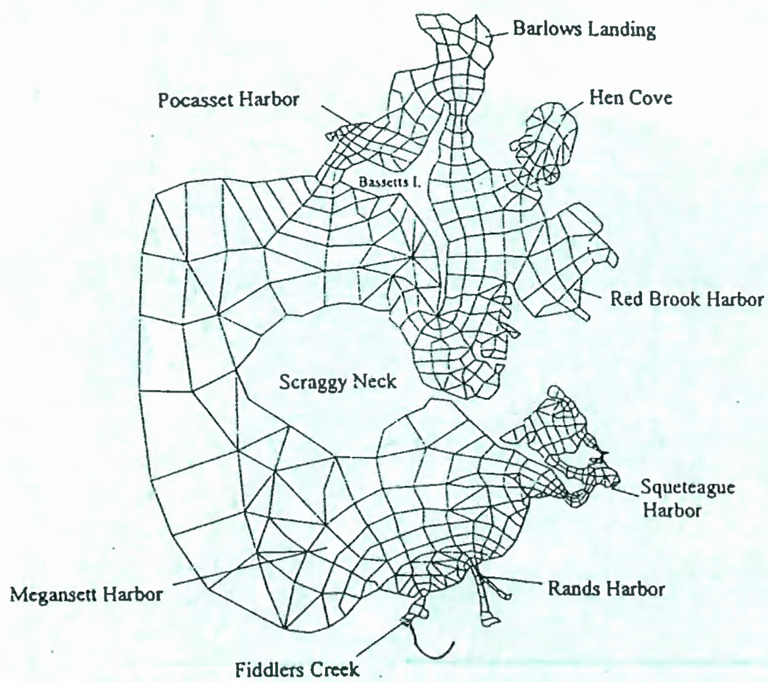
Flushing Characteristics of the Red Brook and Megansett Harbor System: Field Measurements and Numerical Modeling

Final Report



Woods Hole Group
Marine Environmental Solutions

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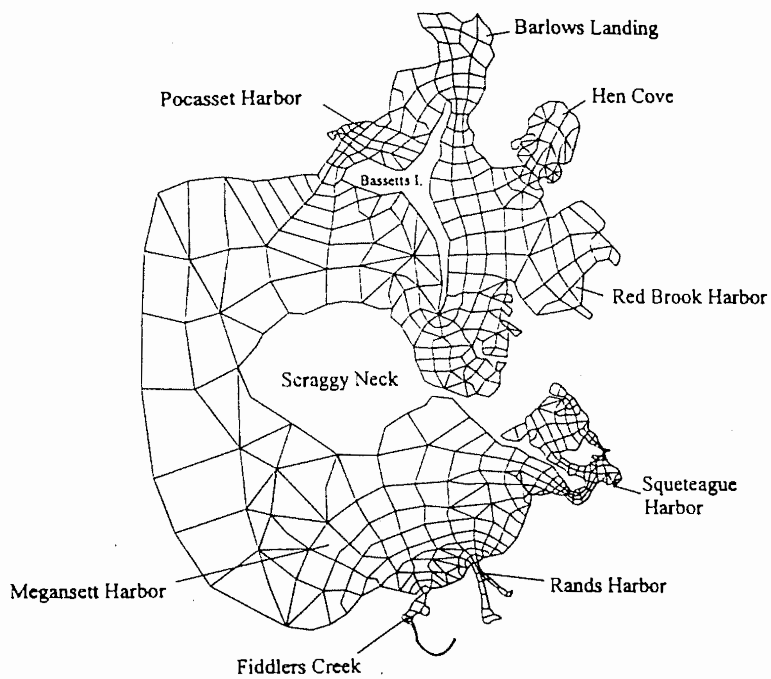

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Flushing Characteristics of the Red Brook and Megansett Harbor System: Field Measurements and Numerical Modeling

FOR:

THE TOWN OF BOURNE

PREPARED BY:

Steven M. Jachec
And
Robert P. Hamilton Jr.

WOODS HOLE GROUP
Division of Coastal Sciences, Engineering, and Planning (CSEP)
81 Technology Park Drive
E. Falmouth, MA 02536
(508) 540-8080

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Executive Summary

The Woods Hole Group, Inc. completed a flushing study of the Red Brook and Megansett Harbor System (the "System" or "Study Area" shown by Figure E-1) for the Town of Bourne. The Town of Bourne funded the study through a technical assistance grant from the Cape Cod Commission. The primary purpose of the flushing study was to characterize the flow of water between the System and Buzzards Bay. In particular, *residence times* were estimated for the System as a whole and for several of its sub-embayments (i.e., smaller bays and harbors within the System). A residence time is an indicator of water quality that essentially estimates the average time water spends in an embayment before it is flushed with *new* water from another water body.

The Town and The Cape Cod Commission will use the results of this study to characterize water quality in the System, and to help guide future planning efforts that may affect water quality in the System. Water quality is of particular interest in this System, because it is potentially threatened by increased nutrient loading associated with residential and commercial development within the watershed, and by groundwater contamination originating from the Massachusetts Military Reservation (MMR). The Cape Cod Commission has worked cooperatively with several Cape Cod Towns to complete similar flushing studies, and has created an extensive database of tidal flushing information for numerous Cape Cod Estuaries. Together, the various flushing studies provide a regional planning tool to help improve water quality on Cape Cod.

The scope of work required for the flushing study consisted of the following components:

- review of existing studies;
- field data collection;
- numerical modeling;
- residence time computations; and
- recommendations.

Also included in the scope of work were meetings with the Technical Advisory Committee, a Public Meeting, a Draft Report, and a Final Report. This Executive Summary was prepared to accompany the Final Report. Each of the scope items defined in the bullets above are summarized briefly below. The reader is encouraged to review the Final Report for more specific details about the technical approach and results of the study.

Existing Studies

Two existing studies were reviewed to provide background information for this flushing study. Geyer, et al. (1997) completed the first existing study that was reviewed. These authors estimated a residence time for Hen Cove using two methods: dye injection and

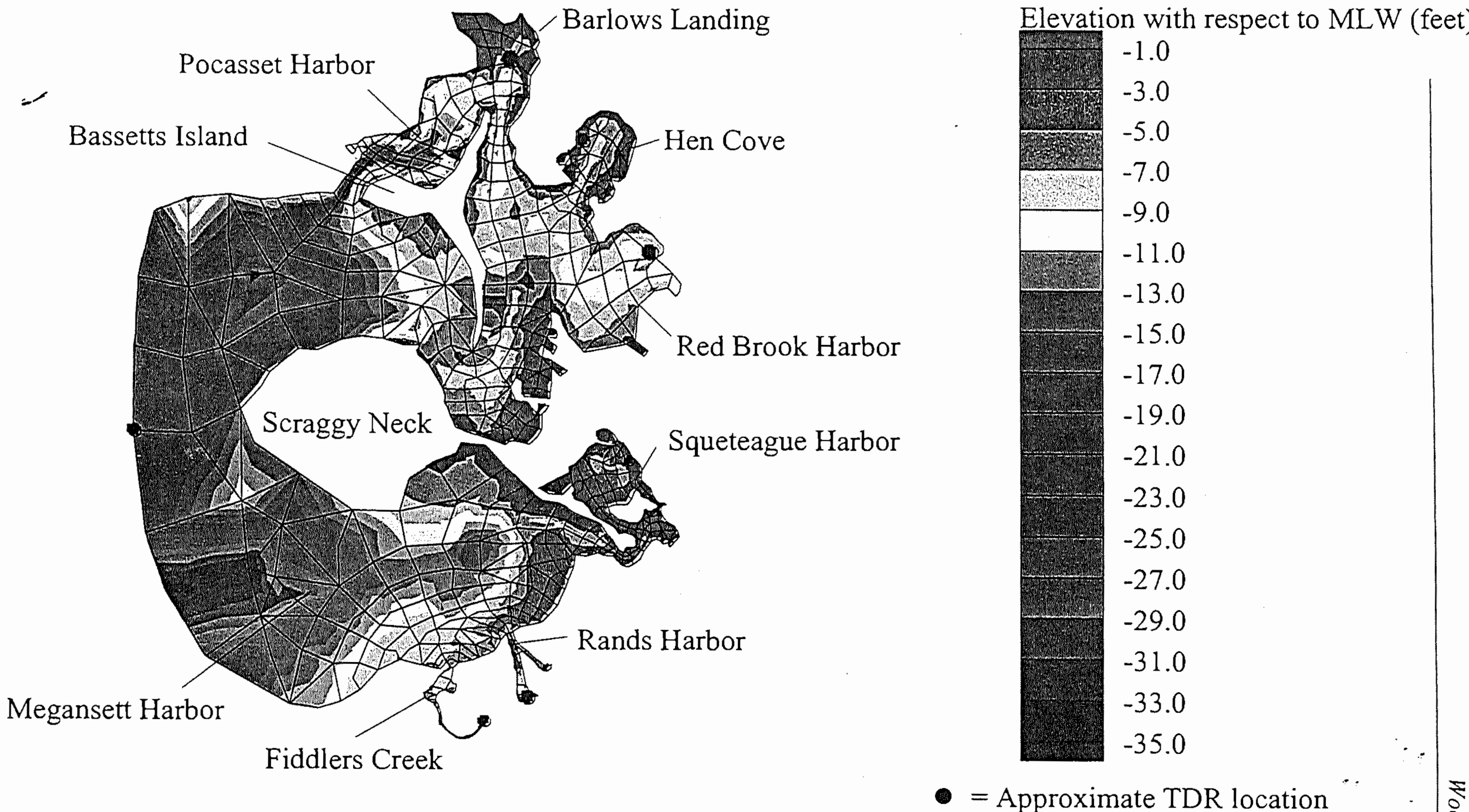

Figure E-1. Layout of 'System,' including bathymetry, TDR locations and finite element grid.

salinity distribution. Based on these two methods, Geyer et al. (1997) determined that the residence time in Hen Cove was between 1.1 and 3.0 days.

The second existing study that was reviewed was completed by Aubrey Consulting, Inc. (ACI, 1995), which is now part of the Woods Hole Group, Inc. The ACI (1995) study utilized two methods (a simplified box model and a spatial model) to estimate residence times for Hen Cove (0.9 to 4.9 days), Red Brook Harbor (1.3 to 3.7 days), and Squeteague Harbor (0.3 to 1.0 days).

The results from these previous studies provided relevant background information as the basis for the present flushing study. This present flushing study improved upon the existing studies by providing more detailed and specific information for additional sub-embayments within the Red Brook and Megansett Harbor System, and the System as a whole.

Field Data

Two types of field data were collected for this flushing study: tide data and bathymetry data. Seven (7) tide gauges were installed throughout the System for over one month. A tide gauge is essentially a waterproof computer that is installed at-depth, and records water depth every 7.5 minutes. The gauges were positioned strategically (Figure E-1) throughout the System to best capture changes in the tide as it travels from Buzzards Bay throughout the channels, harbors, and bays that comprise the Red Brook and Megansett Harbor System. The tide measurements were converted to the Mean Low Water (MLW) datum, using a land survey referenced to known Town benchmarks. The tide data were carefully reviewed and quality-checked. There were no errors in the data, and 100% data return was achieved. The tide data provide important information for the numerical model. The primary observation from the tide data was that the tide travels relatively freely through the System. There was little to no reduction in tide height or time lag, which indicates relatively efficient tidal flushing.

Bathymetry (water depth) data were also collected throughout the entire System. An electronic bathymetry data collection system was installed on a Town boat for the survey, which was performed over several days. The data collection system consisted of a Differential Global Positioning System (DGPS), a fathometer, and a laptop computer, connected to record high-resolution data. Bathymetry data were tide-corrected using the tide gauge data, and were referenced to MLW. The data provided important information for the numerical model, and were used to produce a depth chart (0.5 meter depth contours) in the Massachusetts 1983 State Plane Coordinate System (not for navigation purposes). The Town has a mylar copy of the depth chart.

Numerical Model

A numerical, or computer, model was applied to simulate the flow of water throughout the Red Brook and Megansett Harbor System. It is termed a *model* because it is a replica of the System's flow features (i.e., hydrodynamics) developed on the computer. The basis for the model is a grid of interconnected points that described the shape of the System (Figure E-1). The numerical model has the capability to simulate time-varying (every 10 minutes) changes in tidal height and current velocity at hundreds of points that comprise the grid. This highly detailed information is valuable to understand the tidal flushing characteristics of the System (e.g., dead spots in the flow). Primarily, the model was used to estimate the volume of water within the System and its sub-embayments, as well as the average flow rate of water into each sub-embayment over a series of tidal cycles. Residence times were calculated using the information derived from the numerical model.

Input to the numerical model included water depths from the bathymetry survey, and tidal height in Buzzards Bay measured by the offshore tide gauge. Based on the input information, the model predicted tidal height and current velocity throughout the System. The accuracy of the model predictions within the System was checked through comparisons to tide measurements from the other six tide gauges distributed throughout the System. Adjustments were made to the numerical model to ensure model results compared well with measured data (model "calibration" process). The calibration process provided an appropriate level of confidence that the model was capable of predicting natural tidal flushing in the Red Brook and Megansett Harbor System. The calibrated model, then, was applied to compute residence times.

Residence Times

The calibrated model was applied to simulate a representative 17-day time period that spanned a wide range of tide conditions (e.g., spring ("moon") and neap tides). Based on the 17-day model simulation, average residence times were computed for the entire System and several of its sub-embayments. The residence times are summarized in Table E-1. Two types of residence times were calculated: *system* residence times and *local* residence times. System residence times represent the average time required for water to be flushed completely with new water from Buzzards Bay, whereas local residence times represent the average time required for water to be flushed with an adjacent water body. For instance, the local residence time for Squeteague Harbor, Rands Harbor, and Fiddlers Creek is the time required to flush with Megansett Harbor. System residence times are typically longer than local residence times, since Buzzards Bay is more removed from the sub-embayment than the adjacent water body. For planning purposes, it is valuable to consider both system and local residence times.

Table E-1
Volumes and Residence Times for the
Red Brook and Megansett Harbor System and Sub-embayments

Name of Embayment or Sub-embayment	Volume (million cubic feet at MTL)	System Residence Time (days)	Local Residence Time (days)
Entire Domain [1]	1,880	1.8	1.8 [8]
Area North of Scraggy Neck [2]	765	1.6	1.6 [8]
Red Brook Harbor [2]	54.6	17.2	1.2 [4]
Hen Cove [2]	17.3	45.4	1.0 [5]
Barlows Landing [2]	105	63.6	0.9 [6]
Area South of Scraggy Neck [3]	559	1.6	1.6 [8]
Squeteague Harbor [3]	15.9	20.2	0.6 [7]
Rands Harbor [3]	3.28	226.8	1.4 [7]
Fiddlers Creek [3]	3.45	402.6	2.4 [7]

[1] Considers all embayments north and south of Scraggy Neck
[2] Computed independently from embayments south of Scraggy Neck
[3] Computed independently from embayments north of Scraggy Neck
[4] Flushing with outer Red Brook Harbor
[5] Flushing with Red Brook Harbor
[6] Flushing with Red Brook Harbor
[7] Flushing with Megansett Harbor
[8] Flushing with Buzzards Bay

Based on the system residence time in Table E-1, it is apparent that the entire System flushes rapidly (1.8 days), as do the areas north and south of Scraggy Neck (1.6 days). However, the more remote sub-embayments flush less rapidly with water from Buzzards Bay. For instance, Fiddlers Creek takes more than one year to flush with water from Buzzards Bay by the definition of system residence time. Depending upon the rate of nutrient/pollutant loading, these more remote portions of the System may require careful management to prevent a reduction in water quality.

A long system residence time is not a definitive indicator of poor water quality, though. For the more remote sub-embayments where system residence times are relatively long, it is also important to consider the local residence time. For instance, the local residence time for Squeteague harbor is 0.6 days: much lower than its system residence time of more than 20 days. The local residence time represents the average time required for Squeteague Harbor to flush with water from Megansett Harbor. Since Megansett Harbor flushes rapidly (it is part of the entire area south of Scraggy Neck which flushes in 1.6 days), and Squeteague Harbor flushes rapidly with Megansett Harbor (0.6 days), it may be deduced that tidal flushing is relatively efficient within Squeteague Harbor. Similar analogies exist for the other remote sub-embayments; therefore, the System flushes relatively efficiently through tidal processes. Nonetheless, the flushing times must be combined with nutrient/pollutant loading rates to assess water quality.

Local residence times are also valuable for comparison to previous studies. The residence times estimated by ACI (1995) and Geyer et al. (1997) are essentially local residence times. Comparisons between this present study and the previous studies can be made for Hen Cove, Red Brook Harbor, and Squeteague Harbor. The refined residence time estimates developed for this study are similar to the previous estimates. For Hen Cove and Red Brook Harbor, the residence times developed in this study based on tidal flushing are at the low end or slightly lower (0.1 days) that the previous estimates. This is an expected result, since the tide measurements showed the tide travels through the System relatively freely, an indicator efficient tidal flushing.

Recommendations

- **Next Step**: The Cape Cod Commission should work cooperatively with the Town to incorporate the refined residence times developed in this study into a water quality assessment. At first, the residence times should be evaluated with respect to nutrient/pollutant loading rates to determine whether there are areas of potential concern. Both system and local residence times should be considered. The Cape Cod Commission has completed this process for several other Cape Cod Estuaries.

- **Water Quality Modeling**: If, using the simplified water quality assessment methodologies recommended above, it appears there are areas of concern within the System, then a more detailed water quality model should be developed as an extension to the hydrodynamic model developed in this study. The water quality model has the capability to simulate the transport and dilution of nutrients/pollutants in the Estuary.

- **Other Possible Future Uses of Model**: The Town should consider the model developed in this study as a valuable tool for future planning efforts in the System. For instance, the effects of dredging on tidal circulation can be determined using the model. In addition, the model can be extended to simulate sediment transport within the System. For instance, it is our understanding that some citizens are concerned with the accumulation of fine sediment in certain portions of the System (e.g., in the vicinity of Barlows Landing). The model can be applied to assess this sedimentation problem and to evaluate potential solutions (e.g., culverts).

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1.0 Introduction

1.1 Purpose of Study

This report describes the results of a flushing study of the Red Brook and Megansett Harbor System (the "System" or "Study Area"). The System includes the following sub-embayments shown on Figure 1.1: Red Brook Harbor, Hen Cove, Pocasset Harbor, Barlows Landing, Megansett Harbor, Squeteague Harbor, Rands Harbor, and Fiddlers Creek. The primary purpose of the flushing study was to collect field data and apply a computer (numerical) model to estimate residence times (an indicator of water quality) for the System and several of its sub-embayments. Water quality is of particular interest in this System because it is potentially threatened by increased nutrient loading associated with development in the watershed, and by groundwater contamination originating from the Massachusetts Military Reservation (MMR). The study was funded by the Town of Bourne through a technical assistance grant from the Cape Cod Commission. The Town provided boats and an operator for the field work, as well as additional staff time as required.

Advanced techniques were utilized to complete this study, including precision measurement technology and state-of-the-art numerical modeling methods. The use of numerical modeling was economical because it reduced the required quantity of more expensive field data collection. The methods and results from this study built upon existing information available from previous endeavors (Section 1.2). Important components of the study are listed below, along with the corresponding section of this report:

- review of existing studies (Section 1.2);
- tide data (Section 2.1);
- bathymetry data (Section 2.2);
- a calibrated numerical model that simulated circulation within the System (Section 3.0);
- tables of sub-embayment volumes and residence times, including recommendations (Section 4.1);
- a description of circulation patterns within the System (Section 4.2); and
- summary and conclusions, including recommended possible future analyses, such as water quality measurements and modeling and groundwater modeling (Section 5.0).

