissett Harbor	0.5	1,170	410
Red Brook Harbor	0.6	2,140	810
Sippican Harbor, upper	1.7	5,550	660
Sippican Harbor, total	7.5	8,660	1,140
Slocums River	2.0	5,440	330
Squeteague Harbor	0.3	1,120	410
Wareham River	2.5	3,050	560
West Falmouth Harbor	0.8	1,520	410
Westport River, East Branch	8.0	14,630	1,070
Westport River, West Branch	5.3	8,350	810
Weweantic River	2.4	3,860	460
Widows Cove	0.5	1,170	510
Wild Harbor	0.5	810	560
Wings Cove	0.9	1,690	660

3.2.2. Tidal Range

Estimates of tidal range at the mouth of each embayment were taken from NOAA tide tables (U.S. Department of Commerce, 1990). Approximately 17 NOAA tidal-prediction stations are located around Buzzards Bay. The mean tidal range from the NOAA station closest to the mouth of each embayment was selected as representative for the entrance to that embayment. An analytical technique that predicts the reduction in tidal range due to frictional losses was used to determine the average tidal range at the center of each embayment (Aubrey, in prep.). This technique is based on the zero-inertia momentum equation for well-behaved, cross-sectionally averaged flow. The tidal range (a′) is calculated with the following equation:

$$a' = a \left| \frac{\cosh kx}{\cosh kL} \right| \tag{2}$$

where a = offshore tidal range

L = length of embayment

x = location within the embayment; at entrance x=L

k = $(1+i)/L_f$

i = $\sqrt{-1}$

L_f is the frictional length scale governing the behavior of this first-order solution:

$$L_f = \sqrt{2}\pi^{1/3}\left(\frac{b_c}{b}\right)^{2/3} h^{10/9} a^{-1/3} (n\omega)^{-2/3} \tag{3}$$

where b = average area at mean sea level (MSL)

b_c = average area at MLW

h = average water depth referenced to MSL of area covered at MLW

n = Manning's friction coefficient

ω = frequency of the semi-diurnal (M_2) tide

A more detailed discussion on the development and use of this technique can be found in Aubrey (in prep.).

This analytical technique was used to calculate the mean tidal range at the center of each embayment (Table 3). With the exception of the long and sinuous embayments, there was little reduction in tidal range between the mouth and center of most embayments. The tidal ranges are from 0.5 to 1.3 m.

3.2.3. Half-Tide Water Depth

The HTL water depth (h_{HTL}) was calculated with the following equation:

$$h_{HTL}=\frac{V_{MWL}}{A_0}+0.5a' \tag{4}$$

Average HTL water depths range from a maximum of 4.4 m in Mattapoisett Harbor to a minimum of 1.0 m in the Westport River, East Branch. These depths provide a rough indication of the flushing characteristics of the harbors. An embayment with a small HTL depth may be well-flushed, whereas an embayment with a greater HTL depth may be flushed more slowly.

3.2.4. Tidal Prism

Tidal prism (P) is defined as the volume of water that flows into or out of a harbor or embayment during one-half spring tidal cycle, excluding any freshwater flow. It is computed with the following equation:

$$P=a'*A_0 \tag{5}$$

The tidal range from the mid-point of each embayment was used, rather than the values determined for the mouth of the embayments. Results from the tidal prism calculations are summarized in Table 3. The Acushnet River shows the largest tidal prism, of 12,400,000 m^3, whereas Hens Cove shows the smallest tidal prism, 313,000 m^3.

Table 3. Volume, Tidal Range, Water Depth and Tidal Prism Values for Buzzards Bay Embayments

Embayment	V_{MLW} (m^3)	V_{HTL} (m^3)	a′ (m)	h_{HTL} (m)	P (m^3)
Acushnet River, upper	13,600,000	16,100,000	1.2	3.8	4,950,000
Acushnet River, total	38,700,000	45,000,000	1.1	4.2	12,400,000
Allens Pond	385,000	820,000	1.1	1.1	869,000
Apponagansett Bay, upper	1,080,000	1,950,000	1.1	1.3	1,730,000
Apponagansett Bay, total	5,100,000	6,750,000	1.1	2.3	3,300,000
Aucoot Cove	2,860,000	3,680,000	1.3	2.9	1,650,000
Brant Island Cove	274,000	468,000	1.1	1.4	388,000
Buttermilk Bay	2,550,000	3,710,000	1.1	1.7	2,320,000
Clarks Cove	10,200,000	11,800,000	1.1	4.1	3,140,000
Hens Cove	217,000	374,000	1.2	1.5	313,000
Marks Cove	361,000	620,000	1.2	1.4	519,000
Mattapoisett Harbor, upper	4,520,000	5,470,000	1.2	3.4	1,890,000
Mattapoisett Harbor, total	16,500,000	19,100,000	1.2	4.4	5,130,000
Nasketucket Bay	3,250,000	4,400,000	1.1	2.1	2,310,000
Onset Bay	3,090,000	4,330,000	1.0	1.8	2,480,000
Phinneys Harbor	4,350,000	5,670,000	1.2	2.6	2,650,000
Pocasset River	742,000	1,080,000	1.2	1.5	670,000
Quissett Harbor	738,000	1,020,000	1.2	2.2	561,000
Red Brook Harbor	1,060,000	1,430,000	1.2	2.4	741,000
Sippican Harbor, upper	2,450,000	3,470,000	1.2	2.0	2,030,000
Sippican Harbor, total	18,700,000	23,200,000	1.2	3.1	9,090,000
Slocums River	1,450,000	2,540,000	1.1	1.3	2,160,000
Squeteague Harbor	243,000	424,000	1.2	1.4	361,000
Wareham River	2,400,000	3,920,000	1.2	1.6	3,040,000
West Falmouth Harbor	466,000	932,000	1.2	1.2	932,000
Westport River, East Branch	6,210,000	8,170,000	0.5	1.0	3,910,000
Westport River, West Branch	4,170,000	6,360,000	0.8	1.2	4,380,000
Weweantic River	2,720,000	3,290,000	1.2	3.5	1,140,000
Widows Cove	507,000	830,000	1.2	1.5	645,000
Wild Harbor	573,000	866,000	1.2	1.8	587,000
Wings Cove	1,220,000	1,750,000	1.2	2.0	1,070,000

3.2.5. Hypsometric Curves

Hypsometric curves, or cumulative-depth diagrams, show the distribution of the embayment area with respect to water depth. Separate hypsometric curves for each of the 27 Buzzards Bay embayments are presented in Appendix B. The shapes of the hypsometric curves vary strikingly among embayments. For example, several of the embayments have steeper slopes at greater water depths, such as the Acushnet River, which has a fairly narrow, deeply incised channel. Other embayments, such as Nasketucket and Onset Bays, have flatter slopes indicating more gradual bathymetric changes.

4.0 CALCULATION OF FIRST-ORDER RESIDENCE TIMES

In most Buzzards Bay estuaries, the primary mechanism responsible for flushing is the exchange of open-ocean water with estuarine water, caused by propagation of the tide. Water quality within the estuary depends in part upon the extent of this tidal flushing. River or other freshwater flow in these cases is small compared to this tidal action. One measure of tidal flushing is the residence time, defined as the average time that it takes to renew the water particles within an estuary. A wide range of factors can affect the rate of tidal flushing, including freshwater inflow, winds, tidal range, Coriolis effect, longshore currents at the mouth of the estuary, and bottom friction (Fischer *et al.*, 1979). Just as numerous are the methodologies available for calculating residence time. Some techniques assume complete mixing with oceanic waters and ignore freshwater discharge, others account for freshwater discharge, and still others include mixing caused by winds and salinity gradients. The method used depends on the specific questions to be addressed, and the dominant physical processes at the site.

For this study, three different techniques are used to estimate residence time within the Buzzards Bay embayments. Two techniques described in this section are analytical in their approach and provide first-order estimates of residence time. The third technique is based on a computer simulation of tidal flowage. Results from the computer simulation, which was performed for only four Buzzards Bay embayments, are presented in a later section.

4.1 TECHNIQUE #1 (BOX MODEL)

4.1.1. Methodology

The first technique calculates residence time in terms of dilution of the embayment water by the tidal prism. It assumes that complete mixing of oceanic and embayment water occurs; if known, freshwater inflow can be added to the tidal prism. As water enters the embayment during the flood tide, it mixes with the residual embayment water, thereby diluting the concentrations of nutrients within the estuary. Water leaving the embayment during the ebb tide carries these nutrients with it. The cycle is repeated during the following flood tide. The average length of time that it takes to replace all the water parcels within the estuary is given by the following equation modified from Zimmerman (1988):

$$\tau_r = \left(\frac{V_{MWL}+P}{P}\right)\frac{12.42}{24} \qquad (6)$$

where τ_r is the residence time.

Equation (6) gives the residence time in number of days for a semi-diurnal tide (M_2). Similar calculations can be made if other tidal constituents are dominant. Since the M_2 tide is the dominant tide in Buzzards Bay, this tidal component was applied in the calculations.

The box model is one of the most commonly used techniques for estimating residence time, primarily because of its simplicity and the ease with which the input variables can be determined. Residence times are averaged along the entire embayment. Since the embayment head is commonly flushed more slowly than the mouth, the worst conditions are not represented by this model. Typically, Equation (6) gives a lower bound to the residence time because the total volume introduced during the flood, in general, is not completely mixed with the low-tide volume. Density stratification in deeper embayments can affect this mixing, particularly in summer, when residence times may be increased.

4.1.2. Results

Table 4 summarizes the residence times calculated with the box model. The flushing rates range from 18 hours at Allens Pond to 53 hours at Clarks Cove and Mattapoisett Harbor. In general, the shallowest embayments are those having the shortest residence times, whereas the deeper embayments have longer residence times, as discussed previously. These residence times are of limited use because they lack a complete description of physical processes. However, they indicate the relative flushing rates among the Buzzards Bay embayments.

Table 4. Residence Times for Buzzards Bay Embayments (Technique #1: Box Model)

Embayment	Residence Time (days)	Embayment	Residence Time (days)
Acushnet River, upper	1.9	Pocasset River	1.1
Acushnet River, total	2.1	Quissett Harbor	1.2
Allens Pond	0.7	Red Brook Harbor	1.3
Apponagansett Bay, upper	0.8	Sippican Harbor, upper	1.2
Apponagansett Bay, total	1.3	Sippican Harbor, total	1.6
Aucoot Cove	1.4	Slocums River	0.9
Brant Island Cove	0.9	Squeteague Harbor	0.9
Buttermilk Bay	1.1	Wareham River	0.9
Clarks Cove	2.2	West Falmouth Harbor	0.9
Hens Cove	0.9	Westport River, East Branch	1.3
Marks Cove	0.9	Westport River, West Branch	1.0
Mattapoisett Harbor, upper	1.8	Weweantic River	1.8
Mattapoisett Harbor, total	2.2	Widows Cove	0.9
Nasketucket Bay	1.3	Wild Harbor	1.0
Onset Bay	1.2	Wings Cove	1.1
Phinneys Harbor	1.4		

4.2 TECHNIQUE #2 (SPATIAL MODEL)

4.2.1 Methodology

The second technique calculates residence time as a function of position within the embayment, thereby accounting for one of the deficiencies of the box model. The fluctuation in the tide and its interaction with the bathymetry are the primary mixing mechanisms. Technique #2 assumes a small freshwater inflow; therefore, density stratification does not occur and the embayment is well-mixed vertically. However, the strong vertical mixing in tidal embayments does not necessarily imply strong longitudinal mixing or short residence times for embayment waters; longitudinal density gradients may persist.

The hydrodynamic processes responsible for the flushing of embayment waters result primarily from the incoming and outgoing tides. Two important types of circulation caused by the tides are (1) tide-induced large-scale residual circulations and (2) spatial variation of the oscillatory tidal velocity. Other non-tidal dispersion mechanisms also can be important in certain systems. The magnitude of the residual circulation and the spatial variation in tidal-velocity distribution are controlled by the geomorphology of the embayment. The flushing in wide, large-scale embayments, such as Buzzards Bay proper, tends to result from residual circulations, whereas the spatial variations of the tidal velocity tend to be the dominant factor in embayments with narrow channels.

The residence time for technique #2 is defined as the time it takes for any water parcel to leave the embayment through the embayment's outlet to the sea. It is assumed that the average residence time is independent of the origin of the water parcel, and that the residence time depends only on the location of the water parcel within the embayment. In most tidal embayments the water-quality parameters change mainly in the longitudinal direction, between the head of the embayment and the open-water boundary. If the lateral change in water quality is much smaller than the longitudinal change, it is valid to partition the system in sections perpendicular to the longitudinal axis and to average distributions of water-quality parameters across the channel. This process leads to a one-dimensional analysis of the embayment.

Dronkers and Zimmerman (1982) combine this one-dimensional approach with a dispersion coefficient that approximates the results of the mixing processes. Their equation for residence time is:

$$\tau_r(x) = \frac{1}{2}\frac{L^2 - x^2}{D} \tag{7}$$

where τ_r is the residence time, L is the length of the embayment, x is the position within the embayment (x = 0 is at the head of the embayment), and D is the longitudinal dispersion coefficient. When the units of D are m^2/s, the calculated residence time is in seconds. The residence time can be converted to days by dividing it by the number of seconds in 1 day (86,400). The equation for the longitudinal dispersion coefficient (D) in an embayment due to shear flow is given by Fischer *et al.* (1979):

$$D = 0.1u^2T[(1/T')f(T')] \tag{8}$$

where u is the mean tidal velocity, T is the tidal period, T′ is the dimensionless time scale for cross-sectional mixing, and the function [(1/T′) f(T′)] is plotted in Figure 2. The function f(T′) has a maximum of approximately 0.8 when T′ is about 1.0, and shows that the shear-flow dispersion coefficient will be small if the estuary is wide (T′ small) or narrow (T′ large). Shear-flow dispersion will have its maximum effect if the tidal period is similar to the time required for cross-sectional mixing.

The literature contains numerous reports of observed longitudinal-dispersion coefficients in estuaries (Table 5). Many of these coefficients were obtained through measurements of salinity gradients and dye experiments. The values ranging between 100-300 m^2/s occur in the larger estuaries where the effects of shear flow are coupled with a variety of mixing processes, such as salinity gradients and winds. Estuaries having low dispersion coefficients (10-50 m^2/s) are typically smaller in size; shear flow is the primary mechanism for mixing in these estuaries.

Residence times have been calculated with technique #2 for several large estuaries in The Netherlands (Table 6; Postma, 1954; Dorrestein and Otto, 1960; Zimmerman, 1976 a,b; Dronkers *et al.*, 1981).

