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Pamet River & Estuary Assessment

A Major Qualifying Project Report

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by

Antoinette T. Burns

William F. Schafer

Andrew M. Waite

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Approved:

Dr. Paul P. Mathisen, Advisor

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ABSTRACT

This study assesses the current hydraulic characteristics and water quality of the Pamet Estuary in Truro, Massachusetts. The project focuses on Wilders Dike, which has altered flow characteristics, consequently reducing the tidal prism and natural flushing capability of the system. The current water quality was assessed, and an existing computer model of the system was validated and utilized to determine current hydraulic conditions. Preliminary hydraulic designs of Wilders Dike were presented, and a hydraulic analysis of each was performed.

CONTENTS

CONTENTS

Figures, Tables & Equations

Figures

Tables

Equations

1 INTRODUCTION

The Pamet River Estuary is located on Cape Cod in Truro, MA. This estuary, which is shown in Figure 1.1, has been significantly altered from its natural state due to the construction of a number of dikes. Because of the potential for flooding due to overwashes at Ballston Beach, the town has recently expressed an interest in conducting further research for altering the existing dikes.

The objective of this Major Qualifying Project (MQP) is to evaluate the impacts of dike construction on the Pamet River Estuary and develop a preliminary design for the modification of the channel characteristics in an attempt to maintain or improve the water quality in the Pamet River.

This report is submitted to serve as a Major Qualifying Project (MQP), which is a degree requirement established by the Worcester Polytechnic Institute in Worcester, Massachusetts. The MQP is used to expose students to a tangible application of the theory and design that they have obtained throughout their undergraduate career. Conducting and analyzing several water quality and hydraulic experiments, along with the design of several preliminary alternatives to the existing Wilders Dike in the Pamet River Estuary, fulfills the MQP requirements in the Departments of Civil and Environmental Engineering at WPI.

This project presents the analysis of pertinent past research results, and personally obtained data along with several alternatives to the existing situation. The specific procedures for each component of our project are elaborated on in the body of the report, but an overview can be satisfied here.

A detailed study was completed in 1989 by Graham S. Giese, Carl T. Friedrichs, and David G. Aubrey of Woods Hole Oceanographic Institution in cooperation with

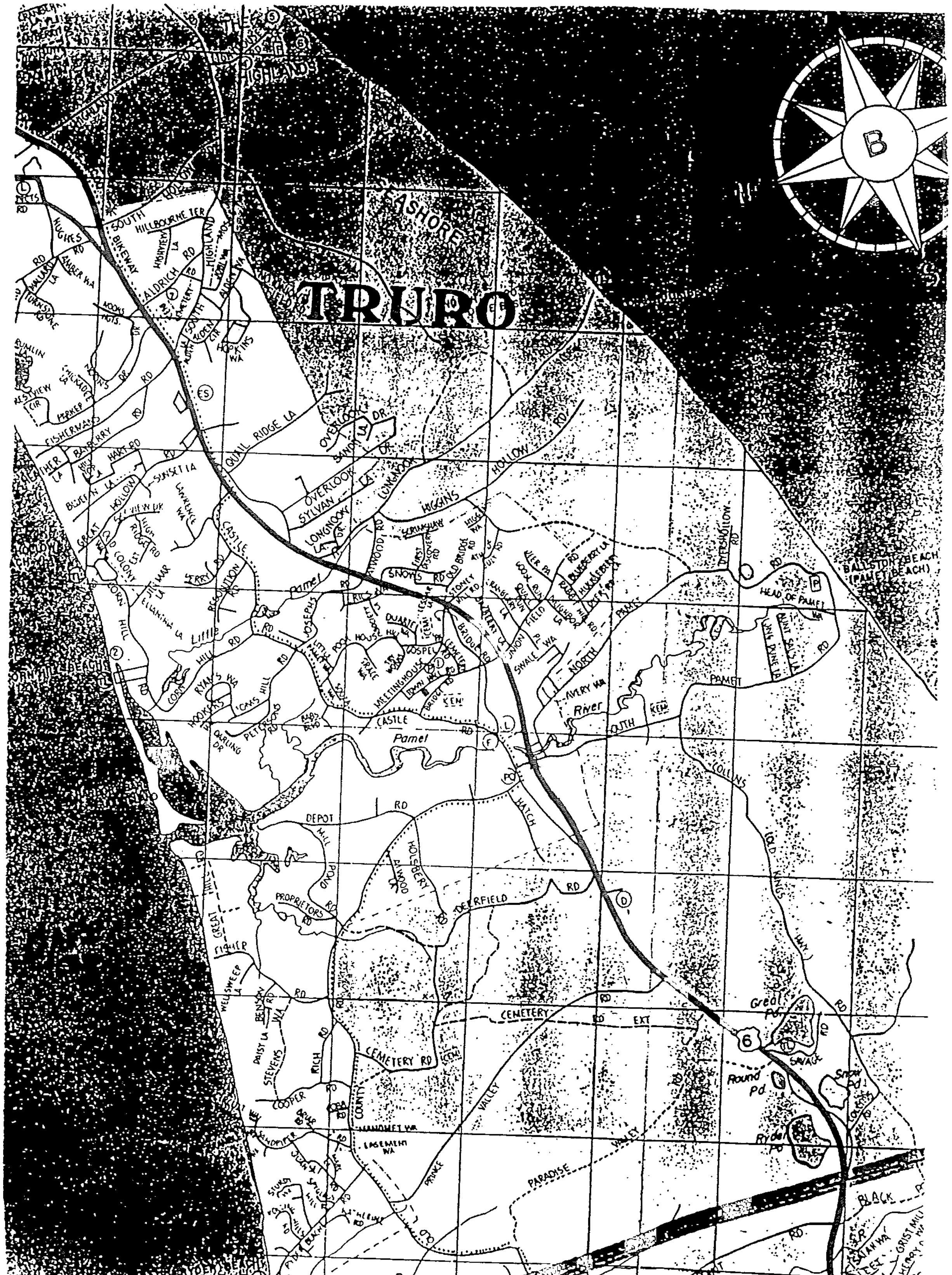


Figure 1.1: Map of Pamet River Estuary
(Taken from The Greenway Management Plan, 1986)

Richard G. Lewis II of Massachusetts Institute of Technology. In that study, a general one-dimensional numerical model was applied to the Pamet River Estuary to determine the hydrodynamic effects involved in the removal of Wilders dike, and several other barriers to tidal flow in the estuary. The resulting shallow-water tidal system model, which is described in Chapter 4 of this report, is a key component in this project. Therefore, field measurements and other analyses were used to verify parameters that may have changed in the past five years.

To update the model, several visits were taken to the Pamet to evaluate the existing conditions. The primary visit to the Pamet included several field surveys for characterizing any changes in channel properties. Four tide gages were checked periodically throughout a complete tidal cycle to determine the changes in volume of flow entering and exiting the estuary. Surveying was also completed to record significant alterations in the topography of the channels and the surrounding area. Additional surveying was performed during a second field trip for predicting the area that could possibly be engulfed in water if the dikes were removed. Measured flow and elevation data were compared to the existing data, and the model was updated. Complete descriptions of the techniques and methods used for obtaining and analyzing this data are detailed in Chapter 4.

The second visit to the Pamet was also used to obtain water quality data for characterizing the present condition as compared to previous data of The Massachusetts Division of Water Pollution Control, and Richard G. Lewis II. The recently collected data includes conductivity, salinity, temperature, and pH analysis along with total and fecal coliform levels, nitrates, nitrites, and ammonia. The results of these tests were used for determining the rate and significance of the water quality changes in the estuary. Chapter 3 discusses the past and present data along with the analysis and comparison of all tests.

With all of the collected and analyzed data, the model was finally verified. The model was then used to predict the effects of dike failures on tidal elevations and flow characteristics in the estuary. It was also used to obtain fairly accurate flow rates necessary in the design phase of our alternatives. Utilizing the model's outputs, several preliminary designs for modifying channel characteristics were prepared. Six alternatives, presented in Chapters 5 and 6, were developed and analyzed to gain an approximate representation of the hydraulic capacity of the Pamet.

While it is noted that additional research is necessary to fully develop an appropriate design for the removal of Wilders Dike, these analyses should provide a better understanding of the effects of dike removal on the flow characteristics in the vicinity of Wilders Dike. In addition, a goal of this project was to provide some preliminary data on the effects that dikes have on the water quality. Therefore, to start the report, some general background is presented in Chapter 2 on estuaries along with some aspects of human intervention on estuaries.

2 BACKGROUND

2.1 Definition of Estuary

A contemporary definition of an estuary is "a semi-enclosed body of water having a free connection with the open sea, and within which the sea water is measurably diluted with fresh water drained from the land. This broad definition may include bays, sounds, inlets, fjords, and lagoons."[1] This report will focus on the bar built estuary. The bar built estuary is a low relief inlet found along sandy coastlines. Generally, a bar built estuary follows an L shaped plan with the lower course parallel to the coastline. (see Figure 2.1).

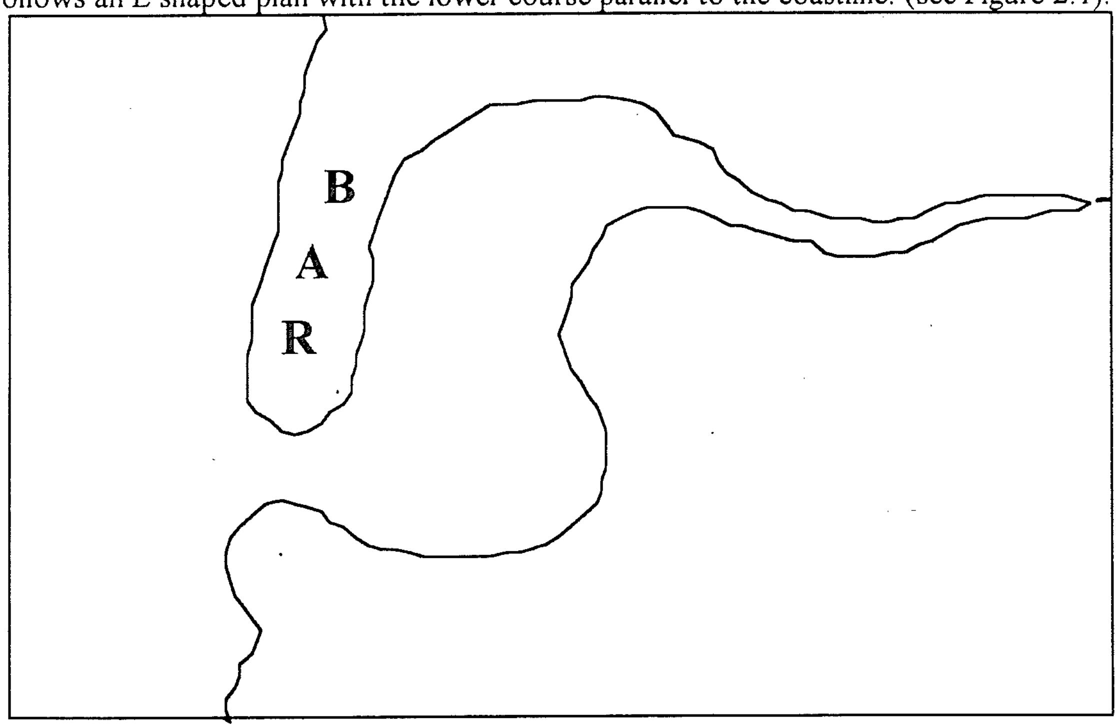


Figure 2.1: Bar Built Estuary

2.1.1 Importance of Estuaries

Estuaries have been of extreme importance to human activities both in the present and the past. The numerous desirable qualities that estuaries have to offer are what makes them so attractive to humankind. An estuary's unique physical qualities, including tidal flats, dunes, salt marshes, shrub swamps, and woodlands, make it an ideal place for a great diversity of plants and wildlife to thrive. The fact that estuaries usually offer some type of barrier to protect against the open sea's rage during stormy weather makes them an excellent harbor for sea vessels. The tidal prism volume (the large volume of water exchanged during the tide cycle) produces a natural flushing ability that removes wastes from estuaries. Keeping these factors in mind, it is easy to understand why many early American settlements were concentrated on estuaries, and it is not surprising that two thirds of the world's larger cities are located on or near estuaries.

2.1.2 Human Intervention With Estuaries

The quality of a water supply is very important in determining the uses that it is suitable for. Pollutants from years of human activities and waste disposal have been extremely detrimental in destroying the quality of water in rivers, streams, and lakes. Our realization of this problem has been too late in far too many areas where the once pristine water supporting various life forms has evolved into foul open sewers with few life forms and fewer beneficial uses.[2] Although these water sources may not always be necessary for providing high quality drinking water, they are instrumental in entertaining safe swimming, boating, and fishing opportunities along with the prevention of water borne diseases, the protection of surrounding wildlife, and the maintenance of an aesthetic natural environment.

Many of the world's estuaries are presently undergoing some kind of stress directly related to past or present human activities. Altered river flows, the filling in of salt and fresh water wetlands, dredging, effluent disposal, industrial cooling and recreational use are some of the numerous activities that cause stress in estuaries. These forms of stress have increased enormously over the last century and will most likely continue to intensify in the future. Until recently, little thought was given to the possible effects of human intervention with estuaries. However, the results of continued estuary pollution have begun to show in the form of:

- eutrophication
- chemicals in estuarine mud deposits
- toxic substances in food chains
- increased coliform counts

2.1.3 Estuary Preservation and Recovery

Today, there is a growing concern about the future of estuaries and the cleaning up of estuarine environments. Meeting the challenge of recovery and preservation in estuarine environments is extremely difficult. The science of estuaries is very complex compared to that of rivers, lakes, and deep oceans. There are many different disciplines required to understand estuaries, including hydrology, geohydrology, oceanography, hydro-dynamics, biology, and chemistry.

Water quality measurements are an essential part of estuary preservation. Water quality monitoring can give clues as to what type of pollution exists as well as where the pollution source is located. Biological water quality analysis includes microbial density determination in the form of fecal and total coliform counts. Physical and chemical water quality analysis includes a much larger variety of tests including pH, salinity, temperature, conductivity, nutrient concentrations and a large list of chemical compound concentration tests.

In attempting to manage the quality of a water source, it is first essential to familiarize oneself with the properties of that source. The assimilation of wastes varies with each water source, and is dependent on the type of pollutant discharged and the manner in which it affects water quality, the mineral heritage of the watershed, the geometry of the terrain, the climate of the region, and various other natural factors.[3]

Along with familiarizing oneself with the properties of the source itself, it is also vital to identify the types of pollutants, and their origins. Domestic sewage and industrial wastes are referred to as point sources since they are connected by a network of pipes and are conveyed to a single point of discharge into the surface water.[4] Non-point sources are characterized by multiple discharge points such as urban and agricultural runoff that may flow over the surface of the land and through natural drainage channels to the water supply. The significant amounts of non-point pollution tend to occur during spring snow melt or rain storms when the flow rates toward the water supply are greatly increased.

The study of estuarine hydraulics is also critical in estuary preservation efforts. Estuaries possess a natural flushing ability that helps minimize pollution concentrations. This flushing process is due to the exchange of a large volume of water during the tide cycle which is referred to as the tidal prism. Estuaries that have been altered naturally, or by man made structures can become stagnant in areas, and therefore lose their original flushing capabilities. Hydraulic measurements including flow, tide measurements, and channel characteristics are important in determining if the existing tidal prism is sufficient for naturally flushing pollutants.

2.2 The Pamet River and Estuary

This study focuses on the Pamet River and Estuary located in Truro, Massachusetts (refer to Figure 1.1). The Pamet River system is of extreme importance not only to surrounding residents, but also to the state of Massachusetts. As a local resource, the Pamet offers beautiful scenery, recreational activity, navigability (only at high tide), shell fishing, and a habitat to several threatened plant species. The Pamet is one of 46 rivers classified as Scenic Rivers in Massachusetts. In 1986, the Pamet was the state's second priority for protection, behind the North River in Marshfield.[5]

2.2.1 History of the Pamet

The Pamet River Valley is rich in historical events directly involved with early explorations of the New World. In November of 1620, the Pilgrims aboard the Mayflower explored the Pamet River Valley with the hopes that they had found a New World home. The Pilgrims found that the Valley offered much of what they were looking for including a harbor, hills, marshes, timber, game, fish and fowl. The one important feature that the valley lacked was a freshwater spring. This one reason alone was enough to turn the Pilgrims away and they discovered Plymouth on their next voyage.[6] However, Pamet Harbor was carefully considered as a settlement due to the outstanding features that it still offers today.

2.2.2 Current Physical Description

The Pamet River system consists of three stream branches that meet before emptying into Cape Cod Bay (refer to Figure 1.1). The Pamet River is the main branch of this system, and it meanders approximately four miles from the head near Ballston beach, adjacent to the Atlantic Ocean on the East, to Pamet Harbor, adjacent to Cape Cod Bay on the West. The Pamet's two smaller tributaries, Little Pamet River to the North, and Eagles Neck Creek to the South, each span a distance of approximately one and a half miles prior to meeting the Pamet at right angles in Pamet Harbor.

The Pamet system's natural physical characteristics have been drastically altered over the last two centuries. During the 1800's, the Pamet was divided into many different sections as a result of the numerous dikes being put into place. Currently, the fresh water head of Pamet River is located approximately 100 yards from the coast at Ballston beach. From here the Pamet flows west towards Pamet harbor. The river does not become tidal until west of the Route 6A dike (Wilders Dike), where a clapper valve prohibits further eastward flow . It is estimated that before Wilders Dike was put in place, the Pamet remained tidal for as much as three quarters of its length. Diking and ditching activity over the centuries have resulted in the Pamet system being separated into 16 different areas, each of which has experienced hydraulic alterations.

2.2.3 Present Day Concerns with the Pamet

The Pamet River Basin requires improvement in many areas. Most problems that are being seen today in the Pamet are directly related to man's altering of the system over the years. This section discusses the important issues of concern in a format that shows how many of the problems are interrelated.

It wasn't until the mid 1980s that the water quality of the Pamet System was seriously assessed. During the summer of 1988, Richard G. Lewis II, an MIT graduate student, conducted a study which revealed that fecal coliform counts in the Pamet exceeded the limit for shell fishing throughout the entire summer. High coliform counts are a serious matter since they are one of the only groups of organisms that act as an indicator species when pathogenic bacteria is present in a water supply. These pathogens, or disease-producing organisms, are discharged along with fecal wastes and are very difficult to detect in water supplies.[7] Shellfish tend to concentrate these pathogens, since they filter water for food, and become extremely toxic when they are exposed to a polluted water.[8] When a body of water is found to contain high coliform counts, it is unsafe not only to harvest shellfish, but also for activities such as swimming and bathing.

Although data collected in the harbor during incoming tide periods was slightly below the shell fishing limits established by The Massachusetts Division of Marine Fisheries of 14 organisms per 100 ml, the limit for swimming closure was frequently exceeded at low tide in the river, at all times in the creeks, and the entire basin after rain events.[19] Since the levels of fecal coliform were higher during a rain event, it is common to assume that the main source of contamination is due to non-point discharges.[10] Even with the low density predominantly seasonal residential land use, the absence of point source discharge, and the presence of broad marshes and wetlands, the runoff that is emptied into the Pamet through pipes found at Wilders Dike, South Pamet Road, and Meeting House Road can carry significant amounts of oils, metals and organic wastes, litter, chemicals, and salts.[11] Most of the runoff from route 6 between Edgewood Farm and Unionfield Road collects in highway catch-basins and eventually discharges into the Pamet River.[12]

Another water quality concern that the Pamet is currently experiencing is eutrophication. The acceleration of the eutrophication process in the Pamet is occurring in the fresh water portions. Man-made nutrient sources, as well as the stagnation of many fresh water areas due to the extensive diking and ditching are the main contributors to this process. Currently, pondweed and water lilies strangle most of the freshwater portions of the Pamet, making any form of navigation difficult.

Although ground water quality is generally good in the Pamet System, there is some concern about possible high groundwater sodium levels in the vicinity of Route 6. There is a possibility that high sodium readings in some well waters may be caused by the nearby salt water environment, however, it is also possible that some of the high readings are directly related to road salting during snowfall. It is vital that Route 6 remain clear during winter weather, and therefore it is heavily salted. This major source as well as smaller surrounding roads may be contributing to higher than normal readings. The reason why sodium contamination is of such great concern is because, unlike other contaminants that can be removed through processes such as filtration or adsorption, salts rapidly dissolve into ground water making them impossible to remove.

2.2.4 Effects of Ditching & Diking

Human intervention with the Pamet in the form of ditching and diking is often referred to in this report, as it is in most other research on the Pamet. These past acts of compartmentalizing the Pamet into many different sections have something to do with most problems that the system is currently experiencing. Reasons for ditching and diking in the past have included better drainage, mosquito control, vehicle travel, and flood protection. All of the original reasons for ditching and diking techniques can be dealt with through the use of modern techniques, such as low maintenance bridge building, advanced culvert design, and biological agents for mosquito control efforts.[13]

Ditching and diking have resulted in various water quality problems due to constricted stream flow, increased sedimentation, less oxygen, reduced flushing capabilities, increased sensitivity to acidity, and more mobilization of toxic metals and sulfides in sediment.[14] Harbor management problems have also risen due to a smaller tidal prism, lower current velocities, increases in shoaling, and again less flushing capability. Wildlife has also paid a price through the reduction of shellfish beds, pollution effects on fish, and the effects of eutrophication. Vegetation has suffered great losses due to the destruction of wetlands, and eutrophication. Problems effecting recreational value include limited opportunity for boating, decreased visual enjoyment, and swimming closures due to high coliform counts.

3 WATER QUALITY

In recent years, water quality in the Pamet estuary has become of great concern. High coliform counts have led to the closing of several shellfishing and recreational areas. Speculation suggests that direct runoff and the reduced tidal prism resulting from various dikes throughout the system are the major contributing factors to the contamination. To evaluate the extent of these water quality problems, a general assessment of the estuary's present water quality conditions was completed. This evaluation included a comparison between past and present data in an attempt to determine if conditions have worsened. More specifically, the objectives of this chapter include (1) obtaining an understanding of water quality conditions in recent years through a review of past research, (2) identifying the current water quality conditions through a selective water quality analysis, and (3) comparing of past and present data, in whether or not water quality conditions have changed.

3.1 General Methodology

To fulfill the objectives, a three step procedure was performed. The first step was to study past water quality analyses performed on the estuary. This was accomplished through a review of the 1976 Massachusetts Division of Water Pollution Control water quality analysis, and the 1988 analysis conducted by Richard G. Lewis II of the Massachusetts Institute of Technology. Once a general understanding of recent water quality conditions and trends was obtained, a selective water quality analysis plan was developed. Water quality parameters were chosen based on their practicality of testing procedures, and their comparability to previous data. Finally, present water quality data was compared to that of previous research, and similarities and discrepancies were noted.

3.2 Past Research

In order to gain a general understanding of past water quality conditions, the 1976 Massachusetts Division of Water Pollution Control (referred to as MDWPC) water quality analysis and the 1988 analysis conducted by Richard G. Lewis II of the Massachusetts Institute of Technology were reviewed.

Table 3.1: Selected results from Massachusetts Division of Water Pollution Control Water Quality Analysis (9/1/76)

	Harbor	Wilders Dike - salt	Wilders Dike - fresh
Temp (C)	20	18.9	18.9
pH	7.7	6.9	6.6
Ammonia (mg/l)	0.02	0.01	0.02
Nitrate (mg/l)	0	0	0
Fecal Coliform	5	50	30
Total Coliform	<10	160	300

Table 3.1 presents selected data from the 1976 MDWPC water quality analysis on 9/1/76. Temperature, pH, ammonia, nitrate, fecal coliform, and total coliform were measured at the Harbor, salt water side of Wilders Dike, and fresh water side of Wilders Dike. As can be seen in Table 3.1, ammonia readings were relatively low at all stations, and there was no concentration of nitrate at any of the stations. These results indicate nitrate is not a significant pollutant in the estuary.

Total coliform counts were high at the salt water side and fresh water side of Wilders Dike. Fecal coliform exceeded the shell fishing limits of 14 colonies per 100ml established by the Massachusetts Division of Marine Fisheries at the salt water side and fresh water side of Wilders Dike.

Table 3.2 presents selected results from the water quality analysis conducted by Richard G. Lewis II throughout the summer of 1988. Temperature, fecal coliform, and salinity were only a few of the parameters measured at both the harbor and the salt water side of Wilders Dike. These selected parameters are presented because they correspond with tests performed in the general water quality analysis completed in this study.

Table 3.2: Selected results from water quality analysis conducted by Richard G. Lewis during the summer of 1988

	Harbor			Wilders Dike - salt			
Date	11 July"	29 July*	11 Aug.*	14 July*	29 July*	11 Aug.*	17 Aug.'
Temp (C)	27	25	28	25	23	25	23
Fecal Coliform	13	10	97	217	188 surface 166 bottom	55 surface 76 bottom	47
Salinity (ppt)	26	33	23	17	2 surface 14 bottom	1 surface 10 bottom	0

(' low tide) (" mid-tide) (* high tide)

As shown in table 3.2, salinity measurements were taken at both the water surface and channel bottom of the Wilders Dike salt water side on August 11 and 17. Salinity measurements were low on top, indicating the presence of fresh water, and high on the bottom, indicating salt water. This indicates that there is stratification in the area directly below Wilders Dike. This stratification of fresh and salt water is a result of fresh water, having a low density, being wedged up against the Dike by salt water, having a higher density. This phenomenon occurs during high and mid tides.

As can be seen in Table 3.2, fecal coliform counts were also taken at both the water surface and channel bottom of the Wilders Dike salt water side on August 11 and 17. These fecal coliform counts exceeded the exceeded the limit of 14 per 100ml at both locations. Fecal coliform limits were also exceeded at the harbor during high tide on August 11, Wilders Dike during high tide on July 14, 29 and August 25, and during low tide on August 17.

During the summer months of 1988, fecal coliform counts both in the river and in the harbor were found to exceed the limit. One exception to the above took place during dry weather on an incoming tide period in the harbor. Dry weather conditions usually result in lower counts due to the absence of runoff for a period of time. Richard G. Lewis II found that the limit for swimming closures was frequently exceeded at low tide in the river, constantly in the creeks, and throughout the basin during rain events.[15]

3.3 Present Water Quality Analysis

In order to assess the current water quality conditions in the Pamet Estuary, a general water quality analysis was performed. It was important to develop a detailed analysis plan in order to make field trips as efficient as possible

3.3.1 Selection of Water Quality Parameters

The first process in planning the analysis involved choosing several water quality parameters. There were several requirements in order to ensure that these tests were a valuable tool for assessing trends in the estuary. The water quality tests performed had to reveal data that could be compared to those in previous studies in order to formulate any valid conclusions about present conditions in the Pamet River Estuary. It was also essential that tests be fairly straightforward to perform. It was require that tests could either be conducted on site, or could provide accurate results after a long day of collecting samples and a three hour trip back to the Worcester Polytechnic Institute water quality lab. In addition, testing procedures were limited to those for which the appropriate equipment was available in the water quality lab.

After considering all of the previously mentioned information, and conducting further research into water quality analysis procedures, a list of tests that would be feasible and beneficial was generated. The list included testing for: ammonia, nitrates, nitrites, salinity, conductivity, pH, temperature, total and fecal coliform. These particular tests were appropriate because they would provide information for preliminary analysis that could eventually be expanded upon in future research.