1.2 Review of Existing Studies

Many estuaries on Cape Cod are experiencing a reduction in water quality due to increased nutrient loading. Nutrients, typically nitrogen and phosphorous, can drain into the coastal environment from fertilizer use, septic systems (including some laundry detergents), road runoff, and other effects of increased development. Excessive nutrient

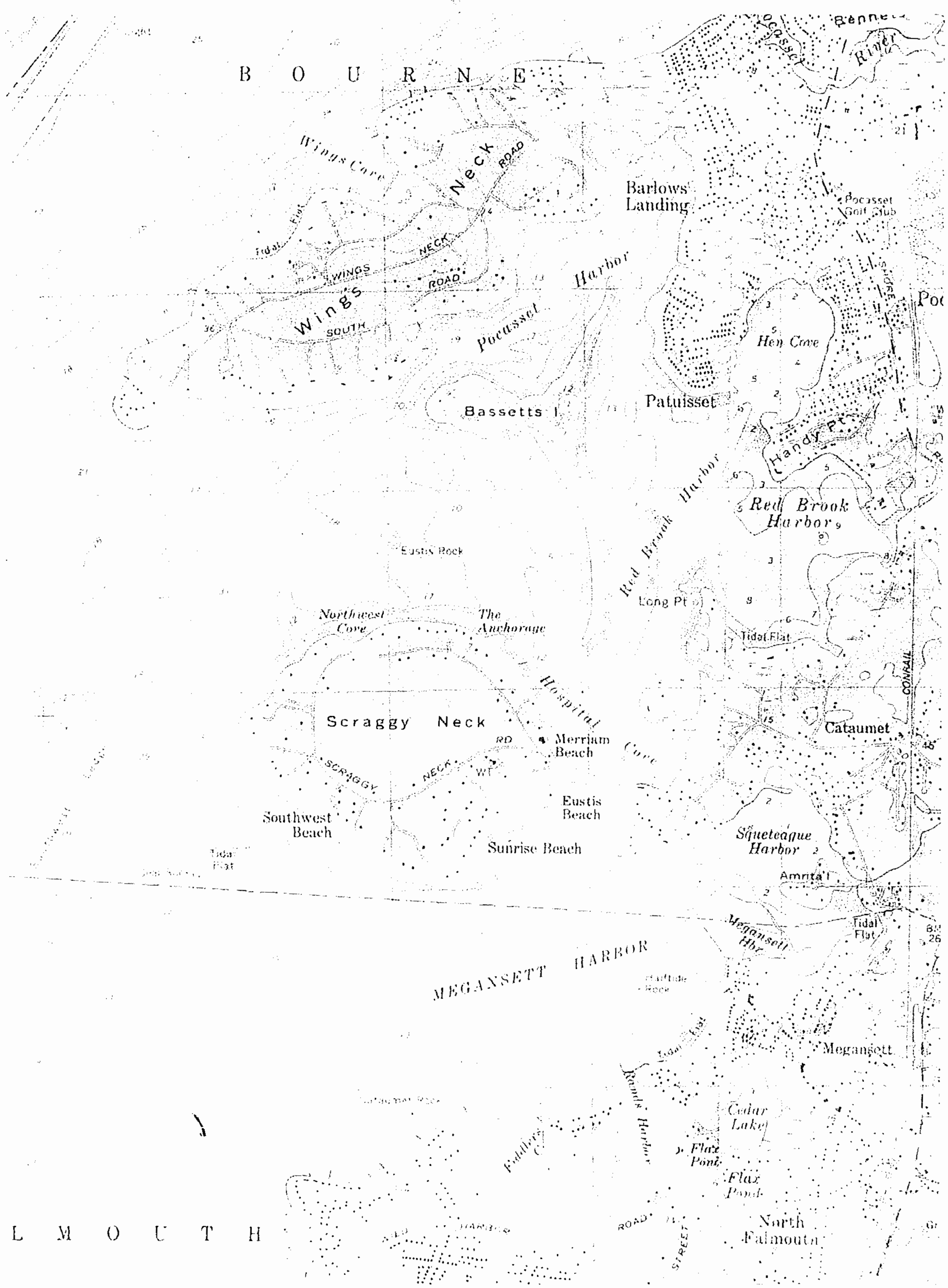

Figure 1.1. Red Brook / Megansett Harbor System, including sub-embayments.

loading can increase the production of algae within a bay (algae blooms), and cause shifts in the species composition of phytoplankton communities (Libes 1992). When the algae subsequently die and decompose, water quality can be reduced as the supply of oxygen is decreased. Fish, shellfish, and benthic organisms are dependent upon oxygen in the water. Under severe algae bloom and subsequent algae decay conditions, the water column can become devoid of oxygen (anoxic), and result in sudden mortality to fish and/or other organisms. Howes and Goehringer (1994) noted episodic dense algal blooms, malodorous conditions, and occasional fish kills within salt estuaries open to Nantucket Sound.

Based on the process described above, water quality is a function of nutrient loading (i.e. concentration) and flushing characteristics. Relatively low nutrient loading and efficient tidal flushing are signs that water quality is high. As water enters an embayment during the flood tide, it mixes with existing embayment water, and dilutes the concentrations of nutrients. Water exiting an embayment during ebb tide carries nutrients out of the system. This cycle is repeated during the following tide. Eventually, tidal circulation causes the entire volume of water in an embayment to be exchanged (flushed). The time required for the volume of water in an embayment to be exchanged with water from an adjacent water body is termed *residence time*. Lower residence times indicate more efficient flushing, and can be an indicator of better water quality.

This study was completed to develop a more in-depth understanding of tidal flushing and residence times within the Red Brook and Megansett Harbor System. This study extends on the findings from previous studies described below. The review of existing relevant studies included specifically the work performed by Geyer et al. (1997) and Aubrey Consulting, Inc. (ACI, 1995). Each of these previous studies partially overlapped study areas encountered in this report, but did not include the level of detail provided herein.

In 1997, a flushing study of three Buzzards Bay harbors was prepared by Geyer et al. Empirical (i.e., based on field data) flushing studies were conducted in Hen Cove, Eel Pond, and Pocasset River. These authors used two independent methods to estimate residence times: 1) dye injection, and 2) salinity. The first method consisted of injecting a known amount of rhodamine WT dye, and measuring the change in dye concentration over time using a fluorometer. Natural levels of background fluorescence in each bay, caused by phytoplankton and organics, were measured prior to dye injection. This background fluorescence was subtracted from the measured fluorescence, providing a measurement of dye concentration only. Residence times of the bays were estimated based on measured time-varying concentrations of dye at various points. Table 1.1 provides the residence time for Hen Cove based on the Geyer et al. (1997) dye study.

In addition to the dye study, Geyer et al. (1997) characterized salinity distributions within Hens Cove, Eel Pond, and Pocasset River based on conductivity-temperature-depth (CTD) measurements. Residence times were calculated based on the salinity method in a different manner than using the dye tracer method. Salinity concentrations were used to determine the volume of freshwater in each bay. Residence times were calculated based on the rate of exchange of freshwater, estimated from the field measurements and knowledge of freshwater inflow rates (e.g., groundwater recharge). Table 1.1 also provides the residence time for Hen Cove based on the Geyer et al. (1997) salinity survey.

Table 1.1. Summary of Hen Cove residence times determined by Geyer et al. (1997).

Embayment	Residence Time from Dye (days)	Residence Time from Salinity (days)
Hen Cove	2.0	1.1-3.0

The residence times computed based on dye and salinity concentrations were dependent upon meteorological conditions (e.g., tide, wind, freshwater inflow, etc.) that prevailed during the survey period.

In 1995, ACI used an analytical approach to determine residence times of selected Buzzards Bay embayments, including Hen Cove, Red Brook Harbor, and Squeteague Harbor. The two models used were a simplified box model, and a spatial model. Using the box model, residence times were calculated based on the volume of water in each embayment and the volume of water that enters the embayment on a flood tide (i.e., tidal prism). The box model assumes complete mixing of oceanic and embayment water, and does not include detailed current patterns within the System that affect flushing characteristics. If known, freshwater inflow can be added to the tidal prism. The ACI (1995) study used an expression derived by Zimmerman (1988) to estimate the average length of time that it takes to replace all the water within the embayment:

$$\tau_r = \left(\frac{V_{MLW} + P}{P}\right) * 12.42 \tag{1.1}$$

In the above equation, τ_r is the residence time in hours, V_{MLW} is the volume of water in the embayment at mean low water (MLW), and P is the tidal prism. This estimate of residence time is based on the assumption that the dominant feature of the tide is the twice-daily lunar tide (M_2), with a period of 12.42 hours.

Residence times estimated by ACI (1995) using the box model for Hen Cove, Red Brook Harbor, and Squeteague Harbor are provided in Table 1.2.

Table 1.2. Summary of residence times based on a simplified box model (ACI, 1995).

Embayment	Residence Time (days)
Hen Cove	0.9
Red Brook Harbor	1.3
Squeteague Harbor	0.9

The second method used by ACI (1995) was a spatial model. This method used an approach derived by Dronkers and Zimmerman (1982), which is a one-dimensional, longitudinal approach with a dispersion coefficient used to approximate mixing processes. The equation these authors derived to calculate residence time is:

$$\tau_r(x) = \frac{1}{2}\frac{L^2 - x^2}{D} \tag{1.2}$$

where τ_r is the residence time; L is the length of the embayment; x is the position of interest; and D is the longitudinal dispersion coefficient. The dispersion coefficient, D, is an empirical quantity. Typical values of D range from 100 to 300 meters^2 / second which can be estimated through empirical dye or salinity mixing measurements. Fischer et al. (1979) provides a thorough discussion of mixing in the coastal waters.

The resulting residence times calculated by ACI (1995) using the spatial model are given in Table 1.3. These values represent the maximum residence time and associated dispersion coefficient calculated at the head of each embayment.

Table 1.3. Summary of residence times and associated dispersion coefficients based on spatial model (ACI, 1995).

Embayment	Maximum Residence Time (days)	Dispersion Coefficient (meters^2 / second)
Hen Cove	1.5–4.9	36-118
Red Brook Harbor	2.8-3.7	7-9
Squeteague Harbor	0.3-1.0	7-19

In summary, there are previous studies that established the need to understand flushing characteristics of Cape Cod estuaries as one step toward evaluating water quality. Specific studies have examined portions of the Red Brook and Megansett Harbor System, and have estimated a range of residence times for Red Brook Harbor, Hen Cove, Squeteague Harbor. This present study provided a more detailed description of circulation and flushing characteristics within the Red Brook and Megansett Harbor System, including many sub-embayments, using an advanced technical approach described in Section 1.3.

1.3 Technical Approach

A technically-advanced approach was utilized for this flushing study. First, field data were collected using precision instrumentation. Second, a state-of-the-art numerical model was developed. The model was calibrated to ensure it reproduced measured tides. Third, once calibrated, the results from the model were applied to characterize flushing characteristics of the System, including the calculation of residence times. Essentially, residence time is defined as the average time required for the volume of water in an embayment to be exchanged with new water from another water body. The methods for computing residence times are discussed in Section 4.1. These calculations required an estimate of the volume of water in an embayment as well as the volume of water exchanged with that embayment via tidal circulation and/or freshwater inflow.

The field data collection program was designed specifically to fulfill the requirements for computing residence times and understanding tidal circulation in the System. Depth (bathymetry) data were collected to estimate the volume of water in each embayment comprising the System. Tide data were collected to determine how much water is exchanged between the various embayments that comprise the System. As described in Section 2.1, the tide gauges were placed strategically to meet project requirements. The bathymetry and tide data were input to a hydrodynamic numerical model, which is a computer program that simulates tidal circulation by solving mathematical equations that govern water flow. Once calibrated, the model was used to simulate current patterns and water surface elevations at hundreds of nodes in the study area over a 17-day period. Snapshots of current patterns provided valuable insight into flushing characteristics. Output from the numerical model was used specifically to compute residence times for Red Brook Harbor, Hen Cove, Megansett Harbor, Squeteague Harbor, Rands Harbor, and Fiddlers Creek.

There are many advantages associated with the technical approach employed for this flushing study that have been demonstrated in numerous previous flushing studies completed by ACI. For instance, similar flushing studies have been completed by ACI for Cape Cod Estuaries, such as West Falmouth Harbor, Upper Bass River, Pleasant Bay, Popponesset Bay, East Bay/Centerville River, and the Three Bays Estuary. Improvements have been made to the model and data collection techniques throughout implementation of these various flushing studies that are incorporated into this study of the Red Brook and Megansett Harbor System.

The primary advantage of this technical approach is the residence times computed using the tidal flushing methods are more representative of typical conditions in the System than estimates of residence times based on other methods. Neither an empirical approach (e.g., salinity and or dye study) nor an analytical model (e.g., box or spatial model) can provide the extensive detailed hydrodynamic results obtained by a numerical model. For one, the residence times were computed in this study based on tidal flushing, which is the dominant mechanism contributing to the exchange of water in the System (e.g., compared to freshwater inflow). This is an improvement over the salinity study approach, where residence times are based strongly on knowledge of freshwater inflow through the ground to an embayment, which cannot be measured directly and is not a well-constrained quantity. Secondly, the residence times computed based on the tidal flushing approach were based on relatively long-term tide data (i.e., at least two weeks). This is an improvement over both a salinity balance and a dye study approach, which typically are based on data conducted over a time period spanning a couple of days. The relatively short-term salinity and/or dye data can be biased by prevailing tidal, freshwater inflow, and meteorological conditions during the survey. For example, conducting the survey following a high rainfall, high tide, and/or storm conditions may artificially reduce residence times. Salinity and/or dye studies spanning two weeks or a month may be cost-prohibitive due to the labor intensive nature of the required salinity and dye concentration field data compared to tide data. The detailed hydrodynamic model employed for this study also represents a marked improvement over a box model because of the detailed nature of the input data as well as the ability of the hydrodynamic model to simulate detailed current patterns.

Other advantages of the technical approach employed for this flushing study are:

- the numerical model provides much more detailed quantitative information than cannot be gathered based on a field data collection program alone. The model provides output at hundreds of points every 10 minutes for 17 days;
- with powerful computers available today, it is possible to perform these numerical modeling calculations relatively quickly and economically;
- numerical modeling is economical because it reduces the quantity of more expensive field data collection required to develop detailed accurate estimates of residence times and other tidal flushing characteristics;
- the numerical model provides a valuable engineering design tool for future studies, such as water quality, sediment transport, and/or evaluating the effects of dredging on the System.

The main assumption incorporated into the tidal flushing method utilized for this flushing study is that residence time computations assume no recirculation of water. For instance, it is assumed that water entering the System from Buzzards Bay on a flood tide contains no water that was flushed out of the System on a previous ebb tide (i.e., water entering the System is "new"). This assumption is reasonable since Buzzards Bay is much larger than the System of interest in this study, and there are tidal currents in the Bay that transport water exiting the System south into larger portions of the Bay. It is expected that only very low concentrations of water are recirculated between Buzzards Bay and the Red Brook and Megansett Harbor System.

2.0 Field Observations

In order to accurately model the circulation and determine residence times, the following field measurements were collected:

- tidal elevations
- bathymetry

The measurements were needed to develop, calibrate, and "drive" the two-dimensional hydrodynamic model. The offshore tide gauge provided the data to force the open boundary of the model while the remaining six gauges within the System were used to calibrate the model. Calibration ensured the model predicted accurately what was observed in nature. Detailed bathymetry data also were required as input into the model. Thus, the field data collection program was designed to support the modeling.

2.1 Tidal Measurements

Long-term tidal records were used to calibrate the hydrodynamic model, because short-term deployments can be biased by climatic events, such as storms, and spring-neap tidal cycles, and rarely represent average hydrodynamic conditions within the study area. The longer-term tide measurements collected for this study included a range of tidal and climatic events; therefore, average conditions were identified using the tidal flushing approach. Generally, the tide measurements showed the tide travels relatively freely throughout the System, which indicates efficient tidal flushing.

Seven temperature-depth-recorders (TDRs) were deployed at predetermined locations in the study area. Deployment location was specified based on the need to quantify flushing at selected embayments, and to measure the tide at the entrance of the study area. Figure 2.1 shows the locations of the seven TDRs. One gauge was deployed in Buzzards Bay west of Scraggy Neck marking the entrance to the study area. Tide data collected from this offshore instrument provided the forcing for tidal circulation within the System. Six TDRs were installed north and south of Scraggy Neck in Barlows Landing, Hen Cove, Red Brook Harbor, Squeteague Harbor, Rands Harbor, and Fiddlers Creek. These were deployed near or at the head of the embayments so that the effects of constrictions could be properly measured. The six gauges deployed within the System were intended to characterize tidal distortion caused primarily by friction, and the irregular geometry and bathymetry of the study area (e.g., the shallow, winding channel leading into Squeteague Harbor). Accurate measurements and modeling of tidal distortion, such as tidal dampening and phase lags, were crucial for the evaluation of flushing characteristics and determination of residence times.

Branker (model TG-205) and SeaPac (2100 model) tide gauges were deployed in the study area (Figure 2.1). Each TDR contained a pressure sensor and a thermistor coupled to a data logger. TDR data were downloaded using a personal computer, using Branker and SeaPac software. The Branker TDR's measured water surface elevation to within approximately 1 inch (2.54 cm) and the SeaPac 2100 measurements were accurate to within approximately 0.4 inch (1 cm).

Gauge installation was accomplished by fastening the gauge either to a pipe anchor or existing pier pile using hose clamps. Pipe anchors were jetted into the bottom where pier piles did not exist. The instruments were deployed on September 25, 1998, except for the Red Brook Harbor gauge, which was deployed on September 19, 1998. The gauges were retrieved November 5 and November 6, 1998. The Branker TDRs logged pressure and temperature every 10 minutes while the SeaPac TDRs recorded data every 7.5 minutes.

2.1.1 Measurements

Pressure data were converted to water surface elevation using the hydrostatic relationship based on the density of water. In order to reference the TDRs to a common vertical datum, a land survey was conducted. This was accomplished using a transit and stadia rod. Data from each gauge was referenced to Mean Low Water (MLW). Water surface referenced to MLW for the seven TDRs are plotted in Figures 2.2 to 2.8.

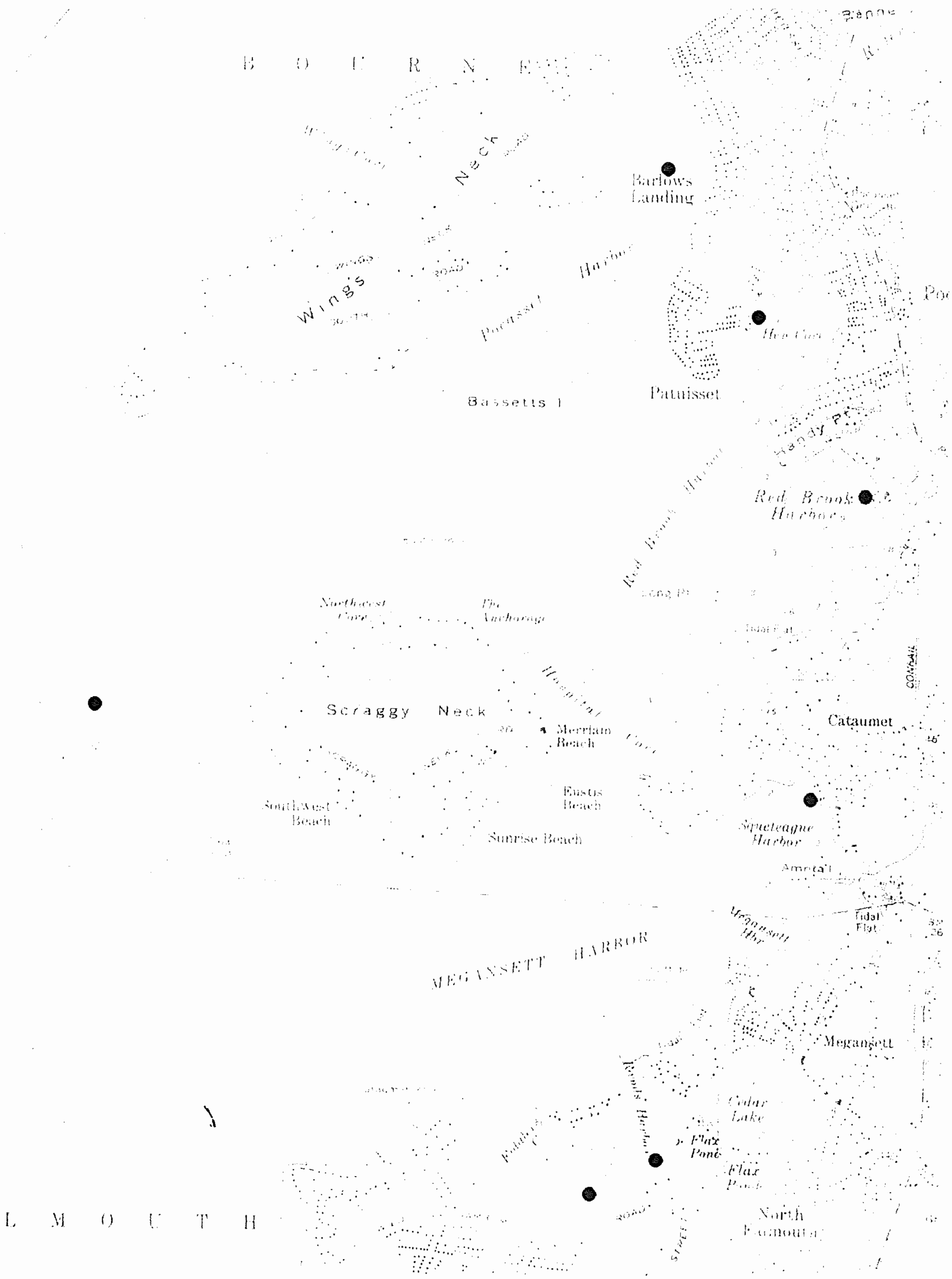

Figure 2.1. Location of TDRs. Black dots represent TDR locations.