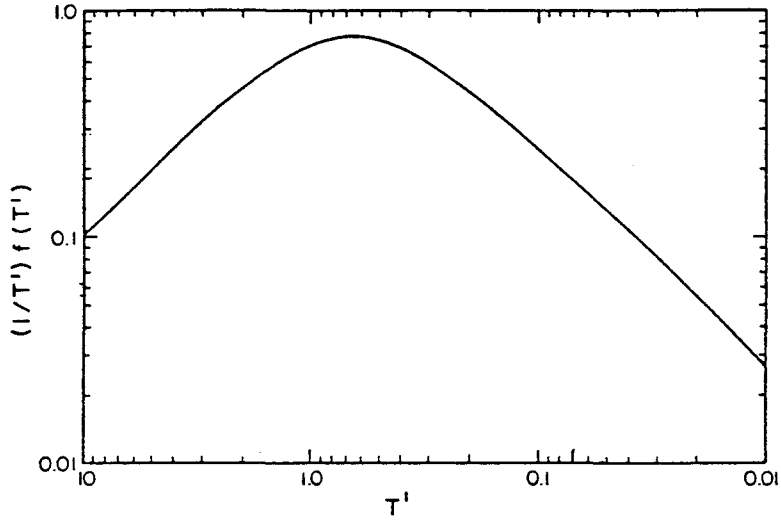

Figure 2. The Function [(1/T′f(T′)] Used To Predict the Longitudinal Dispersion Coefficient. (Fisher *et al.*, 1979)

The residence times given in Table 6 represent the maximum residence time for each estuary, calculated at the head of each estuary. Since the residence time is proportional to the squared length of the estuary, the length is a strong determinant of the residence time. This is apparent from Table 6, where three of the estuaries (Oosterschelde, Westerschelde, and Eems) have similar dispersion coefficients. Only for the Wadden Sea, which is wider than the other three areas, is the dispersion coefficient appreciably larger. Together with its shorter length, the greater width provides more rapid flushing. The values given for the residence times are really only accurate to within an order of magnitude, since in all cases the dispersion coefficient varies according to the position in the estuary and the physical processes acting there. These estuaries are all significantly longer and wider than the Buzzards Bay embayments, and therefore show dispersion coefficients and residences times greater than those calculated by the same technique for the Buzzards Bay embayments.

4.2.2. Results

Residence times for the Buzzards Bay embayments were calculated in 125-m increments along the longitudinal axis of each embayment. Table 7 summarizes the diffusion coefficients and residence times calculated with technique #2 (Dronkers and Zimmerman, 1982). The diffusion coefficients were calculated with Equation (8). Mean tidal velocities ranging from 0.3-0.5 m/s were assumed, and Figure 2 was used to determine the function f(T′). The residence times shown in Table 7 represent an average of the upper one-third of each embayment. The range of residence times shown is based on a range of dispersion coefficients shown in Table 7. The residence times vary widely, with the shortest occurring at Aucoot Cove and Wild Harbor, the longest at the Westport River, East Branch.

The accuracy of these estimates is limited by the available data and approximations of the model. The model idealizes and simplifies many complex physical processes. The dispersion coefficients were selected from the literature. Field measurements would be needed to gain more confidence in these values. However, experience has shown that these values are indicative of relative flushing times between embayments.

Table 5. Observed Longitudinal-Dispersion Coefficients in Estuaries

Estuary	Dispersion Coefficient (m^2/s)	Source
Coral Creek, Missionary Bay	20-40	Wolanski (1980)
Hudson	160	Thatcher and Harleman (1972)
Rotterdam Waterway	280	Thatcher and Harleman (1972)
Potomac	55	Thatcher and Harleman (1972)
Delaware	500-1500	Thatcher and Harleman (1972)
San Francisco Bay	200	Glenne and Selleck (1969)
San Francisco Bay	200	Cox and Macola (1967)
Severn	10-100	Stommel (1953)
Potomac	20-100	Hetling and O'Connell (1966)
Delaware	100	Paulson (1969)
Mersey	160-360	Bowden (1963)
Rio Quayas, Equador	760	Bowden (1963)
Severn (summer)	54-122	Bowden (1963)
Severn (winter)	124-535	Bowden (1963)
Thames (low river flow)	53-84	Bowden (1963)
Thames (high river flow)	338	Bowden (1963)

(modified from Fischer *et al.*, 1979)

Table 6. Dispersion Coefficients and Residence Times for Estuaries in The Netherlands

Estuary	Length (km)	Dispersion Coeff. (m^2/s)	Residence Time (days)
Oosterschelde	50	250	50
Westerschelde	55	150	100
Wadden Sea	30/55	900	5/16
Eems	45	250	40

(modified from Dronkers and Zimmerman, 1982)

Table 7. Residence Times and Dispersion Coefficients for Buzzards Bay Embayments (Technique #2)

Embayment	Range of Dispersion Coefficient (m^2/s)	Residence Time Upper 1/3 (days)
Acushnet River, upper	20-30	15.5-23.2
Acushnet River, total	20-30	27.0-40.4
Allens Pond	14-65	1.2-5.6
Apponagansett Bay, upper	20-30	2.7-4.0
Apponagansett Bay, total	20-30	6.0-9.1
Aucoot Cove	20-30	0.3-0.5
Brant Island Cove	10-25	0.4-1.0
Buttermilk Bay	20-30	2.7-4.0
Clarks Cove	20-30	1.0-1.6
Hens Cove	8-25	1.5-4.9
Marks Cove	8-25	0.3-1.0
Mattapoisett Harbor, upper	20-30	2.8-4.2
Mattapoisett Harbor, total	20-30	6.0-9.0
Nasketucket Bay	20-30	1.3-2.0
Onset Bay	20-30	2.8-4.3
Phinneys Harbor	20-30	1.4-2.1
Pocasset River	7-13	1.0-1.8
Quissett Harbor	12-30	0.3-0.6
Red Brook Harbor	7-9	2.8-3.7
Sippican Harbor, upper	20-30	5.8-8.6
Sippican Harbor, total	20-30	13.9-20.9
Slocums River	10-27	6.1-16.5
Squeteague Harbor	7-19	0.3-1.0
Wareham River	7-12	4.3-7.4
West Falmouth Harbor	7-15	0.9-1.8
Westport River, East Branch	20-30	39.8-59.6
Westport River, West Branch	20-30	13.0-19.4
Weweantic River	14-36	2.3-5.9
Widows Cove	7-12	0.6-1.1
Wild Harbor	7-12	0.3-0.5
Wings Cove	7-9	1.8-2.3

5.0 NUMERICAL MODELING OF TIDAL CIRCULATION AND RESIDENCE TIMES

To quantify the exchange of freshwater and saltwater between an estuary and the open ocean, the residence time of the estuary, or the average time that a particular water parcel spends in the estuarine system, must be determined. For this study, a one-dimensional (1-D) numerical model was used to quantify the exchange of freshwater and saltwater within four Buzzards Bay embayments. The embayments chosen by the BBP for this study were the Westport River, Aucoot Cove, Wareham River, and Apponagansett Bay. These embayments exhibit a wide range of conditions from a small, broad geometry at Aucoot Cove to a long, sinuous geometry at Westport River. The 1-D model used for this study was developed specifically for shallow-water estuaries and tidal-inlet systems to evaluate tidally influenced circulation and water-quality issues.

5.1 NUMERICAL MODEL THEORY

The numerical model solves the cross-sectionally integrated 1-D conservation equations for mass (9) and momentum (10):

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=0 \tag{9}$$

$$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x}\frac{Q^2}{A}=-gA\frac{\partial \xi}{\partial x}-f\frac{|Q|}{A}\frac{Q}{A}p \tag{10}$$

where A(x,t) is the cross-sectional area, Q(x,t) is the cross-sectional volume flux of water, ξ(x,t) is the water surface elevation, g is the acceleration due to gravity, f is the friction factor, and p(x,t) is the wetted channel perimeter.

The 1-D model uses a modified trapezoidal geometry to represent the estuarine channel, where width increases with elevation above the bottom (Figure 3). The model approximates an ideal shallow estuary having two elements: (1) a trapezoidal channel transporting all the momentum of the system and (2) shallow, sloping tidal flats which act in a storage capacity only. Equation (9) is solved over

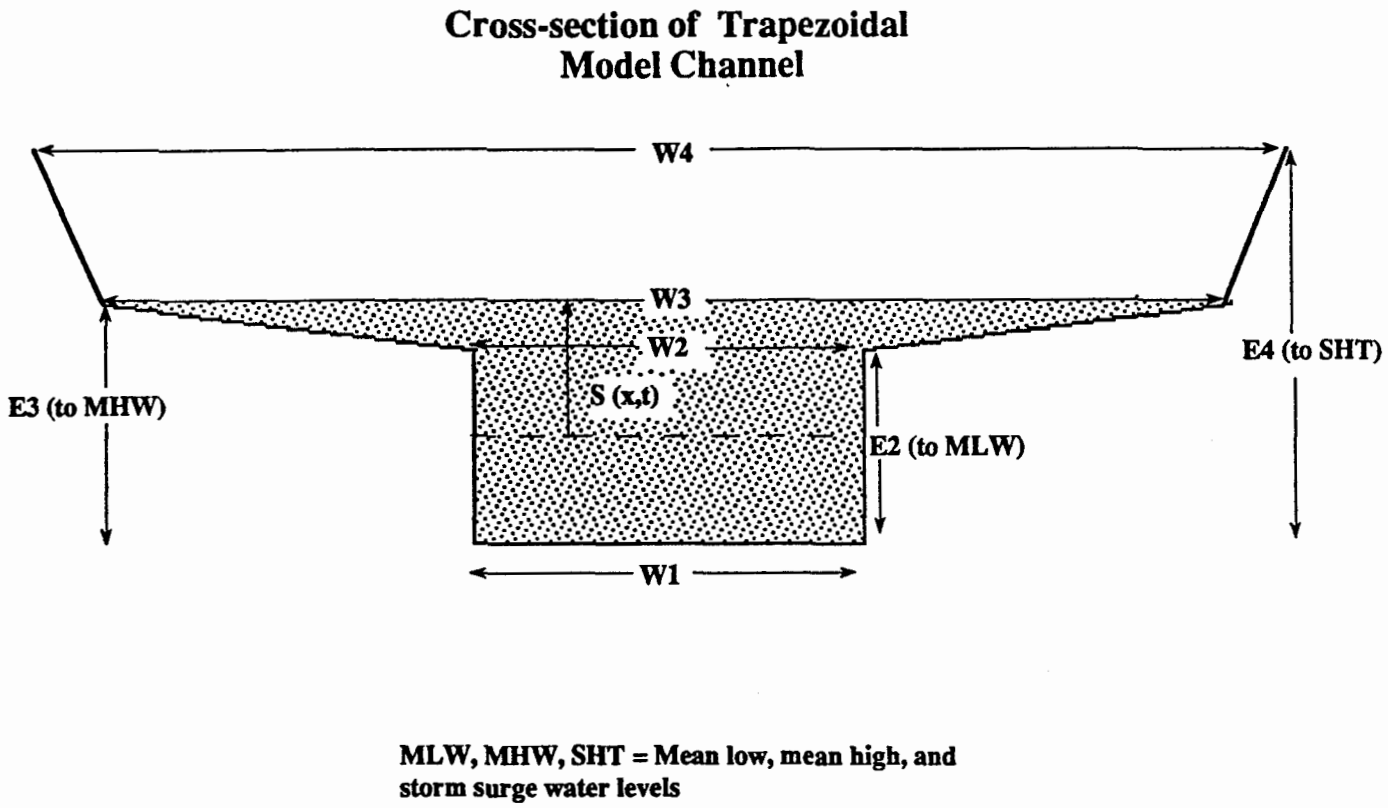

Figure 3. Trapezoidal Geometry Used To Represent Embayment Cross-Sections in the 1-D Numerical Model

the entire channel cross section, whereas Equation (10) is solved over the momentum-transporting portion of the cross section only. In Figure 3, the horizontal dimensions of the channel are given by the variables W1-W4, and the vertical dimensions are given by the variables E1-E4.

The fluctuating variables A, Q, and p are replaced by their discrete analogues in space and time. Continuous derivatives are replaced by centered differences in space and forward differences in time. Thus, the numerical approximations are accurate to first order in time and second order in space. Boundary conditions required to run the model are sea-surface elevation at the ocean boundary and flow conditions at the inland boundaries. Matching conditions at the channel intersections are continuity of sea-surface elevation and conservation of volume flux.

5.2 NUMERICAL MODEL SETUP

Setup for the 1-D numerical model requires that a model grid be developed, covering all areas of the estuarine system that are to be modeled. The grid may be composed of any number of branches (sections of the estuary extending from the main body of water) and nodes (equi-spaced cross sections along the branches). Model grids for the four Buzzards Bay embayments are described in the following paragraphs.

The model grid established for the Westport River is shown in Figure 4. Five branches were required to model the Westport River: the entrance channel, West Branch, the channel connecting West and East Branches, Horseneck Channel, and the East Branch. Nodes were equi-spaced at 125-m intervals within each of these branches. The number of nodes within the branches ranged from seven in the entrance channel to 45 in the East Branch. Ninety-two nodes were used to model the entire Westport River.

The model grid established for Aucoot Cove is shown in Figure 5. Only one branch, extending down the main axis of the embayment, was required to model the Cove. Nodes were equi-spaced at 125-m intervals; 14 nodes were used to model Aucoot Cove.