3.3.2 Field and Laboratory Equipment

Obtaining field equipment that was easy to use was an important factor in making field trips as efficient as possible. After reviewing the proposed test list, the possibility of purchasing a portable kit that could be used for on site analysis of several of the tests was considered. A HACH Saltwater Master Kit was used to complete ammonia, nitrate, nitrite, and pH measurements quickly and accurately. This kit consists of a single carrying case containing all that was needed for the determination of the above mentioned tests. For a detailed description of the procedures for each test, refer to Appendix A. In addition to the Salt Water Master Kit, a salinity meter was obtained in order to read salinity, conductivity, and temperature quickly and accurately.

Since coliform testing requires laboratory procedures, all the necessary laboratory materials including petri dishes, filters and pads, broth and confirmation vials were ordered form HACH Company. These materials were necessary in order to run membrane filter tests for fecal and total coliform. The procedures used to complete these tests were gathered from the Water Analysis Handbook, published by HACH Company, and are detailed in Appendix B.

3.3.3 Development of Field Program

In developing a field program, it was important to consider both the location of sample stations, and sampling times. Sample station locations and sampling times were strategically chosen so that trends could be identified, and present and past data could be compared.

3.3.3.1 Sample Stations

A field sampling program was developed that could be used to define water quality in the vicinity of Wilders Dike and the main branch of the Pamet. As shown in Figure 3.1, three sampling stations were chosen: #1-the salt water side of Wilders Dike,

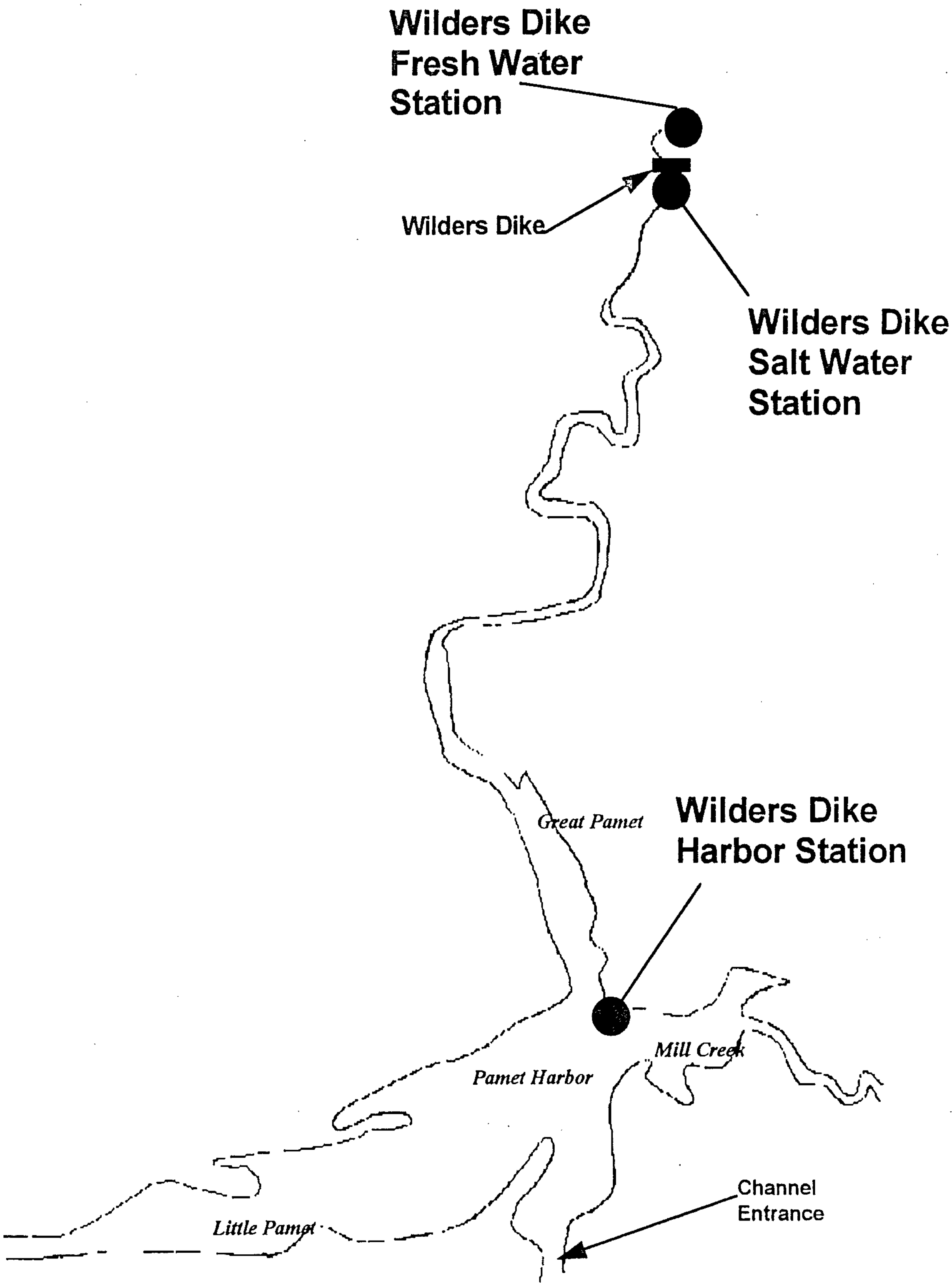


Figure 3.1 Field Sample Stations

could isolate Wilders Dike and station 3 was used to monitor the effects downstream. It was also important that our stations correlated to the stations used in previous research.

3.3.3.2 Sampling Times

Once the list of water quality tests, the necessary equipment, and the sample sites were determined, a day for collecting samples was selected. As noted previously, the water levels and flows in the Pamet vary significantly throughout the day due to the tidal variations. It is likely that the water quality will vary with the tide as well. Therefore, it was vital that samples be taken during several different stages of the tidal cycle. The goal was to capture at least 6 hours of the 12 hour tidal cycle during a one day field trip to the Pamet River. The 1994 High & Low Water tables for Boston, Mass. were used to determine high and low tide would occur at the Pamet harbor during the month of December. A previous field trip to the Pamet on 10/1/94, during which hydraulic characteristics were measured, revealed that high tide at Wilders Dike occurred two hours after high tide in the harbor (refer to section 4.). A combination of this information and tide tables was used to determine that we could capture a six hour portion of the tide cycle on Sunday, 4 December 1994. This six hour portion offered an opportunity to obtain water quality readings from low to high tide. With a high tide in the harbor expected at 11:36 a.m., the high tide at Wilders Dike would occur at approximately 2 p.m. and the low tide would occur six hours earlier at approximately 8 a.m. Therefor, samples were taken between 8am and 2pm.

3.4 Dry Weather Results Analysis

Once the plan was implemented and all of the samples were taken, the data needed to be analyzed. Table 3.3 shows the water quality field data that was obtained during this field trip at three different locations including both the saltwater and freshwater side of Wilders Dike as well as the harbor. These measurements were taken during a warm dry day in December. All of the measurements were taken at three general times during the day. The first time corresponded to low tide (approximately 8:00 - 9:00 a.m.); the second time was midway between low and high tides (approximately 11:00 a.m. - 12:00 p.m.); the third time represented high tide (approximately 2:00 - 3:00 p.m.). Table 3.3 represents the water quality data for the dry weather measurements that were taken on 12/4/94. Following the table is a discussion of the results and their possible significance to the Pamet estuary.

Table 3.3: Dry Weather Field Water Quality Data

	Wilders Dike - salt			Wilders Dike - fresh			Harbor		
	8:00 AM	11:00 AM	2:00 PM	8:45 AM	11:15 AM	2:15 PM	9:00 AM	12:00 PM	3:00 PM
Ammonia	0.00 mg/l	0.6	0.6	0.6	0.6	0.00	0.00	0.00	0.00
Nitrite	0.00 mg/l	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nitrate	0.00 mg/l	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
pH	6.5	6.7	6.9	6.5	6.6	8	8	8.2	8.4
Fecal Coliform	0	0	0	0	0	11	1	1	4
Total Coliform	3	1	0	0	1	37	7	1	4
Temp (°C)	7	7.5	7	7	8	7.5	6.9	7.5	7.8
Salinity	1	20	25	1.4	2.9	24.75	19.5	27.75	28.5
Conductivity	120 (x100)	217 (x100)	260 (x100)	179 (x10)	24 (x10)	260 (x100)	210 (x100)	282 (x100)	295 (x100)

3.4.1 Ammonia, Nitrite, Nitrate, pH, Fecal and Total Coliform, Temperature

Several water quality tests were performed at three different stations throughout the estuary. These stations were the fresh and salt water side of Wilders Dike and the harbor. Each of these three stations was sampled at different times to obtain results which correlated to a half of a full tidal cycle. These tests included ammonia, nitrite, nitrate, pH, fecal and total coliform, temperature, salinity and conductivity. A general discussion of salinity and conductivity will be given here and a more detailed description will be given later in this chapter.

By examining Table 3.3, it is clear that nitrite and nitrate were not a threat to the well-being of the estuary. These measurements were consistently zero throughout the measurement cycle, but ammonia results varied slightly. At the harbor, the level of ammonia was found to be zero at low, mid-, and high tides. This was also true for the low tide measurement on the salt side of Wilders Dike as well as at high tide on the fresh side of Wilders Dike. The other measurements on both sides of Wilders Dike showed an ammonia level of 0.6mg/l at high tide and at mid-tide. These results first indicate that there is no form of ammonia pollution in the harbor at any time during the tidal cycle. This is probably due to the fact that the volume of water is substantial enough to dilute any ammonia that may be present to an extent that makes it undetectable. Considering either side of Wilders Dike gives different results. It is shown in Table 3.3 that traces of ammonia exist on the salt side of Wilders Dike late in the tidal cycle and on the fresh side of Wilders Dike early in the tidal cycle. This indicates that the fresh water exhibited some signs of ammonia pollution. As the fresh water flowed through the culvert, the ammonia content was able to be detected on the salt water side due to the vertical stratification that was present with the mixture of the salt and fresh water. The topic of vertical stratification will be discussed later.

The pH levels throughout the estuary varied from 6.5 on both sides of Wilders Dike to 8.4 in the harbor. These pH levels are normal for conditions such as those in the Pamet and are conducive to aquatic life.

Referring to Table 3.3, it can be noted that fecal and total coliform counts varied for the different sampling locations. Regarding Wilders Dike, the fecal coliform counts were found to be zero according to testing procedures discussed in the HACH Water Analysis Handbook - Second Edition. There was an increase in the amount of detectable fecal coliform during high tide on the fresh water side of Wilders Dike as well as in the harbor at all times during the tidal cycle. The highest fecal coliform count was found at high tide on the fresh water side of Wilders Dike. Although the levels of fecal coliform ranged from 0 to 11 colonies per 100ml sample, it never reached the limit of 14 colonies per 100ml of sample.

The total coliform results differed from the fecal results. It was found that there was no indication of total coliform contamination at Wilders Dike salt water side during high tide and on the fresh side during low tide. Increased levels were noticeable with all the other samples taken. The levels ranged anywhere from 1 colony per 100ml of sample to 37 colonies per 100ml sample. The highest total coliform counts were again found to be on the fresh side of Wilders Dike at high tide. These results indicate that the fresh water on the upstream side of Wilders Dike is a contributor to the coliform contamination in the estuary.

The temperature of the water did not vary significantly throughout the measurement cycle. The temperatures remained very cold in the estuary and ranged from 6.9°C in the harbor to 8.0°C on the freshwater side of Wilders Dike.

Finally, salinity and conductivity were tested and found to be variable. The general observation that appears to be true is that as the tidal stage increases, conductivity and salinity also increase. This could indicate that there are somewhat elevated levels of contaminants such as total dissolved solids during high tide. A more detailed description concerning salinity and conductivity are given in the next section which deals exclusively with Wilders Dike.

3.4.2 Salinity and Conductivity

The following table represents the salinity and conductivity measurements made at Wilders Dike at low tide (8:00 a.m.), mid-tide (11:00 a.m.), and high tide (2:00 p.m.). Following this table is a description of salinity and conductivity, as well as the results of the field tests.

Table 3.4: Salinity and Conductivity Measurements at Wilders Dike

	8:00 AM		11:00 AM				2:00 PM			
	surface	2 ft.	surface	2 ft.	4 ft.	bottom	surface	2 ft.	4 ft.	bottom
Temp (C)	7	6.5	8	7	7	7	8	7	7	7
Salinity (ppt)	1	1	4.6	20	21.5	22	20.5	25	25.5	26
Conduct. (x100)	105 (x10)	120 (x10)	59	217	225	230	225	260	265	266

Salinity and conductivity measurements are directly related. Salinity of water "is determined by measuring its electrical conductivity"[16], whereas the electrical conductivity of water is "a measure of total dissolved solids (TDS)"[17] and together they describe the level of certain contaminants in a water source. These measurements were taken to discover the level of contamination at the dike. It was also possible that because of the presence of a salt wedge or vertical stratification, coliform or other contaminants present in the fresh water might be concentrated into a smaller area, increasing the level of bacterial contamination at this location.

3.4.3 Vertical Stratification - the 'Salt Wedge'

The term 'vertical stratification' (also called a 'salt wedge') refers to a condition that occurs at Wilders Dike at mid- and high tide. At that time, there is fresh water present on the salt side of the dike because as the tide rises, the fresh water on the salt water side remains in the general vicinity of Wilders Dike. Because the density of salt water is higher than that of fresh water, the fresh water remains on the surface while the heavier salt water comprises the volume below. This is important because the effects of this salt wedge could cause contaminants, including coliform, to be concentrated in the fresh water at Wilders Dike.

The salinity and conductivity varied significantly throughout the day due to the differing tidal stages at the dike. They were measured at the three different times mentioned above. At low tide, the salinity was measured at the surface and two feet below the surface. The measurements were the same at this time because the water in the channel at this point consisted of only fresh water flow from the upstream side of the dike. The next time measurements were taken was at 11:00 a.m. Because the tide was substantially higher at this time, the salinity was able to be measured at four different depths instead of only two. Data was obtained at the water surface, two and four feet below the surface, and at the bottom, as seen in the table above. It can be noted that the levels of salinity and conductivity increase with the depth. This occurs because the concentration of fresh water is greater on the surface due to its low specific gravity. Moreover, the water at the channel bottom would have a greater level of salinity due to its higher content of salt water. Finally, measurements were made at 2:00 p.m., the point corresponding to high tide. Measurements were taken at the same four depths, and although the results differed, they again increased with depth for the same reasons given above. Because of the way that the salinity and conductivity meter was calibrated, for many of these measurements it was necessary to use different magnification factors to describe the results, also shown in Table 3.4.

These results of the conductivity and salinity tests indicate the presence of vertical stratification. This salt wedge could potentially contribute to concentrated levels of coliform as well as total dissolved solids.

There was no precipitation to take into consideration in the above analysis, hence snowfall and/or runoff did not play a role in these results. If precipitation was a factor, the results would have most likely been different.

3.5 Wet Weather Results

Water quality testing results will differ between dry weather and wet weather. Precipitation of any type could alter the results if runoff is taken onto account. Generally, during rainstorms, the levels of pollutants increase in this estuary possibly due to sources such as road runoff.

The following table of results indicates the levels of coliform bacteria and salinity found on both sides of Wilders Dike as well as at the harbor.

Table 3.5: Wet Weather Field Water Quality Data

Pamet Estuary Water Sample Tests From 13 January 1995						
	Wilders Dike - salt	Wilders Dike - fresh			Harbor	
	9:30 PM	5:45 PM	9:35 PM	10 PM	5:25 PM	9:45 PM
Total Coliform	40	60	80	20	0	1
Temp. (C)	7	5	6	7	10	4
Salinity (ppt)	3	.05	1	1	17.5	31

It can be seen from this table that there are great differences in the amount of total coliform bacteria during wet weather conditions and dry weather conditions. Samples were taken at both sides of Wilders Dike and at the harbor. On the salt side of Wilders Dike, a measurement was taken at 9:30 p.m. More measurements were taken on the fresh side of Wilders Dike at 5:45 p.m., 9:35 p.m., and at 10:00 p.m. Finally, samples were taken at the harbor at 5:25 p.m. and at 9:45 p.m.

The result of running the coliform tests indicates that there is a very low concentration of coliform bacteria in the harbor. This is probably because the harbor has the capability to dilute the contaminants due to its vast size. The rest of the tests indicate that the coliform levels are greatly increased during a rain event. Recalling Table 3.3, it can be noted that in general, the coliform levels have increased due to the wet weather. For example, on the fresh water side of Wilders Dike, the bacteria level during dry weather reached a maximum level of 37 colonies per 100ml of sample, whereas during wet weather the maximum level attained was 80 colonies per 100ml of sample. The overall increase also holds true for the salt water side of Wilders Dike. During dry weather, the levels of coliform contamination reached a maximum of 3 colonies per 100ml of sample, but during wet weather that value reached 40 colonies per 100ml of sample. The results were slightly different at the harbor, but it appears generally true that during a rain event, the coliform contamination does appear to be elevated.

3.6 Comparison of Past and Present Data

Due to seasonal variations in coliform concentrations, it is inappropriate to compare summer and winter data. Coliform counts are considerably higher during warm weather due to higher water temperatures allowing for optimum conditions. However, dry weather and wet weather trends can be compared. Richard G. Lewis II found that wet weather conditions resulted in higher coliform counts. This trend also occurs in the water quality analysis performed during this study. In most cases, it was found that wet weather coliform counts were higher than that of dry weather counts. This indicates that runoff is probably still a major contributor to microbial contamination.

Salinity measurements taken at Wilders Dike in 1988 by Richard G. Lewis indicated that a salt wedge existed in the area just downstream of Wilders Dike. Current data confirms that this condition has not varied.

Through a comparison of 1976 data and present water quality data, it was determined that nitrate concentrations have remained low. This indicates that nitrate concentrations are not of concern in the Pamet Estuary.

In comparing levels of ammonia found in 1976 to present data, it was found that ammonia concentrations were higher on the fresh water side of Wilders Dike. Levels were measured at .02mg/l in 1976 and approximately 0.6mg/l in 1994. This may indicate the possibility of reduced levels of dissolved oxygen in the fresh water region. However, ammonia toxicity generally should not be of concern for pH values less than 8 and an ammonia concentration of less than 1.0mg/l.[18]

In general, a higher level of water quality will result in the Pamet if there is a greater capability for natural flushing of contaminants. Greater flushing capabilities can be obtained for through the redesigning of Wilders Dike which presently restricts upstream flow. The following chapters will identify current hydraulic conditions and will present several design alternatives for the present Wilders Dike.

4 PAMET SYSTEM HYDRAULICS

4.1 Introduction

The hydraulics of the Pamet are important because they describe fluid transport throughout the estuary and the potential effects upon certain areas in the system. The term hydraulics is defined as "the science that deals with the laws governing water or other liquids in motion and their applications in engineering".[19] With respect to our study of the Pamet estuary, the system hydraulics refers to how and where the water flows in the Pamet as well as the quantity of water flowing throughout the estuary.

To understand the Pamet's hydraulics, we need some way to represent the system as accurately as possible. Since the hydraulics of the Pamet are so complex, a mathematical computer model must be invoked. Fortunately, an existing mathematical model was originally developed to describe the characteristics of the Pamet estuary, discussed in Section 4.2. Because this model was available, it is used here to confirm the existing hydraulic conditions in the estuary. To accurately use this tide model, the effects of certain alterations concerning the Wilders Dike area of the system were analyzed to check their contributions to the system. In Section 4.3, it is shown that these alterations had little effect on the values obtained by the model, and consequently helped demonstrate the validity of this model.

When the project concerning man-made alterations on the natural tidal system was completed by Graham S. Giese et al. (1985), this model was the most accurate representation of the Pamet estuary. However, the model now requires validation because of alterations to the system hydraulics. Since the introduction of this computer model in 1985, the railroad dike breached at Mill Pond and the harbor has experienced additional sedimentation. Therefore, it was unknown whether the model was as accurate as possible.

One of the main objectives of this chapter was to demonstrate that the model was still a good representation of the system's characteristics even after these system changes were taken into consideration. This chapter delves into the question of model validity and it poses several different methods of doing this. It was attempted to prove that this model does, in fact, describe the present hydraulic conditions of the Pamet estuary system.

4.2 Model Description

The Pamet Shallow Water Numerical Tide Model was submitted in 1989 by Carl T. Friedrichs and David G. Aubrey (Woods Hole Oceanographic Institute), and Richard G. Lewis II (Massachusetts Institute of Technology). This is a FORTRAN one dimensional model in which velocity is averaged over cross-sectional area. In order to obtain valid results from this one dimensional model, the length of the tidal channel is assumed to be a much greater value than the width, and the width of the channel is assumed to be much greater than the channel depth. This model is based on the conservation of mass equation and the conservation of linear momentum equation. These two equations can be used to solve for $S(x,t)$ (surface water elevation) and $V(x,t)$ (cross-sectional averaged velocity).[20]

The basic model layout is shown in Figure 4.1. The model is composed of five branches representing the Great Pamet, Little Pamet, Mill Creek, the inlet channel, and a central region connecting all of these branches. Each branch is subdivided into surveyed cross sections referred to as grid points. The grid points are spaced 125 meters apart along the length of the river. Channel characteristics were determined at each grid points in order to obtain cross sections. Figure 4.2 illustrates the idealized cross section obtained from the field measurements.

The model output provides the surface elevations above mean sea level. The cross section consists of a lower channel which extends up to a level defined as h1, and an additional over-marsh region that extends to a level defined by h2 (which is approximately at mean high tide). For some analyses however, the depth of water above the channel bottom was required. For these analyses, to obtain the depth of flow, the difference in elevation between h'(height to mean sea level) and h2 for each particular node must be either added to or subtracted from the S(x,t) value depending on whether the channel bottom lies above or below mean sea level. This new value is the water surface elevation in reference to the channel bottom for the particular node.

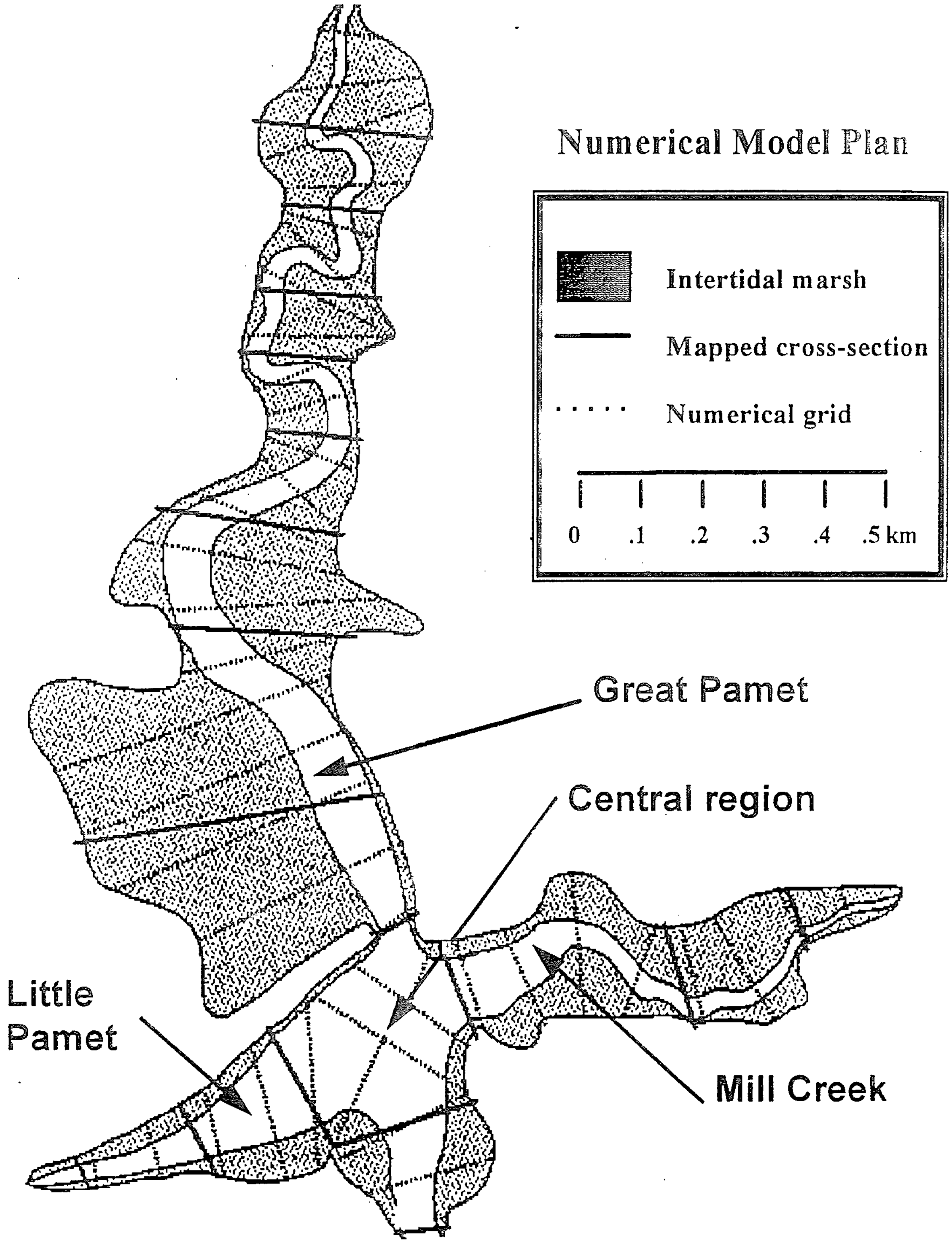
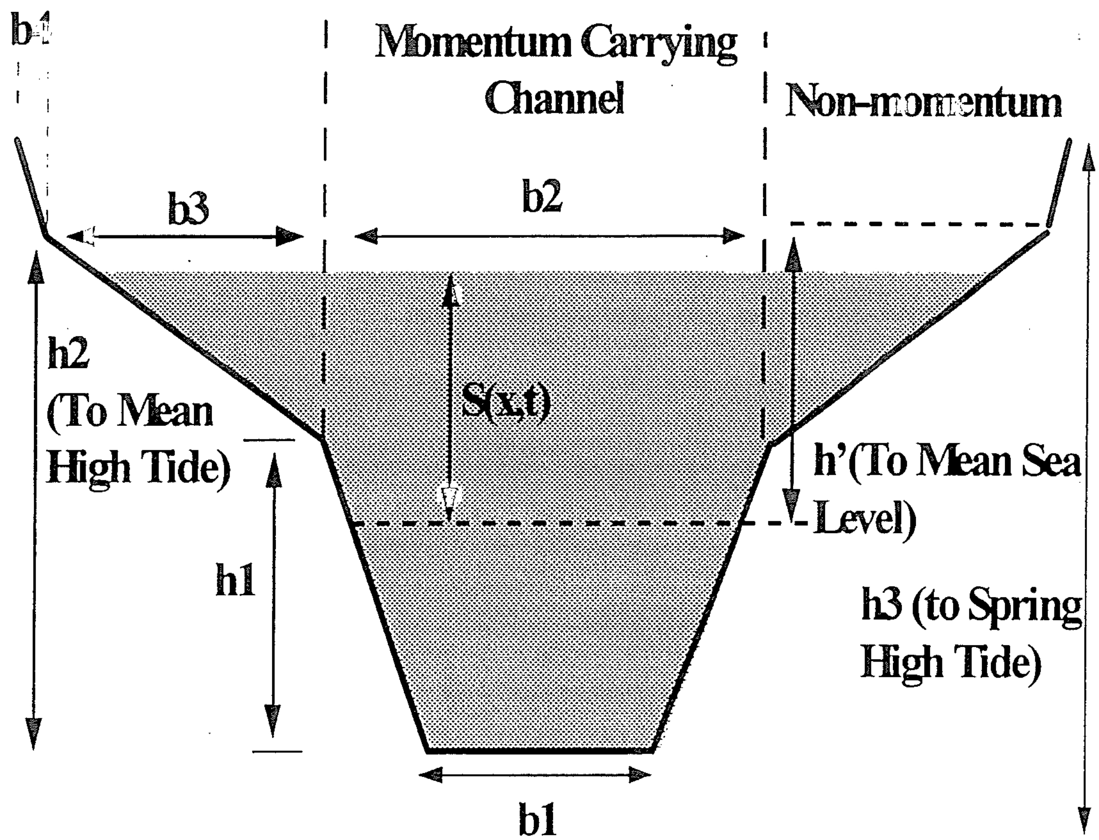


Figure 4.1: Layout of Model
(Taken from "Application of a Shallow Water Tide Model", Carl Friedrichs, 1989)



b1 - b4: horizontal dimensions
h1 - h3: vertical dimensions
S(x,t): tidal elevation

Figure 4.2: Idealized Model Cross Section
(Taken from "Application of a Shallow Water Tide Model", Carl Friedrichs, 1989)

Branch 5 (The Great Pamet) consists of 23 grids when Wilders Dike is assumed to be in place. An additional 23 grids can be attached to branch 5 in order to model the effects of the removal of Wilders Dike. The plan view of the model, shown in Figure 4.1, represents the case where Wilders dike is assumed to be in place. The figure includes the grid points at which channel characteristics were measured, including channel depths and tidal flat areas.