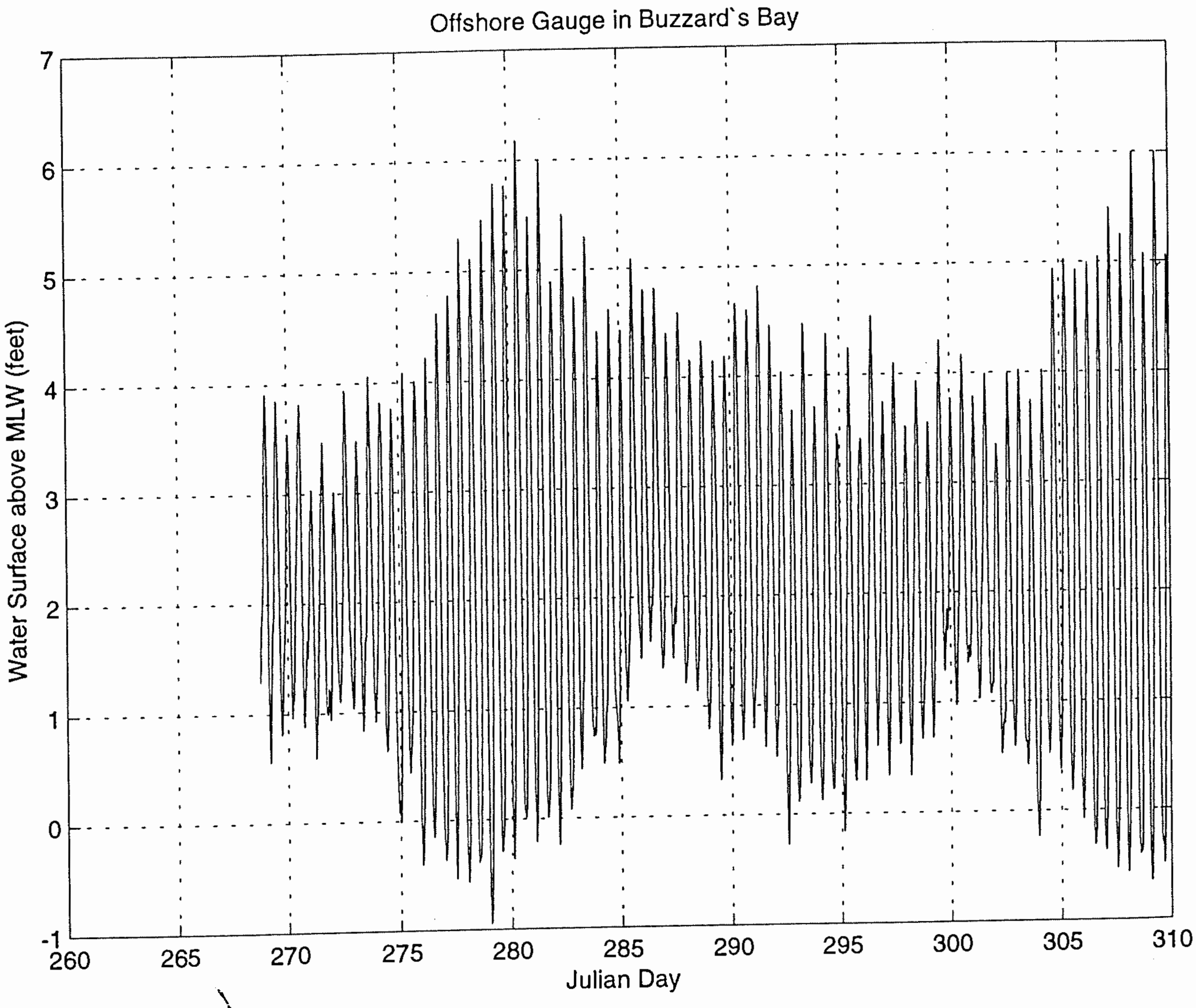

Figure 2.2. Time series of water surface in Buzzard`s Bay

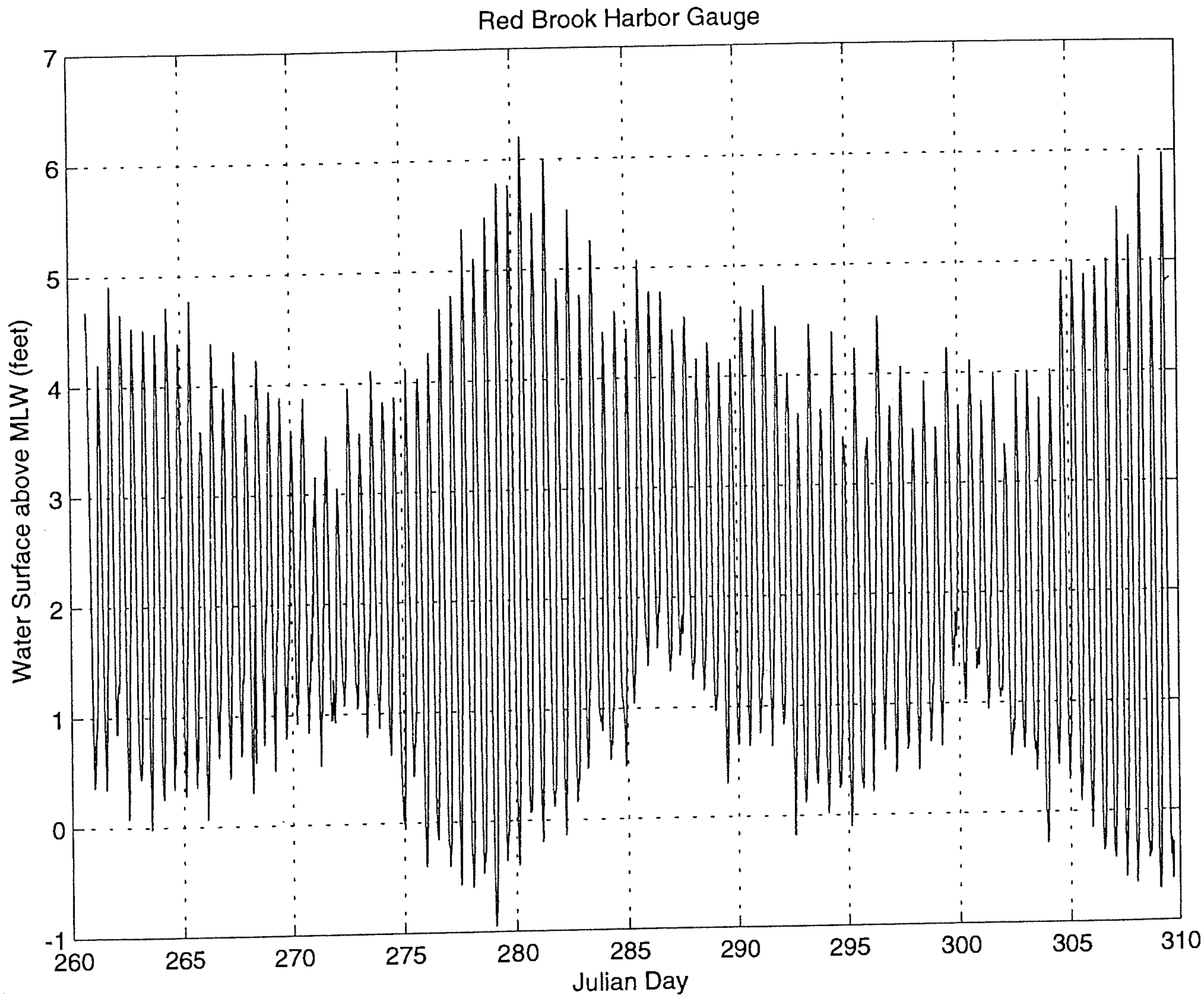

Figure 2.3. Time series of water surface in Red Brook Harbor

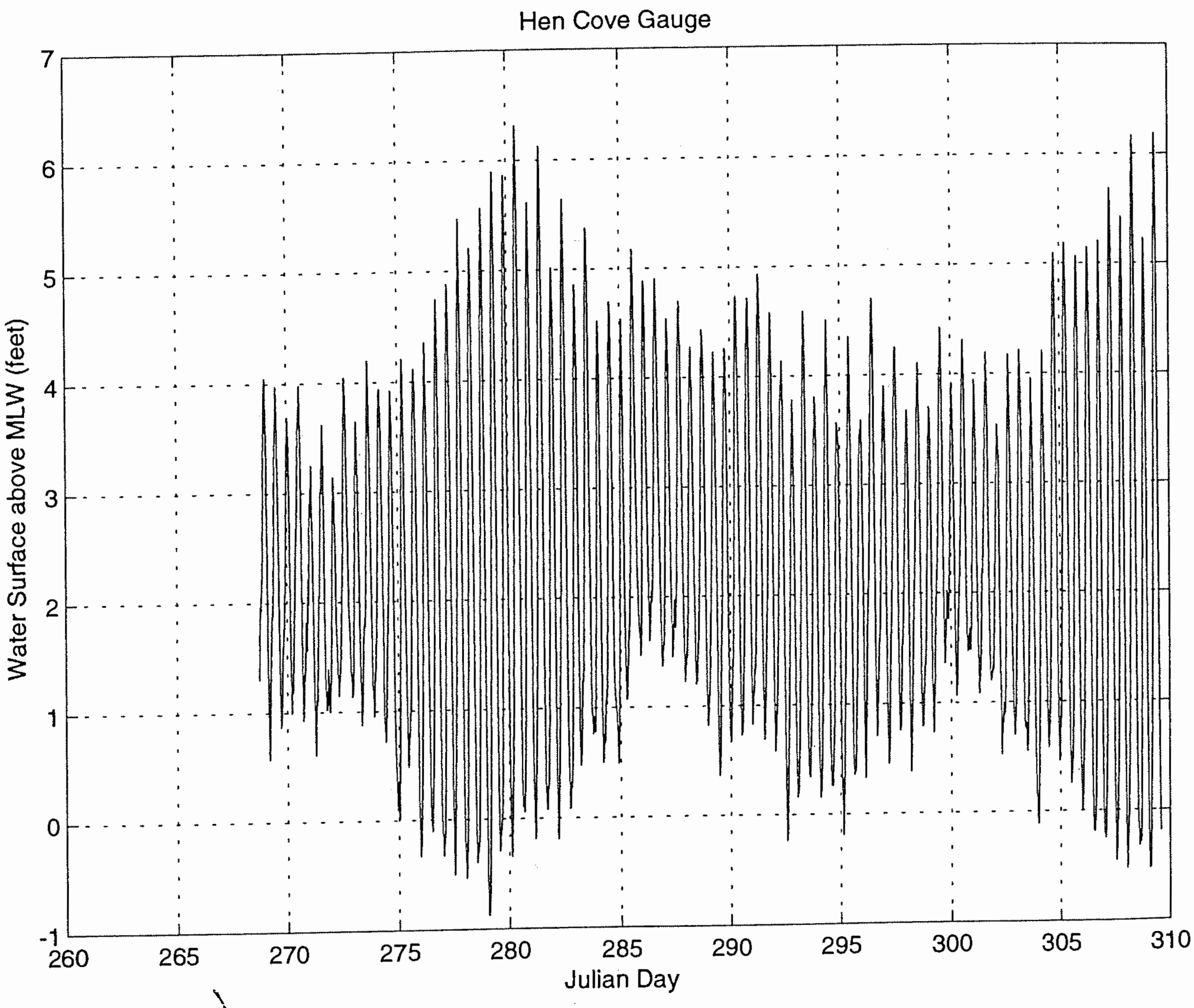

Figure 2.4. Time series of water surface in Hen Cove

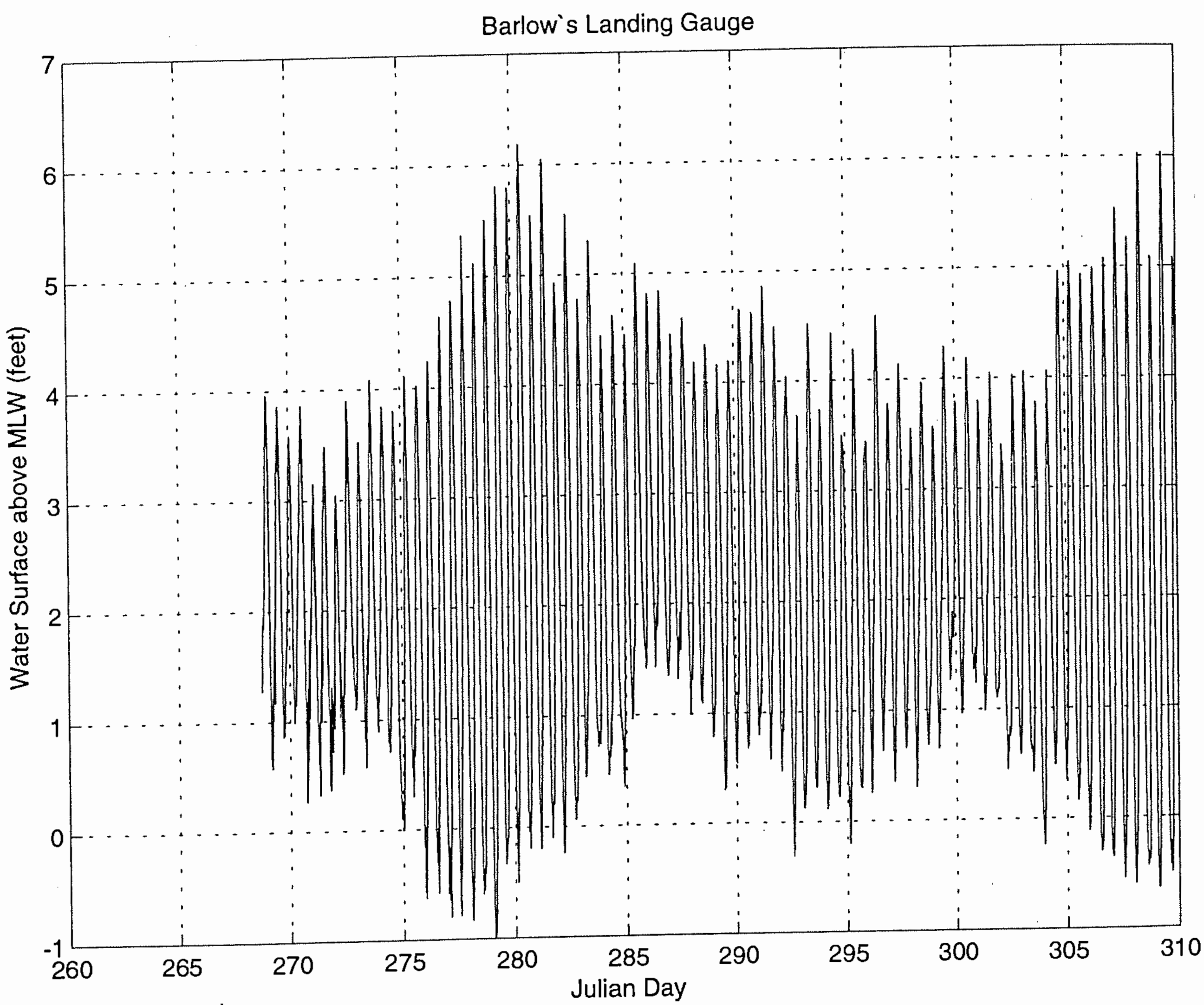

Figure 2.5. Time series of water surface in Barlow`s Landing

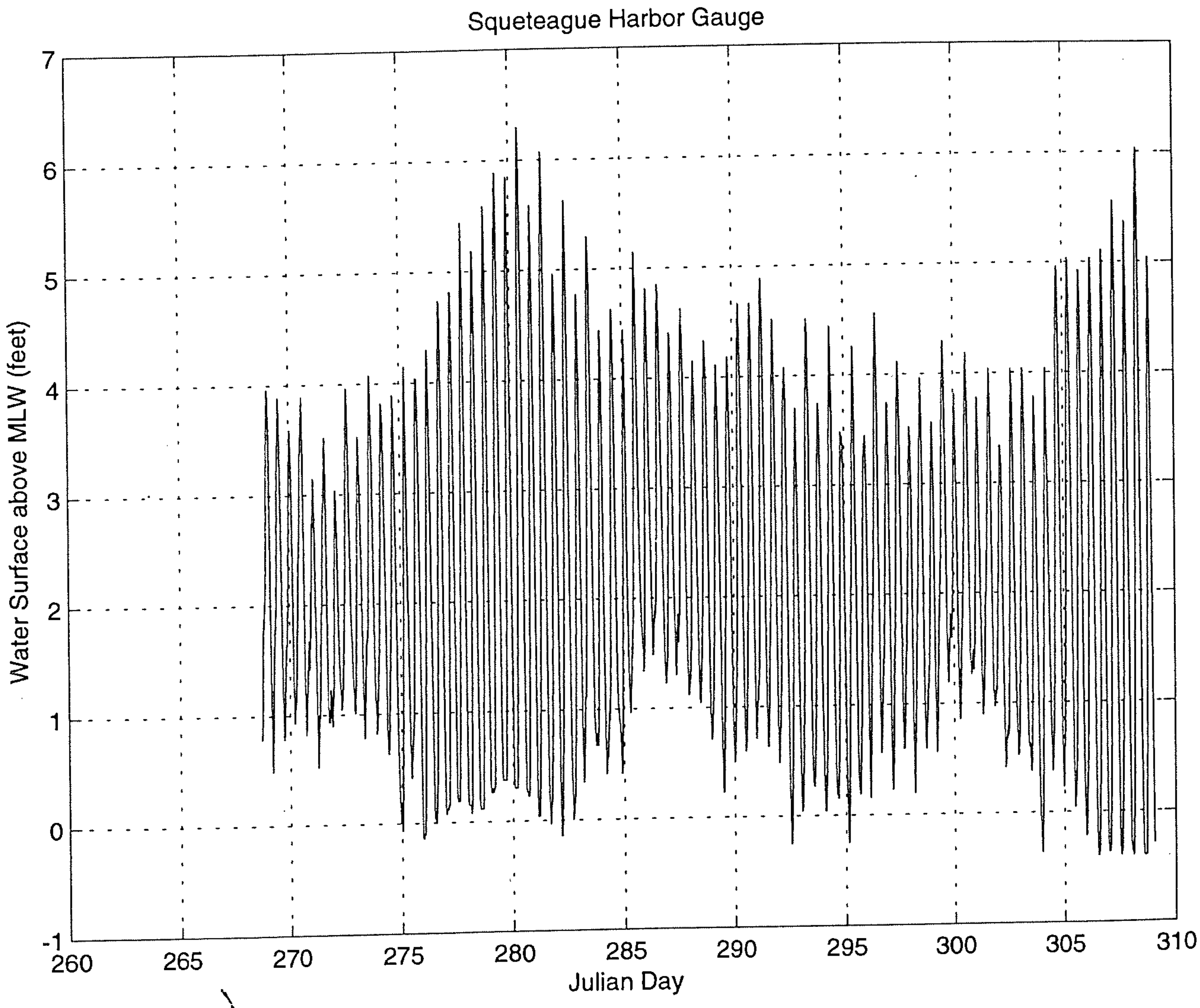

Figure 2.6. Time series of water surface in Squeteague Harbor

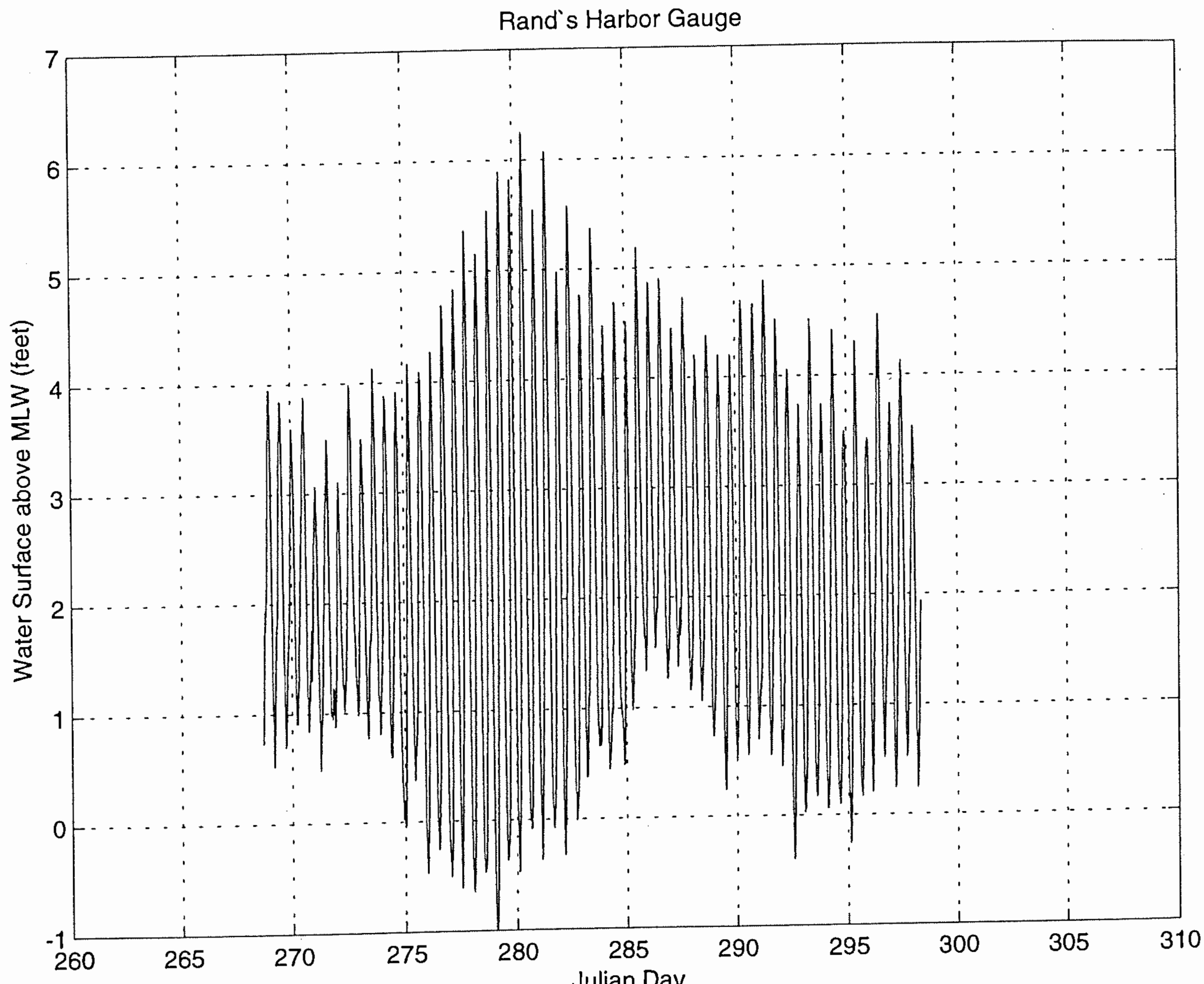

Figure 2.7. Time series of water surface in Rand`s Harbor

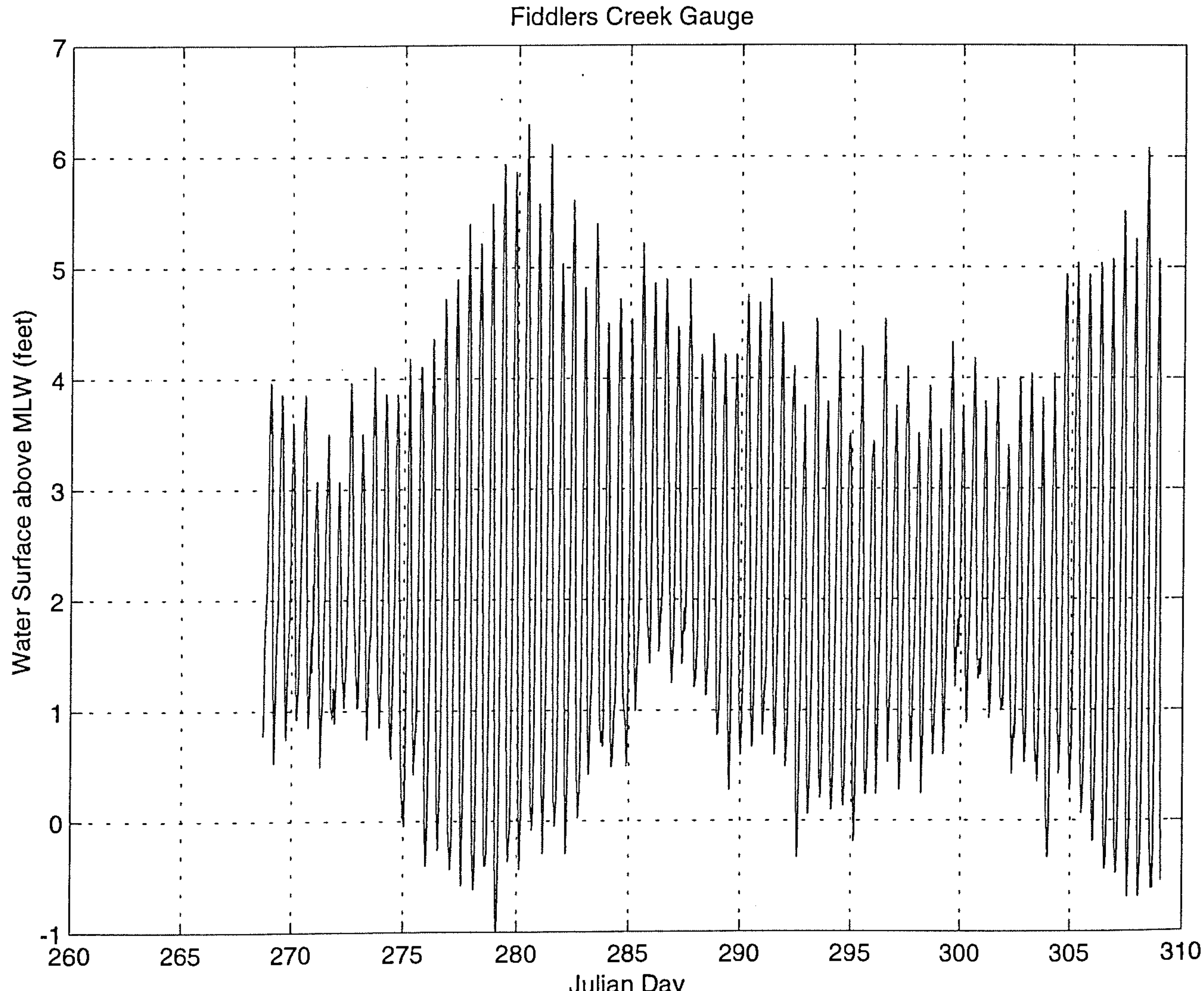

Figure 2.8. Time series of water surface in Fiddlers Creek

The first plot is from Buzzards Bay, which is the overall forcing tide to the System. The remaining time series plots of water surface are: Red Brook Harbor, Hen Cove, Barlows Landing, Squeteague Harbor, Rands Harbor, and Fiddlers Creek. Included in these plots are day-to-day variations in high and low tide, spring and neap tides, and other astronomical tides. For example, the tidal range on October 6 (Julian Day 279) is almost twice as large as the range on October 14 (Julian Day 287). These temporal variations in tide range are caused by the interactions of the moon and sun, as well as local processes (such as wind stresses).

Figure 2.9 provides a close-up view of one day comparing the tides at the seven locations. Based on this close-up, little reduction in tide height and only slight delays between tidal signals occur throughout the System. This slight tidal distortion is discussed further in Section 4.0 and 5.0 of this report.

2.1.2 Tidal Constituent Analysis

This section describes a type of tide data analysis called tidal constituent analysis. This analysis was an important component of the study in terms of calibrating the numerical model, but it is not critical that the reader be intimately familiar with the analysis in order to understand the results of the flushing study.

The tidal constituent analysis, or harmonic analysis, is essentially a method to determine the relative importance of various components of the tide caused by the sun, moon, etc. Some commonly well-known tidal constituents are:

- the roughly twice daily, or semi-diurnal, tides caused by the moon (the M_2 constituent);
- the roughly two-week variability of the tide height caused by the relatively alignment between the moon and the sun (the so-called "moon tide" which are the M_{SF} constituent); and
- the daily effect of the sun, which causes one high tide to be higher each day in this area (the S_2 constituent).

Overall, there are as many as 396 tidal constituents (Doodsen, 1921) that vary in importance depending upon location around the earth. For this study, the top six constituents were analyzed. The purpose of the analysis was to evaluate the accuracy of the numerical model (Section 3.3).

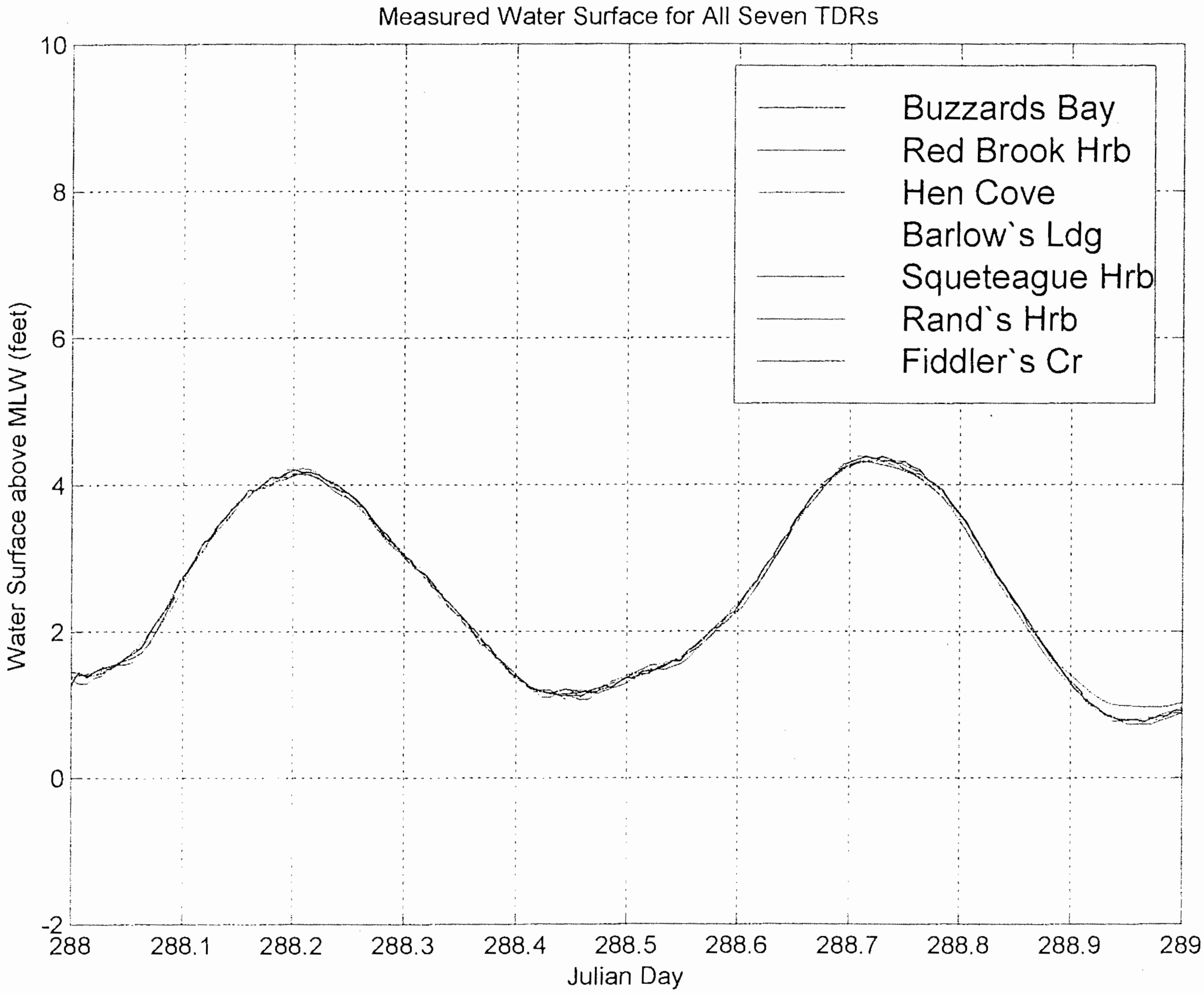

Figure 2.9. Close-up time series of water surface for all seven TDRs.

Harmonic analysis is the most quantitative tool for analyzing and predicting complex tidal heights and tidal currents (Emery and Thomson 1997). A 17-day calibration period was used in the modeling effort. This period of time allowed the daily, as well as spring and neap, tides to be modeled while facilitating computational efficiency. For the 17 day period, 18 tidal constituents were extracted from the harmonic analysis based on: 1) their contribution to the tide-generating potential, and 2) their resolvability given by the length of the tidal record. Each constituent is a wave with a site-specific height and period.

A tidal constituent analysis, a form of harmonic analysis to examine tidal heights, (see Aubrey and Speer 1985 for a thorough discussion) was used to analyze tides measured at the seven gauge locations. Although 18 constituents were resolved, the constituents that compose the majority of the tidal signal were analyzed and are presented below in Tables 2.1-2.3.

These six tables include tidal constituent height (H) and time lag (Φ_{lag}) with respect to the offshore gauge. The constituent tide height in feet (H) is the vertical distance between low and high water for each constituent. The time lag in minutes (Φ_{lag}) is the time required for a particular constituent to travel from Buzzards Bay (the offshore tide gauge) to the tide gauge of interest.