The numerical grid used to model the Wareham River is shown in Figure 6. Five branches were used to model the River: the lower Wareham River, Crooked River, the Central River between the

Figure 4. Numerical Model Grid for Westport River

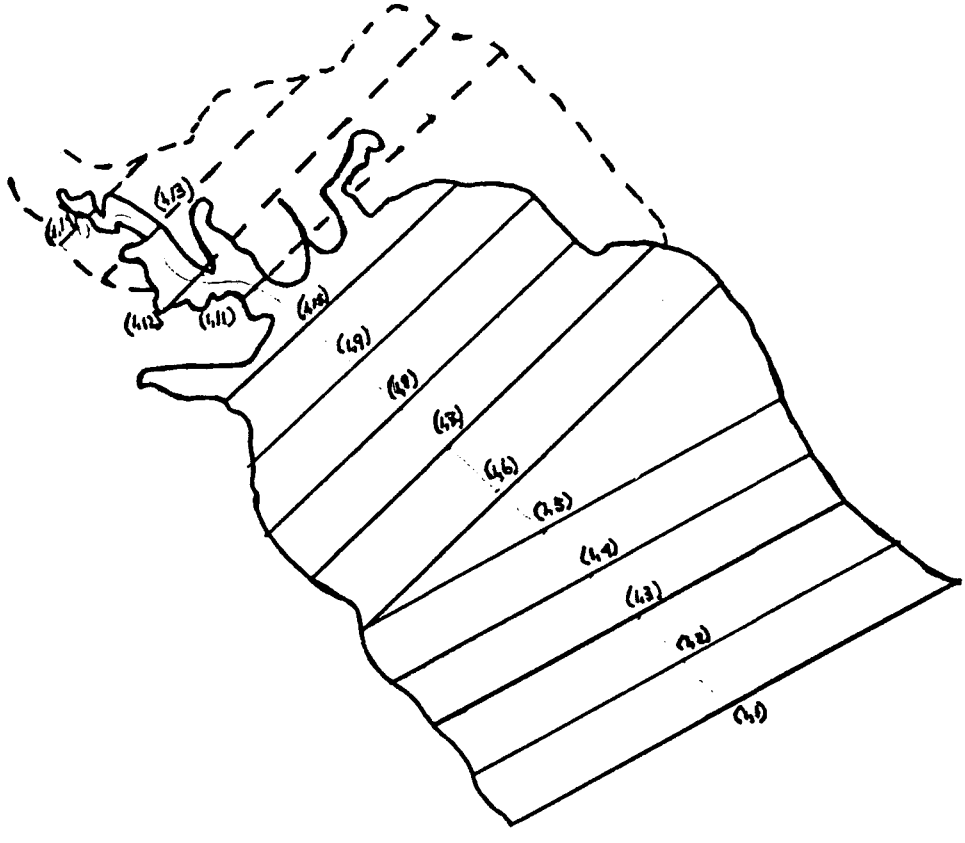

Figure 5. Numerical Model Grid for Aucoot Cove

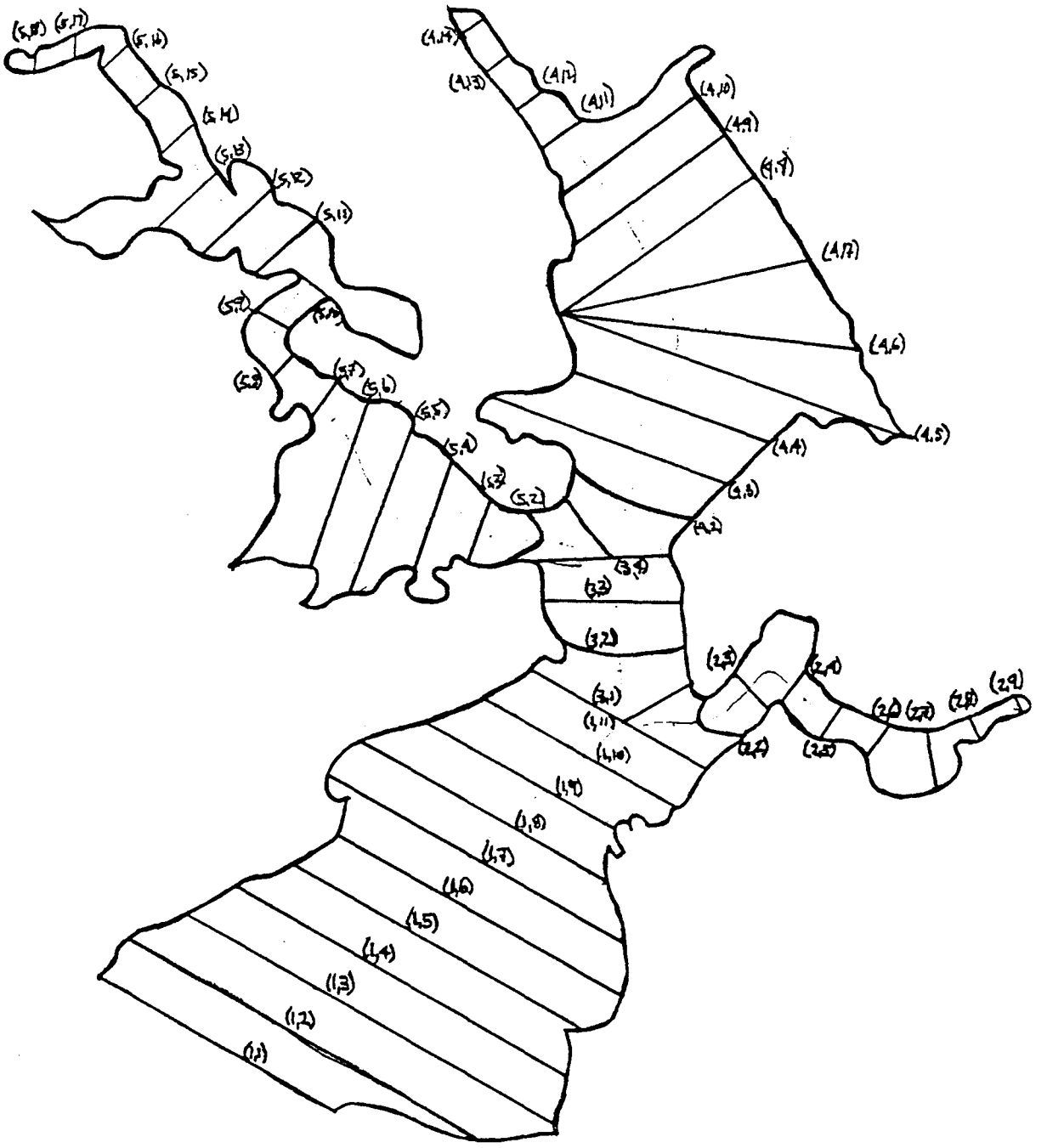

Figure 6. Numerical Model Grid for Wareham River

Crooked and Broad Marsh Rivers, the upper Wareham River, and the Broad Marsh River. Nodes were equi-spaced at 125-m intervals within each of these branches. The number of nodes within the branches ranged from four in the central Wareham River to 17 in the Broad Marsh River. Fifty-four nodes were used to model the Wareham River.

The numerical grid used to model Apponagansett Bay is shown in Figure 7. Five branches were used to model the Bay: the lower Apponagansett Bay, the upper Bay above Little Island, the central portion of the Bay, the northwest portion of the Bay, and the tidal creek and flats to the southwest of Apponagansett Bay. Grid nodes were equi-spaced at 125-m intervals within each of the five branches. The number of nodes within branches ranged from three in the central portion of the Bay to 21 in the lower Apponagansett Bay. Fifty-six nodes were used to model the entire Apponagansett Bay.

The embayment cross-sectional geometry must be supplied to the numerical model at each of the grid nodes. To accomplish this, NOAA bathymetric charts were overlain with the model grids and embayment cross sections were digitized at each of the node locations. The cross-section data were then averaged to fit the trapezoidal channel geometry required by the model. Elevations for the embayment bottom, MLW, mean high water (MHW), and storm surge were entered as E1, E2, E3, and E4, respectively (Figure 3). The corresponding widths of the embayment bottom, MLW, MHW, and storm-surge elevation along each cross-section were entered as W1, W2, W3, and W4, respectively. Therefore, the geometry of the modeled embayments was described in terms of the idealized trapezoidal geometry at each grid node.

5.3 CALIBRATION OF NUMERICAL MODEL

Calibration involves fine-tuning the numerical model so that it accurately reproduces the hydrodynamics of the system being modeled. Various hydrodynamic properties of an embayment can be used to calibrate the model, including tidal elevation, current velocity, and salinity. However, since fluctuations in tidal elevation are the primary factor controlling circulation within the Buzzards Bay embayments, calibration for this study was performed using existing measurements of tidal elevation taken at the Westport River. During calibration, the model results at a specific node in the grid are compared against actual field measurements at the same location. If the field measurements are not

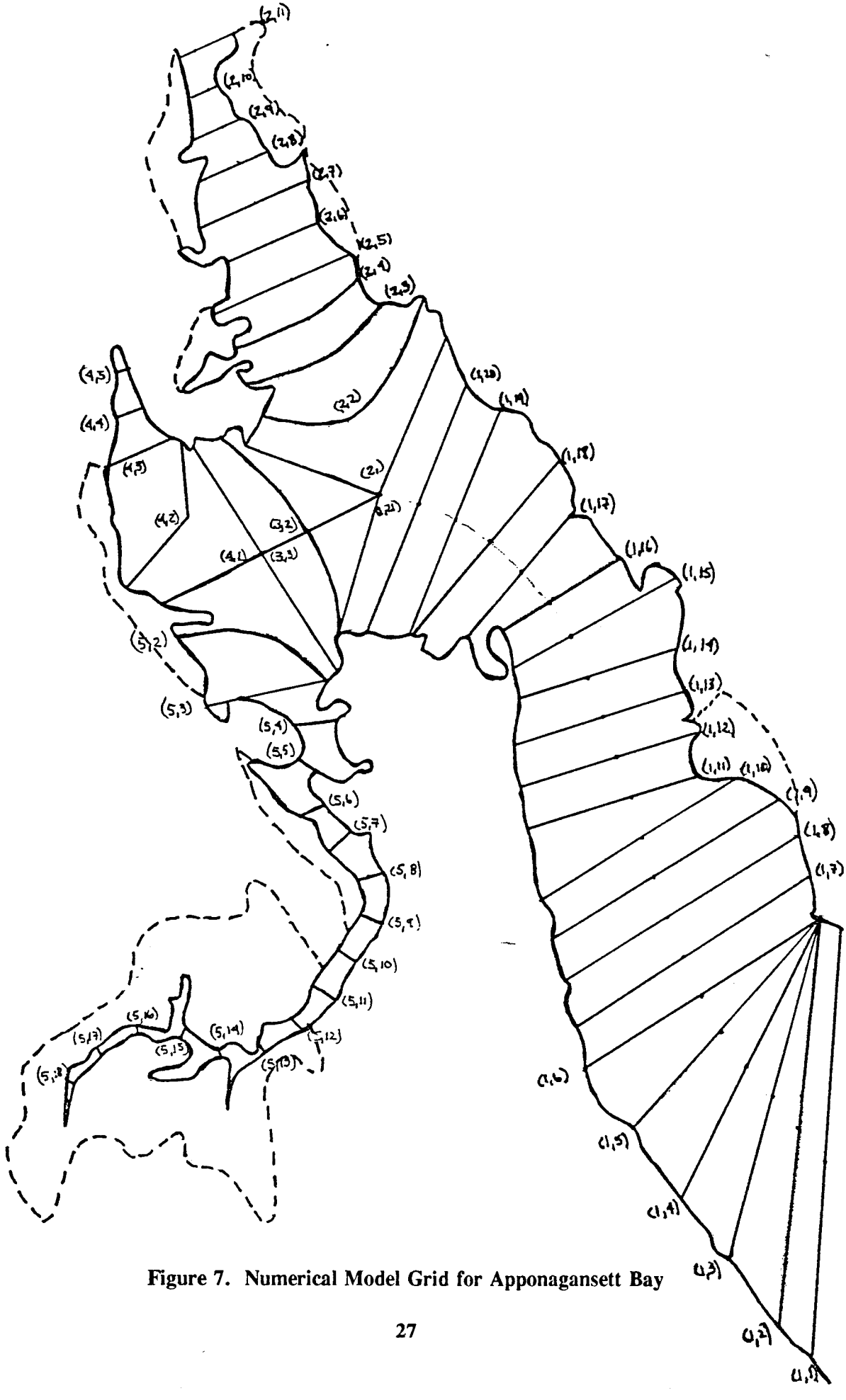

Figure 7. Numerical Model Grid for Apponagansett Bay

reproduced by the model simulations, the model is calibrated, or fine-tuned, by adjustment of the friction factor or the model geometry. This process continues until the field measurements are satisfactorily reproduced by the model.

Calibration of the 1-D model for the Westport River was conducted using existing measurements of tidal elevation collected during June 15-19, 1987, by the Woods Hole Oceanographic Institution. Tidal elevations measured at the Westport River entrance during this 5-day period were used to drive the model (Figure 8). Model results at branch 3 and node 6 (3,6) were compared with field measurements of tidal elevation collected at this location during the same 5-day period. The calibration curve showing a comparison between the model results and the field measurements is shown in Figure 9. The best fit between model predictions and the measured data was found using a friction factor of 0.01 in the Westport River entrance, and 0.03 in the upper reaches of branches 2, 4, and 5. These values are consistent with those found by other studies of shallow embayments in Massachusetts (e.g., Friedhrichs and Aubrey, 1988).

Field measurements of tidal elevation were not available for the remaining three embayments (Aucoot, Wareham, and Apponagansett). Therefore, model calibration was not possible for these areas. However, since the model was successfully calibrated for the Westport River, similar friction values can be used for the remaining embayments, with satisfactory results. Future field measurements collected in the Aucoot, Wareham, or Apponagansett embayments can be used to verify the model results presented in this study. Results from the 1-D model can be used to examine a variety of harbor management issues. For this study, the existing residence times within the four Buzzards Bay embayments were calculated. Results from these model applications are discussed below.

5.4 USE OF NUMERICAL MODEL TO PREDICT RESIDENCE TIMES

The 1-D model was used to examine the exchange of freshwater and saltwater between Buzzards Bay and the four selected embayments. Water quality within these embayments is highly dependent upon this exchange, which can be quantified by calculation of a residence time. The definition of residence time is the average time that a particular water parcel spends in the estuarine system. Long residence times indicate sluggish circulation and, often, poor water quality. Short residence times usually

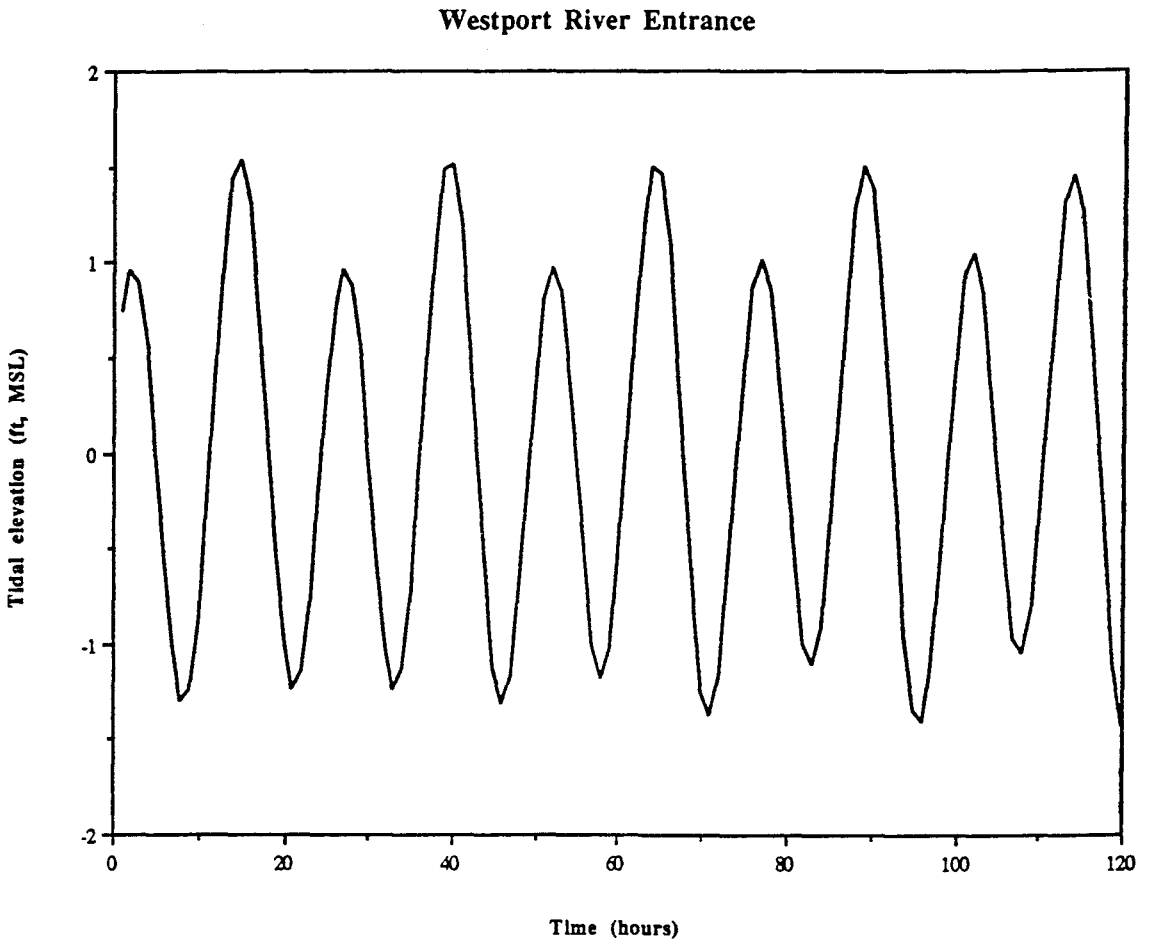

Figure 8. Measured Tidal Elevations at the Westport River Entrance During the Period 15-19 June 1987, Used To Calibrate the Numerical Model