In order to run the model, the user must first choose to examine either 23 (with Wilders Dike) or 46 (without Wilders Dike) nodes. Next, the model offers the user the choice of selecting any combination of four nodes from any of the five branches for analysis. After the user has entered four nodes, the model requires that the user choose mean tide conditions or spring tide conditions. Mean tide conditions account for average tide conditions, and spring tide conditions account for the natural process in which high tide elevations increase approximately every two weeks. After the user has entered all the appropriate data, the model produces an output file consisting of 600 water surface elevations S(x,t) and averaged velocities. This data can then be manipulated on a spreadsheet program in order to obtain tide variations, flow measurements, the tidal prism and other various hydraulic characteristics.

4.3 Model Validation

Since the tide model is so important to this study, a model validation was imperative. The estuary has undergone physical change since the creation of the model. One important change that is continually taking place is known as shoaling. Shoaling is described as the process of sediment deposit in an estuary. As the tide comes in, sediment is transported into the channel and deposited before the tide rushes out. Another change to the Pamet system occurred in 1991 when a storm surge resulted in a breakthrough of the railroad dike in the Mill Pond Region. System changes like these have caused alterations in the hydraulic characteristics of the Pamet. It was essential to check whether or not this change was significant enough to cause discrepancies between the model and actual field characteristics. Model validation was accomplished through a three step process involving:

1. A comparison of elevation vs. time plots of field stations and their corresponding model nodes
2. A comparison of a flow measurement (taken approximately at the midpoint of the Great Pamet) against model flow data.
3. A comparison of channel widths and elevations (obtained both from surveying as well as from topographic maps) with corresponding model widths and elevations.

The data to perform these calculations was obtained during a field trip to the Pamet on 10/1/95.

4.3.1 Tide Measurements - Methodology

In order to obtain flow vs. elevation validation, it was necessary to use tide gauges and to record the river stage elevation with the elapsed time. During the first field trip to the Pamet River and Wilders Dike, tide gauges were installed to record tidal elevations for use in validation of the computer model. The gauges were installed at stations 1 (Harbor), 2 (Wilders Dike), 3 (Wilders Dike fresh side), 4 (Mid-Pamet) and 5 (Railroad Dike breach), as shown in Figure 4.3. These stations were chosen in an attempt to give an accurate representation of flow and river stage throughout the entire system. The stations provide information on hydraulics throughout the Pamet over a representative range of the tidal cycle because of their distributed locations throughout the estuary.

4.3.2 Use of Tide Gauges

The gauges that were utilized in this study were comprised of long, flat wooden sticks with a measuring tape secured on the entire length. The gauges were graduated in increments of one inch with a range between zero and sixty inches. Although the gauges could have been made any length, sixty inches was the maximum acceptable length due to space limitations during transportation. Because of their limited measurement capacity, as

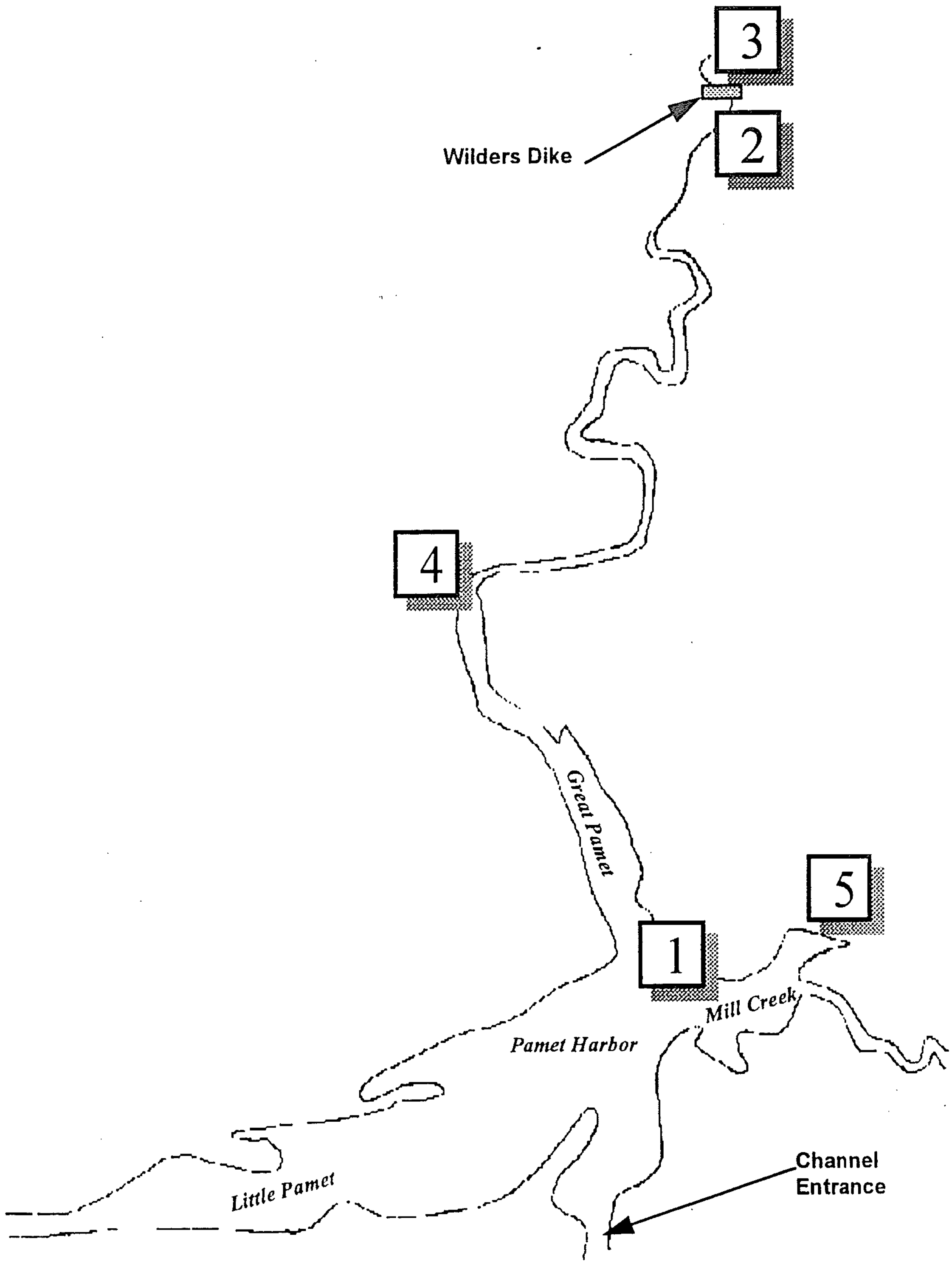


Figure 4.3: Field station locations

the water level rose above sixty inches due to the incoming tide, the gauges would become submerged. The opposite was true regarding the ebbing tide. That is, as the tide went out, the gauges were left suspended out of the water, again making measurements impossible. The tidal range that was measured varied slightly depending on the location of the gauges in the Pamet. A review of the tidal variations in the Pamet show that our tidal range was expected to be about 1.9 meters. Upon arrival at the site, the tide had not quite reached it's peak and the gauges were installed while the stage of the river was still high. To use the gauges in a 1.89 meter tidal range, each gauge had to be referenced to a particular landmark using appropriate surveying equipment. This was done such that each tide gauge could be removed from it's initial location and re-referenced to a higher or lower elevation, depending on the particular river stage at that time. By using the same reference point when moving the gauges, the measured tidal elevations would be on the same scale, which could make it possible to measure the 6-hour tidal cycle using a single elevation reference.

4.3.3 Field Procedures to Develop Tide Surface Plot

The field procedures for each tide location were as follows:

1) Installed tide gauges and made measurements/recording at regular intervals

2) Referenced gauges to established benchmarks

3) Recorded tidal elevations periodically for approximately one half of a tidal cycle (measured high and low tides)

4) Repositioned tide gauges as necessary to compensate for tidal variations by re-referencing them to the previously established benchmarks

5) Reworked field books to reflect the actual elevations after adjustments in the field were made relative to the benchmark

6) Redefined times-of-day to reflect elapsed time instead of instant time measurements

7) Plotted tide surface variations vs. time so that these plots could be compared to those produced by the model. A positive comparison would partially demonstrate the validity of the model to represent the present estuarine conditions. The completed tide plots and comparisons are shown in Figures 4.4 through 4.7

4.3.4 Model Procedures to Develop Tide Surface Plot

In order to obtain a model elevation vs. time plot comparable to the corresponding field plot, the following procedure was followed:

1) The model was run under mean tide conditions with branch 5 consisting of only 23 nodes. This allowed the analysis of the Pamet with Wilders Dike in place (current conditions)

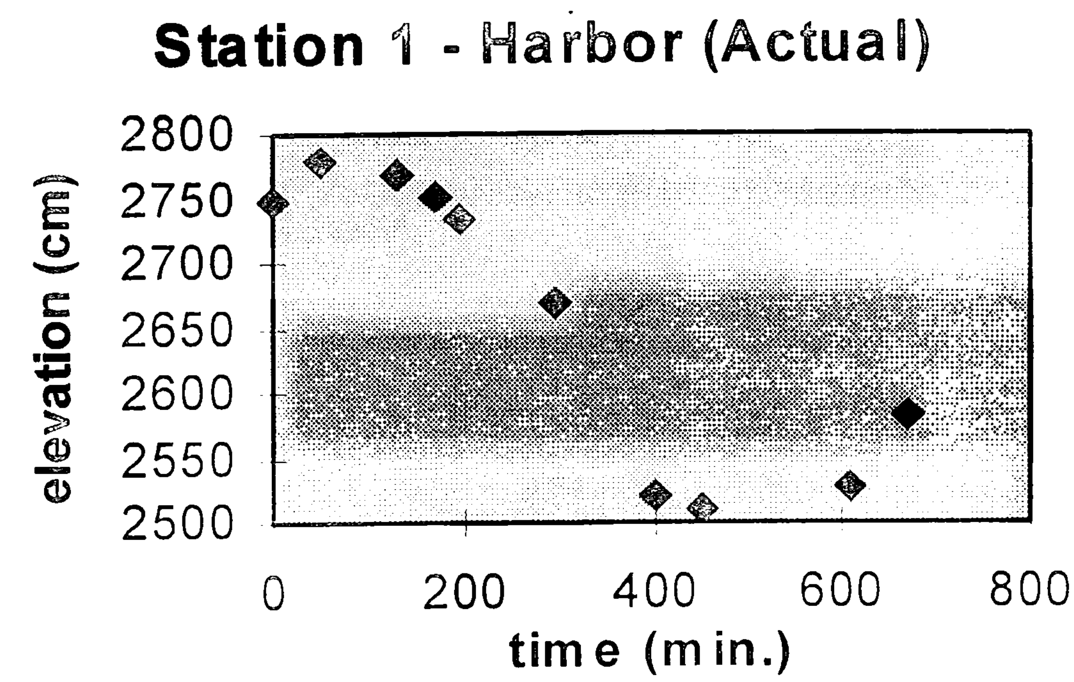
2) The four nodes analyzed were 5,1 (Harbor), 5,23 (Wilders Dike), 5,12 (Mid-Pamet), and 4,4 (Railroad Dike) which corresponded to the points at which the tide gauges were installed (see fig. 4.3)

3) Since field data was only taken for a portion of the tide cycle, model elevation vs. time data was plotted for the portion of the tide cycle coinciding with recorded field data

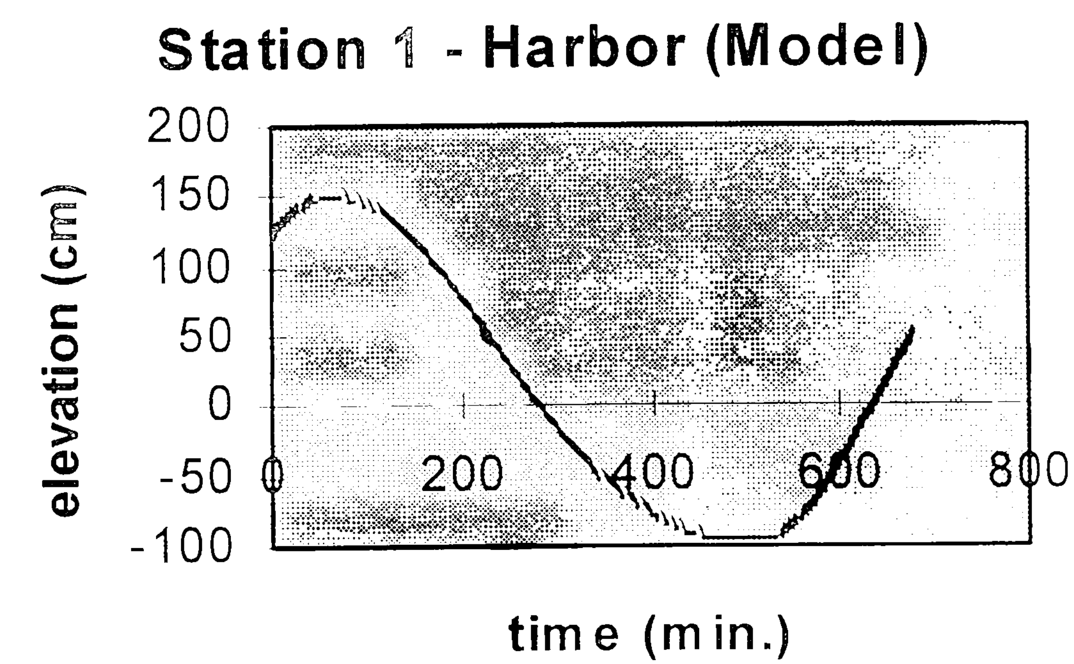
Plots were obtained for both the field and corresponding model data for each of the following four locations: the Harbor, Mid-Pamet, Railroad dike breach and Wilders Dike. Then, comparisons were analyzed as seen below.

Station 1 - Harbor

Comparisons between field data and model data at the harbor can be found in Figure 4.4, which represents tidal elevation vs. time for station 1 (Harbor) and that of the corresponding model node (5,1). The comparison of the plots shows that both curves follow the same general sinusoidal pattern. The field plot has an elevation range of approximately 2.7 m and the model plot has an elevation range of approximately 2.5 m. This 20 cm difference in range could be partially due to human error during field measurement techniques. It could also result if field measurements did not coincide with the extreme high and low tide conditions for that day. Another, more likely, source of discrepancy could be that the model's mean tide conditions are, in fact, an average of tide cycle fluctuations over a period of time. Therefore, differences between the measured variations on a particular day and the model's predicted variation (which represents an average variation) would be expected. Considering all of these, the field station is accurately represented by the model.



Station 1 - Harbor (Actual)
2800
2750
2700
2650
2600
2550
2500
elevation (cm)
0
200
400
600
800
time (min.)

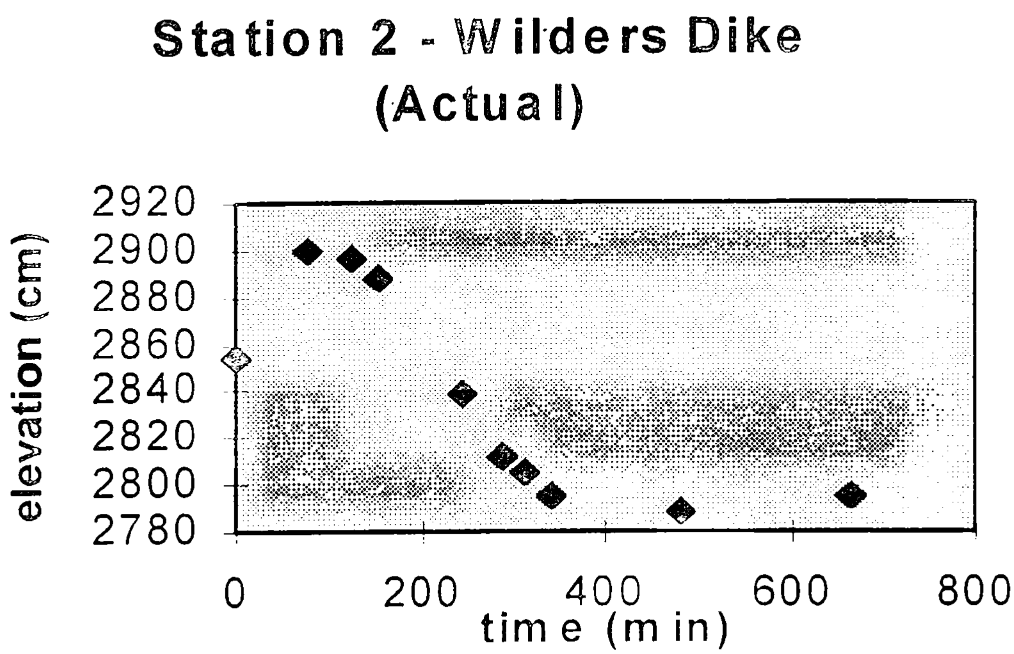


Station 1 - Harbor (Model)
200
150
100
50
0
-50
-100
elevation (cm)
0
200
400
600
800
time (min.)

Figure 4.4

Station 2 - Wilders Dike

The plots in Figure 4.5 represent tidal elevation vs. time for station 2 (Wilders Dike) and that of the corresponding model node (5,23). The comparison of the plots shows that both curves follow the same general pattern. The tide rises to a peak and then immediately begins decreasing until it reaches an extreme low, and then remains constant for approximately 4.6 hours. The tide level remains at this extreme low stage for a long time period because the harbor's tidal elevation has dropped below the elevation of the channel bottom at this location (as is typical of an intertidal estuary). For this reason, the clapper valve at Wilders Dike opens at low tide and a steady water level is attained due to the influx of fresh water. The measured tidal stage is not necessarily constant at this point - instead the amount of fresh water entering from upstream is constant. The type of profile that is seen here is generally expected when dealing with a flood dominant estuary, meaning that the tide rises in the channel much more quickly than it falls. The field plot has an elevation range of approximately 1.1 m and the model plot has an elevation range of approximately 1.25 m. This 15 cm difference in range is possibly due to error involved in tide gauge measurements as well as the failure to obtain the extreme high and low tide measurements. As for station 2, another possible source of discrepancy is that model's mean tide conditions are, in fact, an average of tide cycle fluctuations over a period of time. Again however, the field station is accurately represented by the model.


Station 2 - Wilders Dike
(Actual)
elevation (cm)
2920
2900
2880
2860
2840
2820
2800
2780
0
200
400
600
800
time (min)

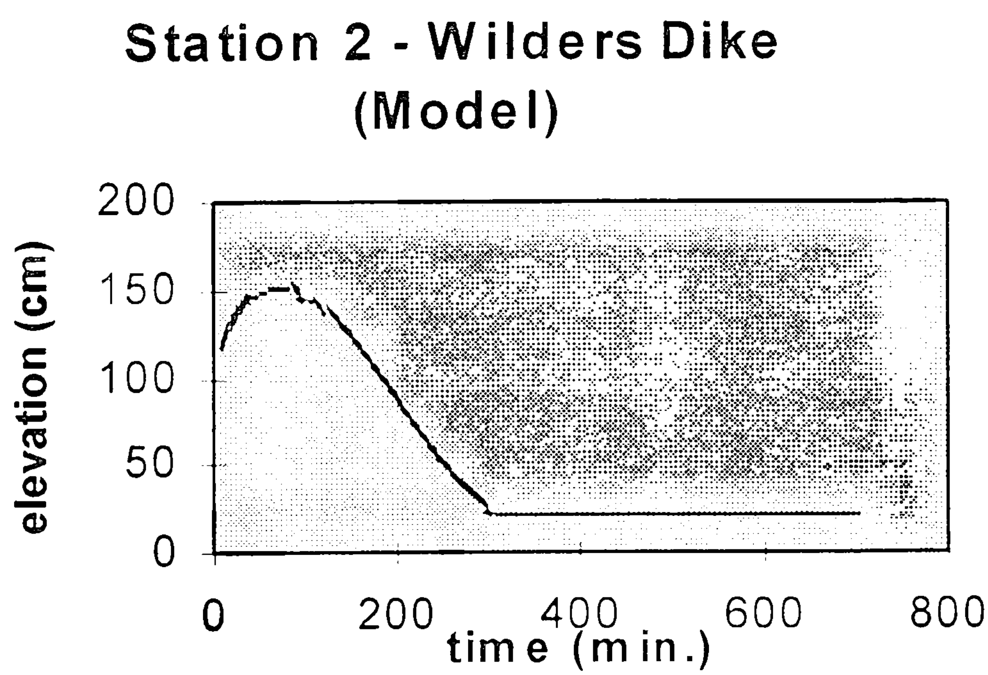
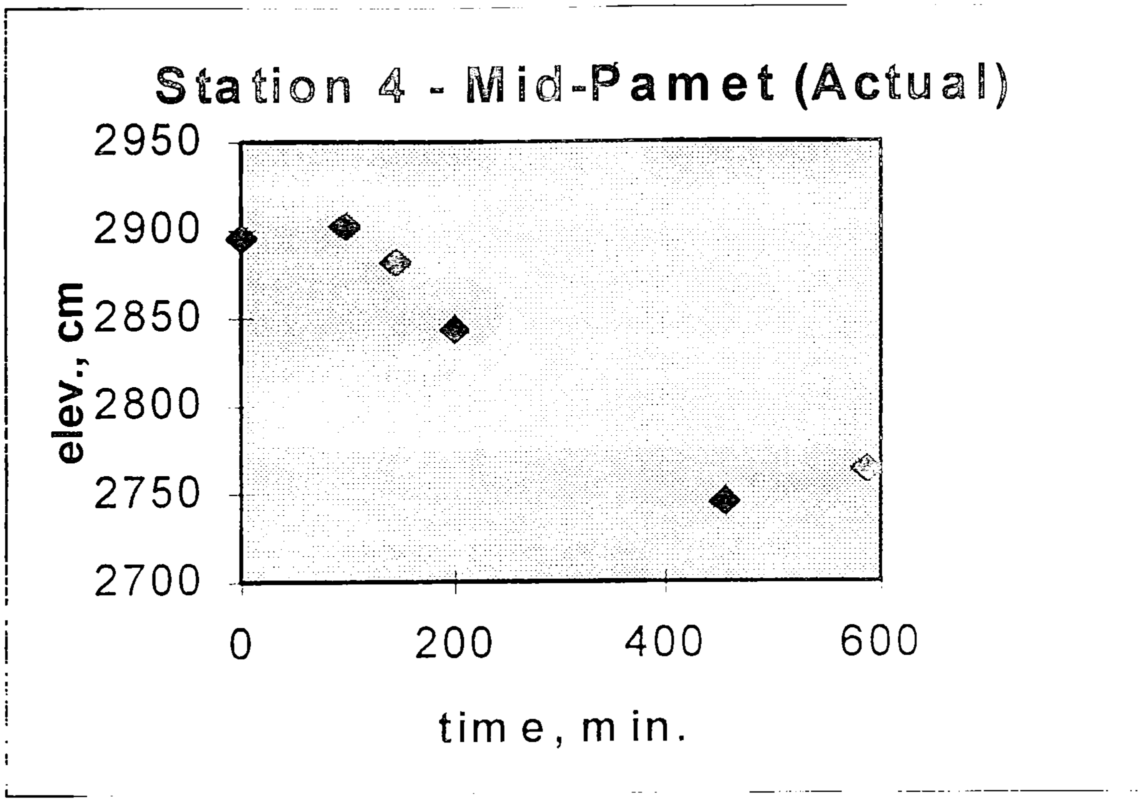

Station 2 - Wilders Dike
(Model)
elevation (cm)
200
150
100
50
0
0
200
400
600
800
time (min.)

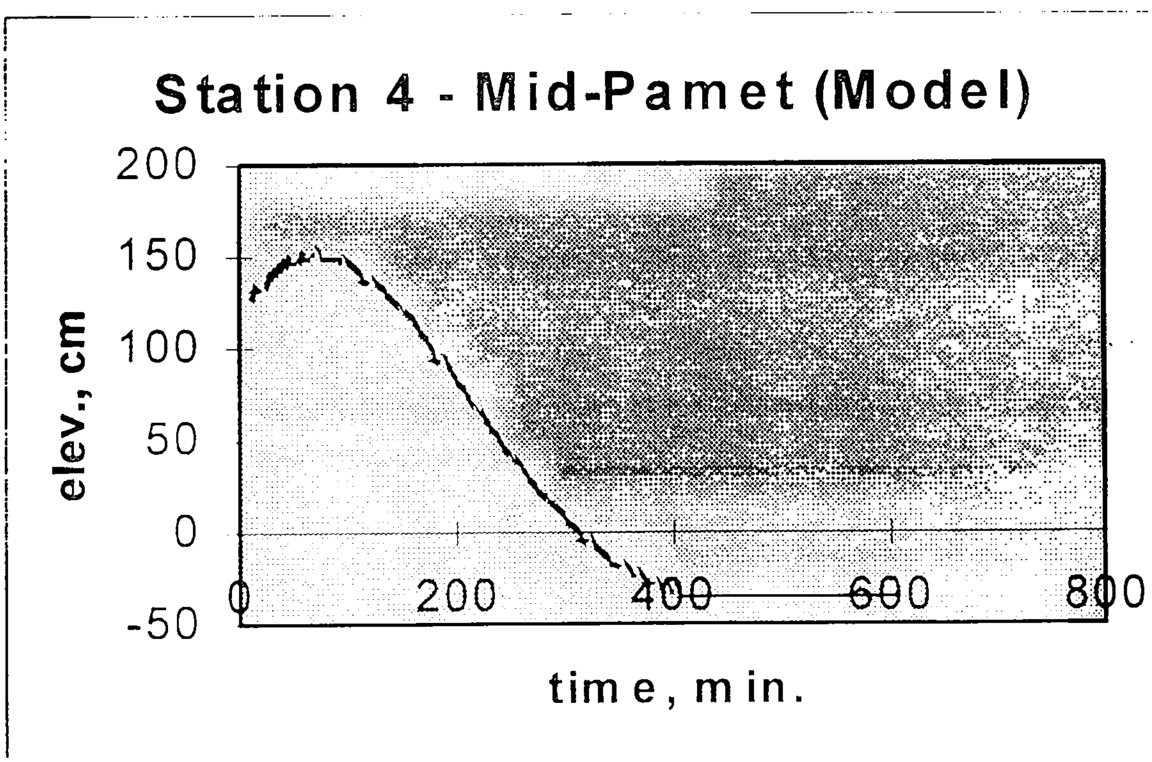
Figure 4.5

Station 4 - Mid-Pamet

The plots in Figure 4.6 represent tidal elevation vs. time for Station 4 (Mid-Pamet) and that of the corresponding model node (5,12). The comparison of the plots shows that the curves differ towards the end of the tide cycle portion. This is probably due to the inherent fluctuations that are present when considering tidal estuaries accompanied with the fact that it was not attended to with the regularity that we anticipated. Due to time constraints during the day, this station was left unattended often and could only be checked occasionally. As a result, only six readings were taken over the tide cycle. Because the proper amount of data was lacking, the plot generated from the field measurements could not be expected to yield the smooth curve that was obtained from the model. For this case, the field plot has an elevation range of approximately 1.65m and the model plot has an elevation range of approximately 1.8m. This 15 cm difference in range could have been due to failure to obtain the extreme high and low tide measurements, or due to the fact that the model's mean tide conditions are an average of tide cycle fluctuations over a period of time. Although the measured profile was limited by the number of readings taken, there is close agreement between the measured and model profiles.