Table 2.1. Tidal constituents at offshore TDR.

Constituent & Period	**Offshore**	
	H	**Φ_{lag}**
(hours)	**(feet)**	**(minutes)**
M_2 (12.42)	3.52	--
S_2 (12.005)	0.83	--
M_4 (6.21)	0.53	--
O_1 (25.82)	0.42	--
K_1 (23.93)	0.40	--
MS_4 (6.01)	0.22	--

Table 2.2. Tidal constituents at Red Brook Harbor, Hen Cove, and Barlows Landing.

Constituent & Period	Red Brook Harbor		Hen Cove		Barlows Landing	
	H	Φ_{lag}	H	Φ_{lag}	H	Φ_{lag}
(hours)	(feet)	(minutes)	(feet)	(minutes)	(feet)	(minutes)
M_2 (12.42)	3.47	6.0	3.56	4.2	3.53	2.4
S_2 (12.005)	0.80	7.8	0.82	4.8	0.82	4.8
M_4 (6.21)	0.54	0.0	0.53	3.0	0.54	2.4
O_1 (25.82)	0.43	20.4	0.42	4.8	0.42	6.0
K_1 (23.93)	0.38	7.2	0.40	4.2	0.40	4.8
MS_4 (6.01)	0.19	4.2	0.21	7.2	0.21	3.6

Table 2.3. Tidal constituents at Squeteague Harbor, Rands Harbor, and Fiddlers Creek.

Constituent & Period	Squeteague Harbor		Rands Harbor		Fiddlers Creek	
	H	Φ_{lag}	H	Φ_{lag}	H	Φ_{lag}
(hours)	(feet)	(minutes)	(feet)	(minutes)	(feet)	(minutes)
M_2 (12.42)	3.58	7.8	3.60	3.6	3.59	3.0
S_2 (12.005)	0.82	9.6	0.84	4.2	0.84	4.2
M_4 (6.21)	0.52	5.4	0.54	3.6	0.54	3.0
O_1 (25.82)	0.42	8.4	0.43	4.8	0.43	5.4
K_1 (23.93)	0.41	15.0	0.40	4.2	0.40	1.8
MS_4 (6.01)	0.20	10.8	0.22	3.0	0.22	4.8

A brief analysis of the results presented in Tables 2.1 through 2.3 reveals that, as expected, the roughly twice-daily (semi-diurnal) influence of the moon (M_2) dominates the tide in this System. For instance at the offshore gauge the height of the M_2 constituent was 3.52 feet during the measurement period, compared to the height of the next most important constituent, S_2, with a height of 0.83 feet. M_2 accounts for at least 75% of the tide height; therefore, it was important to ensure the model accurately simulated the M_2 constituent. Two other fundamental observations based on the tidal constituent analysis are presented below:

- There is no significant decrease in tide height (i.e., tidal height dampening) within the System. For example, the M_2 height remained essentially constant (within 0.1 feet) at all tide gauge locations; and
- There is little time delay of the tide throughout the System. For example, the time required for the M_2 tide to travel from Buzzards Bay (the offshore gauge) to Squeteague Harbor is only approximately 8 minutes.

In summary, tidal constituent analysis was a useful tool for the Red Brook Harbor / Megansett Harbor System flushing study because constituents provide a quantitative basis for calibrating the model, and constituents indicate flushing characteristics of an estuary or bay (Aubrey Consulting Inc. 1997).

2.2 Bathymetry

Bathymetry, or water depth, data also were required as input to the hydrodynamic model. To accurately estimate the volume of water in the System, and to properly simulate the hydrodynamics, an accurate representation of the bathymetry and shoreline position was necessary. Therefore, a combination of United States Geological Survey (USGS) quadrangle maps of the area and an ACI bathymetric survey provided the detailed information needed for input to the model.

The bathymetric data collection system (Figure 2.10) was based on HYPACK navigation integration software, installed on a portable personal computer that logged simultaneous position and depth. Position was recorded using a Northstar 941X Differential Global Positioning System (DGPS) while water depths were recorded using the Odom DF3200 EchoTrac fathometer. This instrument was preferred by ACI for its high resolution (0.1 feet), digital output, and demonstrated reliability. In addition to the digital data, a hardcopy of the data also was generated to ground-truth the electronic data and for contingency purposes. Bathymetric data were collected west of Scraggy Neck, Red Brook Harbor, Hen Cove, Barlows Landing, Pocasset Harbor, Megansett Harbor, Squeteague Harbor, Rands Harbor, and Fiddlers Creek.

Once the data were collected, the data were post-processed. Post-processing was required primarily to reference the data to the MLW vertical datum. Since the boat rides on the tide while the survey is occurring, the tide signal was subtracted from the survey data. Post-processing also removed some other data points (i.e., unrealistic). Once editing was completed, the bathymetric data was reformatted to three columns of northing, easting, and bottom elevation relative to MLW. This allowed the data to be input to the hydrodynamic model. The bathymetry of the study area is presented in Figure 2.11.