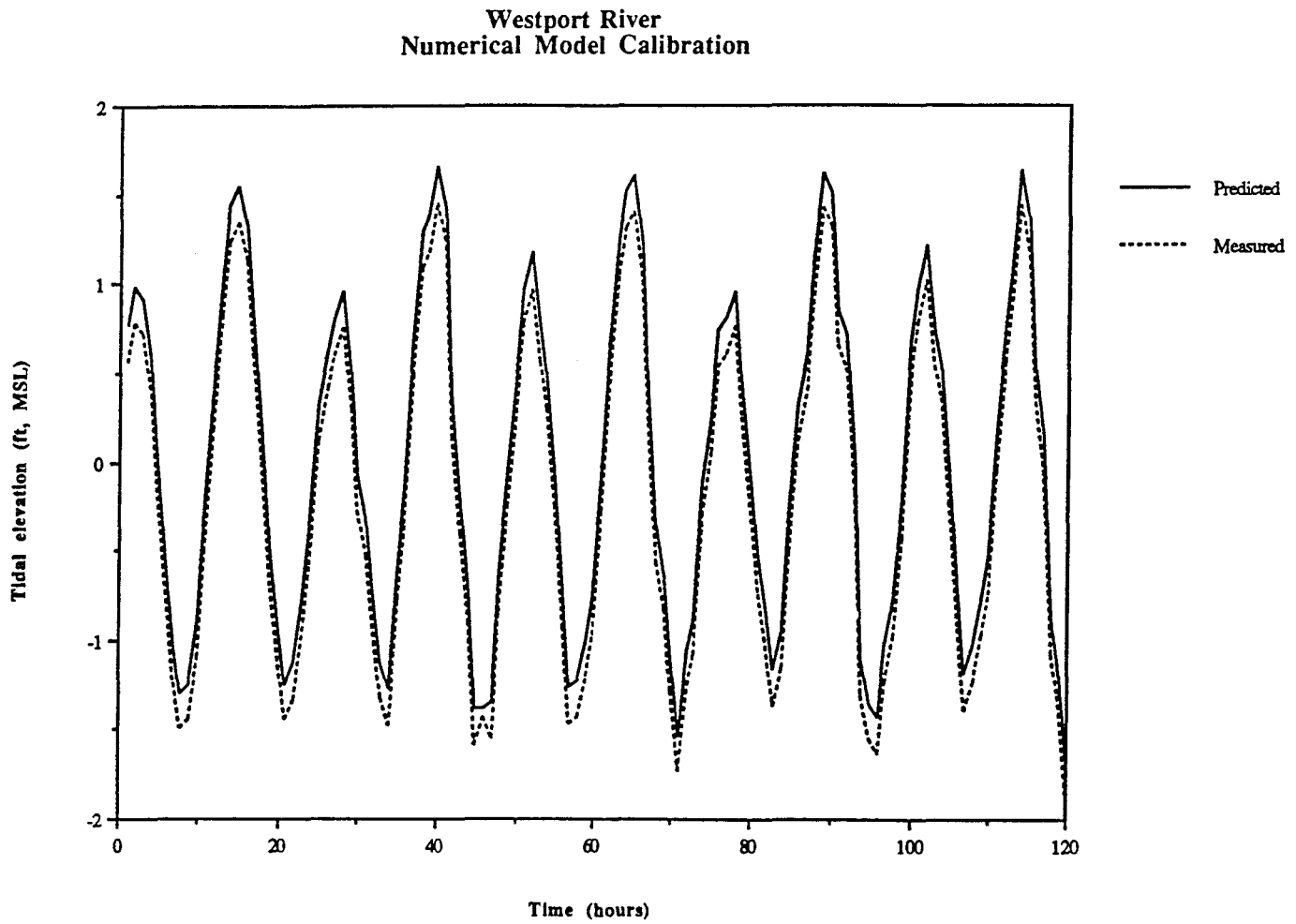

Figure 9. Calibration Curve Showing Measured and Predicted Tidal Elevations At the Westport River Bridge

indicate a rapid exchange of water between the open ocean and estuary, and can often be associated with better water quality.

Residence times were determined for various subsections within each embayment. The beginning and ending grid branch and node location for each subsection are shown in Table 8. The embayments were divided into subsections so that potential problem areas (areas with long residence times) could be identified. One calculation for the entire embayment would simply result in an average residence time, blending together those areas having longer and shorter residence times. From a management standpoint this would not be as desirable as residence time calculated for specific areas within the embayments.

Table 8. Buzzards Bay Embayment Subsections for Residence Time Calculations

Embayment	Subsection	Branch, Node Begin	Branch, Node End
Westport River:			
	West Branch	2,2	2,18
	East Branch	3,7	4,14 & 5,45
	entrance channel	1,1	2,1 & 3,6
Aucoot Cove:			
	central embayment	1,1	1,14
Wareham River:			
	lower embayment	1,1	2,1 & 4,1 & 5,1
	Crooked River	2,2	2,9
	upper embayment	4,2	4,14
	Broad Marsh River	5,2	5,18
Apponagansett Bay:			
	lower embayment	1,1	1,16
	central embayment	1,17	2,2 & 4,5 & 5,1
	upper embayment	2,3	2,11
	southwest marsh area	5,2	5,18

To calculate a residence time, the percent of total water volume exchanged (V_{ex}) during one tidal cycle must first be determined with the following equation:

$$V_{ex} = \frac{\sum Q_{flood}}{V} * 100 \tag{11}$$

where V is the volume of the water body at MLW and Q_{flood} is the cross-sectional volume flux integrated over one flood cycle. Values for Q_{flood} are output from the 1-D numerical model. This ratio represents the percentage of the embayment water volume that is flushed with water from Buzzards Bay during each flood cycle. Using the results from Equation (11), the residence time (T_{res}) can be calculated from the following equation:

$$T_{res} = \frac{1}{V_{ex}/100} * 0.518 \tag{12}$$

The multiplier of 0.518 in Equation (12) converts the units of T_{res} to residence time in number of days.

Embayment residence times fluctuate daily as a result of the diurnal inequalities of the tide. During periods of the fortnightly (14-day) cycle when the tidal range is greatest (spring tide), residence times are shorter because larger volumes of water are exchanged between Buzzards Bay and the adjoining embayments. Conversely, during periods when the the tidal range is lowest (neap tide), residence times are longer because less water is exchanged between Buzzards Bay and the embayments. To model these ranges in residence time properly, it is necessary to use the numerical model with both spring and neap tidal conditions.

The NOAA tidal tables were used to develop spring and neap tidal conditions for each of the four modeled embayments. The times and elevations of high and low water were taken from the tidal tables at NOAA stations located as close as possible to each embayment. A least-squares harmonic analysis was performed on the tidal data to derive the tidal constituents for the spring and neap cycles. The amplitude and phase of the M_2 (semi-diurnal) and K_1 (diurnal) constituents were then used to drive the numerical model. Table 9 summarizes these tidal constituents used for each embayment.

Table 9. Spring and Neap Tidal Constituents for Buzzards Bay Embayments

Embayment	M_2 amp (m)	M_2 phase (rads)	K_1 amp (m)	K_1 phase (rads)
Westport River:				
spring cycle	0.68	3.10	0.05	-1.45
neap cycle	0.30	0.04	0.11	-2.90
Aucoot Cove:				
spring cycle	0.95	0.43	0.29	-2.38
neap cycle	0.42	0.84	0.14	-2.47
Wareham River:				
spring cycle	0.91	-2.26	0.08	-0.71
neap cycle	0.39	-0.05	0.13	-2.89
Apponagansett Bay:				
spring cycle	0.83	0.40	0.08	-2.49
neap cycle	0.37	0.85	0.12	-2.49

5.5 NUMERICAL MODEL RESULTS

Tables 10 through 13 summarize the results from model calculations of residence time for the Westport River, Aucoot Cove, Wareham River, and Apponagansett Bay, respectively. The East and West Branches of the Westport River show residence times ranging from 5 (spring cycle) to 11.5 (neap cycle) days. In both cases, the residence times for the East Branch are greater than those for the West Branch. The entrance channel area shows residence times of 2 to 4 days. Predicted residence times from the numerical model fall in the middle of the predicted residence times resulting from analytical techniques #1 and #2.

Table 10. Predicted Spring and Neap Residence Times for the Westport River

Tidal Cycle	Subsection	% of Total Volume Exchange during One Tidal Cycle	Residence Time (days)
Spring:	West Branch	10.4	5.0
	East Branch	9.5	5.4
	Entrance channel	27.8	1.9
Neap:	West Branch	5.1	10.2
	East Branch	4.5	11.5
	Entrance channel	12.9	4.0

Aucoot Cove shows residence times ranging from 6.6 (spring cycle) to 14.5 (neap cycle) days. These residence times are considerably greater than those predicted by analytical techniques #1 and #2. Model #2 does not work well here because the Cove is so equidimensional that the current velocities are extremely low and shear dispersion is weak. The 1-D model apparently does a poor job in this strongly two-dimensional embayment. The numerical model appears to over-predict the residence time.

Table 11. Predicted Residence Times for Aucoot Cove

Tidal Cycle	Subsection	% of Total Volume Exchange during One Tidal Cycle	Residence Time (days)
Spring:	Central embayment	7.9	6.6
Neap:	Central embayment	3.6	14.5

The Wareham River shows residence times ranging from 1.6 (spring cycle) to 8 (neap cycle) days. The upper embayment consistently displays greater residence times than other sections of the Wareham River. This results from decreased water depths and narrowing of the channel which causes a reduction in the volume of water entering this part of the embayment. The Crooked and

Broad Marsh Rivers both show relatively short residence times compared to other sections of the embayment. This is likely due to the draining of major portions of these rivers during each tidal cycle, which causes complete replacement of water during each tidal cycle. Predicted residence times from the numerical model are comparable to those calculated using analytical technique #2 and longer than those calculated using technique #1.

Table 12. Predicted Residence Times for the Wareham River

Tidal Cycle	Subsection	% of Total Volume Exchange during One Tidal Cycle	Residence Time (days)
Spring:	Lower embayment	22.9	2.2
	Crooked River	31.6	1.6
	Upper embayment	14.8	3.5
	Broad Marsh River	24.6	2.1 3.6
Neap:	Lower embayment	10.4	5.0 2.4
	Crooked River	16.4	3.2
	Upper embayment	6.5	8.0 5.75
	Broad Marsh River	11.6	4.5 3.3

Apponagansett Bay shows residence times which range from 0.9 (spring cycle) to 9.6 (neap cycle) days. The lower embayment exhibits the longest residence time primarily because of its large storage volume and great length. The shortest residence times occur in the southwest marsh area. This section of the embayment contains portions that drain completely during each tidal cycle, causing complete replacement of water during the tidal cycle and correspondingly short residence times. Predicted residence times from the numerical model are comparable to those calculated with analytical technique #2 but longer than those calculated with technique #1.

Table 13. Predicted Residence Times for Apponagansett Bay

Tidal Cycle	Subsection	% of Total Volume Exchange during One Tidal Cycle		Residence Time (days)
Spring:	Lower embayment		11.4	4.6
	Central embayment	31.7		1.6
	Upper embayment	24.2		2.1
	Southwest marsh area	57.4		0.9
Neap:	Lower embayment		5.4	9.6
	Central embayment	15.4		3.4
	Upper embayment	11.8		4.4
	Southwest marsh area	24.9		2.1

6.0 DISCUSSION

First-order flushing rates for Buzzards Bay embayments were computed by two different analytical techniques. The results from the two analytical techniques differ in some embayments but are nearly identical in others. This disagreement is due in part to the limited physics considered by each analytical model.

Analytical technique #1, or the box model, calculates residence time in terms of dilution of the embayment water by the tidal prism. This technique assumes complete mixing of oceanic water with embayment water. The box model typically underestimates the residence time because the total volume introduced during the flood, in general, is not completely mixed with the low tide volume. The tendency for the box model to underestimate the residence time is especially true for the longer and deeper embayments. In these cases, it is clear that the box model assumes more complete mixing, and therefore a shorter residence time, than occurs in nature.

Analytical technique #2, or the spatial model, calculates residence time as a function of position within the embayment. While the model assumes that the embayment is not vertically stratified, it does allow strong longitudinal gradients (salinity, density) to exist. The model assumes that the average residence time is independent of the origin of the water parcel, and that the residence time is

dependent only on the location of the water parcel within the embayment. The effects of mixing in the spatial model are considered through the use of a dispersion coefficient. This coefficient accounts for mixing due to salinity and density gradients, winds, and shear flow.

Since residence times calculated with the spatial model are proportional to the squared length of the embayment, the length is naturally a strong determinant of the residence time. For embayments with similar dispersion coefficients, greater residence times are always found in the longer embayments. Residence times from the spatial model are also strongly dependent on the dispersion coefficient. In general, larger dispersion coefficients result in shorter residence times. Dispersion coefficients reported in the literature vary widely for different areas, depending on a variety of physical parameters including water depth, mean tidal velocity, embayment width, and tidal period. As such, dispersion coefficients vary according to the position within the embayment and the physical processes acting there. Although dispersion coefficients can be determined using empirical approximations, field measurements are desirable to gain more confidence in these values.