Station 4 - Mid-Pamet (Actual)
2950
2900
2850
2800
2750
2700
elev., cm
0
200
400
600
time, min.



Station 4 - Mid-Pamet (Model)
200
150
100
50
0
-50
elev., cm
0
200
400
600
800
time, min.

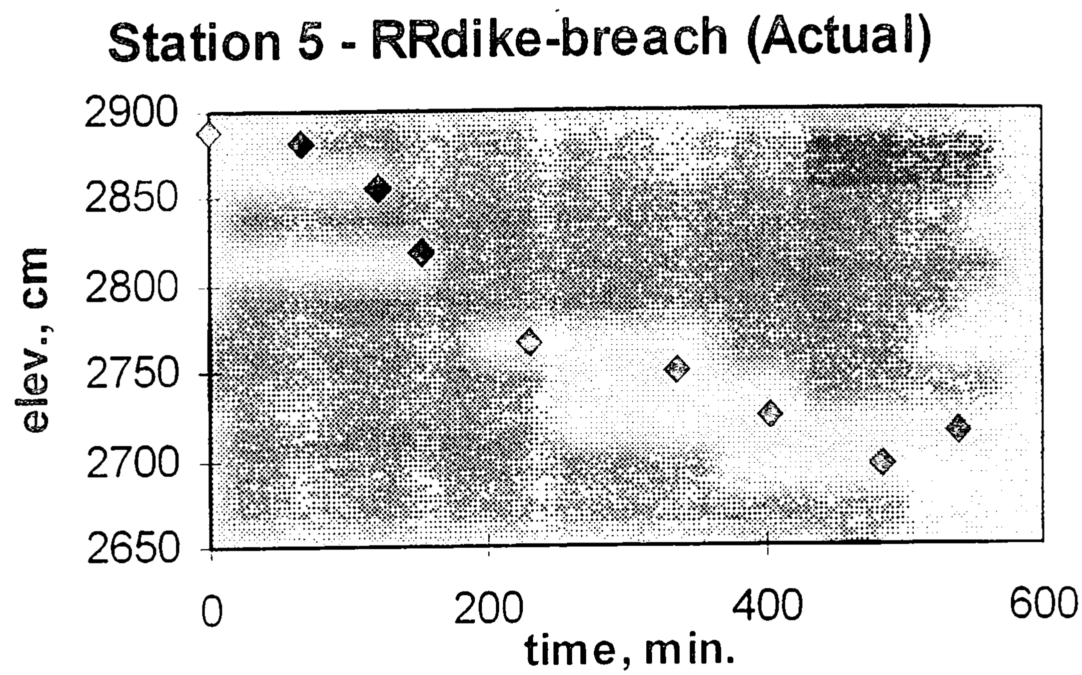
Figure 4.6

Station 5 - Mill Pond Railroad Dike Breach

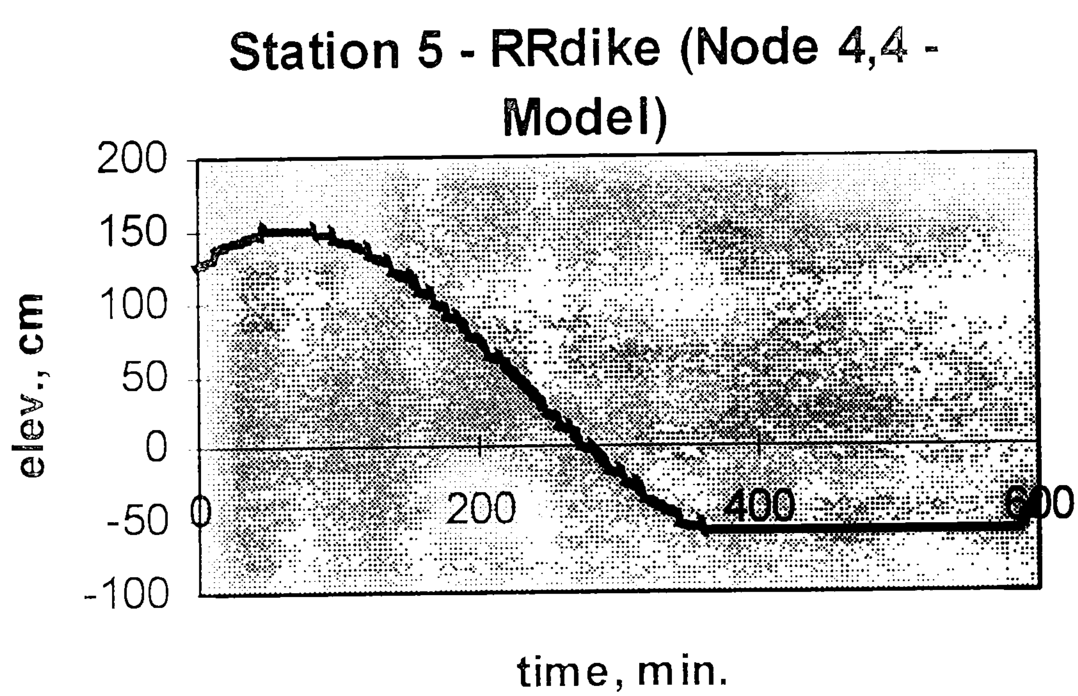
The plots in Figure 4.7 represent tidal elevation vs. time for Station 5 (RR-dike breach) and that of the corresponding model node (4,4). The comparison of the plots shows that the curves have similar ranges. The field plot has an elevation range of approximately 1.9m and the model plot has an elevation range of approximately 2.1m. However the curves do differ throughout the tidal cycle. Measured data shows a slow, relatively uniform decrease in surface elevation. The modeled profile, however, shows a more rapid drop with extremely low steady conditions similar to that at Wilders Dike.

Differences are probably due to a few important factors. First, the model was created in 1985, before the railroad dike break through occurred. This breakthrough resulted in a large volume of water being displaced into this basin, possibly affecting the flow characteristics of the rest of the estuary. It is possible that the model can not account for the new hydraulic characteristics of this section. Second, the tide gauge was unknowingly placed in a poor location because of the fact that the channel bottom was not visible at that time. The first location that was chosen was on a small plateau in the channel. As the water level decreased, the tide gauge was left submerged in water while the surrounding water decreased to a lower level. Due to error, the final two tide readings are not reliable.

From this data, it has been determined that the model no longer accurately represents this portion of the Pamet. Although it seems as though this section of the Pamet does not conform to the model, it must be noted that by using the same procedures, it was found that the remainder of the Pamet system was modeled well.



Station 5 - RRdike-breach (Actual)
2900
2850
2800
2750
2700
2650
elev., cm
0
200
400
600
time, min.



Station 5 - RRdike (Node 4,4 - Model)
200
150
100
50
0
-50
-100
elev., cm
0
200
400
600
time, min.

Figure 4.7

4.3.5 Flow Data Comparison

The second step in validating the model was performed using a single flow measurement at station 4 - the Mid-Pamet (see Fig. 4.3). The field flow data was compared to that given by the model showing their similarities and discrepancies. The measurement was taken as the tide was flowing out toward the harbor. This means that the stage of the river, and consequently the volume, velocity and flowrate, were continuously changing during the measurement period. This estimate of velocity in time at a single location provided a measurement which could be compared to the model for a single output for the same tidal condition. However, it can not be expected that the model would exactly correspond to this measurement. It does, though, give an indication that the model can provide accurate flow rates.

4.3.5.1 Field Flow Measurement

The field flow measurement was taken at the Mid-Pamet using a number of velocity measurements taken over a cross section with a flow meter. The analysis yielded a flow rate of approximately 150 cfs. More specifically, the procedure for taking the flow measurement was as follows:

1) A tape (called a 'tag line') was stretched across the river to get width of entire river and of the measuring section.

2) Measurement locations were determined. These locations were defined in terms of lengths measured along the tag line from the reference on the bank.

3) At each measurement location, a single velocity and depth measurement was taken. This velocity was taken at a depth of .2, .6 or .8 of the overall depth which provided a close approximation of the depth-averaged velocities according to USGS guidelines.

4) Used depth measurement to obtain an area for each interval.

5) Once the velocities and areas for each section were obtained, the flow rate (in cfs) for each area was measured. Then these incremental flow rates were summed to get the overall river flow rate.

It must be noted that the flow measurement was taken during a decreasing tidal period. This means that the stage of the river was constantly changing. If, for instance, the river was not tidal, an accurate flow could have been calculated from a steady velocity multiplied by a steady area. Because of it's tidal nature, however, the Pamet did not conform in this respect. Because the stage was continuously changing over the measurement cycle, the area of the cross section and the velocity of the flow were changing as well. Because flow was calculated using the equation $Q = (V)(A)$, variations existed due to the continual changes in these two parameters. From the start of the measurement to the end, the total change in stage was approximately one foot, or nearly 30.5 centimeters.

4.3.5.2 Model Flow Predictions

Since the tide elevation varied during the field flow rate measurement, the field flow measurement of 150 cfs was compared to the flowrate predicted by the model for the same tidal variation. First, predicted flowrates were obtained from the model by running it under spring high tide conditions and with 23 nodes because the existing conditions include Wilders Dike at node 23. The results gave a plot of elevation versus time in minutes as seen in Figure 4.6. (See also Appendix C)

Arrival in Truro at 7:45 am corresponded to time zero on the model plot. It was necessary to find the point which represented the time that the field flow measurement was taken. The field flow measurement was taken between 12:00 noon and 12:20 pm. The elapsed time between 7:45 am and 12:00 pm was taken and plotted on the x-axis of the graph so that the elevation on the y-axis could be obtained. This elevation was then examined against the elevation given by the model. In addition to elevation, the model also could be used to determine flow. During the period of the measurement, which lasted 20 minutes, the change in flow due to the stage fluctuation was shown to vary between approximately 118 and 158 cfs. Therefore, the field flow measurement of 150 cfs matched relatively well with the model values when the duration of the measurement is taken into consideration.

4.3.6 Channel Width and Elevation Comparison

Validation of the model included alternate methods such as checking different widths of Branch 5 against a USGS topographical map as well as with a map that was utilized by Graham Giese during his previous studies. The widths on the two maps were examined using an engineering scale. Once these measurements were obtained, they were compared with those defined in the model's parameters. For example, in Figure 4.2 the values denoted with a 'b' (including b1 - b4) represent widths of different sections of Branch 5. The ones which were examined most carefully include b2, b3 and b4. The sum total of these parameters represents the surface of the entire cross section and it was these that were verified using the maps and engineering scale.

4.3.7 Mill Pond Volume Calculation

Another measurement was performed on the Mill Pond region of the Pamet estuary to discover the volume enclosed in that area and whether or not that volume affected the model. At the time that the model was developed, the railroad dike at Mill Pond was still intact. However, after the dike failed, an new channel formed and a large volume of salt water pervaded the Mill Pond area. This volume altered the tidal prism for the Pamet and changed the hydraulic characteristics in the vicinity of this land.

To discover if this volume has any effect on the model and it's calculation of flow and velocity, the first thing that needed to be done was to calculate the quantity of water enclosed in the basin. The volume of salt water exchanged in the Mill Pond area was estimated using the data obtained from the surveying and the tide gauge flow measurements.

First, the surface area was calculated by a scale representation of the area encompassed on a topographic drawn on engineering grid paper. The grid paper was divided into one inch sections, each of which was estimated using the topographic map to have a scale length of 800 feet per side. With 25 subdivisions to each 1 inch square plot, the individual subdivisions were approximated at 25,600 ft^2. This value was obtained by making the length of each square subdivision (800 / 5) = 160 ft. Therefore, the are of one subdivision was $(160\ ft)^2 = 25{,}600\ ft^2$. Upon sketching the approximate area of the basin on the grid paper, the number of subdivisions enclosed in the entire area was estimated to be approximately 23.25. Therefore, the total estimated surface area was calculated to be

$$(23.25)(25{,}600\ ft^2) = 595{,}200\ ft^2.$$

Next, the area was surveyed to determine hydraulic elevations so that an accurate topographic representation could be found. This was completed during low tide. While the entire area of land was submerged during relatively high tide periods, a small channel runs through the interior of the region during low tide periods. Elevations of this were also measured when performing topographic surveying. These channel elevations could be used to update the numerical model if necessary. It was estimated that the volume of this channel would most likely have a negligible effect on the total volume exchanged in Mill Pond due to the channel's small size with respect to the entire volume.

Table 4.1: Surveying Calculations at Railroad Dike Region

		BS	HI	FS	Ele.
TP1		13.05			94.46
location 1				10.05	97.46
on sand			104.27	11.6	92.67
in marsh				12.88	91.39
in channel			97.7	10.12	87.58
on bank				6.97	90.73
Mill Pond Road				2.2	95.5
	BS = backsight				
	FS = foresight				
	HI = height of instrument				
	TP = turning point				
	Ele. = elevation				

Table 4.1 shows the different elevations that were obtained while performing the surveying in the Mill Pond region. Different elevation measurements were taken for

different areas in the basin and are showed above. These areas included the original placement location of the tide gauge (location 1) as well as other places on the sand, in the marsh, in the small channel running through the basin as well as on the bank. The average elevations of these areas in the basin were gathered and analyzed with respect to the previously established benchmark. The midpoint of the marsh area in the basin (see Figure 4.8) was approximated to have an elevation of 92.0 feet. This elevation was determined utilizing the elevations obtained in the marsh area and the sandy area of the basin and averaging the two together:

$$(91.39 \text{ feet} + 92.67 \text{ feet}) / 2 = 92.03 \text{ feet} \approx 92.0 \text{ feet}$$

These data were obtained using basic surveying and referencing techniques. All of these points were referenced to a wooden wall-like structure and the values were obtained in reference to this established benchmark

Figure 4.8 shows a representation of the cross section for the Pamet estuary. It is assumed that this cross section also represents the volume of water in the Mill Pond region. In approximating the cross sectional shape for the Mill Pond region as in Figure 4.8, the basis for using the figure 93.27 feet was obtained by solving for '*x*' in the equation

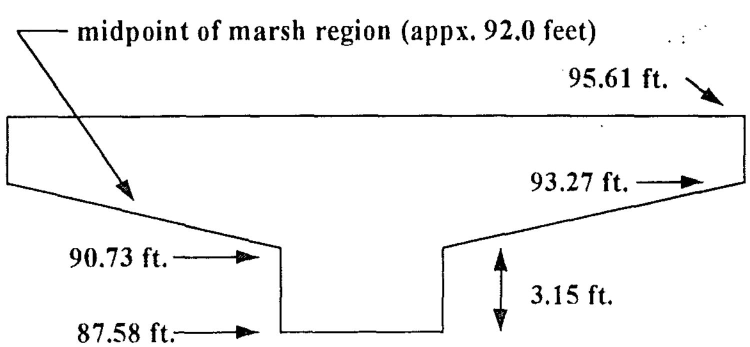


Figure 4.8: Cross section of Mill Pond region

[(x + 90.73)/2] = 92. Finally the total volume was calculated by using the simple formula Vol. = (Area)(Height). Taking the difference in the spring tide elevation and the midpoint of the marsh area gave (95.61 feet - 92.0 feet) = 3.61 feet. This was then multiplied by the previously estimated area of approximately 600,000 square feet to get a final volume of 2,166,000 cubic feet.

The model was run at this station with and without this additional volume incorporated into the system at branch 4 and node 4 to check whether or not it made a difference in the model's flow calculation in the main branch of the Pamet. Although there was a slight difference in the flow calculation, these effects proved to be negligible.

4.4 Conclusion

Since the time when this computer model was created, the Pamet flow characteristics have been altered due to a dike failure and inlet channel shoaling. Because of this it was not known if the model could still be considered adequate with respect to describing the estuarine characteristics. It was of great importance to validate this model because it was going to be used later in the project to estimate the consequences of modifying Wilders Dike.

The model was validated through the use of field and model plots of time vs. elevation, as well as flow comparisons. Surface comparison required comparison of measured tidal elevations with tidal elevations predicted by the model. Extensive fieldwork was completed in order to measure the elevation vs. time plots. This involved installing tide gauges at different locations as well as surveying them with respect to established benchmarks, allowing for comparison of field and model results. These plots were shown to in close agreement, with few exceptions. The fact that the field plots resemble those given by the model proves that the model is a good representation of the field conditions.

Another method of validation included making comparisons of the results between field and model flows at Station 4, the Mid-Pamet. Again, the results of this comparison proved that the model did adequately represent the characteristics of that section of the estuary.

The overall objective of this section was to demonstrate that the model was still a valid representation of the conditions in the Pamet estuary. The flow comparisons between the field conditions and the model were in satisfactory agreement as well as the plots generated using field and model data. Although there are some differences concerning the graph construction, the majority were found to be in agreement. This shows that the model does describe the estuary adequately for our purposes. Some variance did exist with respect to the plots, but overall, branch 5 was represented well by the model. This was the most important section in the model to validate because it was in this branch that Wilders Dike is located. One of the most noticeable differences between the model and the field characteristics existed at the railroad dike breach, but the area around Wilders Dike was represented well. The analysis of Wilders Dike and the alternatives associated with it are the focus of the next chapter. Our objective of validating the model was met and hence the model could be used for further work including Wilders Dike alternatives analysis.

5 WILDERS DIKE ALTERNATIVES

5.1 Objectives

One of the main purposes of this study is to assess Wilders Dike and its impact on the Pamet River System. Wilders Dike has been the subject of some controversy in past years. There many who feel that removing Wilders dike in its entirety would promote better water quality in general. On the other hand, there are also opponents of this plan who are concerned with increased tidal characteristics further up the river and how they will effect freshwater wetlands and privately owned property.

This section explores six possible alternatives for Wilders Dike, and they are as follows:

1. Leave Wilders Dike as is
2. Total removal of Wilders Dike
3. Removal of clapper valve from existing dike
4. Clapper valve removal in conjunction with enlarged culvert
5. Multiple culverts
6. Box Culvert

The above alternatives were evaluted based on hydraulic characteristics, their potential effects on the surrounding environment, and feasibility. This was accomplished by completing the following three objectives. First, the alternatives were defined and reasons for choosing each alternative for evaluation were discussed. This was followed by a general background in culvert hydraulic concepts pertinent to the analysis section. Finally each alternative was analyzed hydraulically, and potential effects resulting from implementation were discussed.

5.1.1 Description of Alternatives

Alternative 1: Leave Wilders Dike as is

Figure 5.1 and 5.2 illustrate the current conditions at Wilders Dike. This alternative was evaluated in order to obtain the present hydraulic characteristcs in the region. Flow is allowed from the fresh side to the salt side during low tide periods through a 42in by 56ft concrete culvert. This is accomplished through the use of a clapper valve in place over the 42 in. culvert on the salt side. The clapper valve is forced open when the fresh water produces enough pressure on the valve. This allows for fresh water flow into the salt water portion of the Pamet. As a result, the portion of river just downstream of Wilders Dike is considered stratified. When there is enough force placed on the valve by salt water during increasing tide periods, the valve closes and ideally eliminates flow in either direction.

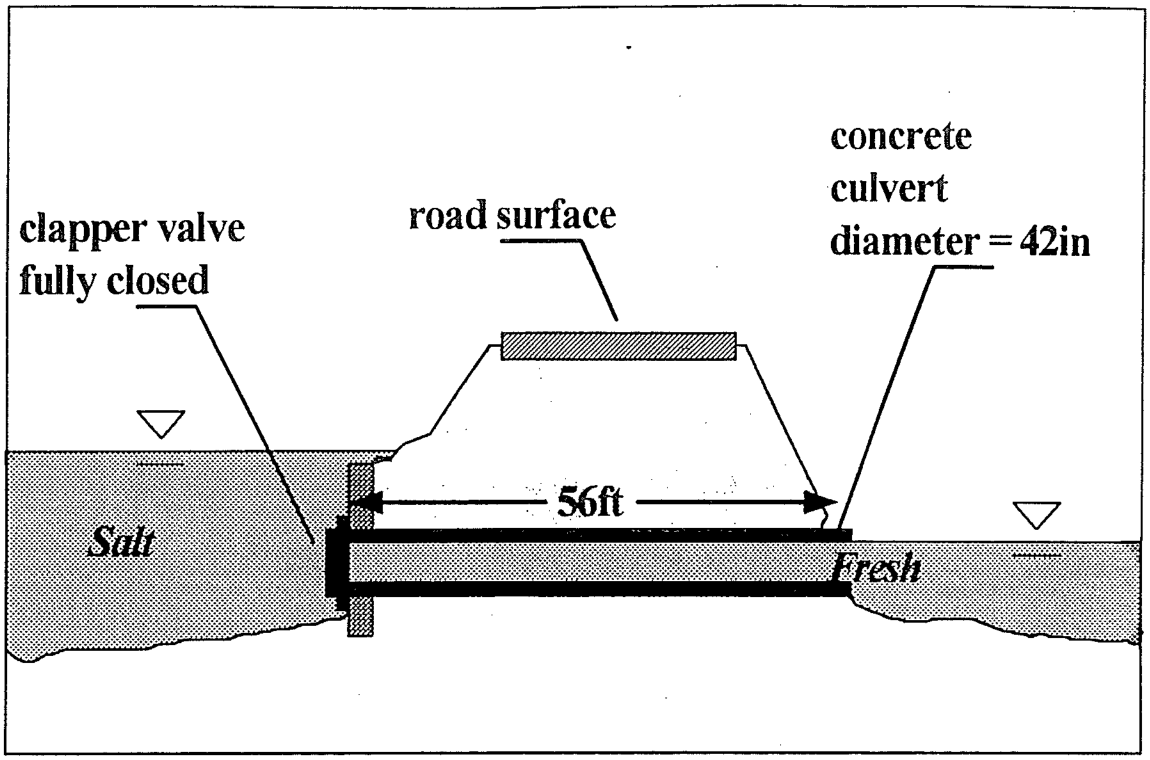


Figure 5.1: Current section of Wilders Dike at high tide

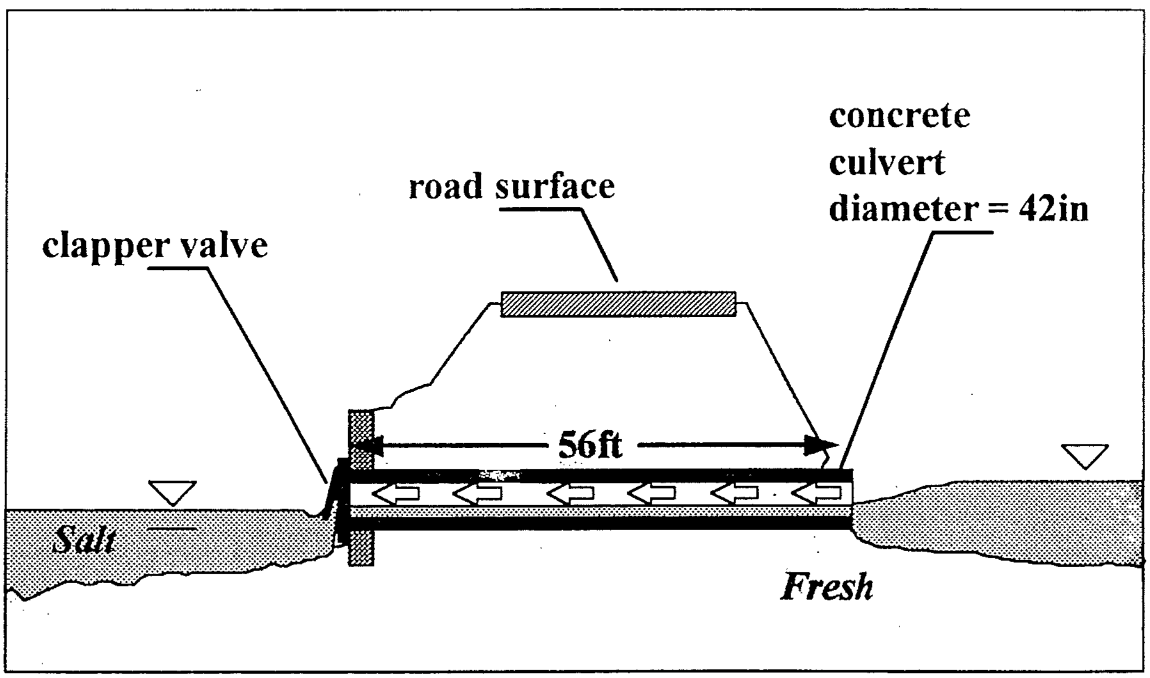


Figure 5.2: Current section of Wilders dike at low tide

Alternative 2: Total Removal of Wilders Dike

Alternative 2 involves the total excavation of Wilders Dike. The Dike would be replaced with a vehicle bridge. This alternative was evaluated because it is most similar to the system's natural state. Unrestricted flow would be allowed in both directions as shown in Figure 5.3. As a result, the river could regain original tidal characteristics that once stretched for as much as three quarters of the river's length. This tremendous increase in flow could increase the estuaries flushing capabilities, which would aid in the flushing pollutants.