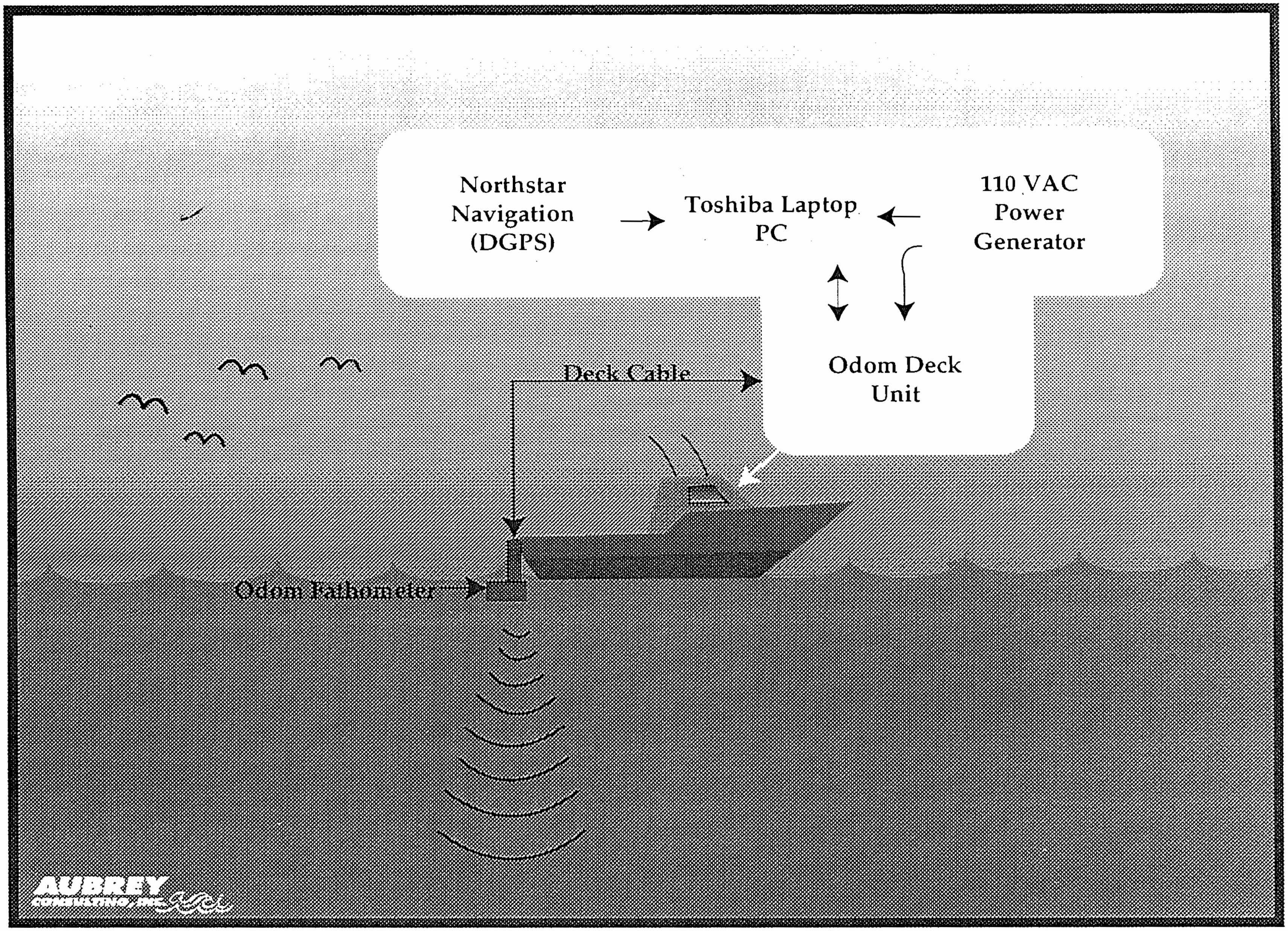

Figure 2.10. Bathymetric measurement system.

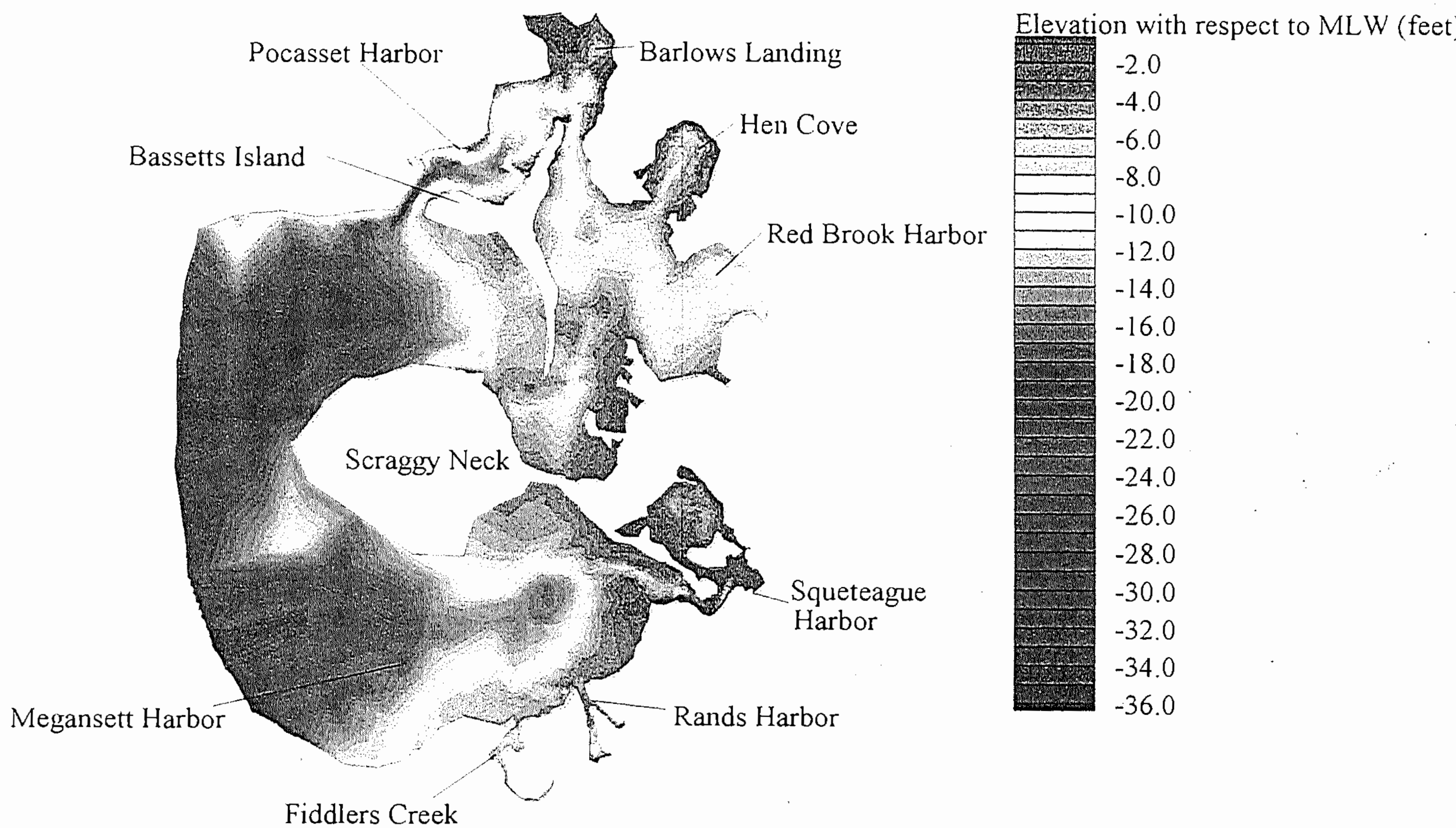

Figure 2.11. Bathymetric map of Study Area.

3.0 Numerical Modeling

Numerical modeling is the application of a computer program to simulate a physical process. Numerical models are valuable tools for evaluating existing conditions and a variety of engineering alternatives. Numerical models are only as accurate as the input data; therefore, high quality field data sets are required. For this flushing study, a hydrodynamic numerical model was used that simulated tidal circulation in the System. Specifically, the hydrodynamic numerical model was used to evaluate tidal circulation and flushing characteristics of the Red Brook and Megansett Harbor System, including residence times. This section discusses the numerical modeling, including a brief description (Section 3.1) of the equations and the solution scheme governing the model used for this flushing study (RMA-2). Section 3.1 is provided to document the model used for this study, but it is not critical that the reader be familiar with the concepts to understand the results of the flushing study. Section 3.2 discusses how RMA-2 was set-up for this site-specific application. Section 3.3 discusses how RMA-2 was calibrated to ensure it could accurately simulate tidal processes measured in the field. A model must be calibrated based on field data in order to provide reliable results. The model provided an economical means to provide a high level of detail. For instance, the model simulated tidal height and currents at hundreds of points every 10 minutes for 17 days. It would be cost-prohibitive to measure this level of information in the field.

3.1 Model Theory

The numerical hydrodynamic model, RMA-2, was developed by William Norton and Ian King for the U.S. Army Corp of Engineers. Since its original development, improvements have been incorporated into the model, such as one-dimensional elements, updated numerical convergence parameters, and an updated eddy viscosity coefficients calculation algorithm. One of the most significant upgrades for presentation purposes was the introduction of a state-of-the-art pre- and post-processing application, called the *Surface-Water Modeling System* (SMS) (BOSS International, Inc. and Brigham Young University, 1995). SMS simplifies grid generation, boundary condition specification, execution of the RMA-2 model, and analysis of results. SMS version 5.08 and RMA-2 version 4.35 (USACE, 1996) were used for this study. ACI has worked with the developers of RMA-2 and SMS to ensure the models are appropriate for flushing studies of this type.

RMA-2 is a finite element model designed for simulating one- and two-dimensional depth-averaged hydrodynamics by solving a simplified version of the Navier-Stokes Equations, which are known as the shallow water wave equations. The dependent variables are velocity (two horizontal components) and water depth. Reynolds assumptions are incorporated as an eddy viscosity effect to represent turbulent energy losses. Other terms in the governing equations permit friction losses (expressed by a Manning's n formulation), and surface wind stresses. All coefficients associated with these terms may vary from element to element.

The two-dimensional, depth-integrated, shallow water wave equations are:

Momentum Equations:

$$\rho\left[h\frac{\partial u}{\partial t} + uh\frac{\partial u}{\partial x} + vh\frac{\partial u}{\partial y}\right] + h\left[\frac{\partial}{\partial x}\left(\rho g[a+h]\right)\right] - h\varepsilon_{xx}\frac{\partial^2 u}{\partial x^2} - h\varepsilon_{xy}\frac{\partial^2 u}{\partial y^2} + \rho S_{f_x} + \tau_x = 0$$

$$\rho\left[h\frac{\partial v}{\partial t} + uh\frac{\partial v}{\partial x} + vh\frac{\partial v}{\partial y}\right] + h\left[\frac{\partial}{\partial y}\left(\rho g[a+h]\right)\right] - h\varepsilon_{yx}\frac{\partial^2 v}{\partial x^2} - h\varepsilon_{yy}\frac{\partial^2 v}{\partial y^2} + \rho S_{f_x} + \tau_y = 0$$

Continuity:

$$\frac{\partial h}{\partial t} + \frac{\partial(hu)}{\partial x} + \frac{\partial(hv)}{\partial y} = 0$$

In these equations, u and v are the respective horizontal x and y velocity components in Cartesian Coordinates; h and a are the water depth and bottom elevation; S_{fx} and S_{fy} are frictional effects at the bottom expressed in terms of Manning's n values; τ_x and τ_y represent the effects of wind stress; and ε_{xx}, ε_{xy}, ε_{yy}, ε_{yx} are the eddy viscosity coefficients.

Eddy viscosity coefficients in the model are an approximate representation of the energy loss due to turbulent effects at the spatial scale of the numerical modeling elements. According to King (1990), these values are proportional to the element size and flow velocities.

A Galerkin weighted residual approach is used to develop the finite element integral equations, and Gaussian quadrature is employed to evaluate the final integral forms. Time dependence of the governing equations is incorporated by using a modified Crank-Nicholson solution, which is an implicit technique to solve the set of simultaneous equations. The equations are non-linear and are solved by using a Newton-Raphson method to develop a locally linear set of equations. Once solved, corrections to the initial estimate of velocity and water elevation are employed through an interactive process, and the equations are resolved until convergence criteria are met.

3.2 Model Set-up

Three steps were required to execute and calibrate the model: 1) generation of the grid, 2) specification of boundary conditions, and 3) assignment of model coefficients.

Summarizing the set-up, the grid boundaries were established using USGS quadrangle maps for Onset, Mass 1967 and Pocasset, Mass 1967. A time varying water surface boundary condition (e.g., tide) was specified seaward of Scraggy Neck. The model was calibrated after developing the finite element grid and specifying the offshore tidal boundary condition. The calibration process ensured that the model accurately predicted what was observed in nature during the time period corresponding to the field measurements. Model coefficients was adjusted within accepted ranges through model calibration to achieve appropriate agreement between model results and field measurements. Once calibrated, the model was able to predict the existing circulation, and flushing characteristics. The calibrated model also may be used in the future for other analyses (Section 5.0).

3.2.1 Grid Generation

The grid defines the region to be modeled. RMA-2 uses a finite element grid as part of its solution procedure. One advantage of a finite element grid is it can be adapted to fit irregular shorelines such as in the Red Brook and Megansett Harbor System. The finite element grid (Figure 3.1) was generated using SMS. The mesh was constructed completely of two-dimensional quadrilateral and triangular elements. Water depths were specified at each node in the model domain. Tighter groups of elements were used in the areas of rapidly changing bathymetry, or at constrictions. This occurs at areas such as Squeteague Harbor where three elements are used across the mouth instead of just one large element.

Grid resolution was governed by two factors: 1) expected flow patterns, and 2) the need to resolve large bathymetric gradients or constrictions. Relatively fine grid resolution was employed where complex circulation was expected, and where bathymetric gradients or constrictions existed. For example, more elements were generated at inlet mouths. Ideally, the grid spacing should be as small as possible, subject to the density of available data as well as computational constraints (i.e., how long it takes to run the model).

3.2.2 Boundary Conditions

RMA-2 computes tide elevation and current velocities throughout the grid based upon the information specified along the domain boundaries. Two types of boundary conditions were employed in this modeling effort:

- Tidal boundaries
- Closed boundaries

A dynamic (i.e., time varying) water surface boundary condition (e.g., tide) was prescribed seaward of Scraggy Neck based on the data collected at the offshore TDR (Figure 3.2). The tidal action at this western boundary was the only forcing boundary to be applied to the System. The tide height specified along this boundary varied every ten minutes. The second type of boundary condition placed a constraint of zero velocity perpendicular to the shoreline. All of the elements with shoreline borders had these closed boundaries, where the direction of flow at this boundary was constrained shore-parallel. A third type of boundary condition, fresh-water inflow, may also be

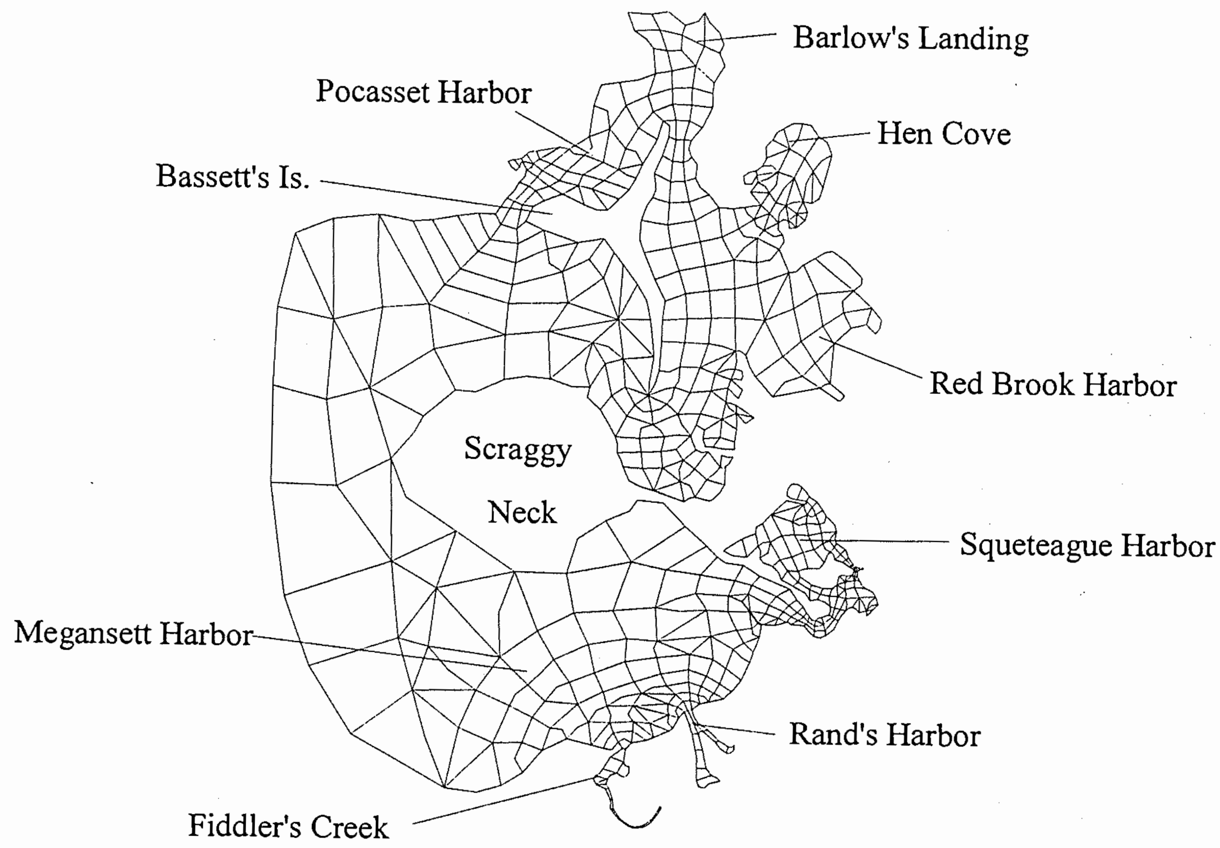

Figure 3.1. Finite element grid of Study Area.

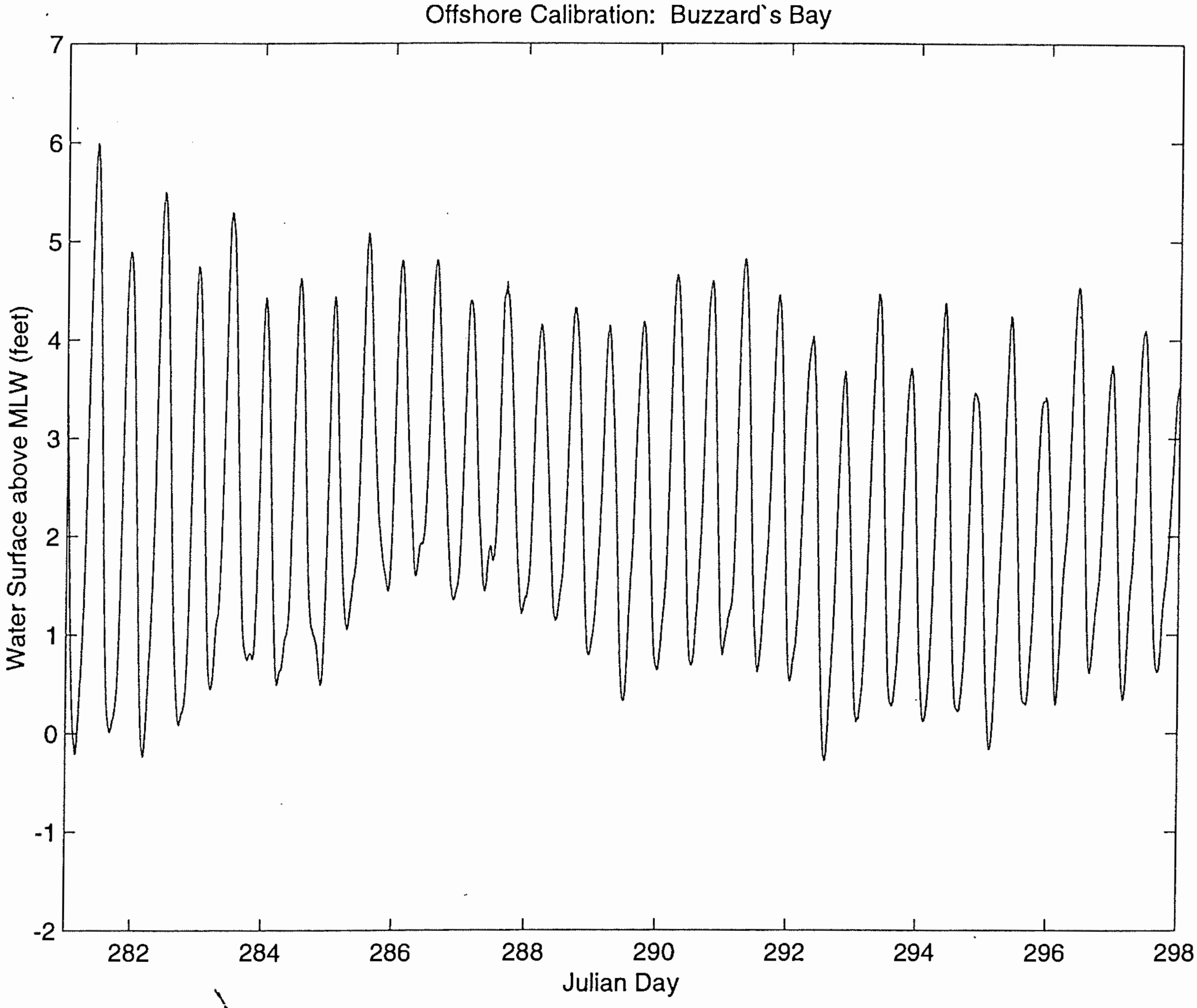

Figure 3.2. Measured versus modeled comparison (solid line=measured, dashed line=modeled) for Buzzard`s Bay (Offshore Calibration).

included; however, this information was not available for this system. The influence of freshwater inflow on residence times in Cape Cod Estuaries is typically small using the tidal flushing methodology.