A third technique, used to estimate flushing rates within four selected Buzzards Bay embayments, involved the use of a 1-D numerical model. This model was used to quantify the exchange of water between Buzzards Bay and the adjoining embayments by solving the cross-sectionally integrated conservation equations for mass and momentum. The geometry of each embayment was described by equally-spaced trapezoidal cross-sections; the true volume of the embayment was thereby maintained throughout the model simulations. Representative spring and neap tidal characteristics for each embayment were used to drive the model.

For all embayments except Aucoot Cove, the numerical model estimates of residence time are consistent with analytical technique #2, and generally higher than technique #1. For Aucoot Cove the numerical model appears to overpredict the residence time. It is likely that the 1-D model does not work well here because of the equi-dimensional shape of the Cove. This morphology causes extremely low current velocities in the numerical model, and therefore results in low shear dispersion and mixing. For the remaining three embayments, the numerical model provides estimates of residence times comparable to those calculated with analytical technique #2. Since the embayment morphology and physical parameters are more accurately defined in the numerical modeling approach,

the numerical model provides a more defensible estimate of residence time than the broader analytical techniques.

For comparison purposes, a limited number of flushing studies on Buzzards Bay embayments currently exist. Fish (1989) conducted a numerical simulation of tidal circulation patterns of Buttermilk Bay. Tidal prism and bay volume data were used to calculate an average residence time of 4 days. Similar estimates for Buttermilk Bay (2.7-4.0 days) were calculated with analytical technique #2. A pollution study of the Westport River, East Branch, was published by Kelly *et al.* (1986). Mean tidal and freshwater discharge data were used to calculate a residence time of 31-34 days for the Westport River, East Branch. Similar estimates of 39.8-59.6 days were calculated with analytical technique #2.

All estimates cited in this report assume that tidal dispersion alone controls the residence time. In fact, residence time can be decreased by wind, freshwater inflow, and complex topography. Residence time also can be increased by density stratification. The present estimates of residence time are consistent, and are representative of the relative ease of flushing, and hence should be defensible for management purposes. However, all of these estimates can be improved by utilizing more complete bathymetry data, better knowledge of the tidal characteristics, and better estimates of local dispersion coefficients.

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Appendix A

CUMULATIVE SURFACE AREAS FOR 1-M CONTOUR INTERVALS

	Water Depth (m)	Area (sq m)	Cumulative % to Depth
Acushnet River, upper:	0-1	1,052,200	24.6
	1-2	1,165,100	51.9
	2-3	609,800	66.1
	3-4	215,900	71.2
	4-5	153,800	74.8
	5-6	130,600	77.9
	6-7	128,800	80.9
	7-8	382,300	89.8
	8-9	298,300	96.8
	9-10	80,800	98.7
	10-11	28,900	99.4
	11-12	4,400	99.5
	12-13	12,900	99.8
	>13	7,800	100.0
Acushnet River, total:	0-1	1,757,200	16.3
	1-2	2,140,300	36.3
	2-3	1,353,500	48.9
	3-4	1,385,300	61.8
	4-5	897,700	70.2
	5-6	883,800	78.4
	6-7	792,800	85.8
	7-8	792,900	93.2
	8-9	591,800	98.7
	9-10	80,800	99.5
	10-11	28,900	99.7
	11-12	4,400	99.8
	12-13	12,900	99.9
	>13	7,800	100.0
Allens Pond:	0-1	770,300	100.0
Apponagansett Bay, upper:	0-1	1,298,200	84.5
	1-2	176,200	95.9
	2-3	47,500	99.0
	>3	14,100	100.0
Apponagansett Bay, total:	0-1	1,600,000	54.6
	1-2	372,000	67.3
	2-3	192,300	73.9
	3-4	327,300	85.0
	4-5	282,700	94.7
	>5	153,800	100.0
Aucoot Cove:	0-1	558,600	43.4
	1-2	179,200	57.4
	2-3	122,400	66.9
	3-4	112,800	75.7
	4-5	106,700	83.9
	>5	205,800	100.0

	Water Depth (m)	Area (sq m)	Cumulative % to Depth
Brant Island Cove:	0-1	256,200	74.4
	1-2	73,300	95.8
	>2	14,400	100.0
Buttermilk Bay:	0-1	870,100	40.0
	1-2	1,136,200	92.4
	>2	164,800	100.0
Clarks Cove:	0-1	357,600	12.5
	1-2	236,800	20.7
	2-3	305,700	31.4
	3-4	498,700	48.8
	4-5	975,500	82.9
	5-6	373,500	96.0
	>6	113,400	100.0
Hens Cove:	0-1	168,100	65.4
	>1	88,800	100.0
Marks Cove:	0-1	308,900	72.6
	1-2	85,000	92.6
	>2	31,500	100.0
Mattapoisett Harbor, upper:	0-1	452,800	28.4
	1-2	100,000	34.7
	2-3	143,800	43.7
	3-4	370,900	67.0
	4-5	396,300	91.9
	>5	128,000	100.0
Mattapoisett Harbor, total:	0-1	1,018,000	23.5
	1-2	215,900	28.5
	2-3	220,500	33.7
	3-4	591,100	47.4
	4-5	803,000	66.0
	5-6	539,400	78.5
	6-7	452,100	88.9
	>7	475,500	100.0
Nasketucket Bay:	0-1	841,000	41.0
	1-2	454,900	63.1
	2-3	501,400	87.6
	>3	253,900	100.0
Onset Bay:	0-1	1,298,400	54.2
	1-2	471,000	73.9
	2-3	445,100	92.6
	>3	176,800	100.0

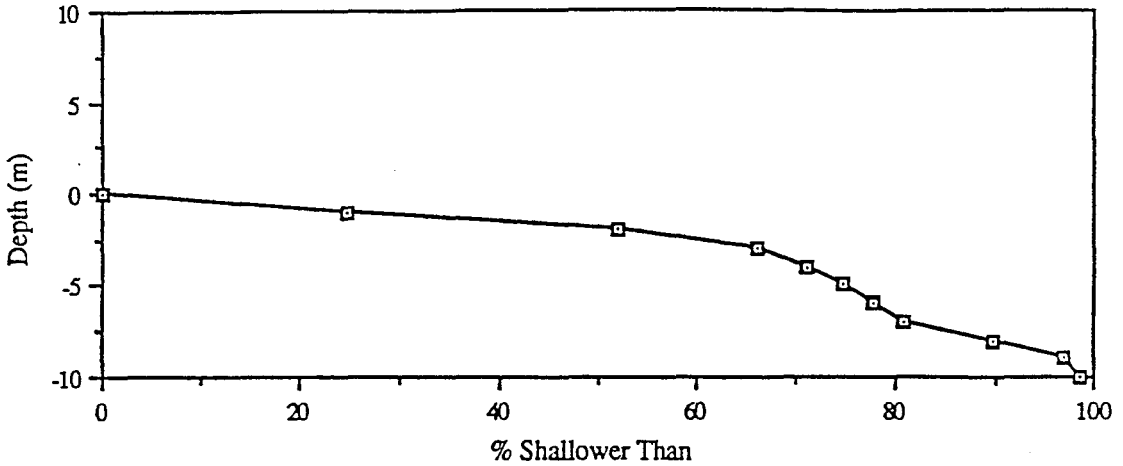
	Water Depth (m)	Area (sq m)	Cumulative % to Depth
Phinneys Harbor:	0-1	924,300	42.5
	1-2	442,000	62.9
	2-3	284,900	76.0
	3-4	185,300	84.6
	4-5	204,800	94.0
	5-6	9,400	94.4
	6-7	31,400	95.9
	7-8	65,600	98.9
	>9	22,500	100.0
Pocassett River:	0-1	526,600	66.0
	1-2	237,300	95.8
	2-3	3,400	96.2
	3-4	19,800	98.7
	>5	9,900	100.0
Quissett Harbor:	0-1	189,700	40.1
	1-2	146,300	71.2
	2-3	76,300	87.3
	3-4	35,800	94.9
	>5	23,800	100.0
Red Brook Harbor:	0-1	177,200	29.1
	1-2	107,000	46.7
	>3	323,800	100.0
Sippican Harbor, upper:	0-1	768,900	45.1
	1-2	367,400	66.7
	2-3	467,300	94.1
	>3	99,900	100.0
Sippican Harbor, total:	0-1	2,092,700	28.0
	1-2	1,558,000	49.0
	2-3	934,600	61.5
	3-4	808,500	72.3
	4-5	1,239,200	89.0
	5-6	786,400	99.5
	>6	31,500	100.0
Slocums River:	0-1	1,662,700	84.3
	1-2	157,300	92.3
	2-3	141,700	99.5
	>3	9,200	100.0
Squeteague Harbor:	0-1	241,000	79.4
	1-2	32,600	90.2
	>2	29,600	100.0
Wareham River:	0-1	1,767,400	70.9
	1-2	354,000	85.1
	2-3	312,800	97.7
	>3	57,200	100.0

	Water Depth (m)	Area (sq m)	Cumulative % to Depth
West Falmouth Harbor:	0-1	740,900	92.0
	>1	63,700	100.0
Westport River, East Branch:	0-1	6,687,000	83.3
	1-2	715,500	92.2
	2-3	445,500	97.8
	3-4	137,800	99.5
	4-5	15,700	99.7
	5-6	20,300	99.9
	>6	2,500	100.0
Westport River, West Branch:	0-1	4,484,800	84.2
	1-2	379,600	91.3
	2-3	253,300	96.1
	>3	206,200	100.0
Weweantic River:	0-1	1,448,500	60.8
	1-2	459,300	80.1
	2-3	355,600	95.0
	>3	118,200	100.0
Widows Cove:	0-1	306,000	56.4
	>1	236,200	100.0
Wild Harbor:	0-1	341,400	69.1
	1-2	70,500	83.4
	2-3	21,000	87.7
	3-4	28,700	93.5
	>4	31,800	100.0
Wings Cove:	0-1	489,400	55.8
	1-2	156,100	73.7
	2-3	105,600	85.7
	3-4	87,100	95.7
	>4	37,700	100.0