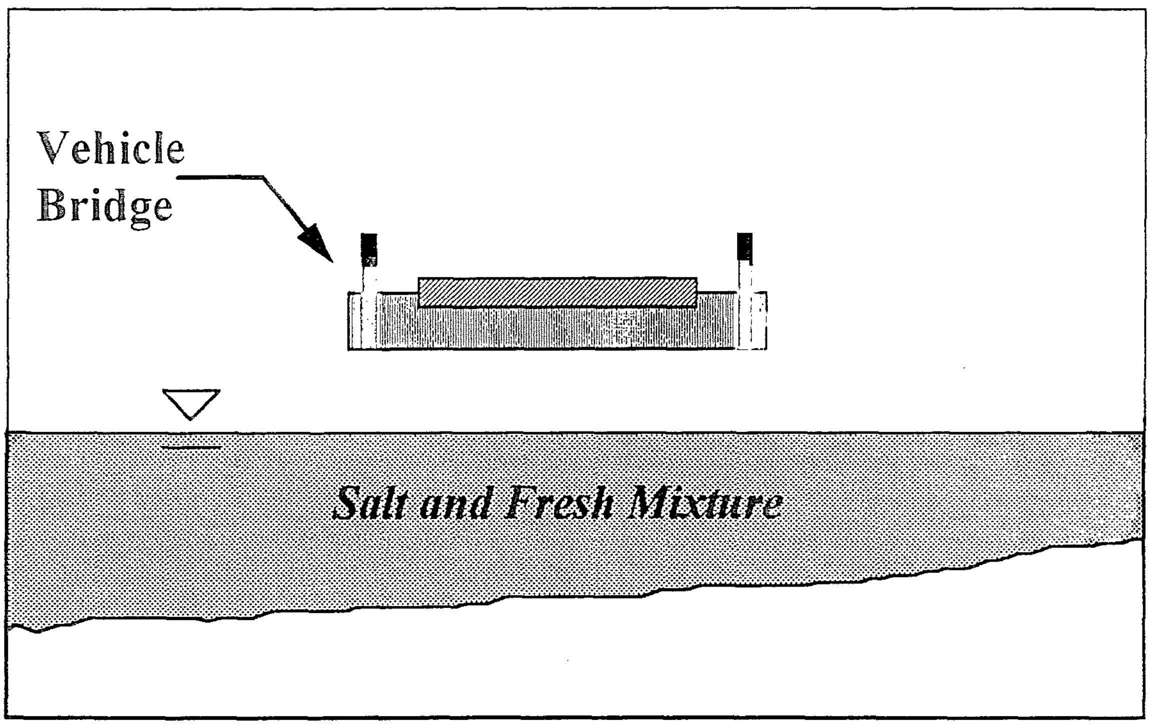


Figure 5.3: Cross sectional view of Wilders Dike region after excavation and replacement with a vehicle bridge

Alternative 3: Removal of Clapper Valve from Existing Dike

Alternative 3 involves leaving Wilders Dike as is with the exception of removing the clapper valve. Evaluation of this alternative was performed due to the fact that it represents the cheapest and labor free method of allowing for two directional flow at Wilders Dike. Removal of the clapper valve will allow for constricted flow in either direction as shown in Figure 5.4.

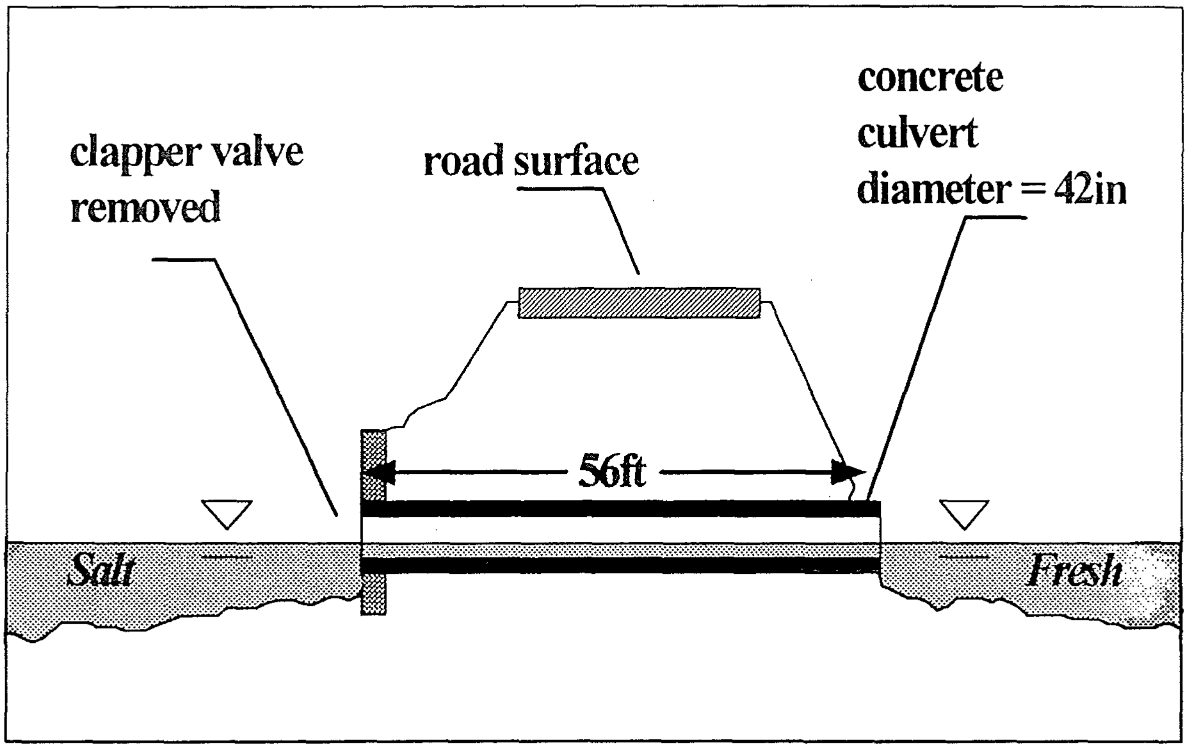


Figure 5.4: Cross sectional view of Wilders Dike with clapper valve removed

Alternative 4: Clapper Valve Removal in Conjunction with Enlarged Culvert

In Alternative 4, the clapper valve is removed, and the existing culvert is replaced with a larger one. This alternative was evaluated in case it was determined that the existing culvert is not sufficient for the increased flowrate. Figure 5.5 shows Wilders Dike with an enlarged culvert in place of the existing culvert. This will increase flow capability in both directions. As a result, salt water would flow further up river and increase tidal characteristics in the system.

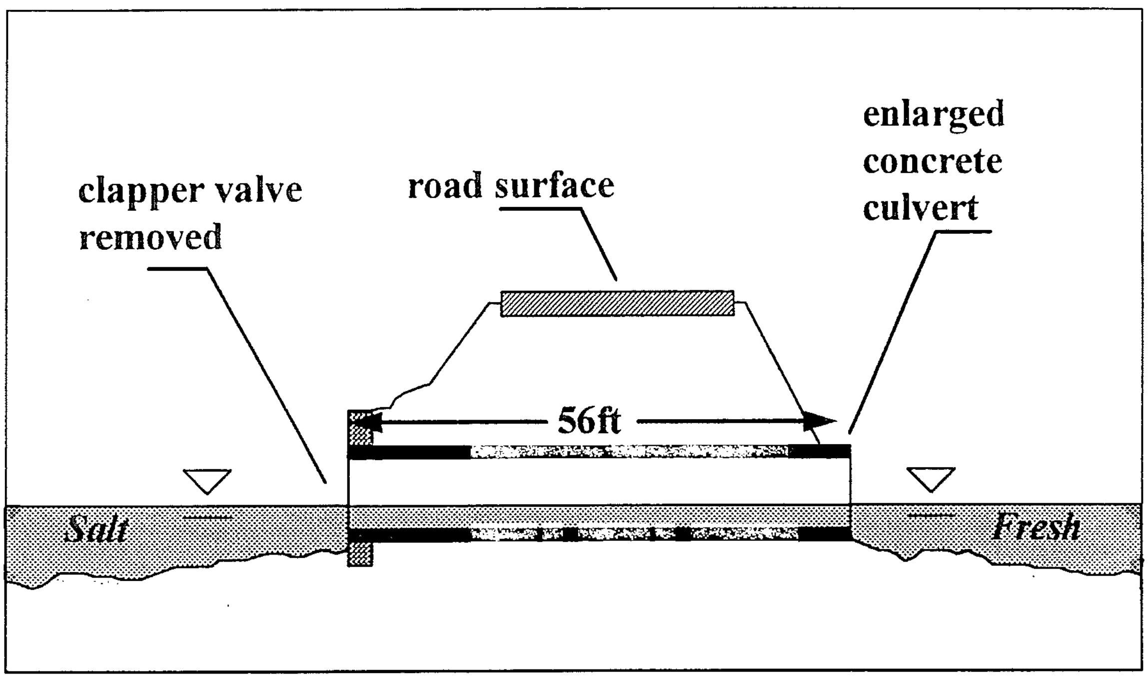


Figure 5.5: Cross sectional view of Wilders Dike with an enlarged culvert in place of the existing culvert

Alternative 5: Multiple Culverts

Alternative 5 would add an additional culvert to the existing culvert with the clapper valve removed. This alternative was evaluated because it may represent the most inexpensive way to obtain a greater flow rate than that of the existing culvert alone. Figure 5.6 shows the additional culvert in place parallel to the existing one.

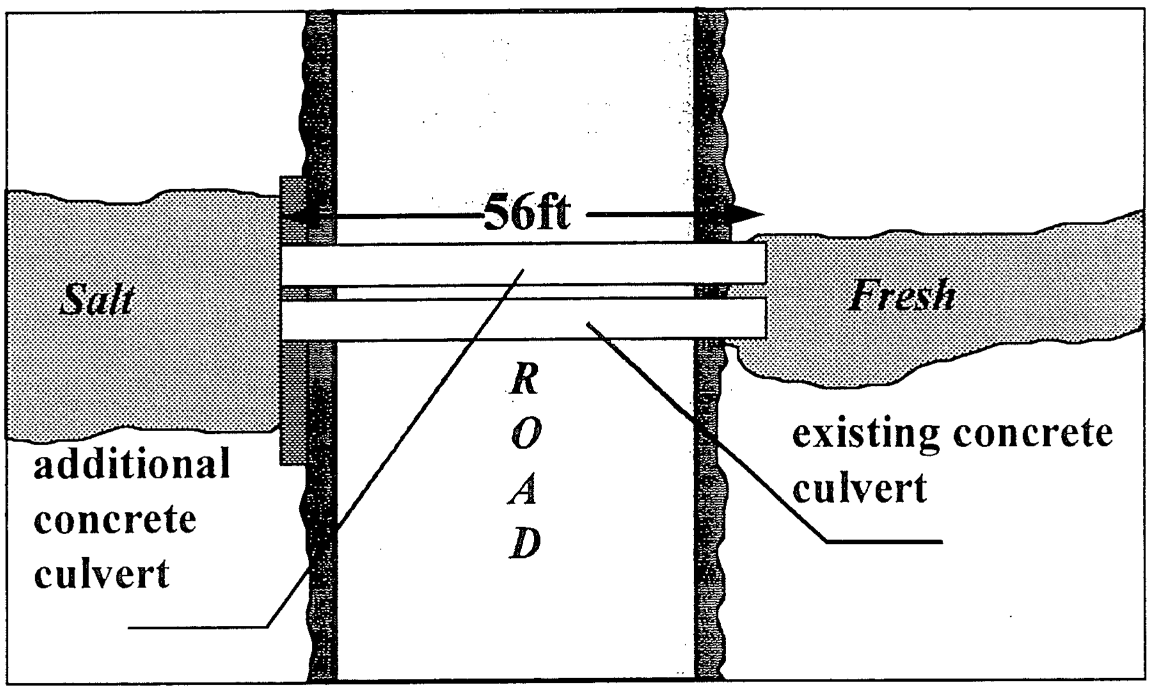


Figure 5.6: Plan view of Wilders Dike with additional culvert installed parallel to the existing culvert

Alternative 6: Box Culvert

Alternative six involves installing a box culvert in place of the existing culvert. This alternative was evaluated because box culverts allow for more flow than do round culverts of the same height. This is due to the fact that box culverts possess a greater cross sectional area than do round culverts. This alternative may prove to be useful at Wilders Dike, because as great a flow rate as possible is desired in a limited space. Figure 5.7 illustrates Wilders Dike with a box culvert in place of the existing culvert.

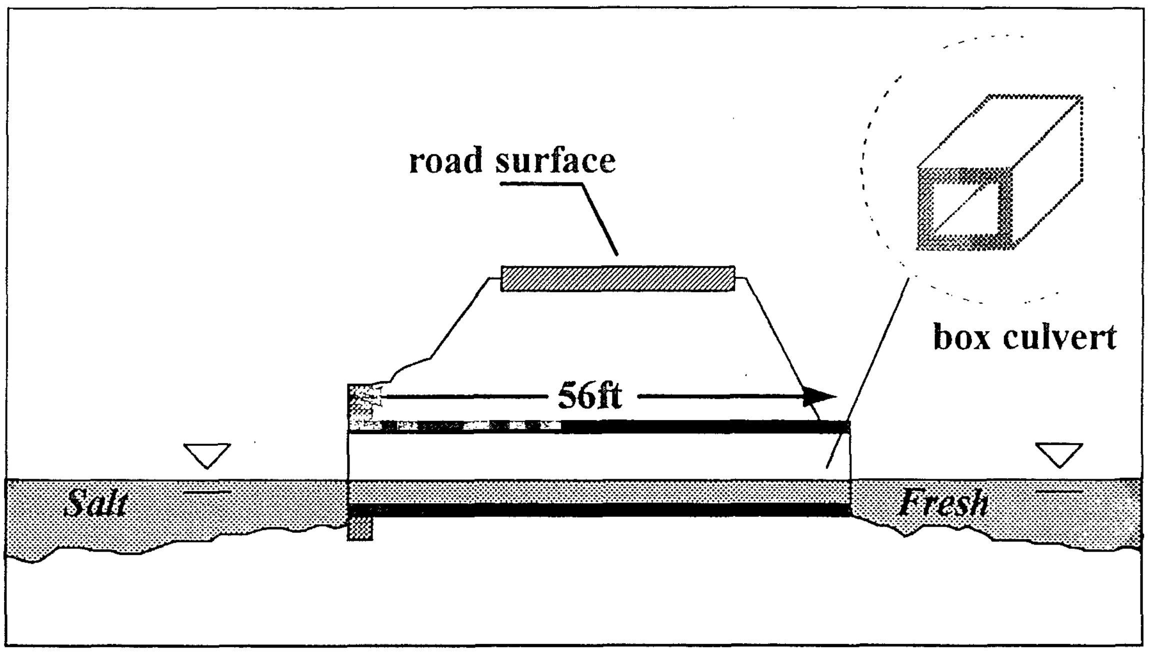


Figure 5.7: Cross sectional view of Wilders Dike with box culvert in place of existing culvert

5.2 General Hydraulics

Before the alternatives in redesigning Wilders Dike can be discussed, a basic understanding of general culvert hydraulics must be understood. This section attempts to describe some basic culvert characteristics as well as general assumptions that must be made while designing culverts. Some of different design considerations which must be taken into account are also discussed here, but most of the ideas presented here relate to the redesign of Wilders Dike, which will be discussed later.

There are as many different styles of culverts as there is applications for culverts. Culverts are systems utilized for the transportation of water from one place to another and are used for a variety of specific applications including wastewater removal, storm water sewers, water distribution systems and others. One of the general applications of a culvert could include exactly what is seen by looking at Wilders Dike, which involves transporting water from one side of the dike to the other.

Culverts come in many different shapes and sizes - each designed specifically to meet the needs presented by the client. The different styles of culverts include rounded culvert pipes, square or rectangular 'box' culverts, trapezoidal culverts, and a variety of other less frequently used styles. Each of these culverts has it's own particular subtleties which make it a challenge to design. For one example, a circular culvert may have either a square edged inlet or a rounded edged inlet. The decision that is made with respect to designing this culvert edge is based on the hydraulic conditions of the area in question as well as what the goal of designing the culvert. An experienced designer will know all of the nuances concerning each style of culvert and can employ some freedom with respect to it's layout.

5.2.1 Design Assumptions

The engineer must make certain assumptions when it comes to the planning and design of each individual culvert. Flowing water (as in most culverts) acts quite differently than stagnant water, which results in characteristics which require alternate assumptions be made. For example, it must be known whether or not the pipe is experiencing full or partially full flow. This is determined, in part, by whether or not the inlet is submerged. If the inlet is submerged, then it is probable that there will be enough head generated before the culvert to propel the water through with greater force than if the inlet was not submerged. If the inlet is submerged and the culvert is flowing full, then it can be assumed that the water will experience different levels of frictional resistance. An increased amount of friction (in the case of full flow) would cause a slower velocity at the edges of the culvert and would therefore produce a different velocity and flow profile.

An additional assumption is made regarding the roughness of the pipe material being utilized. For example, a culvert pipe made of PVC is much smoother than one made of concrete. Although the coefficient of roughness for most materials is tabulated, there is still some debate concerning which would be more valid for particular situations. For the purpose of this project, this means that this value must sometimes be assumed, and can consequently cause a noticeable difference in the characteristics of the culvert.

Another important assumption is whether or not the proposed culvert, as in Wilders Dike, would have a free outfall on either side. This is an important assumption to make because it affects the area around the point of discharge. In other words, it is possible that if the culvert is not placed at the elevation of the channel bottom, the discharge could cause erosion in the area of the free fall.

It is important to know whether or not the culvert has a slope or if it is simply horizontal. If there is a vertical slope, the water will flow through the culvert with a greater velocity than if the slope was horizontal. This could affect the amount of turbulence the flow experiences as well as adding to the amount of erosion that could take place on the discharge side

All of these assumptions contribute to the behavior of the flow through the culvert and thus must be taken into account. There are other assumptions which must be taken into account, but the ones mentioned above were the ones that were focused upon while evaluating Wilders Dike as discussed in section 5.3.

5.2.2 Pamet System Dikes

The Pamet system includes a variety of culverts which allow for the transport of water. This report focuses on Wilders Dike especially, but the others in the system include the Route 6 culvert as well as the culvert that was present in the railroad dike at the Mill Pond region. While it is obviously not necessary to examine the broken railroad dike culvert, it would be essential to examine the culvert under the nearby Mill Pond Road. Although the Route 6 culvert was not taken into consideration during this report, it would also be important to perform an analysis of that region. Alterations in the Route 6 culvert would affect the flow and hydraulics of the rest of the estuary, especially around the area of Wilders Dike due to its proximity to Route 6.

5.2.3 Design Considerations

When redesigning Wilders Dike, two culvert designs were considered. The first one was the round culvert. Although there were different concerns with the utilization of the round culvert (see Section 5.3), the basic design relationships remained the same. For the purpose of this project, a conservative design was used. The pipe was considered to be flowing full, and the upstream head was based on high tide values. This provided estimates for determining flow rates through a round culvert by utilizing the following equation:

$$\frac{H}{D}-\frac{1}{2}+\frac{Z}{D}=\frac{8}{\pi^2 g}\left(1+K_e+\frac{fL}{D}\right)\left(\frac{Q}{D^{\frac{5}{2}}}\right)^2 \quad \textbf{(5-2)}$$

This equation, including all the variables, is discussed in detail in section 5.3.

The other culvert design that was performed was that of a box culvert. Although it requires a different analysis, most of the assumptions remain the same as for a round culvert. It was found that the box culvert could be analyzed using the following equation:

$$H-\frac{D}{2}=\left(1+K_e+f\left(\frac{L}{4R}\right)\right)\left(\frac{Q^2}{B^2D^2}\right)\frac{1}{2g} \quad \textbf{(5-4)}$$

This equation is used in the analysis section (Section 5.3) for the box culvert as well as the description of how this equation was generated.

Now that the general hydraulics of culverts and culvert design have been introduced, the different alternatives that were selected for redesigning Wilders Dike may be examined.

5.3 Preliminary Analysis of Alternatives

Each of the six alternatives described in Section 5.1.1 was analyzed in order to estimate the allowable flow past Wilders Dike. These analyses, including brief discussions on the consequences of each alternative, are summarized below.

Alternative 1: Leave Wilders Dike as is

The effects of the current design of Wilders Dike can be seen on a daily basis. These effects include the fact that the dike has effectively cut off the upper portion of the estuary and allowed for the transformation of salt water wetlands to fresh water wetlands. As a result, the tidal prism of the estuary has been considerably reduced, and flushing capabilities have been decreased.

Another important consideration involves Ballston Beach, which separates the Atlantic Ocean from the head of the Pamet. This barrier has been breached several times during storms. Due to the clapper valve at Wilders Dike, this new volume of salt water can be trapped upstream. As a result, flooding can occur in the upstream portions of the river. While estimating the volume and frequency of flooding is beyond the scope of this project, flooding associated with the recent overwash clearly shows that this is of concern. The dike presently provides only limited capacity to release any salt water which could accumulate due to an overwash.

Alternative 2: Total Removal of Wilders Dike

If Wilders Dike is totally removed, the maximum flow passing through the remaining area would be of interest. The maximum flow, assuming removal of Wilders dike, at Station 2 can be estimated by obtaining the appropriate values of velocity (V) and cross-section area (A) from the existing numerical model described in chapter 4. These values can be used to determine the flow (Q, L^3/t) at any given time through the use of the following equation.

$$Q = VA \qquad \textbf{(5-1)}$$

The model was run with branch 5 consisting of the full 46 nodes, in order to obtain the appropriate values assuming that Wilders Dike was removed. Spring tide conditions were chosen so that maximum values of V, and S(x,t) could be obtained.

As illustrated in Figure 5.8, the cross-sectional area described by the numerical model consists of a momentum carrying channel, and two non-momentum carrying channels. For flow calculating purposes, it is necessary to consider both the area of the momentum carrying channel, and that of the non-momentum carrying channel. The shape of the momentum carrying channel during high tides at Wilders Dike (Node 5,23) consists of a trapezoid of constant area, on top of which lies a rectangle with a variable area that is a function of S(x,t) at any given time. The area of the non-momentum channel is equal to the sum of two triangles located on both sides of the rectangle. During lower tides, the area of the momentum carrying channel consists of only the varying trapezoidal area as a function of S(x,t). At this time, the non-momentum carrying channel area is equal to zero.

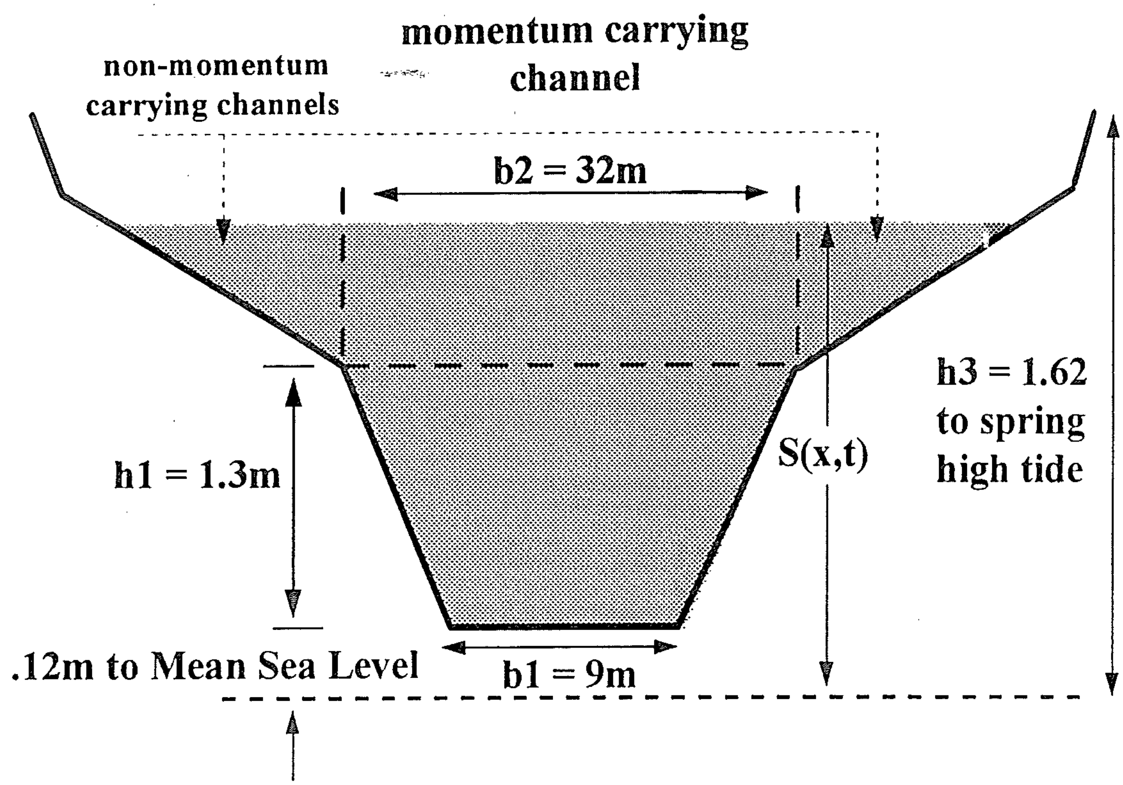


Figure 5.8 : Model cross section at Wilders Dike (5,23)

When obtaining S(x,t) from the model, it is important to note that all measurements are in reference to Mean Sea Level. In the Case of Node 5,23, the distance between the channel bottom elevation and Mean Sea Level was measured to be .12m. If .12m is subtracted from each S(x,t) value, the correct value of S(x,t) in reference to the channel bottom can be obtained. This process of calculating flow was made less cumbersome through the use of a spreadsheet (shown in Appendix D): When all of the higher tide flow rates are calculated, maximum values could be picked. The maximum values of V and S(x,t) were then substituted into Equation 5-1, and the maximum flow

$9m \times \frac{100cm}{m} \times \frac{1in}{2.54cm} \times \frac{ft}{12in} = 29.5'$

(Q_{max}) was determined. The maximum values obtained through the above analysis are presented in Table 5.1.

Table 5.1: Maximum design values for alternative 2

Maximum Velocity, V_{max}, m/s	*Maximum Area, A_{max}, m^2*	*Maximum Design Flow, Q_{max}, m^3/s*
0.33	**32.4**	**10.7**

This alternative allows for a significant amount of flow past Wilders Dike at a reasonable velocity, and would result in the estuary taking on characteristics similar to those of its natural state. However, the values obtained through this process may differ from actual conditions. Through a comparison of channel characteristics directly west of Wilders Dike and channel characteristics at node 5,23 of the model, it was determined that the model's representation of the channel is somewhat larger than that of the area directly adjacent to the west side of Wilders Dike (refer to Section 4.3.6). This discrepancy could exist because node 5,23 is not located directly adjacent to Wilders Dike. Instead, it is located further west (closer to the harbor) than the measured cross section at Wilders Dike. If the available cross section was actually smaller than that assumed by the model, then the model output may predict larger flowrates and smaller velocities than realistically obtained through the removal of the Dike. It is recommended that additional measurements be taken to further address this concern.

Effects of the implementation of this design on the surrounding area cannot be overlooked. Since the time of the Dike's construction in 1869, many parcels of land, including the small public park across from the general store in Truro Center have been developed on what was originally salt marsh. Due to this tremendous increase in volume, it is unavoidable that some land will be reclaimed by the estuary. By performing a rough survey of the park and the immediate surrounding area of Wilders Dike, an estimate was obtained for the determining the reclaimed area if the dike were removed. The extent of this new water line can be seen in Figure 5.9. In order to obtain this estimate, it was assumed that the water would rise to the same elevation east of Wilders Dike as it presently does on the west side of Wilders Dike.