3.2.3 Model Coefficients

The RMA-2 model has certain coefficients that can be adjusted depending upon the characteristics of the System. These coefficients characterize the bottom roughness (friction) and characteristics of the flow, such as turbulence. Friction and turbulence, in part, control how the tide travels through the System; therefore, these coefficients can be adjusted within acceptable ranges to achieve an appropriate match between the model results and field data.

Friction inhibits flow along the sides and bottom of estuaries. It is a measure of the channel roughness, and can cause significant tidal dampening particularly in areas of shallow water depth. In RMA-2, friction is expressed in terms of a Manning's n coefficient. Initially, a Manning's n value of 0.020 was specified throughout the domain. This value corresponds to straight gravel beds (Roberson and Crowe 1995). Based on knowledge of the System's bottom type, Manning's n value were increased to 0.025 throughout the grid to improve model accuracy. This value of Manning's n corresponds approximately to a natural straight earthen channel with some grass, or can apply to a gravel channel, both of which are characteristic of the Red Brook and Megansett Harbor System. This value of Manning's n also produced an excellent match between model results and field data.

Turbulent coefficients (ε_{xx}, ε_{xy}, ε_{yy}, and ε_{yx}), also known as eddy viscosity coefficients, approximate energy losses due to internal friction between fluid particles. The significance of turbulent energy losses increases where flow is more swift, like at channel constrictions. Typically, these coefficients should be kept as low as possible to allow the model to simulate complex flows, such as eddies.

Since there is a large range for eddy viscosity coefficients in published literature, they are treated as calibration parameters. Therefore, sensitivity tests were run to determine the optimal values for this System. A reasonable value of 50 pounds-feet^2 / second was specified throughout the domain. Care must be taken not assign too high of an eddy viscosity coefficient since stable-but unrealistic-results may be obtained. Excessively high values of turbulent energy coefficients can artificially eliminate complex flow features such as eddies.

3.3 Model Calibration

Model calibration was the process by which adjustments were made to the model, within acceptable ranges, to ensure the model appropriately simulated measured tide data. A visual and a quantitative calibration was achieved. The calibrated model results exhibited excellent agreement with the field measurements; therefore, the model was shown to be an excellent tool for evaluating tidal flushing characteristics and for computing residence times. A 17-day period was selected for model calibration from October 8, 1998 through October 25, 1998. This representative time period was selected because it included the range of tidal conditions typical in the study area during the data collection period, including spring and neap tides. The model's ability to simulate a range of tidal conditions is key to developing accurate flushing rates. Other methods, such as dye studies and box models, typically evaluate tidal flushing over shorter periods of time, respond to instantaneous local effects, or use over-simplified equations that may not represent longer term complex conditions. By using the model to evaluate this long-term range of conditions, average, minimum, and maximum residence times can be estimated.

The model was calibrated by comparing modeled and measured tides for height difference, and time lag difference. A visual and a quantitative calibration was completed. The calibrated modeled was used to characterize flow patterns, and compute residence times. A bestfit model predictions with the TDR data was achieved using the aforementioned values for friction and turbulence. Figures 3.3 and 3.4 illustrate a close-up of two M_2 tidal cycles. Measured (solid) and modeled (dashed) are illustrated for: Red Brook Harbor, Hen Cove, Barlows Landing, Squeteague Harbor, Rands Harbor, and Fiddlers Creek. Only two tidal cycles are illustrated to focus on the details of the results. Figures 3.2 and 3.7 confirm visual agreement between the measured and modeled tides in the study area. The model results match the data almost perfectly.

Quantitative agreement between the measured and modeled tides was completed in addition to the visual calibration discussed above. Calibration of the M_2 constituent was of primary interest since it accounted for approximately 75% of the tidal signal. The next five dominant constituents that were calibrated, given the length of the time series, were: S_2, M_4, O_1, K_1, and MS_4. Measured and modeled tidal heights (H), time lags (Φ_{lag}), and differences were calculated at the seven TDRs for the 17 day calibration period. Time lag represents the time required for a constituent to propagate from the offshore boundary to each particular location. The results from the tidal constituent calibration process are provided on Tables 3.1 through 3.7. Results of water surface, from measured and modeled efforts, revealed excellent agreement. Differences associated with each tidal constituent were on the order of 0.07 feet or less.

Particularly excellent agreement is achieved between the dominant M_2 constituent. The phase discrepancies between the measured and model M_2 constituent were within one model time-step: 10 minutes or 0.167 hours. Also, the modeled M_2 tide heights were within 0.07 feet of the measured data. Again, the model's ability to simulate this constituent was most important since it composed more than 75% of the entire tidal signal. M_2's first harmonic, M_4, was used to determine the nonlinearly of the tidal signal. Proper prediction of M_4 provided confidence in the model accuracy, since it indicated that the model was capable of simulating the tidal wave form and size (Aubrey Consulting, Inc. 1997). The maximum difference between measured and modeled tide height was only 0.01 feet with a corresponding time lag error of only 7.8 minutes. A thorough examination of Tables 3.1 through 3.7 reveals that the other modeled constituents agreed well with data.

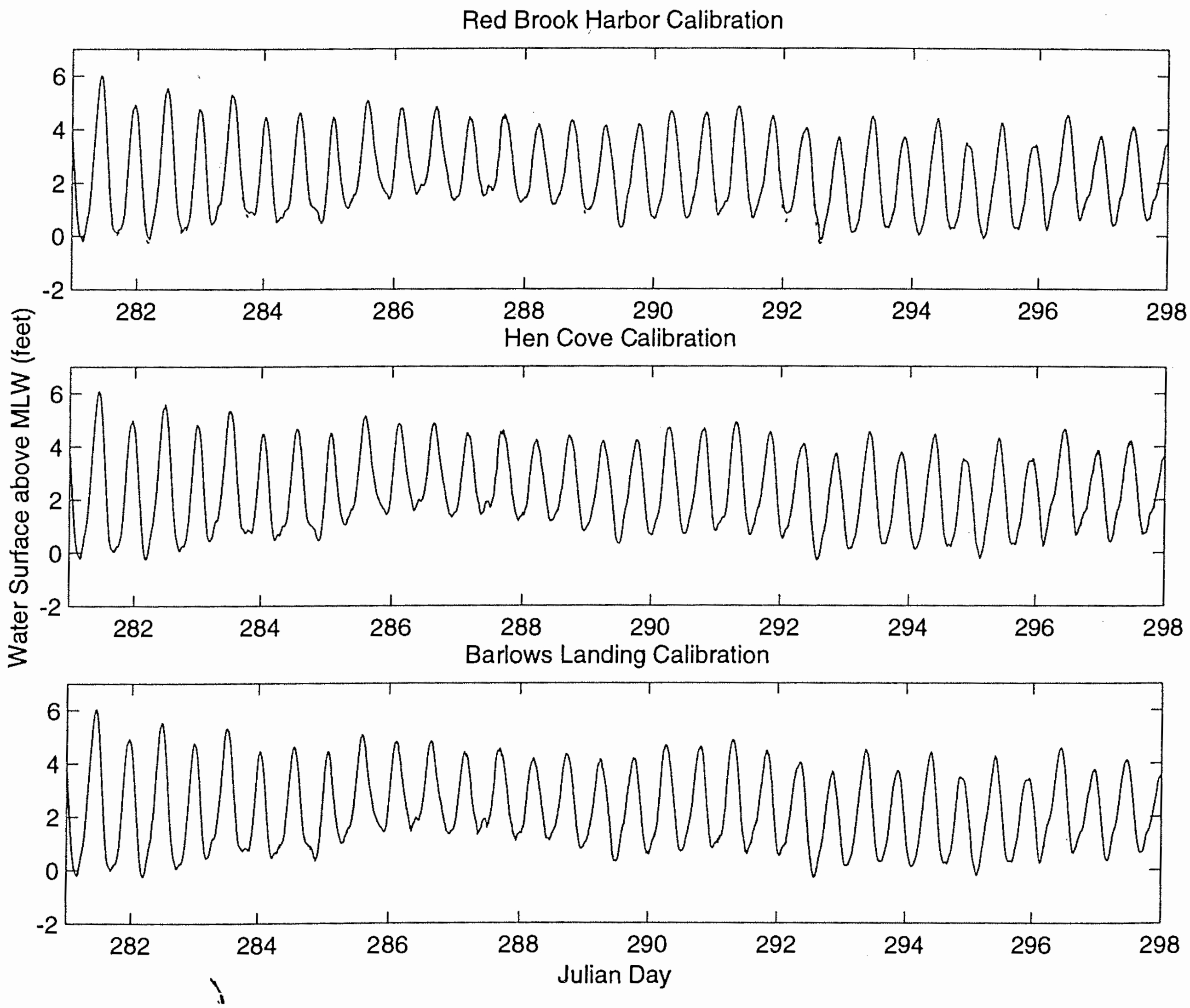

Figure 3.3. Measured versus modeled comparison (solid line=measured, dashed line=modeled) for Red Brook Harbor, Hen Cove, and Barlow`s Landing.

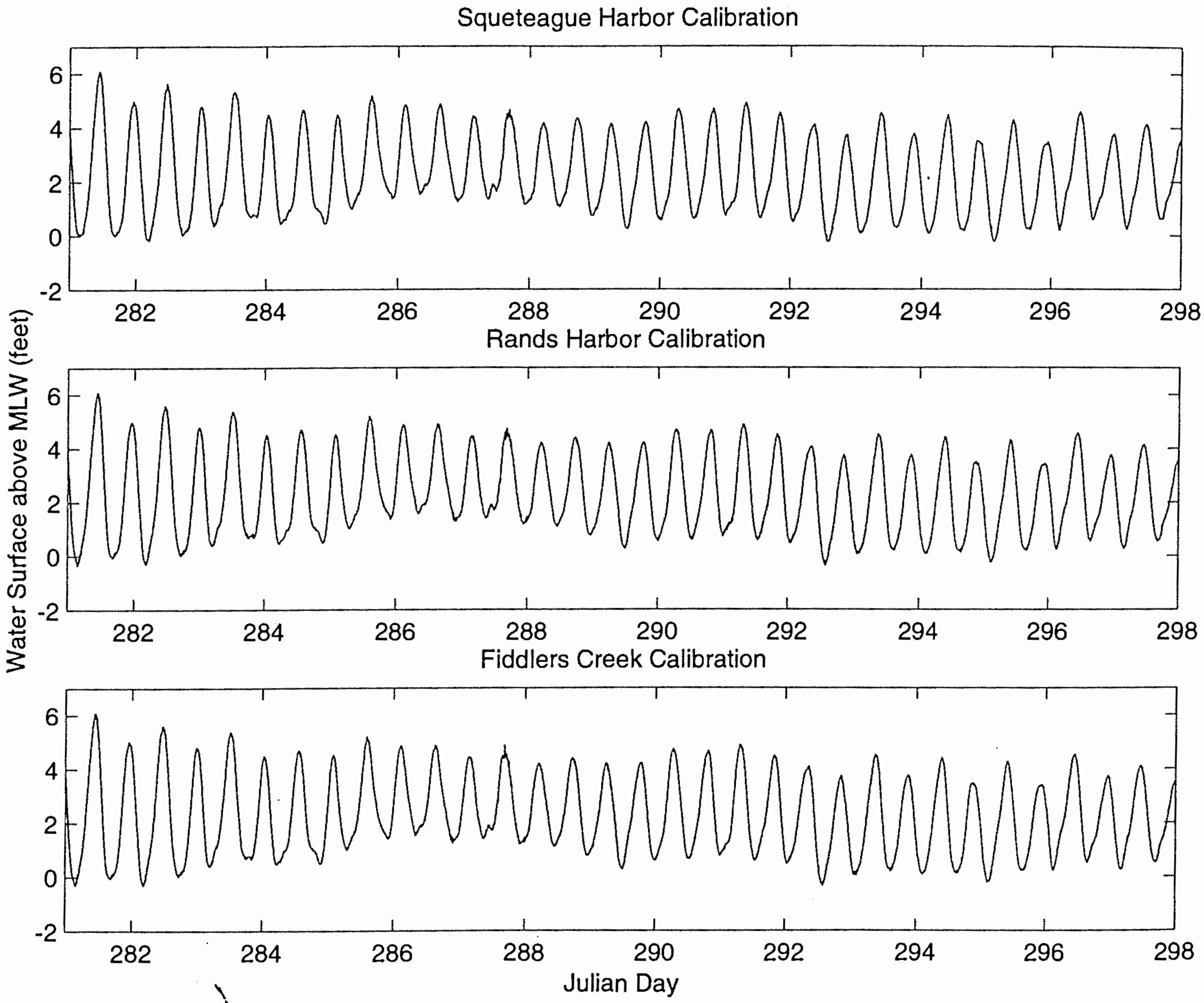

Figure 3.4. Measured versus modeled comparison (solid line=measured, dashed line=modeled) for Squeteague Harbor, Rand`s Harbor, and Fiddler`s Creek.

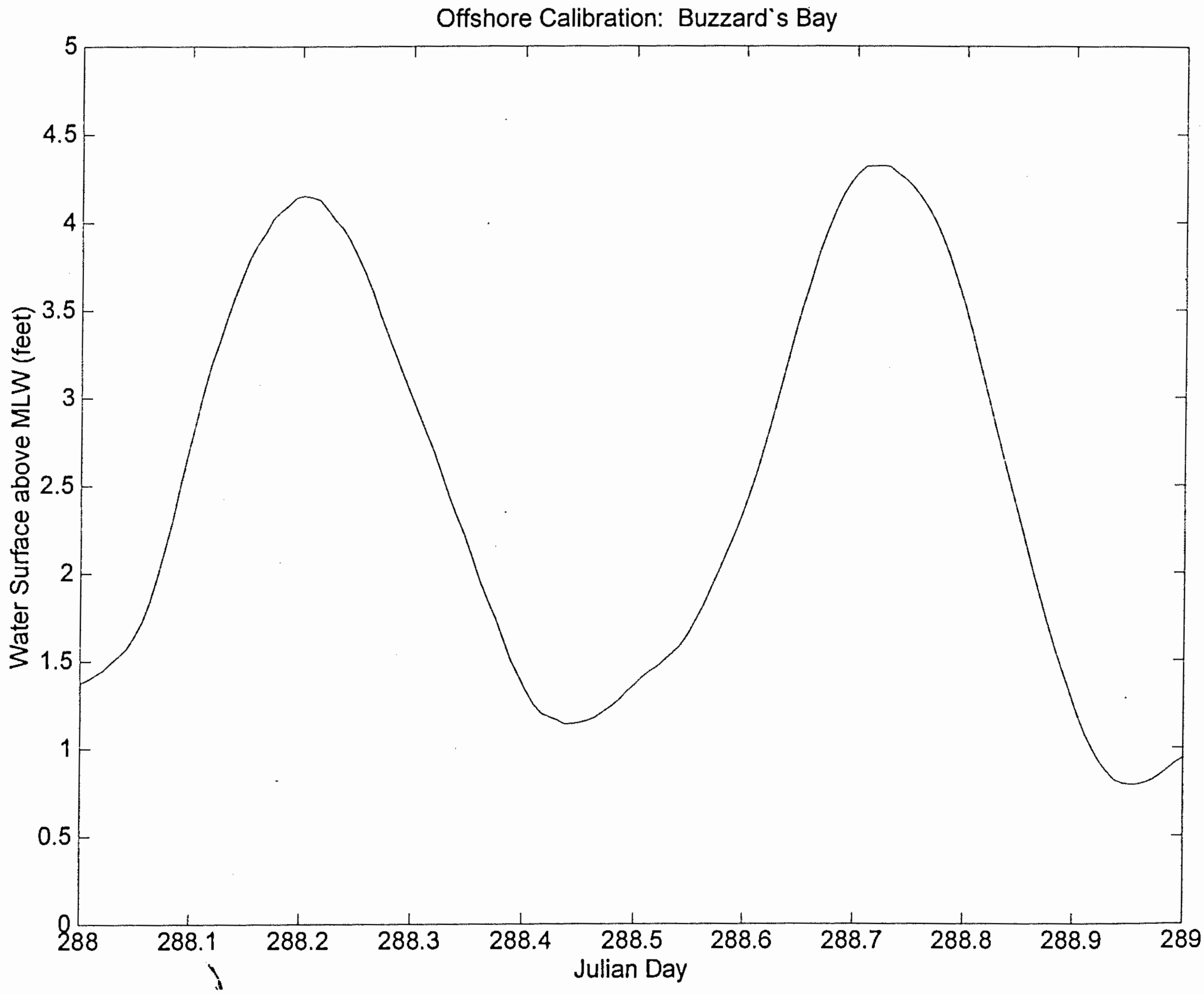

Figure 3.5. Close-up of measured versus modeled comparison (solid line=measured, dashed line=modeled) for Buzzard`s Bay (Offshore Calibration).

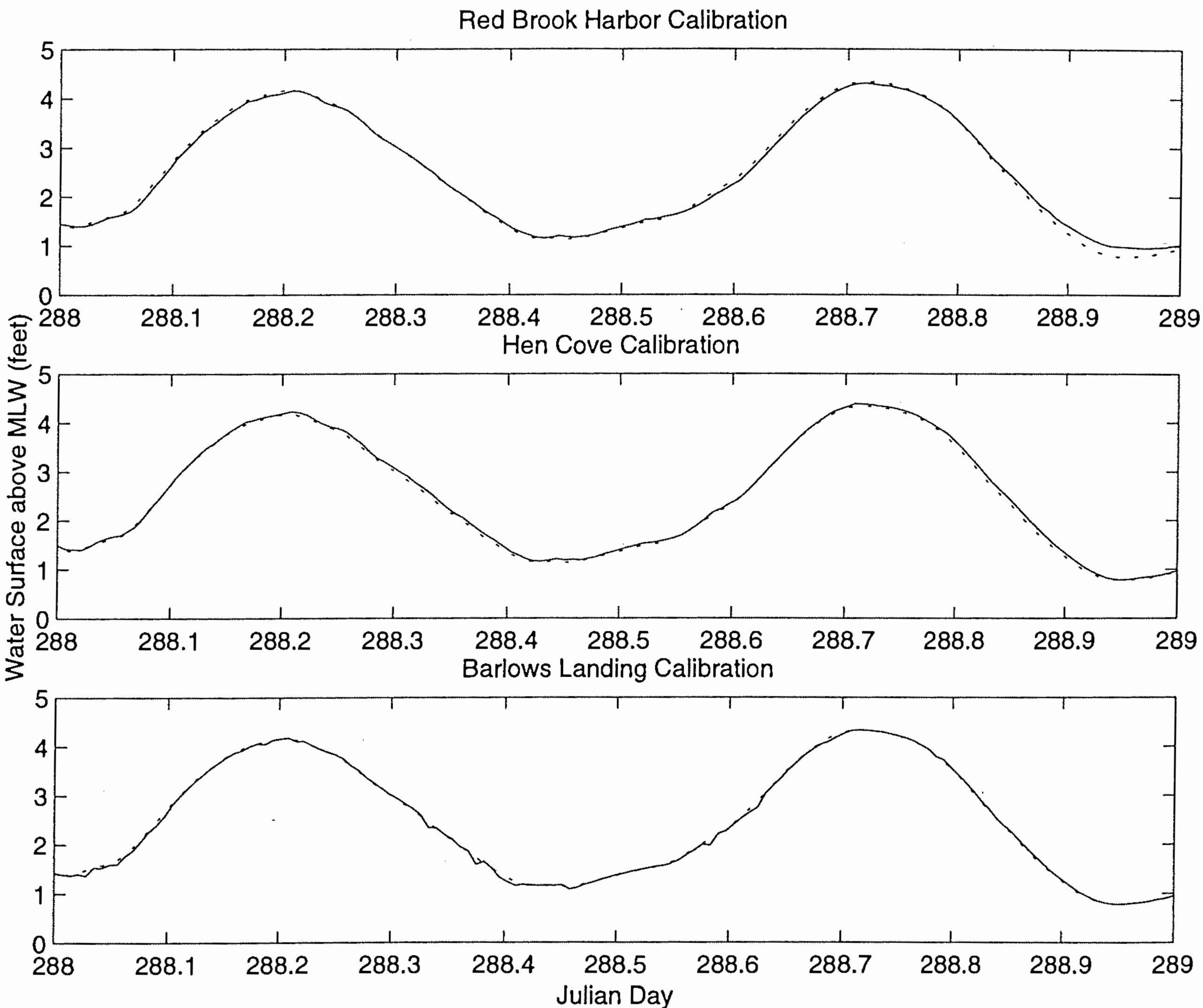

Figure 3.6. Close-up of measured versus modeled comparison (solid line=measured, dashed line=modeled) for Red Brook Harbor, Hen Cove, and Barlow`s Landing.