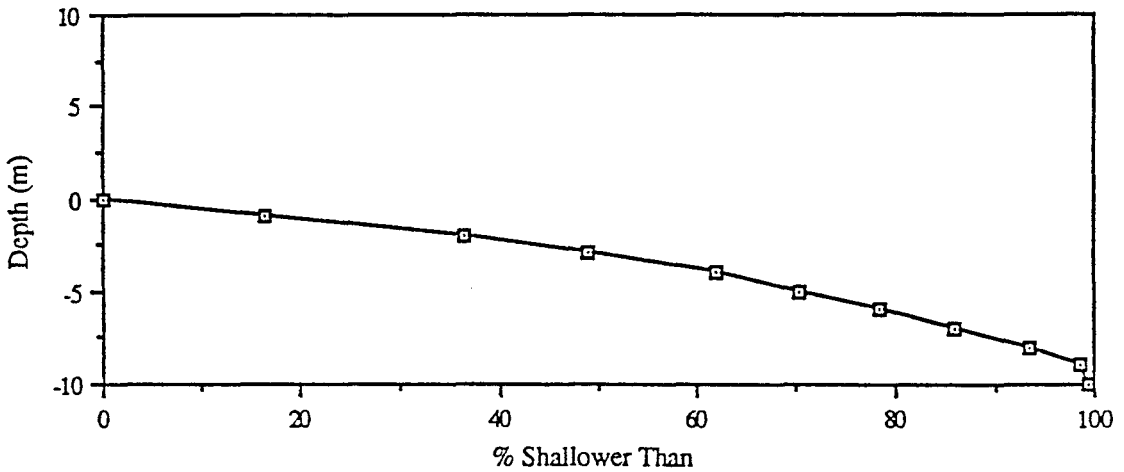
Appendix B

HYPSOMETRIC CURVES

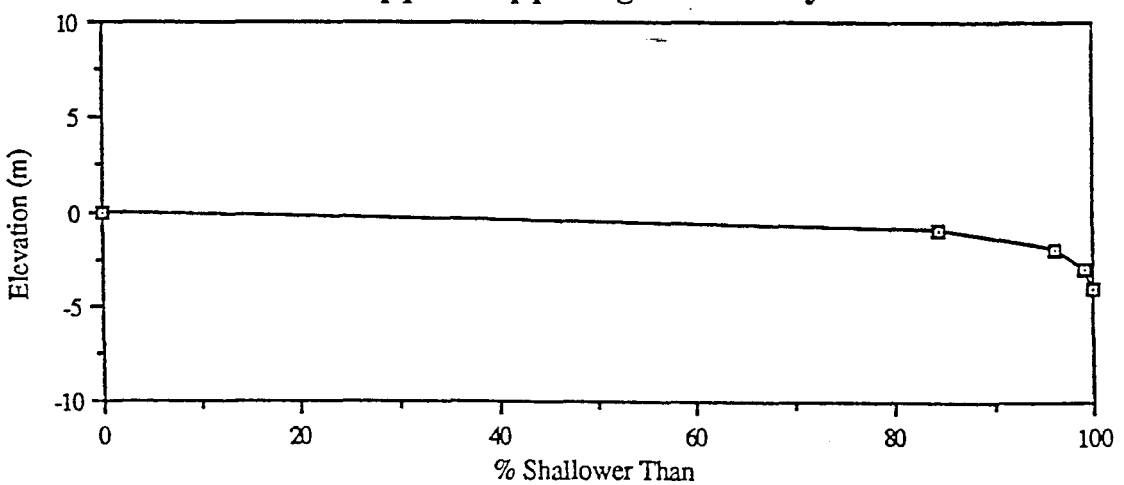
Lower Acushnet River



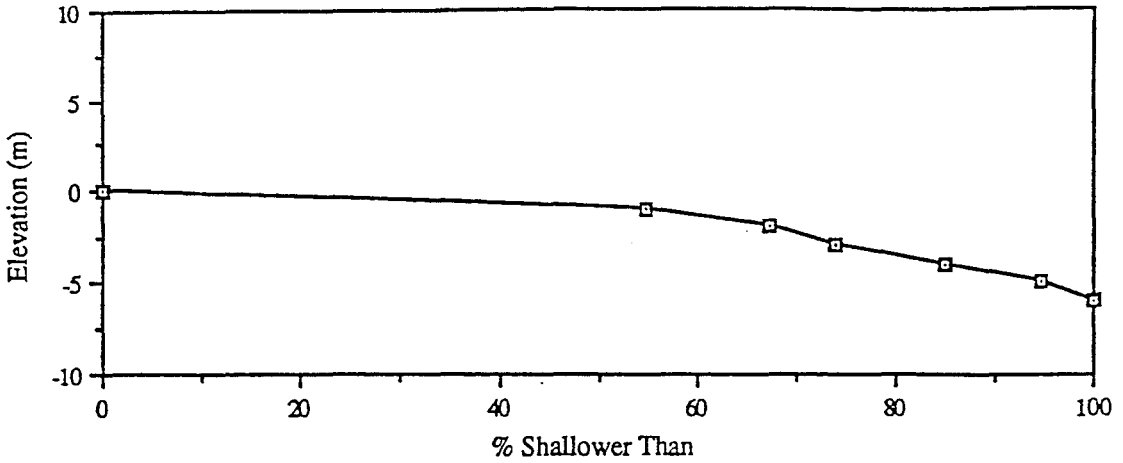
Acushnet River



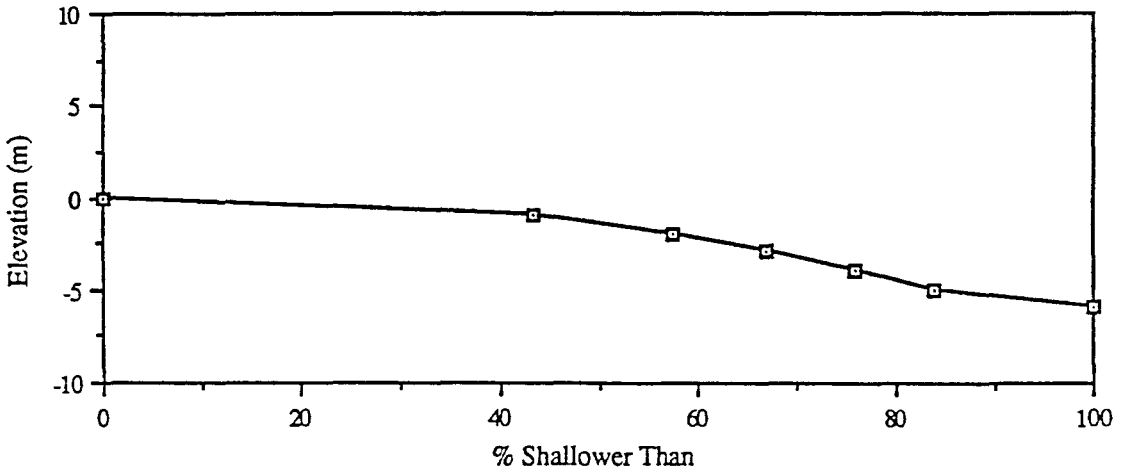
Upper Apponagansett Bay



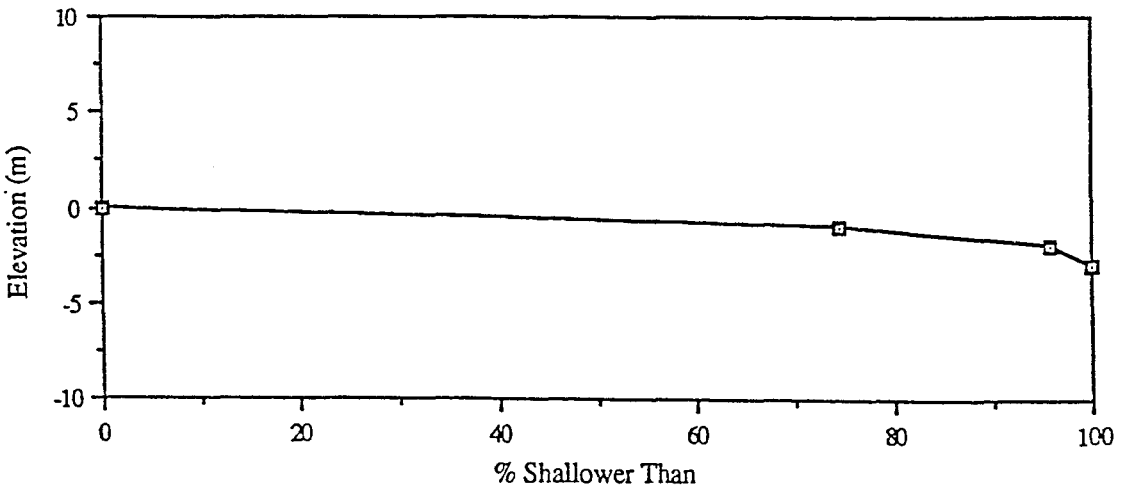
Apponagansett Bay



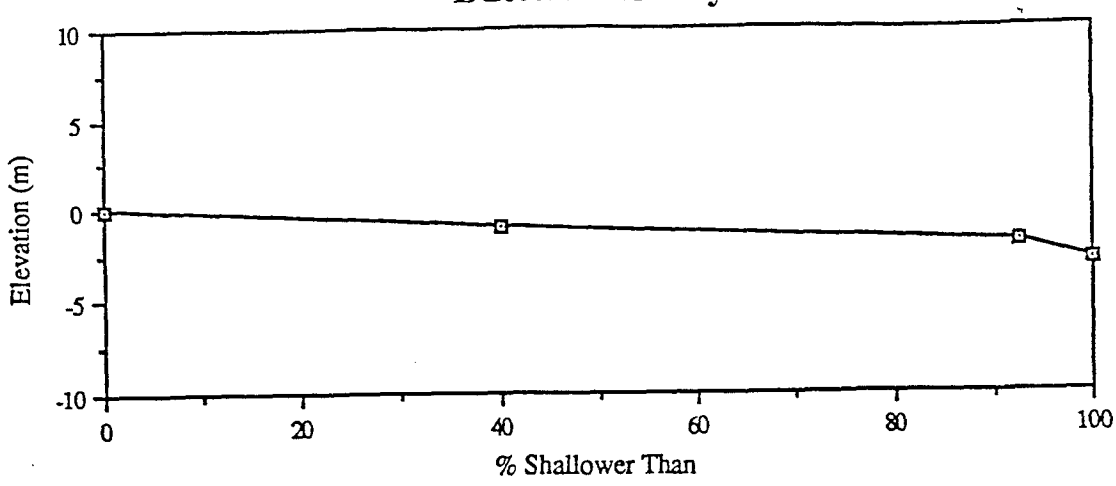
Aucoot Cove



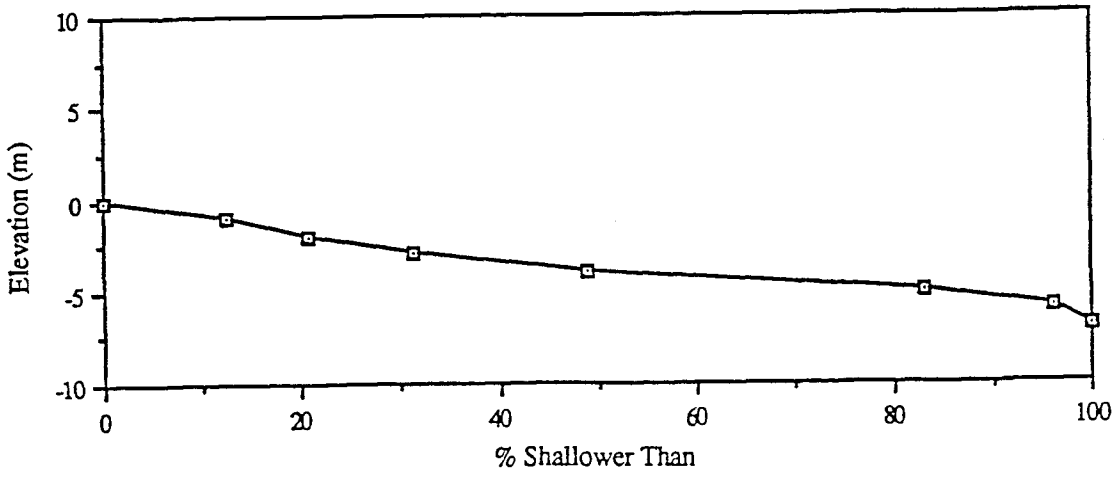
Brant Island Cove



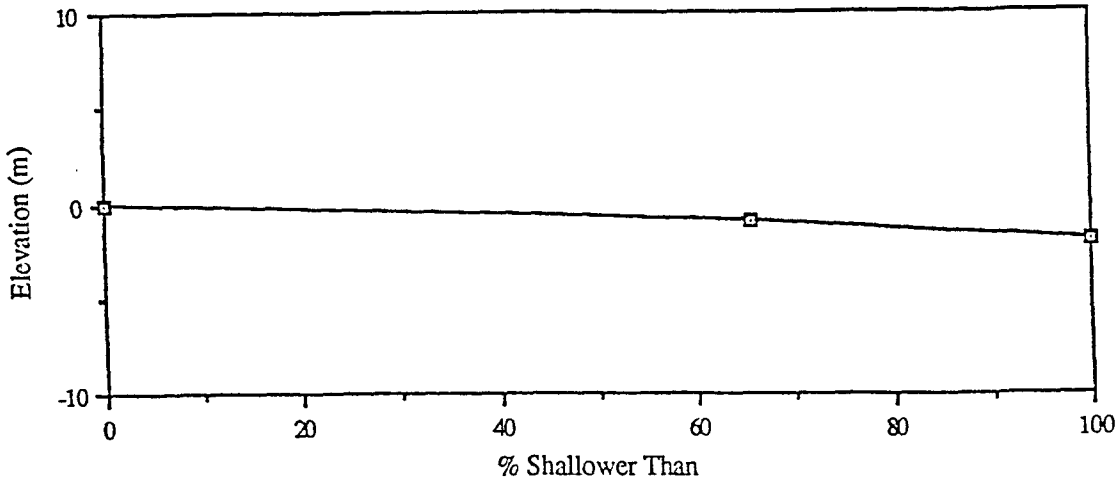
Buttermilk Bay



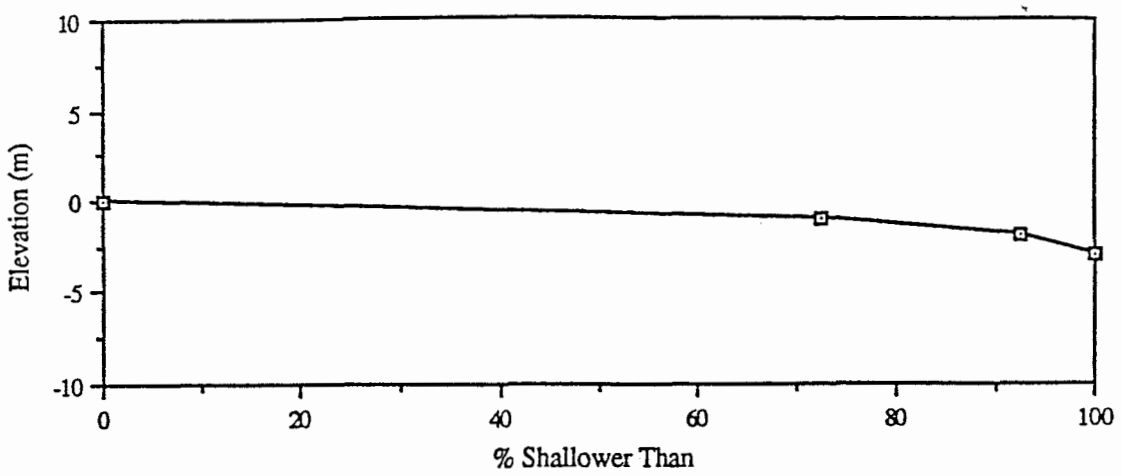
Clarks Cove



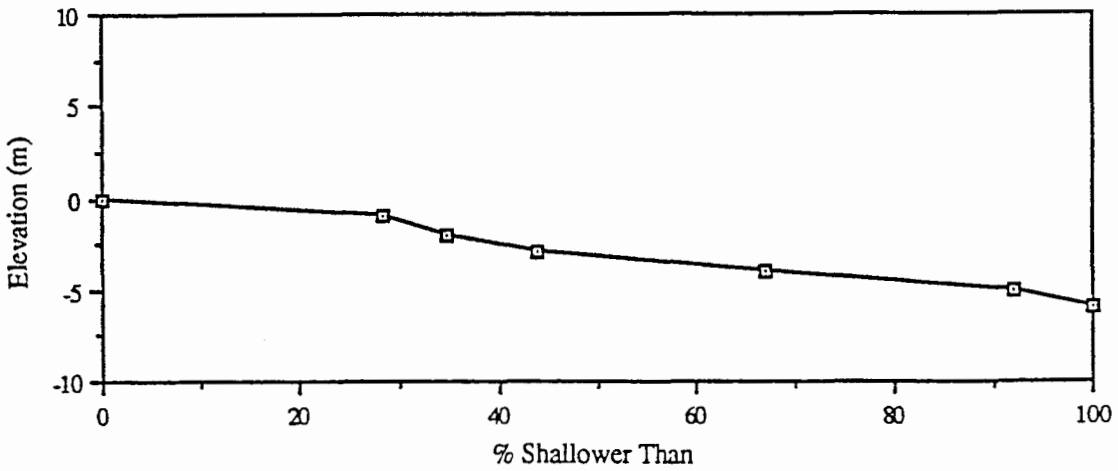