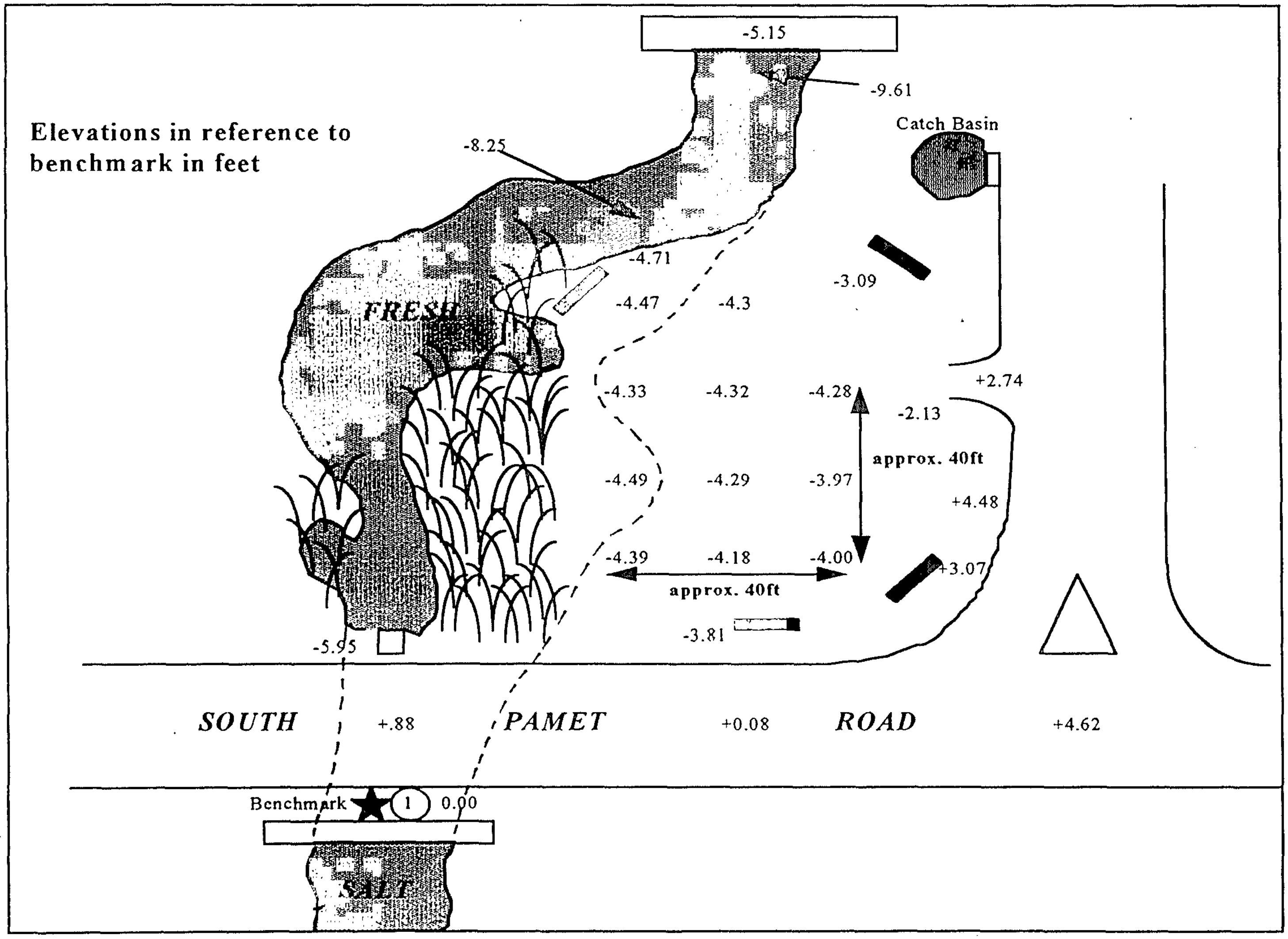


Figure 5.9: Estimated water line before and after removal of Wilders Dike

Alternative 3: Removal of Clapper Valve from Existing Dike

The analysis of Alternative 3 involved estimating how much flow will be allowed by the present culvert if the clapper valve was to be removed. In order to determine the maximum design flow, Q, that the existing culvert can allow, it was necessary to obtain the maximum head above the culvert bottom. This value was obtained by surveying Wilders Dike. It was determined that the maximum head above the culvert bottom on 10/02/94 was 4.56ft. Although the highest head observed was 4.56ft, in order to account for spring tide, it was estimated that the maximum head could reach up to 5ft above the culvert bottom. This estimate is based on the observance of spring tide conditions on 12/4/94 (see Appendix E, 1994 High & Low Water-Boston Mass.). On this day, the tide rose approximately 5 inches higher than on 12/3/94 and subsequently the maximum head was calculated to be approximately 5ft.

Assumed characteristics of the Wilders Dike culvert include a submerged inlet, a free outlet, and a horizontal slope. These characteristics allow for the use of the following equation.

$$\frac{H}{D}-\frac{1}{2}+\frac{Z}{D}=\frac{8}{\pi^2 g}\left(1+K_e+\frac{fL}{D}\right)\left(\frac{Q}{D^{\frac{5}{2}}}\right)^2 \qquad \textbf{(5-2)}$$

Where:
H = Head(ft)
D = Culvert Diameter(ft) = 3.5ft
Z = vertical drop in culvert length, L = 0 for horizontal slope
K_e = entrance loss coefficient = .5
L = culvert length = 56ft
f = friction loss coefficient for full flow = .02

Figure 5.10 shows the general schematic of Alternative 3 including the removal of the existing clapper valve. Utilizing Equation 5-2, it was determined that the existing culvert dimensions will allow for a maximum flow (Q_{max}) of 103.12ft^3/s, and a velocity (V) of 9.37ft/s when the head above the culvert bottom is equal to 5ft.

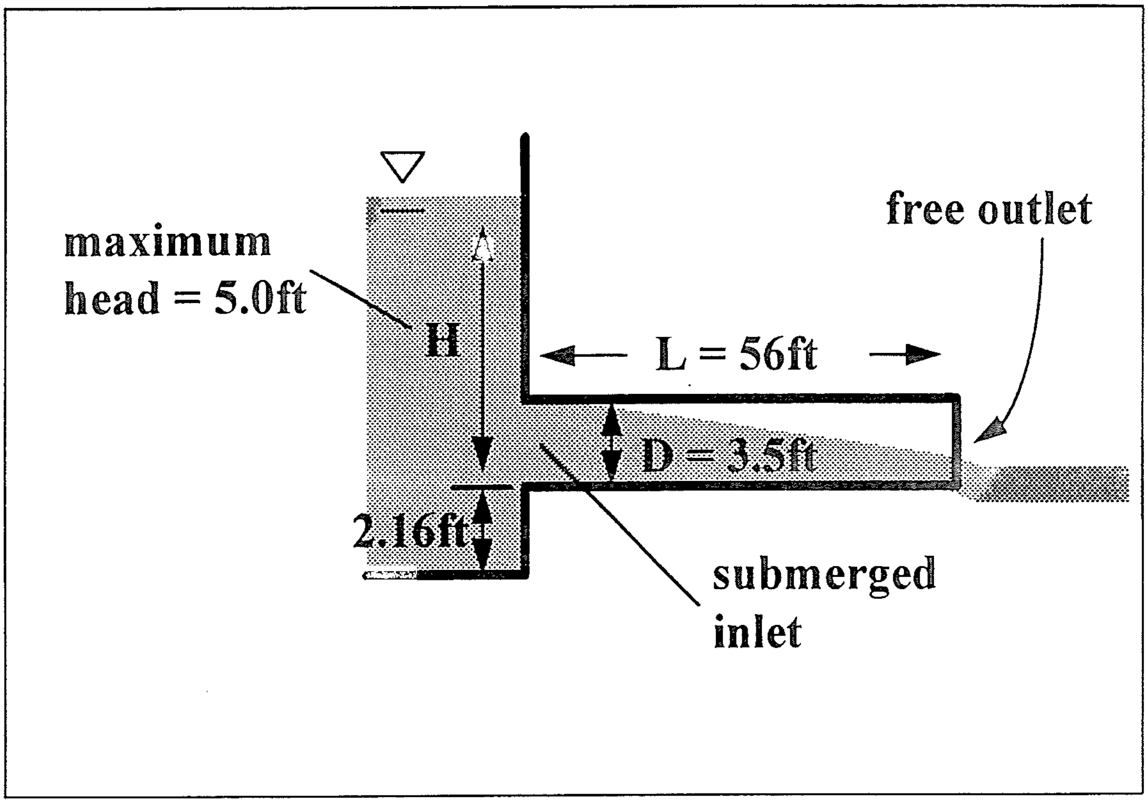


Figure 5.10: Alternative 3, submerged inlet with maximum head equal to 5ft.

This flow is considerably less than that achieved through Alternative 2 (Total Removal of Wilders Dike). Velocity is approximately ten times the velocity obtained through Alternative 2. A velocity of 9.37 is generally considered to be too high in recreational areas such as Wilders Dike. This high velocity may be a potential danger to canoeists and fisherman, and might also result in erosion in the immediate area.

Alternative 4: Clapper Valve Removal in Conjunction with Enlarged Culvert

The amount of flow allowed by an enlarged culvert will increase with diameter (D). Several diameters larger than that of the existing culvert were chosen, and then plugged into Equation 5-2. Equation 5-2 was simplified into equation 5-3 in order to make spreadsheet calculations more convenient. The corresponding flow rates were then solved for.

$$Q = \sqrt{\frac{HD^4 - \frac{1}{2}D^5}{\frac{8}{\Pi^2 g}\left(1 + Ke + \frac{fl}{D}\right)}} \quad \textbf{(5-3)}$$

Since equation Eq. 5-3 can only be applied in the case of a submerged inlet, the chosen diameter could not exceed 5ft, the maximum head above the culvert bottom. Table 5.2 presents the corresponding Q and V values of various culvert diameters.

Table 5.2: Varying culvert diameters using Eq. 5-3

Head(ft)	*Culvert Diameter*(ft)	*Flow(Q)*(ft^3/s)	*Velocity(V)*(ft/s)
5	3.5	103.12	9.38
5	3.6	108.52	9.60
5	3.8	119.55	10.01
5	4.0.	130.85	10.41
5	4.2	142.37	10.79
5	4.4	154.06	11.15
5	4.6	165.88	11.48
5	4.8	177.76	11.79
5	5.0	189.64	12.07

When designing concrete culverts, it is generally excepted that velocities below 10ft/s are safe. However, velocities near 10ft/s are considered high in recreational areas. As shown in table 5.2, culvert diameters above approximately 3.8ft result in velocities above 10ft/s. This may result in culvert damage or excessive erosion, and a possible hazard to people in recreational areas. It should also be noted that as culvert diameters near 5ft, the design head above culvert, drawdown will result in a case where the culvert is no longer submerged. In this case, equation 5-3 is no longer valid.

Alternative 5: Multiple Culverts

A detailed analysis was not performed on this alternative. However, it is assumed that adding an additional culvert with the same dimensions as that of the existing culvert will allow for double the original flow. This new flow of approximately 200cfs is still considerable less than allowed in Alternative 2 (Total Removal of Wilders Dike). In addition velocities would be approximately 9ft/s, which is too high in recreational areas such as Wilders Dike. However, the implementation of this alternative may be advantageous due to the limited ground cover at Wilders Dike.

Alternative 6: Box Culvert

In order to estimate the amount of flow allowed through a box culvert, Equation 5-2 was altered in such a manner as to incorporate a rectangular cross sectional area rather than a circle. This was accomplished by substituting 4(R), where R is equal to the hydraulic radius of the box culvert, for D (diameter of a circle). The hydraulic radius (R) is obtained by dividing the product of the base and height by two times the sum of the base and height. This yields the following equation:

$$H - \frac{D}{2} = \left(1 + K_e + f\left(\frac{L}{4R}\right)\right)\left(\frac{Q^2}{B^2 D^2}\right)\frac{1}{2g} \qquad \textbf{(5-4)}$$

Where:
H = Head (ft)
B = *Culvert base* (ft)
D = Culvert height (ft)
Z = vertical drop in culvert length, L = 0 for horizontal slope
K_e = entrance loss coefficient = .5
L = culvert length = 56ft
f = friction loss coefficient for full flow = .02

A culvert base of six feet was chosen in order to maximize the cross sectional area of the culvert, while keeping in mind that wider rectangular culverts allow for less overhead support than do narrow culverts. A height of 4.25ft was chosen on the basis that heights near 5ft, the maximum head above the culvert bottom, allow for a drawdown condition, therefore rendering Equation 5-4 invalid.

A culvert base of 6ft and a height of 4.25ft will allow for approximately 150cfs and a velocity of 9.8 ft/s. The box culvert is the most efficient single culvert design in terms of flow. However resulting velocity is still to high for a recreational area such as Wilders dike.

5.4 Summary of Analysis

Table 5.3 presents a summary of the preliminary design results. According to this analysis, total removal of Wilders Dike (Alternative 2) and replacing the existing culvert with a box culvert (Alternative 5) allow for the two highest flowrates. However, it is important to note that further analysis is necessary to verify whether the flow and velocity values obtained for the total removal of Wilders Dike would match field conditions. In addition, it has been determined that the addition of any type of culvert, including Alternative 5 (box culvert), will result in velocities much too high for a recreational area such as Wilders Dike.

Table 5.3: Summary of Preliminary Analysis Results.

Alternative	Maximum Flow, Q_{max} cfs	Maximum Velocity, V_{max} f/s
2) Total Removal of Wilders Dike	377.6	1.1
3)Removal of Clapper Valve	103	9.4
4) Enlarged Culvert (4ft Diameter)	131	10.4
5) Multiple Culverts	103 per culvert	9.4 per culvert
6) Box Culvert	150	9.0

6 CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER STUDY

6.1 Conclusions

The objective of this project was to evaluation the impacts of dike construction on the Pamet River Estuary in Truro, MA and develop a preliminary design for the modification of channel characteristics in an attempt to maintain or at improve the water quality in the Pamet River. Analyses of water quality and hydraulic characteristics were used to meet this objective.

First, water quality testing was performed to examine the present water quality and compare the results with past water quality in an attempt to determine whether improvement was necessary. Ammonia, nitrate, nitrite, and pH were estimated using a HACH Saltwater Master Kit which was taken out into the field. Fecal and total coliform were determined from laboratory analyses of samples taken back to a laboratory at Worcester Polytechnic Instititute. Water quality measurements were taken during dry weather and wet weather conditions. In addition, the measurements were taken at different times during the tidal cycle to better define the variation of water quality for different tidal conditions.

Results of the tests indicate that the water quality of the Pamet River in the winter months is similar to that of previous years and has not changed substantially. Low concentrations for nitrogen compounds confirmed that nitrogen is not presently a significant problem in the Pamet River.Fecal and total coliform were found to exceed criteria for shellfishing during dry and wet weather, and total coliform counts were found to be somewhat higher during wet weather. Water quality measurements also showed that salt water leaks through Wilder's Dike and that salinity stratification exists at in the vicinity of Wilder's Dike at high tide conditions. It is noted that these measurements were completed in relatively cold conditions (in December and January) and represent Winter conditions. It is likely that the coliform counts and nutrient concentrations would be higher during summer conditions. Therefore, it is likely that criteria would be exceeded during summer conditions as well. It is also noted that wet weather data was limited to total coliform. Additional wet weather measurements over a tidal cycle are recommended to better define the water quality in the Pamet River.

In addition to water quality measurements, tidal measurments were obtained and used to verify the accuracy of a previously completed hydraulic model of the estuary. Flow analysis was performed to check the current hydraulics of the Pamet River and to determine if a mathematical computer model could be used. The model was developed by Giese et al in 1989, but due to alterations in channel characteristics in the estuary, the model required validation before it could be used. Specific methods for validating the model were presented in Chapter 4. Through these methods, it was shown that the model provided an adequate representation of the estuary. Therefore, the model could be used to estimate flowrates which would provide general guidelines for developing preliminary design alternatives for modifications to Wilders Dike.

The preliminary alternative designs were developed for allowing flow past Wilder's Dike. Allowing tidal flow past Wilder's Dike would increase the tidal prism and increase tidal flushing in the vicinity of Wilder's Dike. The preliminary designs were developed using estimated flows from the model along with standard hydraulic equations for culverts.

Five alternatives include no change to Wilder's Dike, complete removal of the dike, use of the existing culvert with removal of the clapper valve, use of one or more enlarged circular culverts, and use of a box culvert.These alternatives are described and evaluated in Chapter 5. Of the three alternatives making use of a culvert, the box culvert would most likely be the optimum design. This culvert would allow for the most flow to pass by Wilder's Dike, consequently increasing the tidal prism from its present state. As noted above, it is anticipated that the increased prism would have the ability to transport a greater amount of contamination (eg as indicated by fecal and total coliform) out of the estuary. However, it is noted that the velocity estimated for the box culvert at maximum flow conditions is quite high, which could pose a hazard for recreational use in the vicinity of the culvert. Therefore, while use of a culvert is a cheaper alternative, use of a bridge (full removal of the dike) would be a preferred alternative is funds are available.

6.2 Recommendations for Future Study

Although this project did involve somewhat rigorous analysis of water quality, hydraulics and culvert design in an estuary, the corresponding results can only be used as a preliminary assessment of dike construction in the Pamet River. There are several areas which require further research in order to develop a complete assessment. First, the culvert under Route 6 should be investigated for redesign in order to allow for increased flow into the upper Pamet. Second, more water quality data should be obtained to better understand the water quality characteristics in dry and wet weather, as well as in warm conditions in the summer. Third, a more detailed analysis of the flow conditions in the vicinity of Wilder's Dike are necessary. Channel characteristics near Wilder's Dike which would exist upon removal of the dike should be more accurately defined in the future. Also, a more accurate culvert flow model (such as the HEC2 Model) should be used to characterize flow in the region. This more accurate model would also require more accurate information on the topography in the Upper Pamet Basin. Finally, it is noted that the use of a flow control device should be investigated to control velocities near the Dike and to allow for slow introduction of tidal flow into the Upper Pamet Region.

Appendix.A

Ammonia Test Procedures

1. Rinse and fill the test cube with water from sample up to the indicated mark
2. Empty one Ammonia Reagent No. 1 Powder Pillow into cube
3. Invert the cube several times to mix
4. Empty one Ammonia Reagent No. 2 Powder Pillow into cube
5. Shake for one minute
6. Match the color of sample to the closest color on cube

Nitrate Test Procedures

1. Rinse and fill the test cube with water from sample up to the indicated mark
2. Empty one Nitrate Low Range Reagent Powder Pillow into cube
3. Invert for one and one-half minutes to mix
4. Empty one Nitrite Reagent Powder Pillow into cube
5. Invert the cube for 30 seconds
6. Wait five minutes, then match sample to closest color on cube

Nitrite Test Procedures

1. Rinse and fill the test cube with water form sample up to the indicated mark
2. Empty one Nitrite Reagent Powder Pillow into cube
3. Shake cube for one minute
4. Wait ten minutes, then match sample to the closest color on cube

pH Test Procedures

1. Rinse and fill the test cube with water from sample up to the indicated mark
2. Empty one pH High Range Indicator Powder Pillow into cube
3. Shake to mix
4. Match the sample to the closest color on cube

Appendix B

Total Coliform Test Procedures

1. Autoclave the filtering apparatus (membrane filter, filter holder, filter flask, and aspirator) along with 50 ml graduated cylinders, and beakers
2. Clean the counter top with a 90% ethanol solution
3. Wash hands with a 70% ethanol solution
4. Set up the Membrane Filter Assembly
5. Using forceps, place one absorbent pad in a sterile petri dish and label
6. Empty the contents of one m-Endo medium onto the pad, replace the lid
7. Using sterile forceps, place one membrane filter (grid side up) onto the assembly
8. Mix the sample, pour 50 ml through the assembly
9. Rinse through with distilled water
10. Turn off the vacuum
11. Using sterile forceps, remove the filter from the assembly, and place grid side up in petri dish
12. Be sure the filter touches the pad completely, and no air bubbles are trapped beneath it
13. Invert the petri dish and incubate at 35 +/- 5 degrees C for 48 hours
14. After filtering each sample, boil the apparatus for at least 20 min. and repeat
15. Confirm the samples
    1. Sterilize an inoculating needle by heating to red hot in a Bunsen burner
    2. Let needle cool, touch it to the sheen colony and transfer to a single-strength Lauryl Tryptose Broth Tube
    3. Touch the needle to the same colony and transfer to a Brilliant Green Bile Broth Tube
    4. Invert both tubes and place in an incubator at 35 +/- .5 degrees C
    5. If gas bubbles appear in one hour, invert tubes to remove them
    6. After 24 +/- 2 hours, gas bubbles in both tubes confirms the colony
    7. If no gas is found in the Lauryl Tryptose, the colony is not a coliform
    8. If gas is found in the Lauryl Tryptose only, inoculate another BGB and check after 24 hours

Fecal Coliform Test Procedures

1. Autoclave the filtering apparatus (membrane filter, filter holder, filter flask, and aspirator) along with 50 ml graduated cylinders, and beakers
2. Clean the counter top with a 90% ethanol solution
3. Wash hands with a 70% ethanol solution
4. Set up the Membrane Filter Assembly
5. Using forceps, place one absorbent pad in a sterile petri dish and label
6. Empty the contents of one m-FC medium onto the pad, replace the lid
7. Using sterile forceps, place one membrane filter (grid side up) onto the assembly
8. Mix the sample, pour 50 ml through the assembly
9. Rinse through with distilled water
10. Turn off the vacuum
11. Using sterile forceps, remove the filter from the assembly, and place grid side up in petri dish
12. Be sure the filter touches the pad completely, and no air bubbles are trapped beneath it
13. Invert the petri dish and incubate at 44.5 +/- 5 degrees C for 24 hours
14. After filtering each sample, boil the apparatus for at least 20 min. and repeat
15. Confirm the samples
    1. Sterilize one inoculating needle to red hot in a Bunsen burner
    2. Let needle cool, touch to a typical blue colony and transfer to a Lauryl Tryptose broth tube
    3. Invert the tube and incubate for 48 +/- 3 hours at 35 +/- degrees C
    4. If gas is not produced, the colony was not fecal coliform
    5. If gas is produced, use a sterile loop to inoculate one EC Medium Broth tube from each gas positive tube
    6. Incubate the EC Medium tubes at 44.5 +/- .2 degrees C for 24 +/- 2 hours
    7. Any gas confirms the presence of fecal coliforms

Appendix C

Model Flow Data (23 Nodes - Mean High Tide) (Branch, Node)*							
Flow (m^3/s)	Flow (m^3/s)	Flow (m^3/s)	Flow (m^3/s)	Elevation (cm)	Elevation (cm)	Elevation (cm)	Elevation (cm)
*(5,1)	(5,12)	(5,18)	(5,23)	*(5,1)	(5,12)	(5,18)	(5,23)
27.403	12.362	6.284	0	177.662	176.341	174.377	174.079
20.375	10.881	5.727	0	177.857	177.574	176.225	176.078
11.098	8.814	4.901	0	177.581	178.46	177.831	177.859
-2.058	5.909	3.714	0	176.688	178.888	179.095	179.326
-16.858	1.494	1.969	0	175.448	178.641	179.86	180.34
-26.777	-5.437	-0.943	0	174.03	177.419	179.811	180.679
-32.305	-10.23	-4.784	0	172.388	175.978	178.59	179.889
-36.229	-11.94	-6.234	0	170.535	174.533	176.968	177.866
-39.036	-12.219	-5.913	0	168.582	172.967	175.196	175.742
-41.149	-12.059	-5.442	0	166.483	171.229	173.347	173.936
-43.003	-11.81	-5.299	0	164.208	169.389	171.578	172.183
-44.67	-11.856	-5.256	0	161.775	167.502	169.827	170.472
-46.304	-12.078	-5.281	0	159.181	165.546	168.068	168.762
-48.009	-12.37	-5.368	0	156.405	163.514	166.274	167.04
-49.587	-12.731	-5.493	0	153.405	161.394	164.437	165.282
-50.88	-13.484	-5.627	0	150.144	158.968	162.553	163.482
-51.762	-14.168	-5.973	0	146.586	156.245	160.481	161.636
-52.164	-14.862	-6.413	0	142.657	153.128	158.105	159.561
-52.073	-15.587	-6.808	0	138.205	149.446	155.358	157.02
-49.923	-16.483	-7.148	0	133.314	144.774	151.998	153.981
-46.334	-15.936	-7.655	0	127.977	138.963	147.494	150.05
-43.129	-14.59	-7.243	0	122.101	133.242	140.603	143.688
-41.259	-12.936	-4.952	0	115.904	127.055	132.868	133.448
-39.053	-11.176	-3.995	0	109.748	120.622	125.45	126.736
-36.619	-10.269	-3.597	0	103.629	114.377	119.078	120.505
-34.505	-9.442	-3.33	0	97.43	108.349	113.116	114.615
-32.672	-8.794	-3.072	0	91.285	102.519	107.43	108.918
-31.147	-8.237	-2.847	0	85.165	96.831	101.955	103.513
-29.753	-7.75	-2.663	0	79.084	91.27	96.643	98.299
-28.396	-7.316	-2.496	0	73.062	85.823	91.484	93.259
-27.1	-6.907	-2.345	0	67.094	80.484	86.464	88.369
-25.841	-6.517	-2.202	0	61.186	75.255	81.581	83.621
-24.643	-6.143	-2.064	0	55.352	70.135	76.833	79.016
-23.456	-5.782	-1.933	0	49.594	65.123	72.221	74.555
-22.29	-5.433	-1.806	0	43.919	60.221	67.745	70.24

-21.149	-5.096	-1.685	0	38.331	55.433	63.405	66.075			
-20.035	-4.772	-1.568	0	32.838	50.764	59.205	62.065			
-18.95	-4.46	-1.457	0	27.444	46.217	55.147	58.211			
-17.897	-4.161	-1.351	0	22.153	41.795	51.234	54.518			
-16.879	-3.875	-1.25	0	16.967	37.5	47.466	50.988			
-15.897	-3.602	-1.154	0	11.889	33.337	43.846	47.623			
-14.954	-3.342	-1.063	0	6.921	29.305	40.374	44.426			
-14.049	-3.096	-0.977	0	2.063	25.406	37.051	41.397			
-13.184	-2.863	-0.896	0	-2.685	21.642	33.875	38.539			
-12.355	-2.643	-0.82	0	-7.317	18.012	30.847	35.852			
-11.563	-2.435	-0.749	0	-11.831	14.516	27.964	33.335			
-10.791	-2.241	-0.683	0	-16.198	11.155	25.224	30.989			
-10.071	-2.058	-0.621	0	-20.431	7.926	22.624	28.814			
-9.392	-1.887	-0.564	0	-24.543	4.83	20.162	26.808			
-8.754	-1.728	-0.51	0	-28.534	1.866	17.832	24.97			
-8.16	-1.58	-0.461	0	-32.417	-0.969	15.632	23.3			
-7.604	-1.442	-0.416	0	-36.197	-3.677	13.556	22			
-7.091	-1.315	-0.374	0	-39.891	-6.262	11.6	22			
-6.627	-1.196	-0.337	0	-43.541	-8.726	9.765	22			
-6.201	-1.087	-0.305	0	-47.17	-11.074	8.081	22			
-5.801	-0.986	-0.278	0	-50.771	-13.308	6.568	22			
-5.413	-0.894	-0.254	0	-54.303	-15.433	5.208	22			
-5.051	-0.809	-0.233	0	-57.766	-17.452	3.982	22			
-4.704	-0.73	-0.214	0	-61.12	-19.369	2.875	22			
-4.361	-0.658	-0.198	0	-64.284	-21.187	1.877	22			
-4.002	-0.592	-0.183	0	-67.063	-22.913	0.978	22			
-3.666	-0.531	-0.17	0	-69.452	-24.548	0.171	22			
-3.343	-0.475	-0.159	0	-71.399	-26.099	-0.551	22			
-3.029	-0.423	-0.149	0	-72.861	-27.567	-1.194	22			
-2.716	-0.375	-0.141	0	-73.805	-28.956	-1.752	22			
-2.395	-0.331	-0.134	0	-74.218	-30.266	-2.218	22			
-2.061	-0.291	-0.129	0	-74.114	-31.498	-2.608	22			
-1.714	-0.254	-0.124	0	-73.53	-32.651	-2.936	22			
-1.373	-0.244	-0.124	0	-72.545	-33	-3	22			
-1.105	-0.244	-0.124	0	-71.352	-33	-3	22			
-0.986	-0.242	-0.124	0	-70.292	-33	-3	22			
-0.883	-0.239	-0.124	0	-69.375	-33	-3	22			
-0.815	-0.236	-0.125	0	-68.564	-33	-3	22			
-0.757	-0.233	-0.125	0	-67.843	-33	-3	22			
-0.709	-0.231	-0.125	0	-67.184	-33	-3	22			
-0.657	-0.23	-0.126	0	-66.568	-33	-3	22			