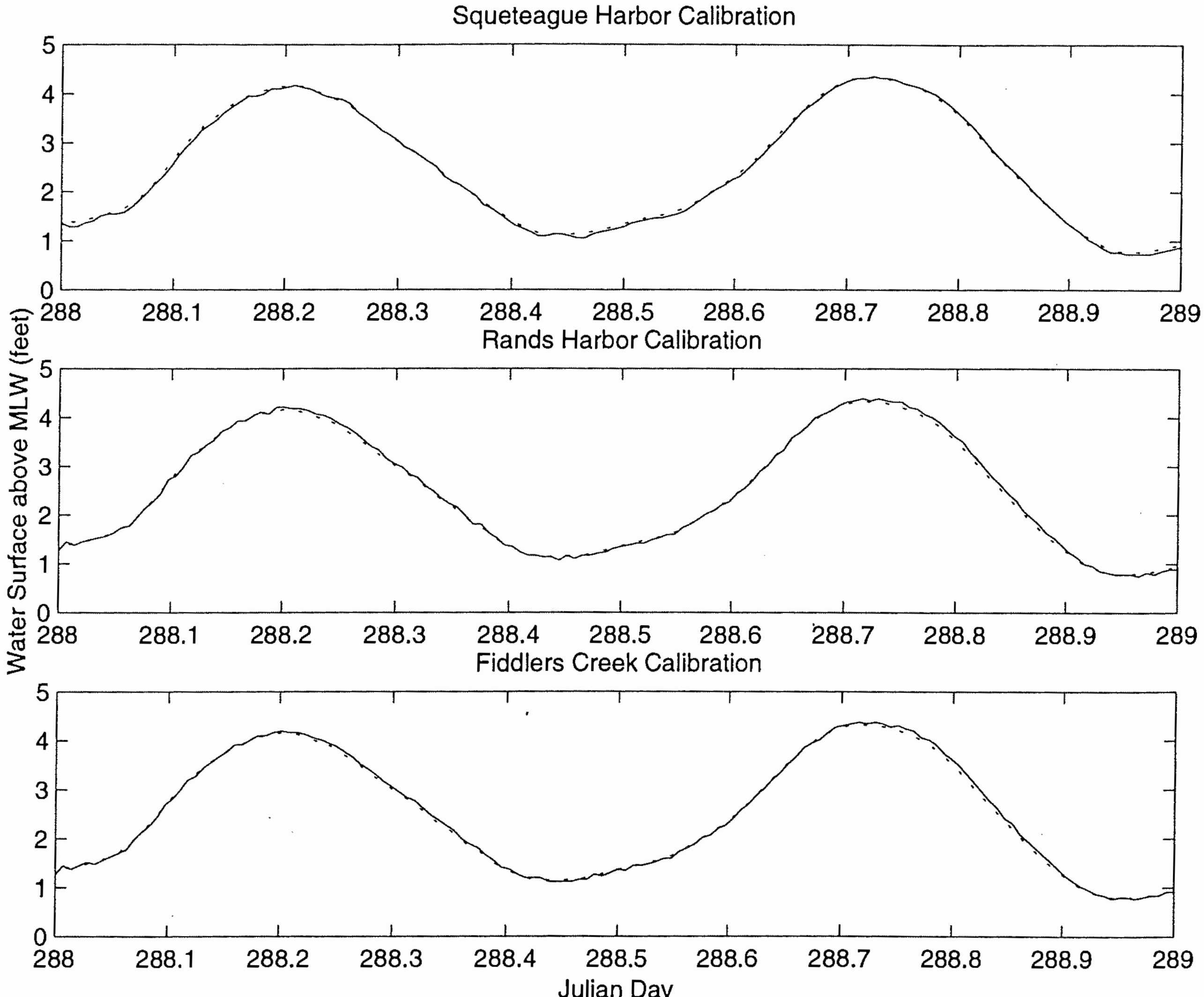

Figure 3.7. Close-up of measured versus modeled comparison (solid line=measured, dashed line=modeled) for Squeteague Harbor, Rand's Harbor, and Fiddler's Creek.

Table 3.1. Tidal constituent calibration at the offshore boundary

Constituent & Period	Measured		Modeled		Error	
	H	Φ_{lag}	H	Φ_{lag}	H	Φ_{lag}
(hours)	(feet)	(minute)	(feet)	(minute)	(feet)	(minute)
M_2 (12.42)	3.52	--	3.52	--	0.00	--
S_2 (12.005)	0.83	--	0.83	--	0.00	--
M_4 (6.21)	0.53	--	0.53	--	0.00	--
O_1 (25.82)	0.42	--	0.42	--	0.00	--
K_1 (23.93)	0.40	--	0.40	--	0.00	--
MS_4 (6.01)	0.22	--	0.22	--	0.00	--

Table 3.2. Tidal constituent calibration at Red Brook Harbor.

Constituent & Period	Measured		Modeled		Error	
	H	Φ_{lag}	H	Φ_{lag}	H	Φ_{lag}
(hours)	(feet)	(minute)	(feet)	(minute)	(feet)	(minute)
M_2 (12.42)	3.47	6.0	3.54	1.2	-0.07	4.8
S_2 (12.005)	0.80	7.8	0.83	1.2	-0.03	6.6
M_4 (6.21)	0.54	0.0	0.54	0.6	0.00	-0.6
O_1 (25.82)	0.43	20.4	0.42	0.6	0.01	19.8
K_1 (23.93)	0.38	7.2	0.40	0.6	-0.02	6.6
MS_4 (6.01)	0.19	4.2	0.22	1.8	-0.03	2.4

Table 3.3. Tidal constituent calibration at Hen Cove.

Constituent & Period	Measured		Modeled		Error	
	H	Φ_{lag}	H	Φ_{lag}	H	Φ_{lag}
(hours)	(feet)	(minutes)	(feet)	(minutes)	(feet)	(minutes)
M_2 (12.42)	3.56	4.2	3.54	1.2	0.02	3.0
S_2 (12.005)	0.82	4.8	0.83	1.2	-0.01	3.6
M_4 (6.21)	0.53	3.0	0.54	1.2	-0.01	1.8
O_1 (25.82)	0.42	4.8	0.42	1.2	0.00	3.6
K_1 (23.93)	0.40	4.2	0.40	1.2	0.00	3.0
MS_4 (6.01)	0.21	7.2	0.22	1.8	-0.01	5.4

Table 3.4. Tidal constituent calibration at Barlows Landing.

Constituent & Period	Measured		Modeled		Error	
	H	Φ_{lag}	H	Φ_{lag}	H	Φ_{lag}
(hours)	(feet)	(minutes)	(feet)	(minutes)	(feet)	(minutes)
M_2 (12.42)	3.53	2.4	3.54	0.6	-0.01	1.8
S_2 (12.005)	0.82	4.8	0.82	1.2	0.00	3.6
M_4 (6.21)	0.54	2.4	0.54	0.6	0.00	1.8
O_1 (25.82)	0.42	6.0	0.42	1.2	0.00	4.8
K_1 (23.93)	0.40	4.8	0.40	0.00	0.00	4.8
MS_4 (6.01)	0.21	3.6	0.22	1.2	-0.01	2.4

Table 3.5. Tidal constituent calibration at Squeteague Harbor.

Constituent & Period	Measured		Modeled		Error	
	H	Φ_{lag}	H	Φ_{lag}	H	Φ_{lag}
(hours)	(feet)	(minutes)	(feet)	(minutes)	(feet)	(minutes)
M_2 (12.42)	3.58	7.8	3.54	6.0	0.04	1.8
S_2 (12.005)	0.82	9.6	0.80	10.2	0.02	-0.6
M_4 (6.21)	0.52	5.4	0.51	0.0	0.01	5.4
O_1 (25.82)	0.42	8.4	0.42	2.4	0.00	6.0
K_1 (23.93)	0.41	15.0	0.40	3.0	0.01	12.0
MS_4 (6.01)	0.20	10.8	0.17	3.6	0.03	9.0

Table 3.6. Tidal constituent calibration at Rands Harbor.

Constituent & Period	Measured		Modeled		Error	
	H	Φ_{lag}	H	Φ_{lag}	H	Φ_{lag}
(hours)	(feet)	(minutes)	(feet)	(minutes)	(feet)	(minutes)
M_2 (12.42)	3.60	3.6	3.53	< 0.6	0.07	3.6
S_2 (12.005)	0.84	4.2	0.82	< 0.6	0.02	4.2
M_4 (6.21)	0.54	3.6	0.54	< 0.6	0.00	3.6
O_1 (25.82)	0.43	4.8	0.42	< 0.6	0.6	4.8
K_1 (23.93)	0.40	4.2	0.40	< 0.6	0.00	4.2
MS_4 (6.01)	0.22	3.0	0.22	0.6	0.00	2.4

Table 3.7. Tidal constituent calibration at Fiddlers Creek

Constituent & Period	Measured		Modeled		Error	
	H	Φ_{lag}	H	Φ_{lag}	H	Φ_{lag}
(hours)	(feet)	(minutes)	(feet)	(minutes)	(feet)	(minutes)
M_2 (12.42)	3.59	3.0	3.52	< 0.6	0.07	3.0
S_2 (12.005)	0.84	4.2	0.82	< 0.6	0.02	4.2
M_4 (6.21)	0.54	3.0	0.54	< 0.6	0.00	3.0
O_1 (25.82)	0.43	5.4	0.42	< 0.6	0.01	5.4
K_1 (23.93)	0.40	1.8	0.40	< 0.6	0.00	1.8
MS_4 (6.01)	0.22	4.8	0.22	0.6	0.00	4.2

4.0 Residence Times and Tidal Circulation

Results from the calibrated RMA-2 numerical model were utilized to compute residence times and to characterize tidal circulation in the Red Brook and Megansett Harbor System. Section 4.1 presents the residence time calculations and results, which are the primary product of this flushing study. Section 4.2 provides a discussion, supported by graphical plots, of current patterns throughout a tidal cycle.

4.1 Residence Times

Residence time can be interpreted as the average amount of time that a parcel of water spends in an embayment (Knauss 1978) or the time required to flush the volume of water in an embayment. One of the primary goals/products of this flushing study was a table of residence times that can be used by the Town and the Cape Cod Commission as an indicator of water quality for planning purposes. For this study, residence times were computed using the following formula:

$$\text{Residence Time} = \frac{\text{Volume of water to be flushed (cubic feet)}}{\text{Volmetric flow rate into an embayment (cubic feet per second)}}$$

All of the information required for the residence time calculation was output from the numerical model. The model provides an accurate estimate of water volume based on the area of each embayment within the shoreline that bounds the grid and the water depths from the bathymetry survey. Water volumes are provided for the mid-tide level (MTL) during the tide gauging period. ACI has modified the model to provide the volumetric flow rate into and out of each embayment. Therefore, our version of the model is directly applicable for residence time calculations.

As stated above, residence times indicate the average time that a parcel of water spends in a water body. Residence times, therefore, indicate how quickly a water body is flushed, which is an indicator of water quality. If the embayment volume is small or if flow rate is large, residence times will be relatively small, which suggests the embayment is being flushed quickly. Lower residence times generally correspond to higher water quality; however, water quality also is dependent upon pollutant / nutrient loading, naturally occurring chemical breakdown processes, and the rate of the quality of water outside the embayment.

For example, the rate of pollutant / nutrient loading and the quality of water outside the embayment both must be evaluated in conjunction with residence times to obtain a clear picture of water quality. Efficient tidal flushing (low residence time) is not necessarily an indication of high water quality if pollutants and nutrient are loaded into the embayment faster than can be flushed out of the embayment. Neither are low residence times an indicator of water quality if the water being flushed into the embayment is of poor quality. Advanced understanding of water quality can be obtained from the calibrated hydrodynamic model by extending the model to include pollutant / nutrient dispersion and mixing. However, the residence times provided herein are valuable for planning purposes, and can be used in conjunction with nutrient loading information to assess water quality.

Two types of residence times are provided: *system* residence times and *local* residence times. Results from the calibrated model were used to calculate system and local residence times based on the 17-day tide recorded. The system residence time of a sub-embayment was based the tidal exchange with Buzzards Bay while the local residence time calculation of a sub-embayment was based on the tidal exchange with an adjacent body of water. For instance the system residence time of Squeteague Harbor indicates the time required to flush with new water from Buzzards Bay, whereas the local residence time indicates how long it takes to flush Squeteague Harbor with new water from Megansett Harbor. In order to characterize the entire study period, the average flood discharge was used to provide average residence times.

Residence times were computed for the entire study region, as well as several sub-embayments within the study area. Figure 4.1 shows the model divisions defined for the basins within the study domain. Table 4.1 provides system residence times. Note that system residence time for the whole study area was based on the entire volume of the

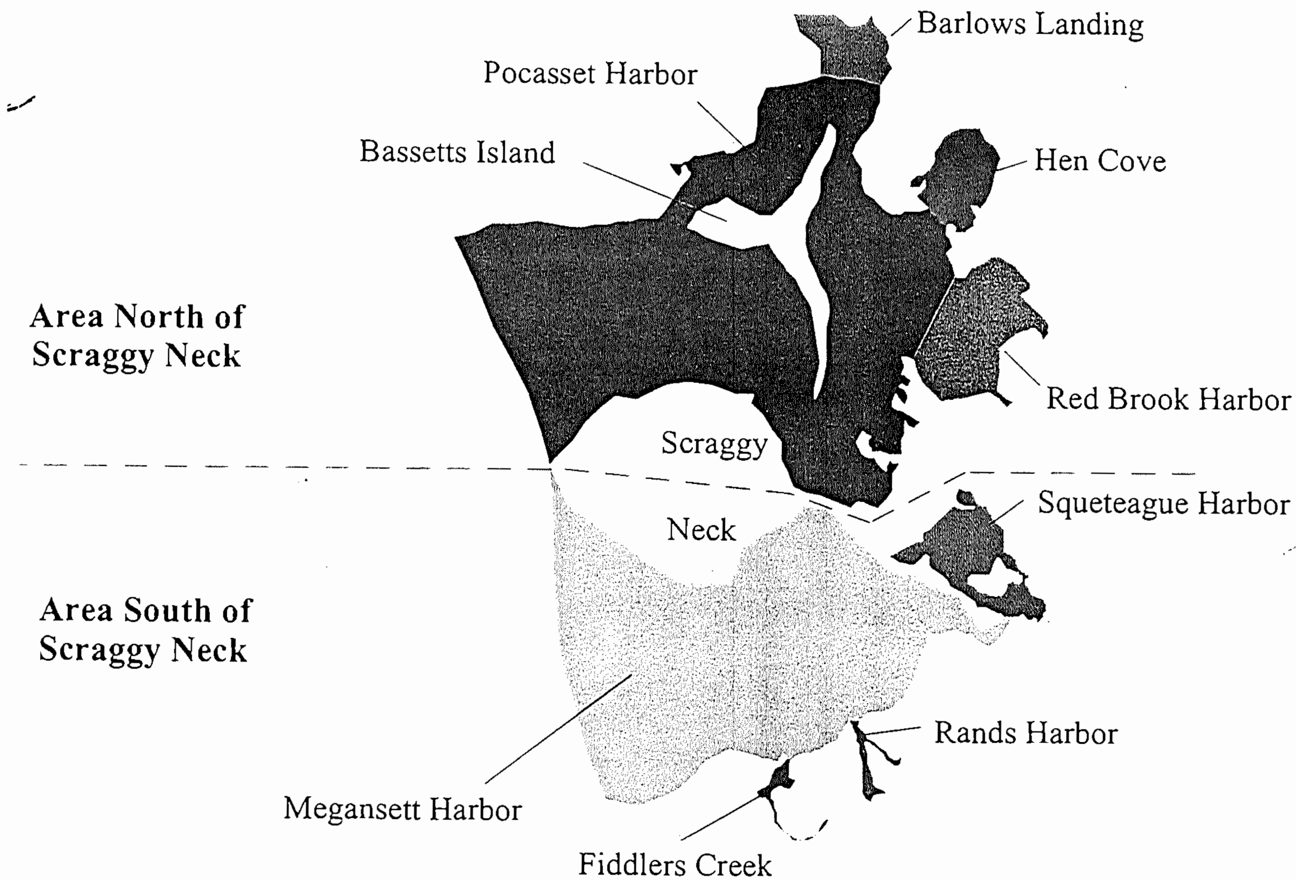

Figure 4.1. Model divisions utilized for computing flushing rates

System, whereas the other system residence times assumed no recirculation of water between the portions of the System north and south of Scraggy Neck (Figure 4.1). In this manner, although the System was modeled as a whole, the areas north and south of Scraggy Neck was treated independently for the purposes of calculating system residence times.

Table 4.1 Volumes and **system residence times** for Red Brook / Megansett System and sub-embayments.

Embayment / Sub-embayment	**Volume**	**Residence Time**
	(feet^3, MTL)	**(days)**
Entire Domain	$1.88 * 10^9$	1.8
Area North of Scraggy Neck	$7.65 * 10^8$	1.6
Red Brook Harbor	$5.46 * 10^7$	17.2
Hen Cove	$1.73 * 10^7$	45.4
Barlows Landing	$1.05 * 10^8$	63.6
Area South of Scraggy Neck	$5.59 * 10^8$	1.6
Squeteague Harbor	$1.59 * 10^7$	20.2
Rands Harbor	$3.28 * 10^6$	226.8
Fiddlers Creek	$3.45 * 10^6$	402.6

The system residence times shown on Table 4.1 indicate that, on the whole, the System flushes rapidly. For instance, the whole System, and the portions of the System north and south of Scraggy Neck exchange water with Buzzards Bay in less than two days. However, more remote portions of the System exchange water with Buzzards Bay less rapidly. For instance, Red Brook Harbor and Squeteague Harbor flush in 21 days or less, and Hen Cove is flushed with new water from Buzzards Bay in 45.4 days. The highest system residence times are for Rands harbor and Fiddlers Creek, which require, on average, approximately 226.8 and 402.6 days, respectively, to flush with Buzzards Bay. Depending upon the rate of nutrient/pollutant loading, these more remote portions of the System may require careful management to prevent a reduction in water quality.

A long system residence time is not an indicator of poor water quality, though. When system residence times are high, it is important to compute a local residence time for each embayment and sub-embayment. A local residence time is the time it takes for a parcel of water of leave a particular sub-embayment and mix with an adjacent body of water. For example, a local residence time for Fiddlers Creek represents the time it takes a parcel of water to flush into Megansett Harbor. Table 4.2 lists the local residence times for selected embayments.

Table 4.2 Volumes and **local residence times** for Red Brook / Megansett System and sub-embayments.

Embayment / Sub-embayment	Volume	Residence Time
	(feet^3, MTL)	(days)
Entire Domain	$1.88 * 10^9$	1.8
Area North of Scraggy Neck	$7.65 * 10^8$	1.6
Red Brook Harbor	$5.46 * 10^7$	1.2
Hen Cove	$1.73 * 10^7$	1.0
Barlows Landing	$1.05 * 10^8$	0.9
Area South of Scraggy Neck	$5.59 * 10^8$	1.6
Squeteague Harbor	$1.59 * 10^7$	0.6
Rands Harbor	$3.28 * 10^6$	1.4
Fiddlers Creek	$3.45 * 10^6$	2.4

The local residence times in Table 4.2 are lower than the system residence times presented in Table 4.1. For instance, the average local residence time for Fiddlers Creek less than three days whereas its system residence time is over four hundred. This indicates that Fiddlers Creek exchanges water rapidly with Megansett Harbor, but not so rapidly with Buzzards Bay. Therefore, if future planning analyses show that water quality in Megansett Harbor is acceptable, than water quality in Fiddlers Creek may be acceptable as well (independent of its ability to exchange with Buzzards Bay). A similar argument may apply to Rands Harbor, which flushes with Megansett harbor in less than 1.5 days on average. Also, a similar analogy can be made between Hen Cove/Red Brook Harbor and the embayment seaward of Bassetts Island, with which Red Brook flushes in little over one day.

Overall, the residence times indicate the System is flushed efficiently. System residence times indicate the larger portions of the System (e.g., areas north and south of Scraggy Neck) exchange water efficiently with Buzzards Bay, and local residence times indicate more remote embayments (e.g., Squeteague Harbor, Hen Cove, etc.) exchange rapidly with the adjacent water body. That the residence times indicate rapid tidal flushing is not surprising, since the tide measurements indicated relatively little tidal dampening throughout the System. We recommend that future water quality assessments by the Cape Cod Commission and Town consider both the system and local residence times presented in this flushing study.