Hens Cove



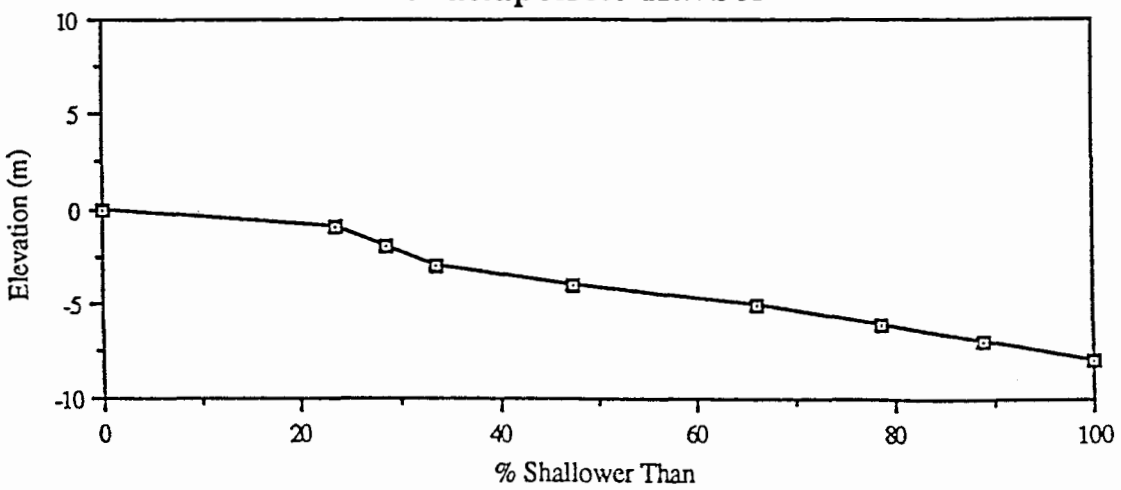
Marks Cove



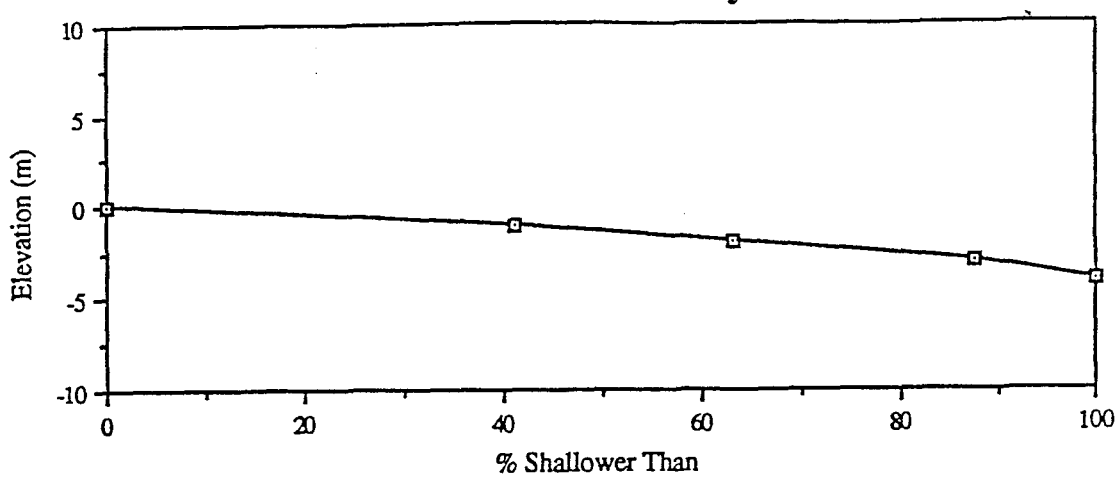
Upper Mattapoisett Harbor



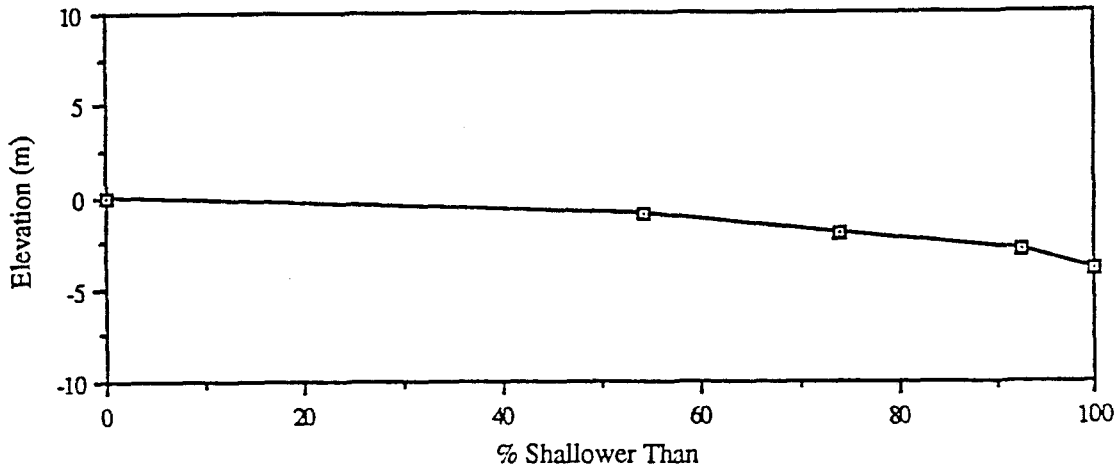
Mattapoisett Harbor



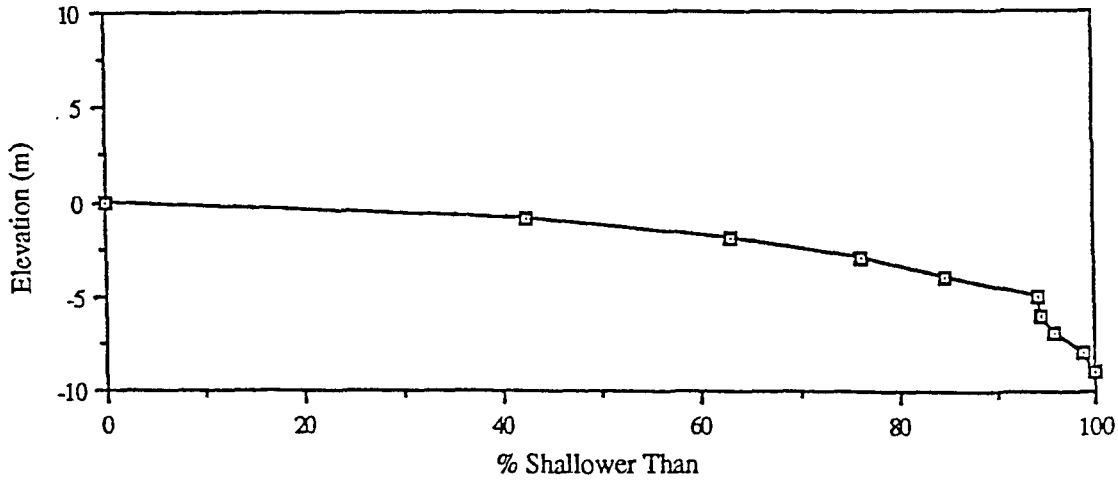
Nasketucket Bay



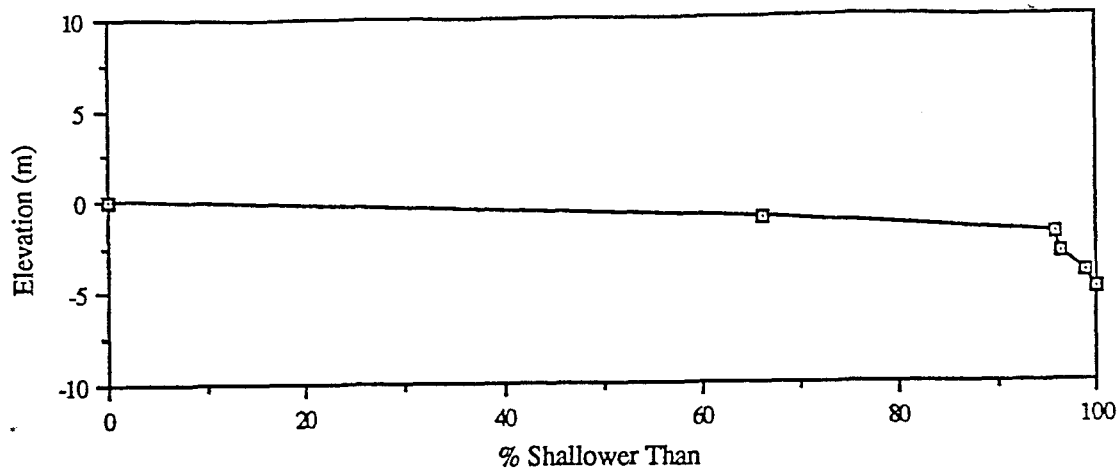
Onset Bay



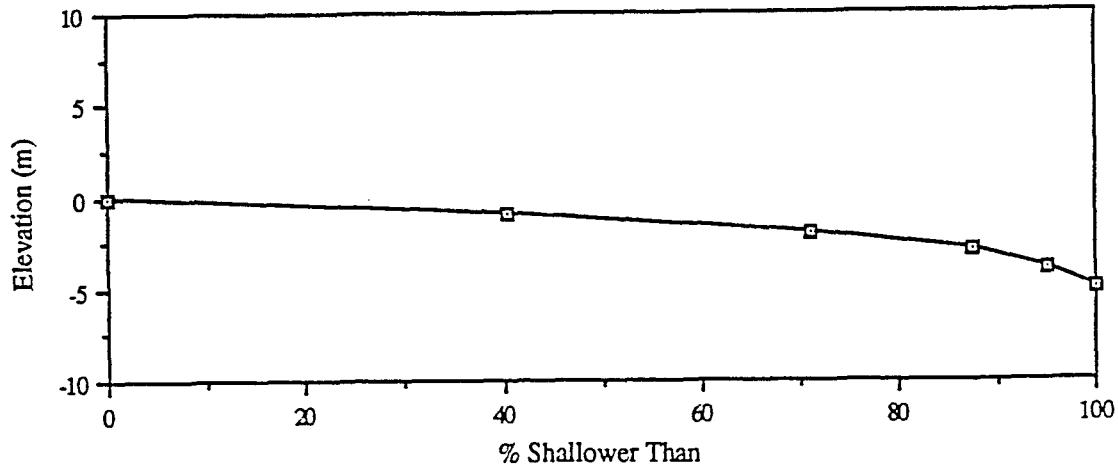
Phinneys Harbor



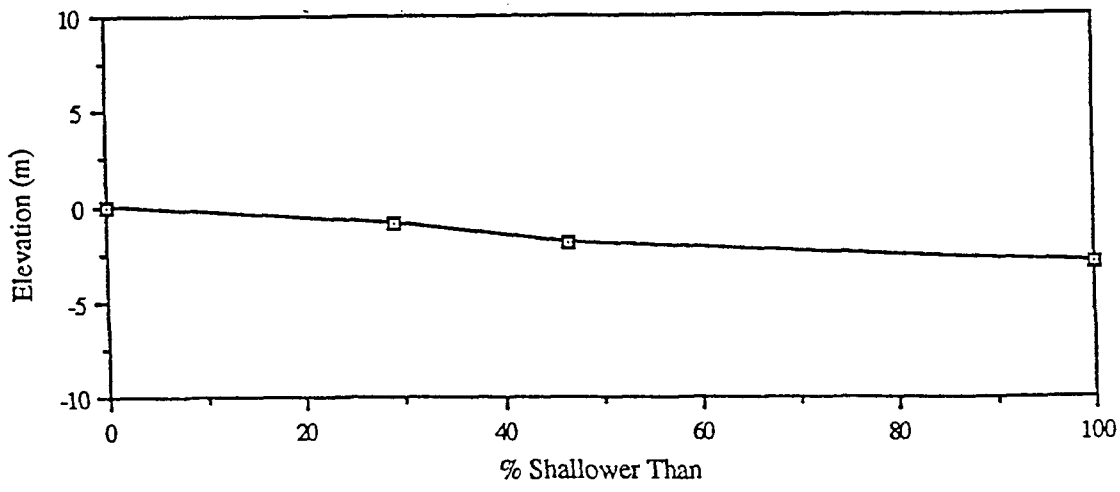
Pocasset River



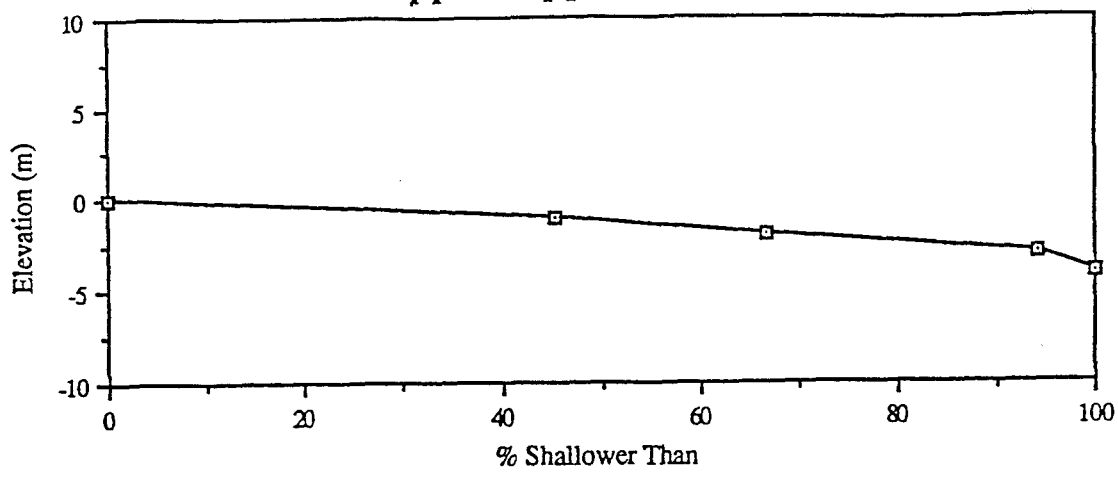
Quissett Harbor



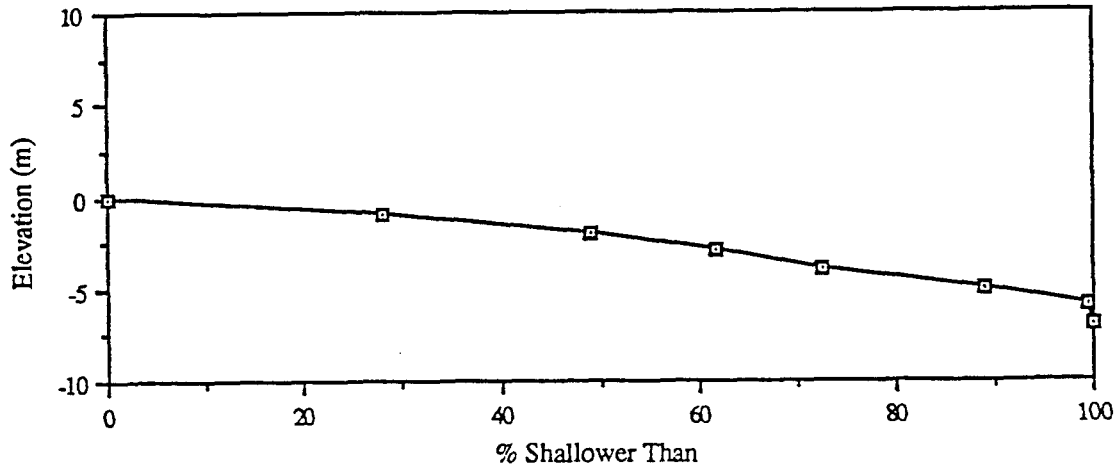
Red Brook Harbor



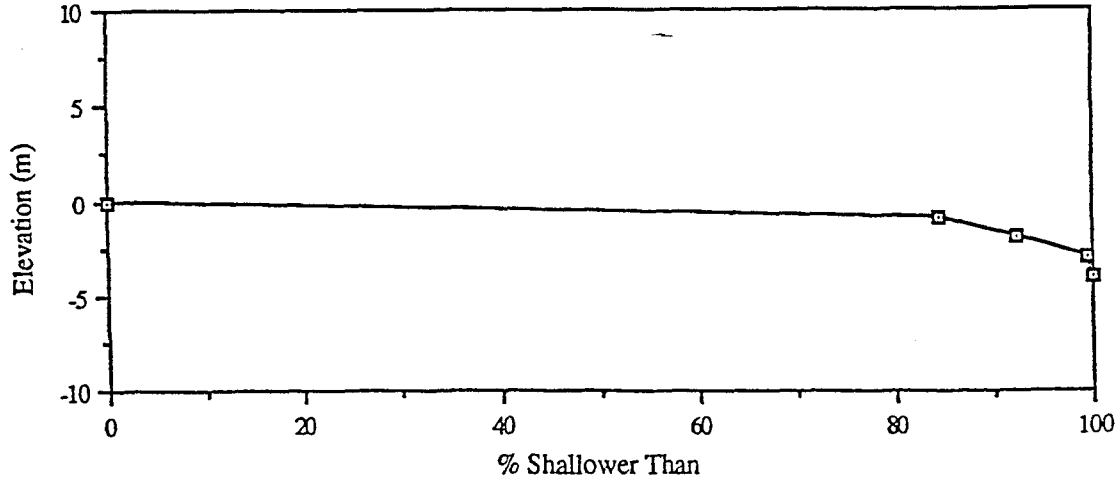