-0.621	-0.23	-0.127	0	-66	-33	-3	22			
-0.576	-0.237	-0.128	0	-65.474	-33	-3	22			
-0.542	-0.244	-0.129	0	-64.985	-33	-3	22			
-0.509	-0.251	-0.129	0	-64.541	-33	-3	22			
-0.482	-0.258	-0.13	0	-64.135	-33	-3	22			
-0.46	-0.264	-0.131	0	-63.773	-33	-3	22			
-0.441	-0.27	-0.132	0	-63.447	-33	-3	22			
-0.427	-0.275	-0.133	0	-63.158	-33	-2.992	22			
-0.414	-0.28	-0.134	0	-62.901	-33	-2.966	22			
-0.404	-0.284	-0.135	0	-62.671	-33	-2.932	22			
-0.395	-0.288	-0.136	0	-62.465	-33	-2.895	22			
-0.387	-0.288	-0.137	0	-62.278	-33	-2.862	22			
-0.38	-0.288	-0.137	0	-62.109	-33	-2.833	22			
-0.373	-0.288	-0.138	0	-61.955	-33	-2.811	22			
-0.374	-0.288	-0.138	0	-61.825	-33	-2.795	22			
-0.391	-0.288	-0.138	0	-61.746	-33	-2.784	22			
-0.424	-0.288	-0.138	0	-61.745	-33	-2.777	22			
-0.468	-0.288	-0.138	0	-61.843	-33	-2.773	22			
-0.561	-0.288	-0.138	0	-62.109	-33	-2.772	22			
-0.795	-0.288	-0.138	0	-62.817	-33	-2.772	22			
-1.084	-0.288	-0.138	0	-64.203	-33	-2.774	22			
-1.233	-0.288	-0.138	0	-66.055	-33	-2.776	22			
-1.126	-0.288	-0.138	0	-67.766	-33	-2.78	22			
-0.614	-0.288	-0.138	0	-68.346	-33	-2.784	22			
0.729	-0.288	-0.138	0	-66.244	-33	-2.788	22			
1.187	-0.288	-0.138	0	-62.441	-33	-2.792	22			
2.131	-0.288	-0.138	0	-58.321	-33	-2.796	22			
2.557	-0.288	-0.138	0	-53.564	-33	-2.8	22			
3.45	-0.288	-0.138	0	-48.257	-33	-2.803	22			
4.017	-0.288	-0.138	0	-42.991	-33	-2.804	22			
4.875	-0.288	-0.138	0	-37.405	-33	-2.804	22			
5.857	-0.288	-0.138	0	-31.442	-33	-2.802	22			
6.985	-0.288	-0.138	0	-25.205	-33	-2.799	22			
8.21	-0.288	-0.138	0	-18.701	-33	-2.797	22			
9.476	-0.282	-0.138	0	-12.056	-33	-2.797	22			
10.916	-0.246	-0.137	0	-5.287	-32.988	-2.801	22			
12.389	-0.196	-0.137	0	1.51	-31.771	-2.81	22			
14.063	0.059	-0.137	0	8.404	-28.227	-2.826	22			
15.831	0.505	-0.136	0	15.392	-23.08	-2.847	22			
17.735	0.901	-0.135	0	22.426	-16.973	-2.87	22			
19.734	1.415	-0.135	0	29.498	-9.805	-2.887	22			

21.833	2.073	-0.134	0	36.606	-1.567	-2.885	22			
24.007	2.771	-0.131	0	43.727	7.171	-2.756	22			
26.204	3.551	-0.113	0	50.844	16.219	-2.173	22			
28.383	4.419	-0.044	0	57.931	25.455	1.026	22			
30.539	5.328	0.284	0	64.971	34.681	7.013	22			
32.584	6.301	0.639	0	71.956	43.848	14.881	22			
34.497	7.323	1.154	0	78.875	52.912	24.223	22			
36.268	8.358	1.802	0	85.719	61.801	34.497	22			
37.887	9.406	2.482	0	92.477	70.495	44.698	22.7			
39.504	10.438	3.222	0	99.133	78.961	54.74	28.421			
40.987	11.448	4.002	0	105.674	87.182	64.587	39.963			
42.254	12.433	4.784	0	112.071	95.155	74.25	55.507			
43.237	13.359	5.475	0	118.293	102.875	83.89	70.912			
43.91	14.109	5.949	0	124.271	110.342	93.714	85.054			
43.623	14.581	6.164	0	129.839	117.603	103.76	98.185			
43.791	14.694	6.126	0	134.951	124.621	113.732	110.17			
44.188	14.336	5.866	0	139.63	131.079	123.226	120.937			
44.109	13.522	5.41	0	144.024	137.086	131.804	130.4			
43.363	12.36	4.841	0	148.134	142.677	139.337	138.538			
43.015	10.413	4.129	0	151.84	146.795	144.99	144.944			
43.614	9.883	3.68	0	155.181	150.16	148.268	147.986			
44.373	10.205	4.002	0	158.214	153.05	150.87	150.401			
45.283	10.905	4.436	0	160.998	155.667	153.223	152.734			
46.072	11.626	4.826	0	163.53	158.093	155.477	154.97			
46.645	12.241	5.187	0	165.86	160.389	157.633	157.089			
46.781	12.783	5.498	0	168.02	162.572	159.706	159.141			
46.39	13.493	5.773	0	170.038	164.796	161.703	161.142			
45.335	13.963	6.225	0	171.889	166.981	163.76	163.072			
43.541	14.242	6.57	0	173.546	169.104	165.865	165.179			
40.966	14.281	6.769	0	174.981	171.133	168.003	167.4			
37.549	14.03	6.771	0	176.166	173.03	170.165	169.63			
33.161	13.417	6.627	0	177.066	174.764	172.283	171.845			
27.654	12.411	6.301	0	177.645	176.286	174.299	173.996			
20.695	10.951	5.754	0	177.856	177.531	176.155	176.001			
11.533	8.911	4.94	0	177.603	178.432	177.772	177.793			
-1.453	6.048	3.77	0	176.732	178.881	179.052	179.275			
-16.34	1.718	2.055	0	175.501	178.669	179.842	180.311			
-26.49	-5.158	-0.79	0	174.09	177.479	179.836	180.683			
-32.12	-10.113	-4.663	0	172.46	176.035	178.653	179.95			
-36.095	-11.907	-6.225	0	170.611	174.593	177.035	177.957			
-38.938	-12.219	-5.935	0	168.663	173.033	175.27	175.82			

-41.072	-12.071	-5.455	0	166.57	171.302	173.419	174.007			
-42.932	-11.816	-5.301	0	164.302	169.463	171.648	172.252			
-44.606	-11.85	-5.257	0	161.875	167.578	169.897	170.54			
-46.234	-12.068	-5.278	0	159.289	165.626	168.14	168.831			
-47.943	-12.358	-5.364	0	156.521	163.597	166.347	167.11			
-49.527	-12.709	-5.488	0	153.53	161.484	164.511	165.354			
-50.835	-13.455	-5.62	0	150.28	159.07	162.63	163.555			
-51.736	-14.14	-5.953	0	146.735	156.361	160.571	161.711			
-52.157	-14.834	-6.397	0	142.823	153.262	158.206	159.654			
-52.094	-15.557	-6.793	0	138.395	149.609	155.478	157.129			
-50.053	-16.439	-7.133	0	133.519	144.993	152.149	154.117			
-46.47	-15.998	-7.629	0	128.201	139.179	147.713	150.235			
-43.25	-14.645	-7.358	0	122.349	133.48	140.879	144.059			
-41.347	-13.005	-5.043	0	116.151	127.309	133.192	133.673			
-39.153	-11.239	-4	0	109.994	120.884	125.704	126.965			
-36.712	-10.296	-3.601	0	103.878	114.621	119.32	120.738			
-34.582	-9.47	-3.336	0	97.678	108.584	113.347	114.844			
-32.74	-8.817	-3.08	0	91.532	102.75	107.653	109.139			
-31.206	-8.258	-2.855	0	85.409	97.056	102.172	103.726			
-29.809	-7.768	-2.67	0	79.327	91.491	96.853	98.505			
-28.449	-7.333	-2.503	0	73.302	86.04	91.688	93.458			
-27.151	-6.923	-2.351	0	67.332	80.696	86.663	88.563			
-25.889	-6.532	-2.207	0	61.422	75.462	81.774	83.809			
-24.691	-6.158	-2.07	0	55.585	70.338	77.021	79.198			
-23.503	-5.796	-1.938	0	49.824	65.322	72.403	74.731			
-22.337	-5.447	-1.811	0	44.145	60.416	67.922	70.41			
-21.195	-5.11	-1.69	0	38.554	55.623	63.577	66.239			
-20.079	-4.785	-1.573	0	33.057	50.949	59.371	62.223			
-18.993	-4.473	-1.461	0	27.658	46.397	55.307	58.363			
-17.939	-4.173	-1.355	0	22.363	41.97	51.388	54.663			
-16.919	-3.886	-1.254	0	17.173	37.67	47.614	51.126			
-15.936	-3.613	-1.157	0	12.091	33.501	43.988	47.755			
-14.991	-3.353	-1.066	0	7.118	29.464	40.51	44.551			
-14.084	-3.106	-0.98	0	2.256	25.56	37.181	41.516			
-13.218	-2.872	-0.899	0	-2.496	21.79	34	38.651			
-12.388	-2.651	-0.823	0	-7.134	18.155	30.966	35.956			
-11.594	-2.443	-0.752	0	-11.652	14.654	28.077	33.433			
-10.821	-2.248	-0.685	0	-16.025	11.287	25.331	31.08			
-10.099	-2.065	-0.623	0	-20.263	8.053	22.726	28.898			
-9.419	-1.894	-0.566	0	-24.38	4.952	20.258	26.885			
-8.779	-1.734	-0.512	0	-28.376	1.983	17.923	25.04			

-8.183	-1.586	-0.463	0	-32.263	-0.858	15.718	23.364		Graphing Points:	
-7.625	-1.448	-0.417	0	-36.047	-3.571	13.637	22		0	142.677
-7.11	-1.319	-0.376	0	-39.744	-6.16	11.676	22		5	146.795
-6.645	-1.201	-0.339	0	-43.395	-8.63	9.837	22		10	150.16
-6.218	-1.091	-0.306	0	-47.025	-10.982	8.145	22		15	153.05
-5.817	-0.99	-0.279	0	-50.628	-13.221	6.626	22		20	155.667
-5.428	-0.897	-0.255	0	-54.162	-15.35	5.26	22		25	158.093
-5.066	-0.812	-0.234	0	-57.628	-17.373	4.029	22		30	160.389
-4.717	-0.733	-0.215	0	-60.989	-19.294	2.918	22		35	162.572
-4.375	-0.661	-0.199	0	-64.164	-21.116	1.915	22		40	164.796
-4.016	-0.595	-0.184	0	-66.959	-22.845	1.012	22		45	166.981
-3.679	-0.534	-0.171	0	-69.365	-24.484	0.202	22		50	169.104
-3.356	-0.477	-0.159	0	-71.33	-26.038	-0.523	22		55	171.133
-3.042	-0.425	-0.149	0	-72.812	-27.51	-1.17	22		60	173.03
-2.728	-0.377	-0.141	0	-73.777	-28.902	-1.731	22		65	174.764
-2.408	-0.333	-0.134	0	-74.212	-30.215	-2.201	22		70	176.286
-2.075	-0.293	-0.129	0	-74.128	-31.45	-2.594	22		75	177.531
-1.729	-0.256	-0.124	0	-73.562	-32.606	-2.923	22		80	178.432
-1.387	-0.244	-0.124	0	-72.59	-33	-3	22		85	178.881
-1.112	-0.244	-0.124	0	-71.397	-33	-3	22		90	178.669
-0.988	-0.242	-0.124	0	-70.329	-33	-3	22		95	177.479
-0.888	-0.239	-0.124	0	-69.41	-33	-3	22		100	176.035
-0.818	-0.237	-0.125	0	-68.594	-33	-3	22		105	174.593
-0.76	-0.234	-0.125	0	-67.871	-33	-3	22		110	173.033
-0.712	-0.231	-0.125	0	-67.21	-33	-3	22		115	171.302
-0.659	-0.23	-0.126	0	-66.592	-33	-3	22		120	169.463
-0.622	-0.23	-0.127	0	-66.022	-33	-3	22		125	167.578
-0.577	-0.237	-0.128	0	-65.495	-33	-3	22		130	165.626
-0.543	-0.244	-0.128	0	-65.004	-33	-3	22		135	163.597
-0.51	-0.251	-0.129	0	-64.558	-33	-3	22		140	161.484
-0.483	-0.258	-0.13	0	-64.151	-33	-3	22		145	159.07
-0.461	-0.264	-0.131	0	-63.787	-33	-3	22		150	156.361
-0.442	-0.269	-0.132	0	-63.46	-33	-3	22		155	153.262
-0.427	-0.275	-0.133	0	-63.169	-33	-2.993	22		160	149.609
-0.415	-0.28	-0.134	0	-62.911	-33	-2.968	22		165	144.993
-0.405	-0.284	-0.135	0	-62.68	-33	-2.933	22		170	139.179
-0.396	-0.288	-0.136	0	-62.473	-33	-2.897	22		175	133.48
-0.387	-0.288	-0.137	0	-62.285	-33	-2.863	22		180	127.309
-0.38	-0.288	-0.137	0	-62.116	-33	-2.835	22		185	120.884
-0.373	-0.288	-0.138	0	-61.961	-33	-2.812	22		190	114.621
-0.374	-0.288	-0.138	0	-61.83	-33	-2.795	22		195	108.584

-0.39	-0.288	-0.138	0	-61.748	-33	-2.784	22		200	102.75
-0.423	-0.288	-0.138	0	-61.744	-33	-2.777	22		205	97.056
-0.466	-0.288	-0.138	0	-61.837	-33	-2.773	22		210	91.491
-0.555	-0.288	-0.138	0	-62.092	-33	-2.772	22		215	86.04
-0.783	-0.288	-0.138	0	-62.776	-33	-2.772	22		220	80.696
-1.074	-0.288	-0.138	0	-64.135	-33	-2.774	22		225	75.462
-1.231	-0.288	-0.138	0	-65.978	-33	-2.776	22		230	70.338
-1.136	-0.288	-0.138	0	-67.711	-33	-2.78	22		235	65.322
-0.649	-0.288	-0.138	0	-68.366	-33	-2.783	22		240	60.416
0.733	-0.288	-0.138	0	-66.364	-33	-2.787	22		245	55.623
1.158	-0.288	-0.138	0	-62.595	-33	-2.792	22		250	50.949
2.117	-0.288	-0.138	0	-58.5	-33	-2.796	22		255	46.397
2.533	-0.288	-0.138	0	-53.763	-33	-2.8	22		260	41.97
3.417	-0.288	-0.138	0	-48.473	-33	-2.803	22		265	37.67
3.988	-0.288	-0.138	0	-43.205	-33	-2.804	22		270	33.501
4.84	-0.288	-0.138	0	-37.638	-33	-2.804	22		275	29.464
5.815	-0.288	-0.138	0	-31.686	-33	-2.802	22		280	25.56
6.937	-0.288	-0.138	0	-25.461	-33	-2.799	22		285	21.79
8.16	-0.288	-0.138	0	-18.966	-33	-2.797	22		290	18.155
9.421	-0.283	-0.138	0	-12.325	-33	-2.797	22		295	14.654
10.857	-0.248	-0.138	0	-5.56	-32.993	-2.8	22		300	11.287
12.328	-0.199	-0.137	0	1.238	-31.878	-2.809	22		305	8.053
13.993	0.033	-0.137	0	8.125	-28.4	-2.825	22		310	4.952
15.757	0.491	-0.136	0	15.111	-23.314	-2.846	22		315	1.983
17.656	0.883	-0.135	0	22.143	-17.232	-2.87	22		320	-0.858
19.651	1.39	-0.135	0	29.214	-10.117	-2.886	22		325	-3.571
21.747	2.046	-0.134	0	36.32	-1.91	-2.886	22		330	-6.16
23.919	2.742	-0.131	0	43.441	6.814	-2.766	22		335	-8.63
26.116	3.518	-0.114	0	50.559	15.851	-2.225	22		340	-10.982
28.296	4.384	-0.051	0	57.647	25.084	0.843	22		345	-13.221
30.453	5.291	0.272	0	64.69	34.312	6.722	22		350	-15.35
32.505	6.261	0.623	0	71.677	43.482	14.542	22		355	-17.373
34.423	7.282	1.13	0	78.599	52.551	23.822	22		360	-19.294
36.2	8.317	1.775	0	85.446	61.448	34.082	22		365	-21.116
37.825	9.364	2.454	0	92.207	70.15	44.293	22.578		370	-22.845
39.441	10.397	3.192	0	98.868	78.626	54.34	28.084		375	-24.484
40.932	11.408	3.97	0	105.414	86.857	64.196	39.396		380	-26.038
42.208	12.395	4.753	0	111.817	94.84	73.864	54.864		385	-27.51
43.205	13.323	5.451	0	118.049	102.57	83.501	70.322		390	-28.902
43.889	14.087	5.935	0	124.036	110.047	93.314	84.505		395	-30.215
43.643	14.567	6.161	0	129.624	117.316	103.356	97.679		400	-31.45

43.756	14.7	6.132	0	134.757	124.348	113.338	109.713		405	-32.606
44.185	14.358	5.881	0	139.447	130.83	122.86	120.529		410	-33
44.131	13.561	5.431	0	143.855	136.853	131.479	130.047		415	-33
43.414	12.432	4.865	0	147.977	142.472	139.056	138.237		420	-33
43.002	10.456	4.156	0	151.699	146.644	144.833	144.768		425	-33
43.586	9.879	3.681	0	155.053	150.036	148.15	147.877		430	-33
44.34	10.184	3.985	0	158.097	152.939	150.773	150.303		435	-33
45.249	10.874	4.419	0	160.892	155.566	153.131	152.647		440	-33
46.047	11.598	4.811	0	163.433	157.998	155.388	154.884		445	-33
46.633	12.218	5.175	0	165.77	160.299	157.548	157.002		450	-33
46.785	12.756	5.486	0	167.936	162.484	159.624	159.06		455	-33
46.416	13.469	5.761	0	169.96	164.707	161.624	161.064		460	-33
45.389	13.948	6.207	0	171.819	166.894	163.676	162.992		465	-33
43.626	14.235	6.558	0	173.484	169.02	165.78	165.09		470	-33
41.083	14.285	6.765	0	174.929	171.054	167.917	167.312		475	-33
37.702	14.046	6.774	0	176.125	172.957	170.079	169.54		480	-33
33.356	13.449	6.636	0	177.036	174.698	172.2	171.757		485	-33
27.899	12.459	6.318	0	177.63	176.229	174.22	173.912		490	-33
									495	-33
									500	-33
									505	-33
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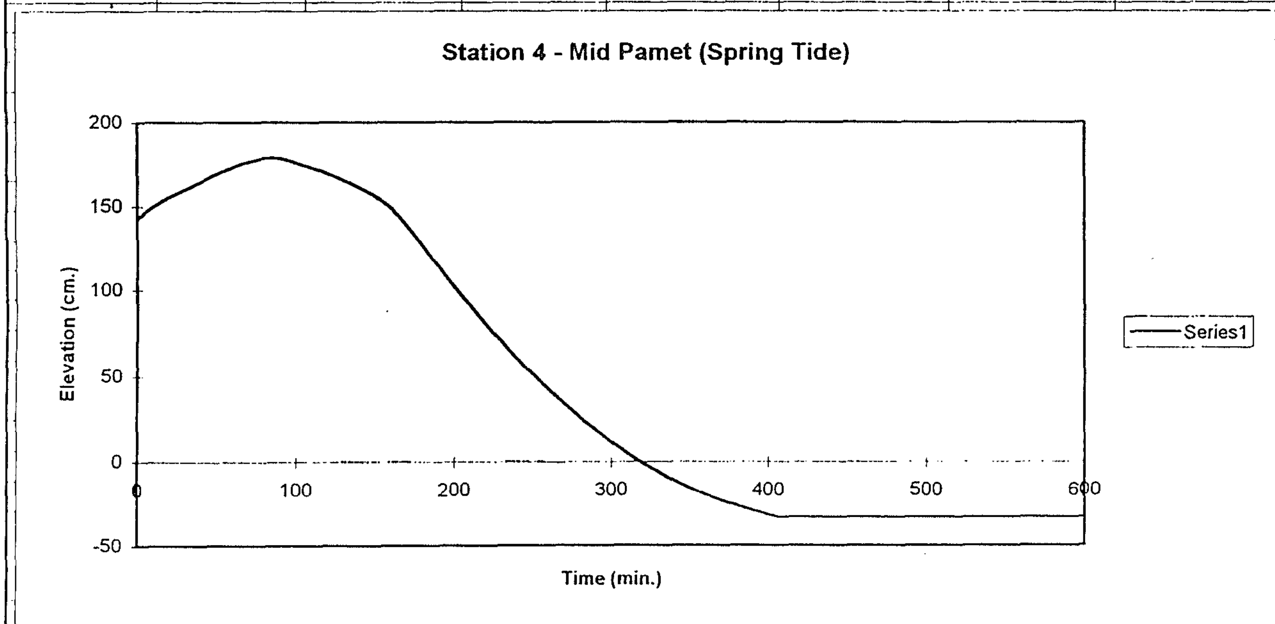

Appendix D

Numerical Model Flow Calc. Spreadsheet

t(min)	U(cm/s)	S(x,t) to MSL(cm/s)	S(x,t) to CB(cm/s)	Area(m^2)	Area(m^2)	Q(m^3/s)	Q(ft3/s)
0	32.93	153.675	141.675	30.236	30.236	9.95671	418.3494
5	33.103	155.246	143.246	30.73872	30.73872	10.1754	427.5394
10	33.212	156.716	144.716	31.20912	31.20912	10.3652	435.5115
15	33.243	158.089	146.089	31.64848	31.64848	10.5209	442.0548
20	33.173	159.363	147.363	32.05616	32.05616	10.634	446.8063
25	32.891	160.482	148.482	32.41424	32.41424	10.6614	447.9586
30	32.299	161.389	149.389	32.70448	32.70448	10.5632	443.8328
35	31.204	162.003	150.003	32.90096	32.90096	10.2664	431.362
40	29.35	162.193	150.193	32.96176	32.96176	9.67428	406.4822
45	26.977	161.965	149.965	32.8888	32.8888	8.87241	372.7904
50	24.55	161.488	149.488	32.73616	32.73616	8.03673	337.6776
55	22.03	160.813	148.813	32.52016	32.52016	7.16419	301.0164
60	19.246	159.936	147.936	32.23952	32.23952	6.20482	260.7066
65	16.138	158.845	146.845	31.8904	31.8904	5.14647	216.2384
70	12.436	157.526	145.526	31.46832	31.46832	3.9134	164.4286
75	7.853	155.911	143.911	30.95152	30.95152	2.43062	102.127
80	2.255	153.958	141.958	30.32656	30.32656	0.68386	28.73378
85	-3.353	151.9	139.9	29.668	29.668	-0.99477	-41.797
90	-8.322	149.865	137.865	29.0168	29.0168	-2.41478	-101.461
95	-13.26	147.559	135.559	28.27888	28.27888	-3.74978	-157.554
100	-18.66	144.567	132.567	27.32144	27.32144	-5.09845	-214.221
105	-21.27	141.923	129.923	26.47536	0	0	0
110	-22.93	139.497	127.497	25.69904	0	0	0
115	-24.44	137.139	125.139	24.94448	0	0	0
120	-25.76	134.908	122.908	24.23056	0	0	0
125	-26.95	132.768	120.768	23.54576	0	0	0
130	-28	130.746	118.746	22.89872	0	0	0
135	-28.92	128.805	116.805	22.2776	0	0	0
140	-29.7	126.945	114.945	21.6824	0	0	0
145	-30.35	125.132	113.132	21.10224	0	0	0
150	-30.86	123.341	111.341	20.52912	0	0	0
155	-31.3	121.591	109.591	19.96912	0	0	0
160	-31.66	119.878	107.878	19.42096	0	0	0
165	-31.92	118.184	106.184	18.87888	0	0	0
170	-32.06	116.487	104.487	18.33584	0	0	0
175	-32.07	114.75	102.75	17.78	0	0	0
180	-31.96	112.95	100.95	17.204	0	0	0
185	-31.78	111.083	99.083	16.60656	0	0	0
190	-31.62	109.201	97.201	16.00432	0	0	0
195	-31.47	107.337	95.337	15.40784	0	0	0
200	-31.32	105.502	93.502	14.82064	0	0	0
205	-31.16	103.703	91.703	14.24496	0	0	0
210	-31.01	101.945	89.945	13.6824	0	0	0
215	-30.85	100.229	88.229	13.13328	0	0	0
220	-30.68	98.558	86.558	12.59856	0	0	0
225	-30.51	96.931	84.931	12.07792	0	0	0
230	-30.33	95.349	83.349	11.57168	0	0	0