4.2 Tidal Circulation

Tides affect water circulation, and in turn the water circulation affects pollutant/nutrient and sediment transport. Numerical hydrodynamic models can predict, temporally and spatially, the water's behavior. Such insight is key if future water quality and/or sediment transport models are to be utilized.

Snapshots of current patterns were output from the model to illustrate tidal circulation patterns, and are shown in Figure 4.2 through 4.5. Currents are represented by vectors pointing in the direction of flow, with the length of the arrow proportional to current speed.

Figures 4.2 and 4.3 illustrate the flood flow of water into the embayments north and south of Scraggy Neck, respectively. Due to the higher water level in Buzzard's Bay, the water flows "downhill" into the System and its sub-embayments. In Figure 4.2, the area north of Scraggy Neck, the water takes two paths into, Pocasset Harbor and Hospital Cove, as it floods into Red Brook Harbor and Hen Cove. The flow is swiftest at the mouth of Pocasset Harbor and Hospital Cove. The swift flow is due to the narrow channels. In order to conserve mass, the flow must accelerate in these constricted areas. Flow is weakest at the mouth of Red Brook Harbor, Hen Cove, and Barlows Landing since the entrances are wide. In Figure 4.3, the area south of Scraggy Neck, flow is swift as it floods into Squeteague Harbor while it is weak at Rands Harbor, Fiddlers Creek, the surrounding area of Eustis Beach, and the nearshore area between Rands Harbor and Squeteague Harbor. As the water enters into the System, it flows in response to the System's physical characteristics, such geometry, bathymetry, and bottom roughness.

On the ebbing stage of the tide, the water flows from the embayments and sub-embayments into Buzzard's Bay. This is due to the higher water level in the interior of the System compared to Buzzard's Bay. Figure 4.4 shows a snapshot of the water circulation on the ebbing stage in the area north of Scraggy Neck. Water flow is swiftest at the mouth of Pocasset Harbor and Hospital Cove while the flow is weak at the mouths

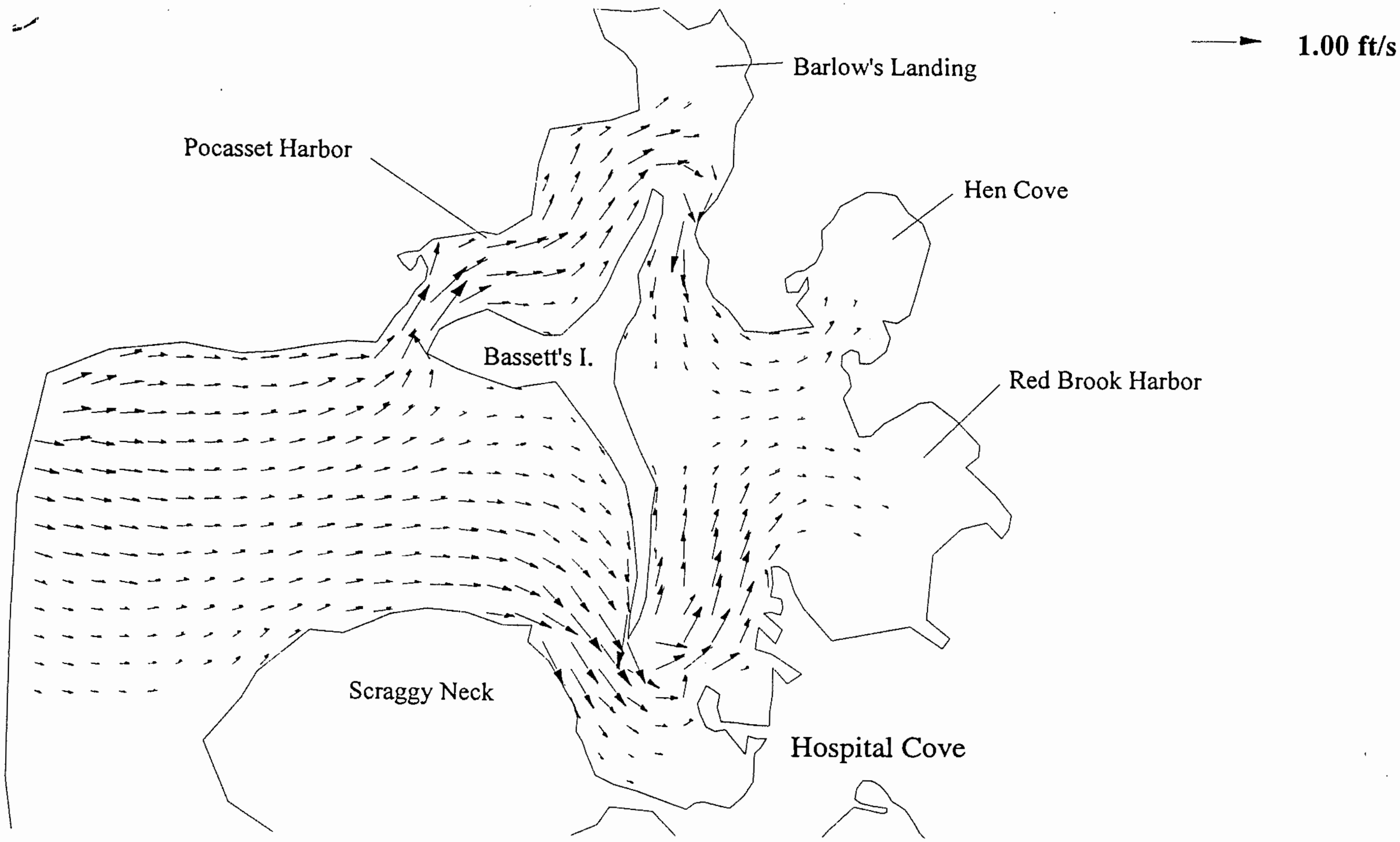

Figure 4.2. Modeled flood tidal circulation north of Scraggy Neck.

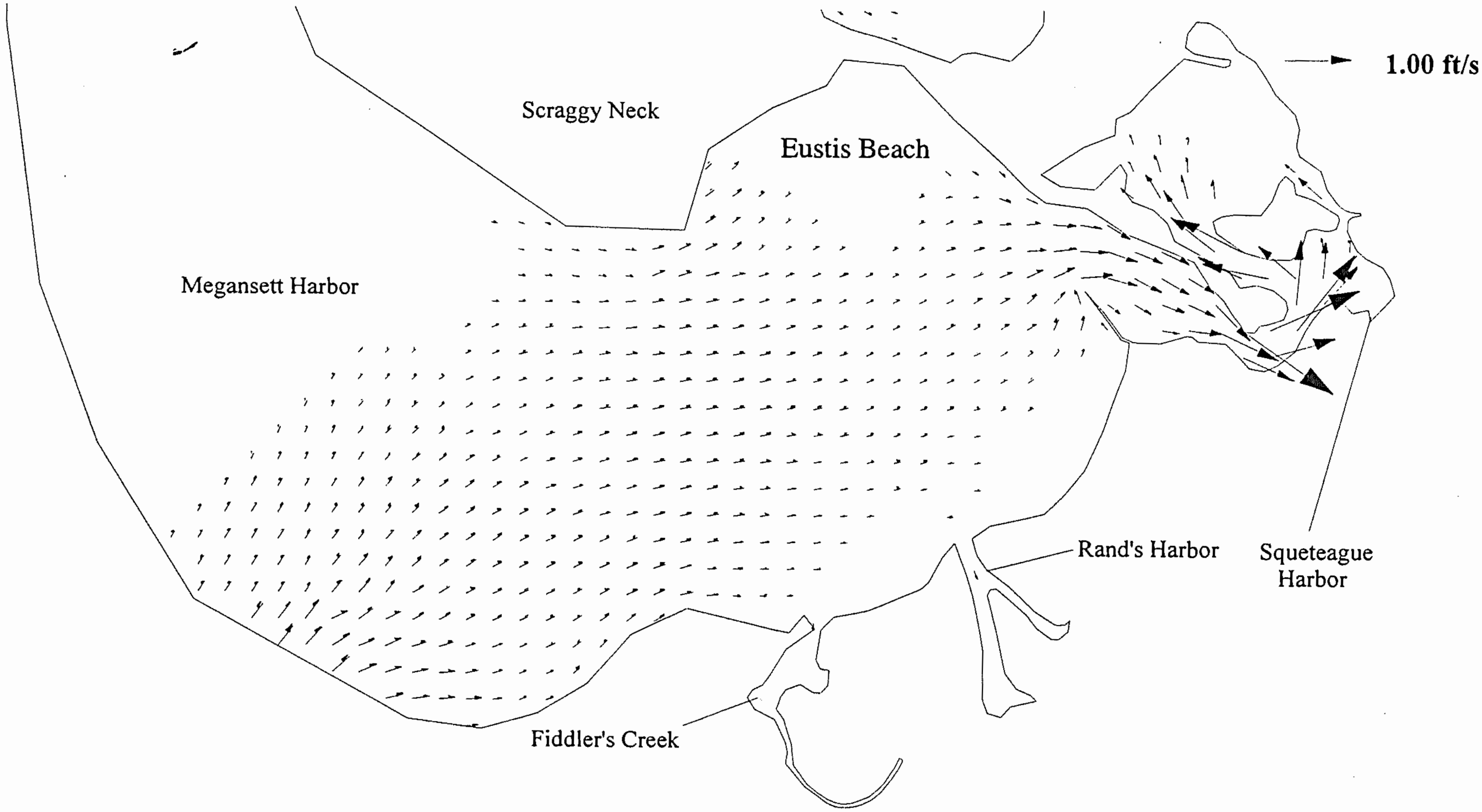

Figure 4.3. Modeled flood tidal circulation south of Scraggy Neck.

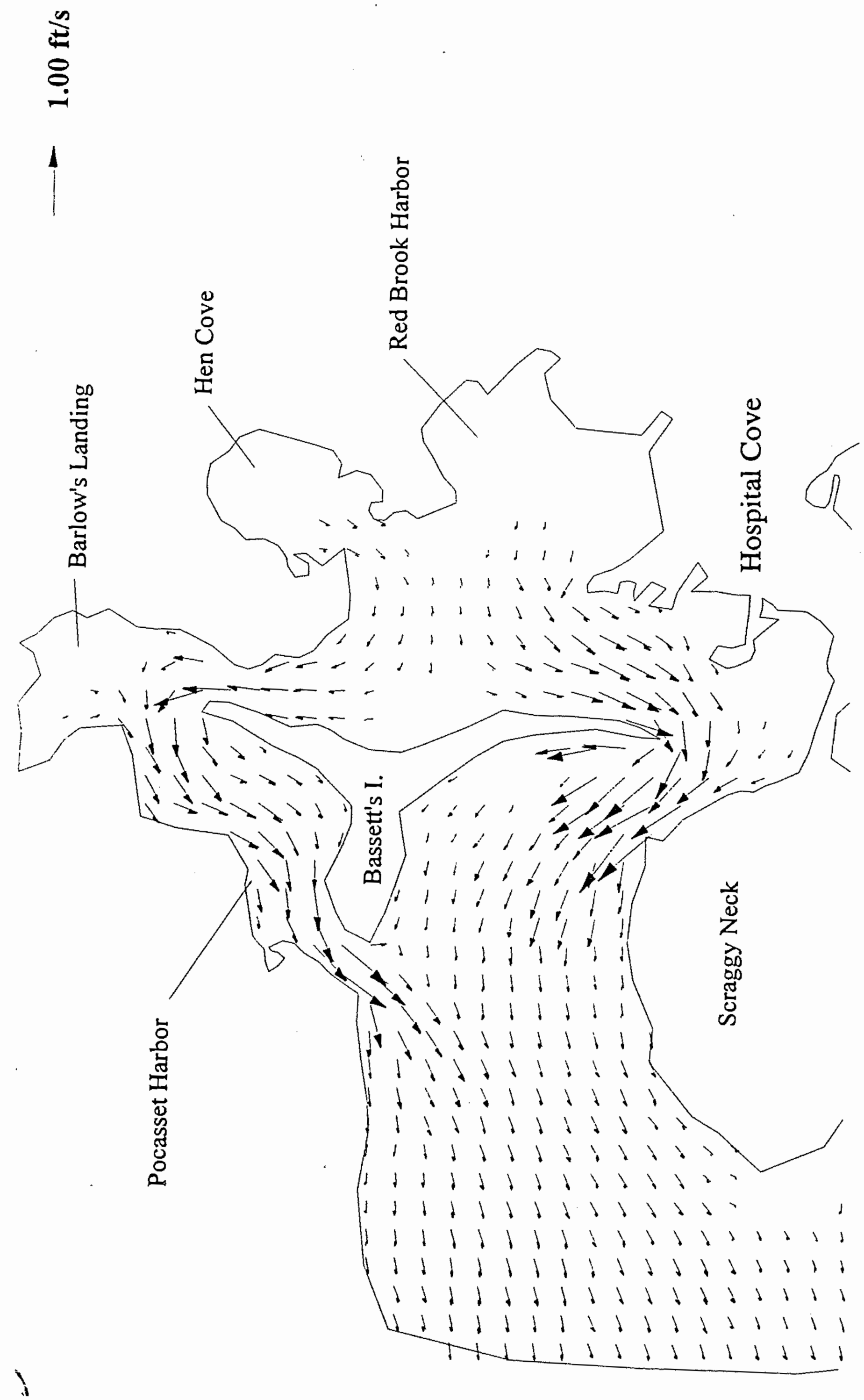

Figure 4.4. Modeled ebb tidal circulation north of Scraggy Neck.

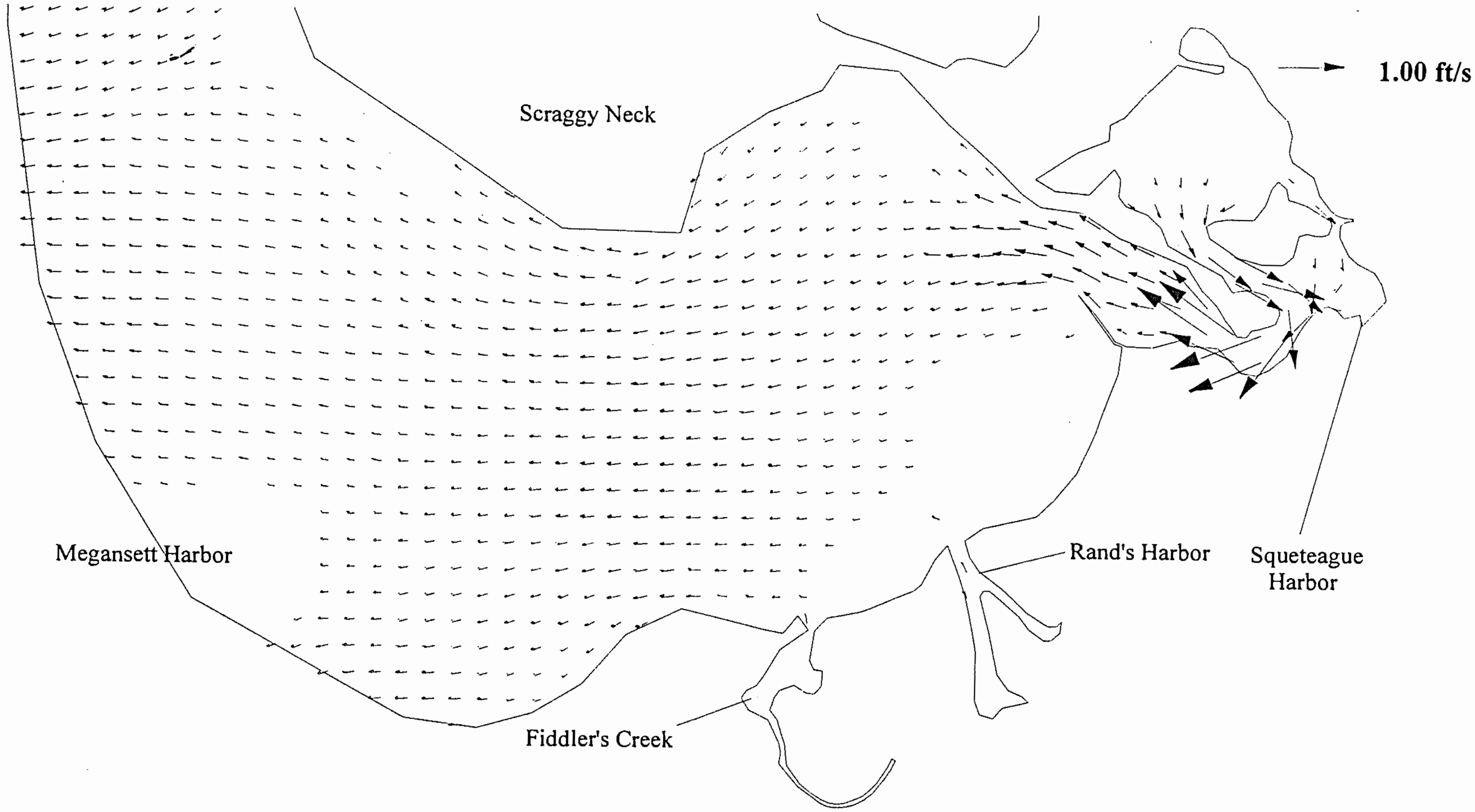

Figure 4.5. Modeled ebb tidal circulation south of Scraggy Neck.

of Red Brook Harbor, Hen Cove, and Barlows Landing. As seen in this figure, the water from Hen Cove exits through Pocasset Harbor while the majority of the water ebbing from Red Brook Harbor travels through Hospital Cove on its way out to Buzzard's Bay. Figure 4.5 illustrates ebb flow south of Scraggy Neck. Locations of weak flow include the nearshore areas between Squeteague Harbor and Rands Harbor, and Rands Harbor and Fiddlers Creek, as well in these respective sub-embayments. The swiftest flow is found at the mouth of Squeteague Harbor.

5.0 Summary and Conclusions

Tidal flushing of the Red Brook Harbor / Megansett Harbor System (Figure 1.1) was evaluated using field measurements and a calibrated hydrodynamic computer model (RMA-2). Field data included measured tides at seven locations (Figure 2.1), and detailed bathymetric measurements (Figure 2.2). These field measurements were required as input into the model, and also were used to calibrate the model, which ensured the model had the ability to simulate measured tides. The hydrodynamic model simulated the water surface and currents in the study area at hundreds of points every 10 minutes for 17 days. The modeled tides and resulting currents were used to evaluate flushing based on system and local residence times.

The following conclusions were determined from this study:

- Tides propagate freely from Buzzards Bay (offshore TDR) into the harbors and creeks north and south of Scraggy Neck. Minimal tide height reduction and time lag was observed throughout the System. There seem to be three reasons to explain this behavior: 1) the relatively large entrances to Red Brook Harbor and Megansett Harbor do not impede the tide; 2) the relatively deep water offshore does not impede the tide, 3) the System is relatively small.

- Model results were used to compute system (Table 4.1) and local (Table 4.2) residence times for existing conditions in the Red Brook Harbor / Megansett Harbor System. System residence times show that larger portions north and south of Scraggy Neck exchange water freely with Buzzards Bay (e.g., less than 1 day), but that more remote regions take longer to exchange water with the Bay (e.g., the System residence times for Rands Harbor and Fiddlers Creek can exceed 100 days). However, an examination of local residence times showed that the more remote embayments (e.g., Fiddlers Creek, Rands Harbor, Squeteague Harbor, and Hen Cove) flush rapidly with their adjacent water body (e.g., Megansett Harbor and Red Brook Harbor). Consequently, future planning analyses should consider both the system and local residence times when assessing water quality.

- The hydrodynamic model developed for this flushing study also may be used for future evaluations of water quality, sediment transport, and the effects of dredging on the System. The model can be used to guide future planning efforts and/or engineering design projects in the System. If the Cape Cod Commission's analysis of water quality based on these residence times indicate areas of concern, a more detailed water quality model should be considered.

- Depending upon the interests of the Town, more information could be gathered regarding groundwater inflow to this System. This may be of particular interest given the proximity of the System to the LF1 plume from the Massachusetts Military Reservation (MMR). The model developed in this study can accept groundwater inflow information as input, and could be used to evaluate the circulation and flushing of potential pollution arising from MMR.

- From the public meeting, interest has developed to investigate sedimentation patterns in the northern sector of the System. The culverts could be numerically incorporated into the model to examine their effects. Specifically, the desire to determine whether the addition of culverts would reduce sedimentation.

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