Upper Sippican Harbor



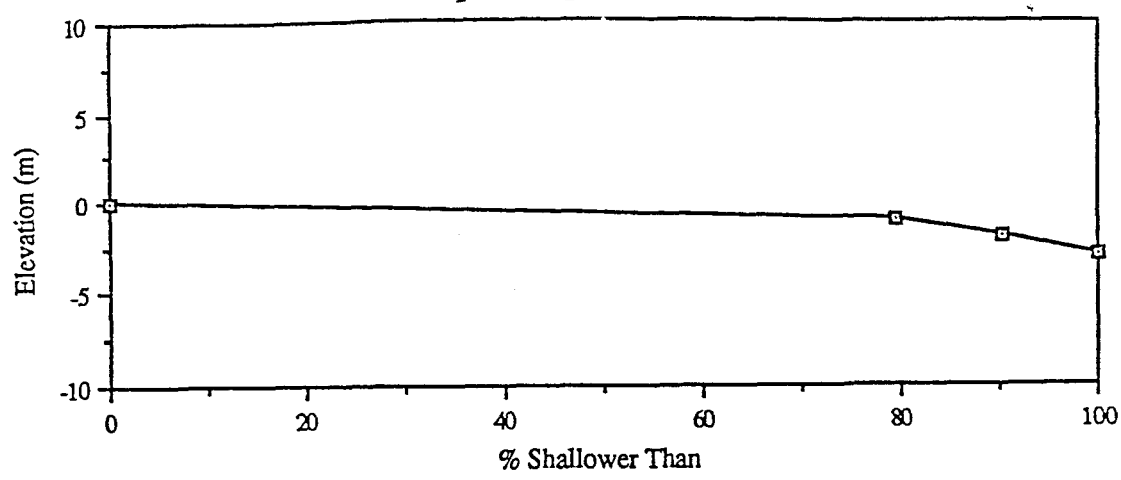
Sippican Harbor



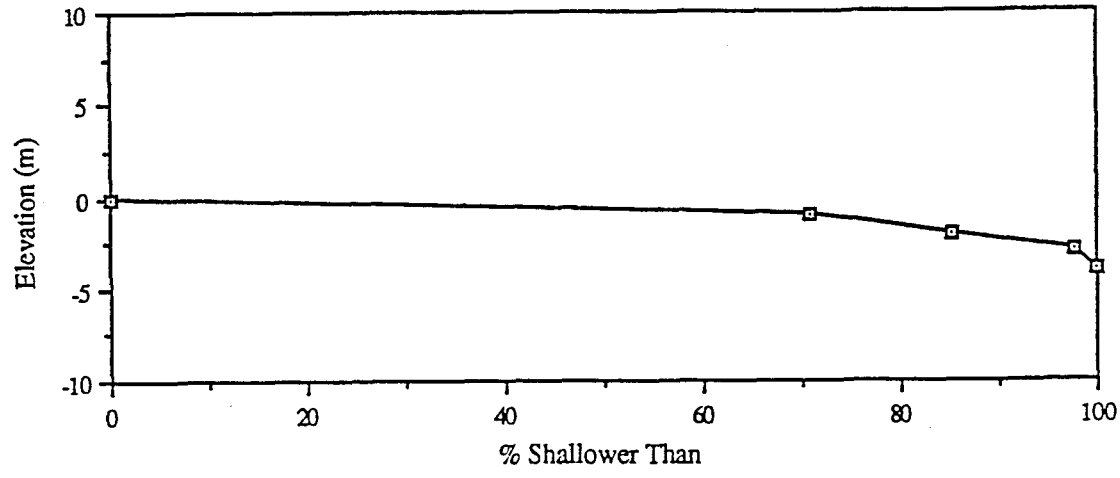
Slocums River



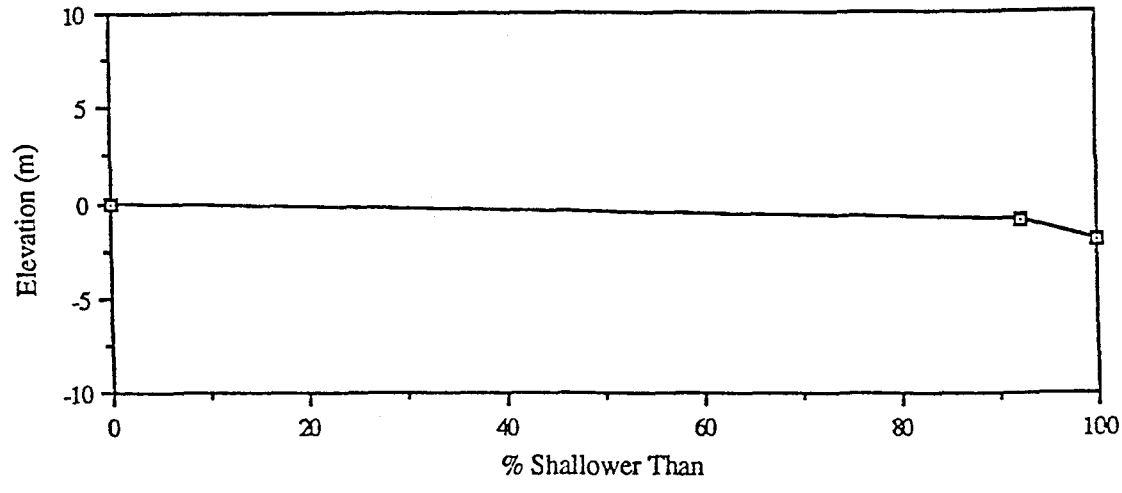
Squeteague Harbor



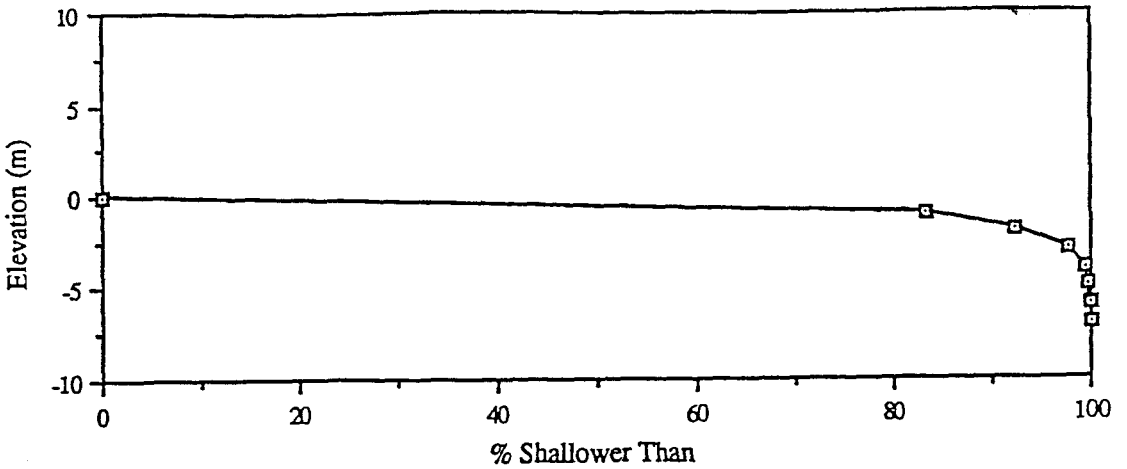
Wareham River



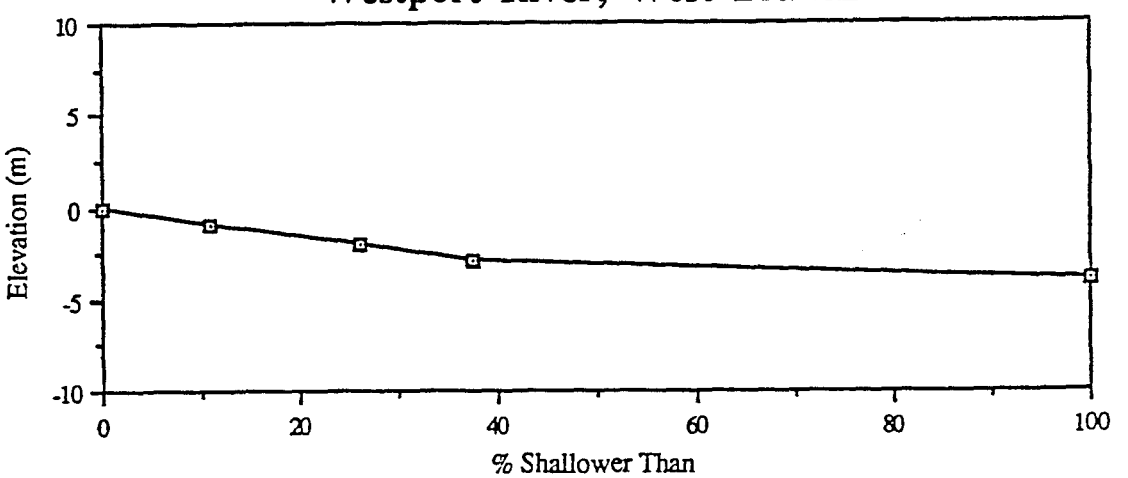
West Falmouth Harbor



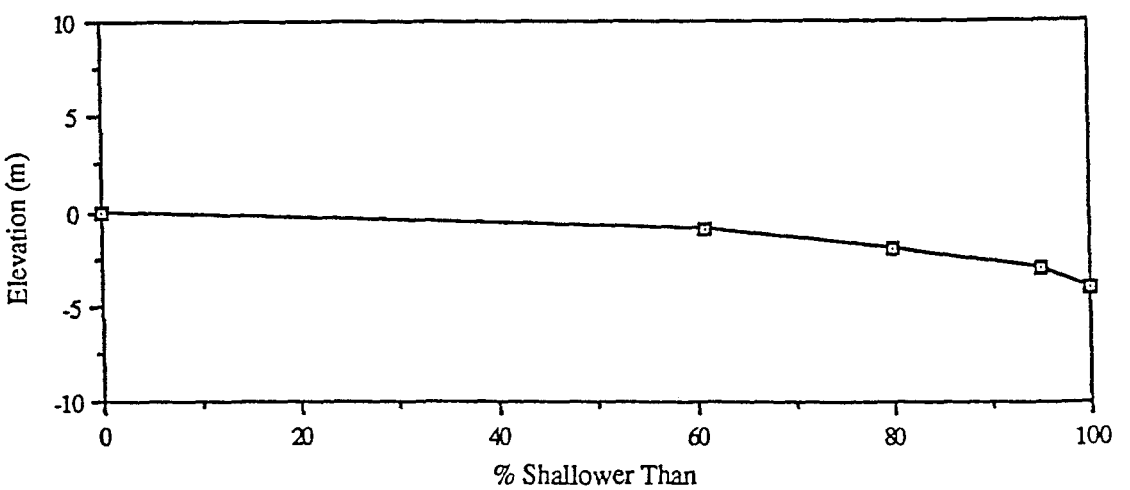
Westport River, East Branch



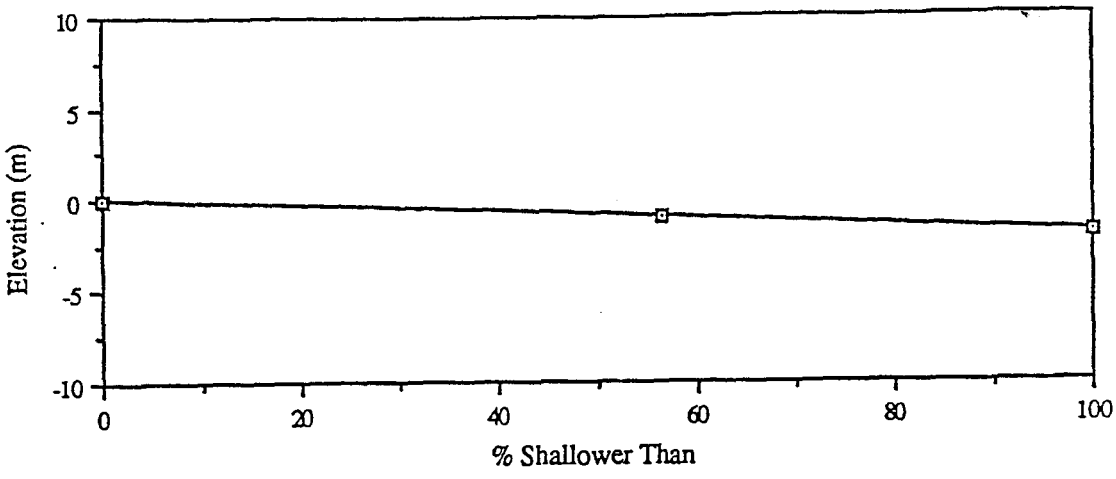
Westport River, West Branch



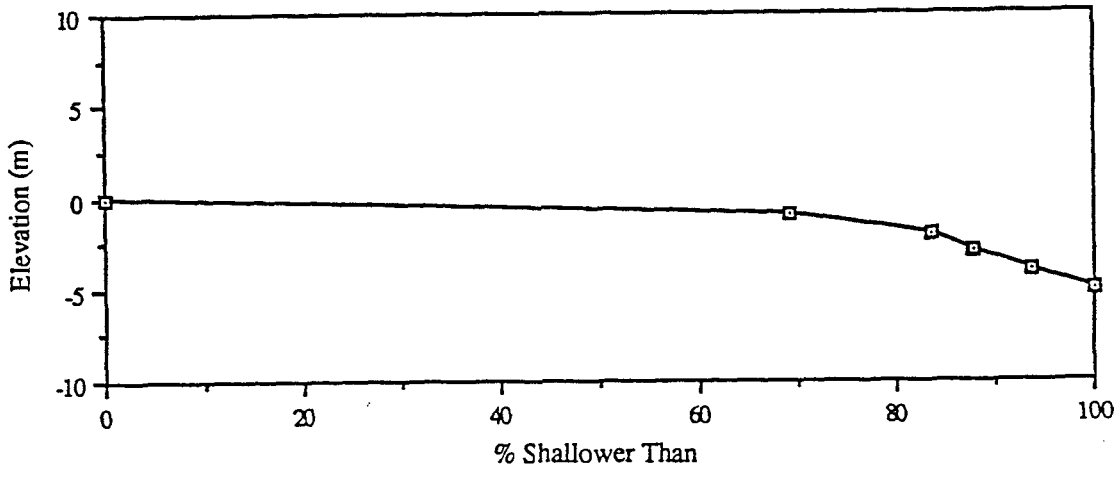
Weweantic River



Widows Cove



Wild Harbor



Wings Cove