235	-30.16	93.811	81.811	11.07952	0	0	0
240	-29.98	92.316	80.316	10.60112	0	0	0
245	-29.79	90.863	78.863	10.13616	0	0	0
250	-29.61	89.451	77.451	9.68432	0	0	0
255	-29.43	88.079	76.079	9.24528	0	0	0
260	-29.24	86.747	74.747	8.81904	0	0	0
265	-29.06	85.453	73.453	8.40496	0	0	0
270	-28.88	84.196	72.196	8.00272	0	0	0
275	-28.7	82.976	70.976	7.61232	0	0	0
280	-28.52	81.792	69.792	7.23344	0	0	0
285	-28.35	80.643	68.643	6.86576	0	0	0
290	-28.18	79.529	67.529	6.50928	0	0	0
295	-28.01	78.449	66.449	6.16368	0	0	0
300	-27.85	77.403	65.403	5.82896	0	0	0
305	-27.7	76.392	64.392	5 50544	0	0	0
310	-27.55	75.415	63.415	5.1928	0	0	0
315	-27.41	74.472	62.472	4.89104	0	0	0
320	-27.28	73.562	61.562	4.59984	0	0	0
325	-27.16	72.687	60.687	4.31984	0	0	0
330	-27.04	71.844	59.844	4.05008	0	0	0
335	-26.92	71.034	59.034	3.79088	0	0	0
340	-26.81	70.254	58.254	3.54128	0	0	0
345	-26.7	69.504	57.504	3.30128	0	0	0
350	-26.59	68.779	56.779	3.06928	0	0	0
355	-26.48	68.076	56.076	2.84432	0	0	0
360	-26.35	67.39	55.39	2.6248	0	0	0
365	-26.2	66.717	54.717	2.40944	0	0	0
370	-26.04	66.052	54.052	2.19664	0	0	0
375	-25.86	65.389	53.389	1.98448	0	0	0
380	-25.66	64.725	52.725	1.772	0	0	0
385	-25.44	64.056	52.056	1.55792	0	0	0
390	-25.2	63.381	51.381	1.34192	0	0	0
395	-24.95	62.7	50.7	1.124	0	0	0
400	-24.7	62.013	50.013	0.90416	0	0	0
405	-24.44	61.32	49.32	0.6824	0	0	0
410	-24.18	60.623	48.623	0.45936	0	0	0
415	-23.92	59.923	47.923	0.23536	0	0	0
420	-23.66	59.223	47.223	0.01136	0	0	0
425	-23.41	58.523	46.523	-0.21264	0	0	0
430	-23.16	57.826	45.826	-0.43568	0	0	0
435	-22.92	57.134	45.134	-0.65712	0	0	0
440	-22.69	56.447	44.447	-0.87696	0	0	0
445	-22.46	55.766	43.766	-1.09488	0	0	0
450	-22.24	55.094	43.094	-1.30992	0	0	0
455	-22.03	54.431	42.431	-1.52208	0	0	0
460	-21.82	53.777	41.777	-1.73136	0	0	0
465	-21.62	53.135	41.135	-1.9368	0	0	0
470	-21.43	52.503	40.503	-2.13904	0	0	0
475	-21.24	51.882	39.882	-2.33776	0	0	0
480	-21.06	51.273	39.273	-2 53264	0	0	0
485	-20.88	50.677	38.677	-2 72336	0	0	0
490	-20.71	50.092	38.092	-2.91056	0	0	0

495	-20.55	49.52	37.52	-3.0936	0	0	0
500	-20.39	48.959	36.959	-3.27312	0	0	0
505	-20.23	48.411	36.411	-3.44848	0	0	0
510	-20.08	47.875	35.875	-3.62	0	0	0
515	-19.94	47.351	35.351	-3.78768	0	0	0
520	-19.8	46.838	34.838	-3.95184	0	0	0
525	-19.66	46.338	34.338	-4.11184	0	0	0
530	-19.53	45.851	33.851	-4.26768	0	0	0
535	-19.4	45.375	33.375	-4.42	0	0	0
540	-19.27	44.911	32.911	-4.56848	0	0	0
545	-19.15	44.458	32.458	-4.71344	0	0	0
550	-19.03	44.017	32.017	-4.85456	0	0	0
555	-18.92	43.586	31.586	-4.99248	0	0	0
560	-18.8	43.165	31.165	-5.1272	0	0	0
565	-18.68	42.753	30.753	-5.25904	0	0	0
570	-18.56	42.348	30.348	-5.38864	0	0	0
575	-18.45	41.95	29.95	-5.516	0	0	0
580	-18.33	41.562	29.562	-5.64016	0	0	0
585	-18.22	41.184	29.184	-5.76112	0	0	0
590	-18.08	40.814	28.814	-5.87952	0	0	0
595	-17.88	40.454	28.454	-5.99472	0	0	0
600	-17.5	40.124	28.124	-6.10032	0	0	0
605	-16.56	39.903	27.903	-6.17104	0	0	0
610	-13.87	40.096	28.096	-6.10928	0	0	0
615	-6.748	41.616	29.616	-5.62288	0	0	0
620	5.86	45.743	33.743	-4.30224	0	0	0
625	11.666	49.956	37.956	-2.95408	0	0	0
630	17.399	53.993	41.993	-1.66224	0	0	0
635	22.136	58.981	46.981	-0.06608	0	0	0
640	26.224	64.716	52.716	1.76912	0	0	0
645	29.583	71.073	59.073	3.80336	0	0	0
650	32.276	77.835	65.835	5.9672	0	0	0
655	34.387	84.794	72.794	8.19408	0	0	0
660	35.999	91.768	79.768	10.42576	0	0	0
665	37.21	98.622	86.622	12.61904	0	0	0
670	38.054	105.249	93.249	14.73968	0	0	0
675	38.555	111.566	99.566	16.76112	0	0	0
680	38.751	117.495	105.495	18.6584	0	0	0
685	38.44	122.818	110.818	20.36176	0	0	0
690	37.785	127.369	115.369	21.81808	0	0	0
695	36.985	131.262	119.262	23.06384	0	0	0
700	36.225	134.594	122.594	24.13008	0	0	0
705	35.369	137.519	125.519	25.06608	0	0	0
710	34.677	140.07	128.07	25.8824	0	0	0
715	33.902	142.432	130.432	26.63824	26.63824	9.0309	379.4494
720	33.326	144.561	132.561	27.31952	27.31952	9.1045	382.5422
725	32.847	146.577	134.577	27.96464	27.96464	9.18555	385.9473
730	32.728	148.502	136.502	28.58064	28.58064	9.35387	393.0198
735	32.762	150.298	138.298	29.15536	29.15536	9.55188	401.3395
740	32.81	152.002	140.002	29.70064	29.70064	9.74478	409.4445
745	32.907	153.645	141.645	30.2264	30.2264	9.9466	417.9244
750	33.08	155.216	143.216	30.72912	30.72912	10.1652	427.1089

755	33.19	156.689	144.689	31.20048	31.20048	10.3554	435.1025
760	33.225	158.065	146.065	31.6408	31.6408	10.5127	441.7082
765	33.159	159.343	147.343	32.04976	32.04976	10.6274	446.5286
770	32.886	160.468	148.468	32.40976	32.40976	10.6583	447.8266
775	32.308	161.385	149.385	32.7032	32.7032	10.5657	443.9391
780	31.236	162.013	150.013	32.90416	32.90416	10.2779	431.8464
785	29.41	162.221	150.221	32.97072	32.97072	9.69669	407.4239
790	27.042	162.005	150.005	32.9016	32.9016	8.89725	373.8341
795	24.612	161.536	149.536	32.75152	32.75152	8.0608	338.6892
800	22.096	160.867	148.867	32.53744	32.53744	7.18947	302.0787
805	19.321	159.998	147.998	32.25936	32.25936	6.23283	261.8837
810	16.225	158.915	146.915	31.9128	31.9128	5.17785	217.5568
815	12.547	157.605	145.605	31.4936	31.4936	3.9515	166.0295
820	8.001	156.004	144.004	30.98128	30.98128	2.47881	104.1518
825	2.43	154.064	142.064	30.36048	30.36048	0.73776	30.99831
830	-3.194	152.007	140.007	29.70224	29.70224	-0.94869	-39.8609
835	-8.148	149.984	137.984	29.05488	29.05488	-2.36739	-99.4702
840	-13.05	147.709	135.709	28.32688	28.32688	-3.69751	-155.357
845	-18.5	144.733	132.733	27.37456	27.37456	-5.06539	-212.831
850	-21.22	142.071	130.071	26.52272	26.52272	-5.62865	-236.498
855	-22.88	139.639	127.639	25.74448	0	0	0
860	-24.4	137.276	125.276	24.98832	0	0	0
865	-25.73	135.041	123.041	24.27312	0	0	0
870	-26.93	132.896	120.896	23.58672	0	0	0
875	-27.97	130.871	118.871	22.93872	0	0	0
880	-28.9	128.927	116.927	22.31664	0	0	0
885	-29.69	127.065	115.065	21.7208	0	0	0
890	-30.35	125.254	113.254	21.14128	0	0	0
895	-30.86	123.464	111.464	20.56848	0	0	0
900	-31.31	121.714	109.714	20.00848	0	0	0
905	-31.67	120.003	108.003	19.46096	0	0	0
910	-31.93	118.314	106.314	18.92048	0	0	0
915	-32.08	116.623	104.623	18.37936	0	0	0
920	-32.1	114.897	102.897	17.82704	0	0	0
925	-32.01	113.109	101.109	17.25488	0	0	0
930	-31.82	111.252	99.252	16.66064	0	0	0
935	-31.66	109.372	97.372	16.05904	0	0	0
940	-31.5	107.51	95.51	15.4632	0	0	0
945	-31.35	105.674	93.674	14.87568	0	0	0
950	-31.19	103.873	91.873	14.29936	0	0	0
955	-31.03	102.112	90.112	13.73584	0	0	0
960	-30.87	100.394	88.394	13.18608	0	0	0
965	-30.7	98.719	86.719	12.65008	0	0	0
970	-30.53	97.09	85.09	12.1288	0	0	0
975	-30.36	95.504	83.504	11.62128	0	0	0
980	-30.18	93.962	81.962	11.12784	0	0	0
985	-30	92.464	80.464	10.64848	0	0	0
990	-29.82	91.008	79.008	10.18256	0	0	0
995	-29.63	89.592	77.592	9.72944	0	0	0
1000	-29.45	88.218	76.218	9.28976	0	0	0
1005	-29.26	86.882	74.882	8.86224	0	0	0
1010	-29.08	85.585	73.585	8.4472	0	0	0

1015	-28.9	84.325	72.325	-8.044	0	0	0
1020	-28.72	83.102	71 102	7.65264	0	0	0
1025	-28.54	81.915	69.915	7.2728	0	0	0
1030	-28.37	80.763	68.763	6.90416	0	0	0
1035	-28.2	79.646	67.646	6.54672	0	0	0
1040	-28.03	78.563	66.563	6.20016	0	0	0
1045	-27.87	77.515	65.515	5.8648	0	0	0
1050	-27.72	76.501	64.501	5.54032	0	0	0
1055	-27.57	75.521	63.521	5.22672	0	0	0
1060	-27.43	74.576	62.576	4.92432	0	0	0
1065	-27.3	73.664	61.664	4.63248	0	0	0
1070	-27.17	72.786	60.786	4.35152	0	0	0
1075	-27.05	71.941	59.941	4.08112	0	0	0
1080	-26.94	71.128	59.128	3.82096	0	0	0
1085	-26.83	70.346	58.346	3.57072	0	0	0
1090	-26.72	69.593	57.593	3.32976	0	0	0
1095	-26.61	68.866	56.866	3.09712	0	0	0
1100	-26.49	68.161	56.161	2.87152	0	0	0
1105	-26.36	67.474	55.474	2.65168	0	0	0
1110	-26.22	66.8	54.8	2.436	0	0	0
1115	-26.05	66.133	54.133	2.22256	0	0	0
1120	-25.87	65.469	53.469	2.01008	0	0	0
1125	-25.67	64.803	52.803	1.79696	0	0	0
1130	-25.45	64.133	52.133	1.58256	0	0	0
1135	-25.21	63.458	51.458	1.36656	0	0	0
1140	-24.97	62.776	50.776	1.14832	0	0	0
1145	-24.71	62.087	50.087	0.92784	0	0	0
1150	-24.45	61.393	49.393	0.70576	0	0	0
1155	-24.19	60.695	48.695	0.4824	0	0	0
1160	-23.93	59.995	47.995	0.2584	0	0	0
1165	-23.68	59.293	47.293	0.03376	0	0	0
1170	-23.42	58.593	46.593	-0.19024	0	0	0
1175	-23.18	57.895	45.895	-0.4136	0	0	0
1180	-22.93	57.201	45.201	-0.63568	0	0	0
1185	-22.7	56.513	44.513	-0.85584	0	0	0
1190	-22.47	55.832	43.832	-1.07376	0	0	0
1195	-22.25	55.158	43.158	-1.28944	0	0	0
1200	-22.04	54.494	42.494	-1.50192	0	0	0
1205	-21.83	53.839	41.839	-1.71152	0	0	0
1210	-21.63	53.195	41.195	-1.9176	0	0	0
1215	-21.44	52.562	40.562	-2.12016	0	0	0
1220	-21.25	51.941	39.941	-2.31888	0	0	0
1225	-21.07	51.331	39.331	-2.51408	0	0	0
1230	-20.89	50.733	38.733	-2.70544	0	0	0
1235	-20.72	50.148	38.148	-2.89264	0	0	0
1240	-20.56	49.574	37.574	-3.07632	0	0	0
1245	-20.4	49.013	37.013	-3.25584	0	0	0
1250	-20.24	48.463	36.463	-3.43184	0	0	0
1255	-20.09	47.926	35.926	-3.60368	0	0	0
1260	-19.95	47.401	35.401	-3.77168	0	0	0
1265	-19.8	46.888	34.888	-3.93584	0	0	0
1270	-19.67	46.387	34.387	-4.09616	0	0	0

1275	-19.53	45.898	33.898	-4.25264	0	0	0
1280	-19.4	45.422	33.422	-4.40496	0	0	0
1285	-19.28	44.957	32.957	-4.55376	0	0	0
1290	-19.16	44.503	32.503	-4.69904	0	0	0
1295	-19.04	44.061	32.061	-4.84048	0	0	0
1300	-18.92	43.63	31.63	-4.9784	0	0	0
1305	-18.81	43.208	31.208	-5.11344	0	0	0
1310	-18.69	42.795	30.795	-5.2456	0	0	0
1315	-18.57	42.389	30.389	-5.37552	0	0	0
1320	-18.45	41.991	29.991	-5.50288	0	0	0
1325	-18.34	41.602	29.602	-5.62736	0	0	0
1330	-18.22	41.223	29.223	-5.74864	0	0	0
1335	-18.09	40.852	28.852	-5.86736	0	0	0
1340	-17.89	40.492	28.492	-5.98256	0	0	0
1345	-17.52	40.159	28.159	-6.08912	0	0	0
1350	-16.62	39.93	27.93	-6.1624	0	0	0
1355	-14.03	40.095	28.095	-6.1096	0	0	0
1360	-7.118	41.539	29.539	-5.64752	0	0	0
1365	5.451	45.57	33.57	-4.3576	0	0	0
1370	11.411	49.841	37.841	-2.99088	0	0	0
1375	17.2	53.832	41.832	-1.71376	0	0	0
1380	21.961	58.795	46.795	-0.1256	0	0	0
1385	26.075	64.496	52.496	1.69872	0	0	0
1390	29.46	70.83	58.83	3.7256	0	0	0
1395	32.178	77.578	65.578	5.88496	0	0	0
1400	34.311	84.53	72.53	8.1096	0	0	0
1405	35.942	91.505	79.505	10.3416	0	0	0
1410	37.167	98.364	86.364	12.53648	0	0	0
1415	38.026	105	93	14.66	0	0	0
1420	38.54	111.329	99.329	16.68528	0	0	0
1425	38.749	117.275	105.275	18.588	0	0	0
1430	38.462	122.629	110.629	20.30128	0	0	0
1435	37.814	127.207	115.207	21.76624	0	0	0
1440	37.019	131.124	119.124	23.01968	0	0	0
1445	36.257	134.474	122.474	24.09168	0	0	0
1450	35.4	137.416	125.416	25.03312	0	0	0
1455	34.703	139.977	127.977	25.85264	0	0	0
1460	33.927	142.346	130.346	26.61072	26.61072	9.02822	379.3369
1465	33.348	144.482	132.482	27.29424	27.29424	9.10208	382.4405
1470	32.864	146.501	134.501	27.94032	27.94032	9.18231	385.8112
1475	32.728	148.43	136.43	28.5576	28.5576	9.34633	392.703
1480	32.76	150.231	138.231	29.13392	29.13392	9.54427	401.0198
1485	32.808	151.938	139.938	29.68016	29.68016	9.73747	409.1373
1490	32.9	153.582	141.582	30.20624	30.20624	9.93785	417.5568

Appendix E

BOSTON, MASS.

42–21N x 71–03W

DAY OF MONTH	DAY OF WEEK	SEPTEMBER HIGH a.m.	Ht.	p.m.	Ht.	LOW a.m.	p.m.
1	T	7 21	8.4	7 35	9.5	1 06	1 18
2	F	8 12	8.7	8 26	9.9	1 58	2 10
3	S	9 00	9.2	9 14	10.3	2 46	3 00
4	S	9 44	9.8	10 00	10.7	3 32	3 48
5	M	10 28	10.4	10 46	11.1	4 16	4 35
6	T	11 11	10.9	11 32	11.2	5 00	5 21
7	W	11 55	11.3	...	...	5 44	6 09
8	T	12 19	11.2	12 41	11.6	6 30	6 58
9	F	1 09	11.0	1 29	11.6	7 18	7 49
10	S	2 01	10.7	2 21	11.5	8 08	8 44
11	S	2 57	10.2	3 16	11.1	9 02	9 42
12	M	3 57	9.7	4 17	10.8	10 00	10 44
13	T	5 01	9.4	5 22	10.5	11 02	11 48
14	W	6 08	9.2	6 28	10.3	...	12 07
15	T	7 14	9.3	7 33	10.3	12 53	1 11
16	F	8 14	9.5	8 33	10.4	1 55	2 12
17	S	9 08	9.8	9 26	10.4	2 50	3 07
18	S	9 55	10.1	10 13	10.4	3 38	3 56
19	M	10 37	10.3	10 56	10.4	4 21	4 41
20	T	11 15	10.3	11 36	10.2	5 02	5 23
21	W	11 53	10.3	...	...	5 40	6 03
22	T	12 16	10.0	12 30	10.3	6 19	6 44
23	F	12 56	9.7	1 08	10.1	6 58	7 25
24	S	1 37	9.4	1 49	9.9	7 38	8 08
25	S	2 21	9.0	2 32	9.6	8 21	8 54
26	M	3 07	8.7	3 20	9.4	9 07	9 43
27	T	3 58	8.4	4 11	9.2	9 57	10 35
28	W	4 52	8.3	5 06	9.1	10 51	11 30
29	T	5 47	8.3	6 02	9.2	11 47	...
30	F	6 42	8.6	6 57	9.5	12 25	12 44

DAY OF MONTH	DAY OF WEEK	OCTOBER HIGH a.m.	Ht.	p.m.	Ht.	LOW a.m.	p.m.
1	S	7 33	9.1	7 51	9.9	1 18	1 38
2	S	8 22	9.8	8 41	10.4	2 08	2 30
3	M	9 08	10.5	9 31	10.8	2 56	3 20
4	T	9 54	11.1	10 20	11.1	3 43	4 09
5	W	10 40	11.7	11 09	11.3	4 30	4 58
6	T	11 27	12.1	11 59	11.3	5 17	5 47
7	F	...	...	12 15	12.2	6 05	6 38
8	S	12 50	11.1	1 06	12.1	6 55	7 30
9	S	1 44	10.7	2 00	11.7	7 47	8 25
10	M	2 41	10.2	2 53	11.2	8 43	9 24
11	T	3 43	9.8	4 00	10.7	9 42	10 26
12	W	4 47	9.5	5 06	10.2	10 46	11 30
13	T	5 54	9.4	6 14	10.0	11 52	...
14	F	6 58	9.5	7 18	9.9	12 34	12 58
15	S	7 55	9.7	8 17	9.9	1 34	1 58
16	S	8 46	10.0	9 08	9.9	2 26	2 52
17	M	9 30	10.2	9 53	9.9	3 13	3 38
18	T	10 10	10.3	10 34	9.8	3 54	4 20
19	W	10 47	10.4	11 13	9.7	4 33	5 00
20	T	11 23	10.4	11 52	9.6	5 11	5 39
21	F	11 59	10.3	...	...	5 49	6 18
22	S	12 30	9.4	12 37	10.2	6 28	6 58
23	S	1 10	9.2	1 17	10.0	7 08	7 39
24	M	1 52	8.9	1 59	9.7	7 50	8 23
25	T	2 37	8.7	2 45	9.5	8 35	9 09
26	W	3 25	8.5	3 34	9.3	9 24	9 59
27	T	4 16	8.5	4 28	9.2	10 17	10 51
28	F	5 09	8.7	5 24	9.3	11 13	11 45
29	S	6 03	9.1	6 20	9.5	...	12 10
30	S	6 55	9.6	7 16	9.8	12 39	1 06
31	M	7 45	10.3	8 11	10.2	1 31	2 01

Average Rise and Fall 9 1/2 ft.

When a high tide exceeds av. ht., the *following* low tide will be lower than av.

Since there is a high degree of correlation between the height of High Water and the velocities of the Flood and Ebb Currents for that same day, we offer a rough rule of thumb for estimating the current velocities, for ALL the Current Charts and Diagrams in this book.

Rule of Thumb: Refer to Boston High Water. If the height of High Water is 11.0' or over, use the Current Chart velocities as shown. When the height is 10.5', subtract 10%; at 10.0', subtract 20%; at 9.0', 30%; at 8.0', 40%; below 7.5', 50%.

BOSTON, MASS.

42–21N x 71–03W

DAY OF MONTH	DAY OF WEEK	NOVEMBER HIGH a.m.	Ht.	p.m.	Ht.	LOW a.m.	p.m.
1	T	8 35	11.0	9 04	10.6	2 22	2 54
2	W	9 24	11.7	9 56	10.9	3 12	3 45
3	T	10 13	12.2	10 47	11.1	4 02	4 36
4	F	11 02	12.5	11 40	11.1	4 52	5 27
5	S	11 53	12.5	...	...	5 42	6 19
6	S	12 33	10.9	12 46	12.3	6 34	7 12
7	M	1 28	10.6	1 41	11.8	7 28	8 07
8	T	2 25	10.3	2 39	11.2	8 24	9 04
9	W	3 25	9.9	3 41	10.6	9 24	10 03
10	T	4 27	9.7	4 45	10.0	10 26	11 04
11	F	5 30	9.6	5 51	9.6	11 32	...
12	S	6 31	9.6	6 54	9.4	12 05	12 36
13	S	7 27	9.7	7 52	9.3	1 03	1 37
14	M	8 16	9.9	8 43	9.3	1 55	2 30
15	T	9 00	10.1	9 29	9.3	2 42	3 16
16	W	9 41	10.2	10 11	9.3	3 24	3 58
17	T	10 19	10.3	10 51	9.3	4 04	4 37
18	F	10 56	10.3	11 29	9.3	4 43	5 16
19	S	11 33	10.3	...	...	5 22	5 54
20	S	12 08	9.2	12 11	10.2	6 01	6 33
21	M	12 47	9.1	12 50	10.1	6 41	7 13
22	T	1 27	9.0	1 31	9.9	7 23	7 55
23	W	2 10	8.9	2 15	9.7	8 07	8 39
24	T	2 55	8.9	3 02	9.5	8 55	9 26
25	F	3 42	9.0	3 54	9.4	9 46	10 15
26	S	4 33	9.2	4 49	9.4	10 41	11 08
27	S	5 25	9.5	5 46	9.4	11 38	...
28	M	6 18	10.1	6 45	9.6	12 02	12 36
29	T	7 12	10.7	7 42	9.9	12 57	1 34
30	W	8 05	11.3	8 39	10.2	1 51	2 30

DAY OF MONTH	DAY OF WEEK	DECEMBER HIGH a.m.	Ht.	p.m.	Ht.
1	T	8 58	11.8	9 35	10.5
2	F	9 50	12.3	10 29	10.7
3	S	10 43	12.5	11 23	10.8
4	S	11 36	12.4	...	...
5	M	12 17	10.7	12 29	12.2
6	T	1 11	10.6	1 23	11.7
7	W	2 05	10.3	2 19	11.1
8	T	3 01	10.1	3 17	10.4
9	F	3 59	9.8	4 16	9.7
10	S	4 56	9.6	5 18	9.2
11	S	5 53	9.5	6 19	8.9
12	M	6 48	9.5	7 18	8.7
13	T	7 40	9.6	8 12	8.7
14	W	8 27	9.8	9 01	8.7
15	T	9 11	9.9	9 46	8.8
16	F	9 52	10.1	10 27	8.9
17	S	10 31	10.2	11 07	9.0
18	S	11 10	10.2	11 45	9.1
19	M	11 48	10.3	...	...
20	T	12 24	9.1	12 27	10.2
21	W	1 03	9.2	1 07	10.1
22	T	1 43	9.2	1 49	10.0
23	F	2 25	9.4	2 35	9.8
24	S	3 10	9.5	3 24	9.6
25	S	3 58	9.7	4 18	9.5
26	M	4 50	10.0	5 16	9.4
27	T	5 45	10.3	6 17	9.4
28	W	6 42	10.7	7 19	9.5
29	T	7 40	11.2	8 19	9.7
30	F	8 37	11.6	9 18	10.0
31	S	9 33	11.9	10 14	10.3

Average Rise and Fall 9 1/2 ft.

When a high tide exceeds av. ht., the *following* low tide will be lowe

Since there is a high degree of correlation between the height of High Wa
velocities of the Flood and Ebb Currents for that same day, we offer a rough ru
for estimating the current velocities, for ALL the Current Charts and Diagr
book.

Rule of Thumb: Refer to Boston High Water. If the height of High Wate
over, use the Current Chart velocities as shown. When the height is 10.5', su
at 10.0', subtract 20%; at 9.0', 30%; at 8.0', 40%; below 7.5', 50%.

MAI..., Outer Coast

	H.M.			Rise in feet
Richmond Island	0 15	*before*	BOSTON	8.9
Wood Island Harbor	0 15	"	"	9.0
Cape Porpoise	same as		"	8.8
Kennebunkport	same as		"	8.6
York Harbor	0 10	*before*	"	8.6

NEW HAMPSHIRE

	H.M.			Rise in feet
Portsmouth	0 05	*after*	BOSTON	8.1
Gosport Harbor, Isles of Shoals	0 15	*before*	"	8.8
Hampton	same as		"	8.3

MASSACHUSETTS, Outer Coast

	H.M.			Rise in feet
Newburyport	0 30	*after*	BOSTON	7.8
Annisquam	same as		"	8.7
Rockport	0 05	*after*	"	8.6
Gloucester	same as		"	8.7
Manchester	same as		"	8.8
Salem	same as		"	9.0
Marblehead	0 05	*before*	"	9.1
Broad Sound				
Nahant	same as		"	9.0
Lynn Harbor	0 10	*after*	"	9.2
Neponset	0 05	*before*	"	9.5
Weymouth, Back River	0 05	*after*	"	9.5
Hingham	same as		"	9.5
Cohasset Harbor	same as		"	8.8
Scituate	same as		"	9.0
Cape Cod Bay				
Gurnet Point	same as		"	9.2
Plymouth	same as		"	9.5
Cape Cod Canal East	same as		"	8.7
Wellfleet	0 15	*after*	"	10.0
Provincetown	0 15	"	"	9.1
Race Point	0 05	*before*	"	9.0
Cape Cod				
Nauset Harbor	high 0 30 *after*, low 0 55	*after*	"	6.0
Chatham, Stage Harbor	0 55	"	"	4.0
Chatham, Outside	0 30	"	"	6.7
Monomoy Point	0 35	"	"	3.7
Meeting House Pond	2 19	"	"	4.1
Nantucket Sound				
Dennisport	high 1 00 *after*, low 0 35	*after*	BOSTON	3.4
South Yarmouth, Bass R. Bridge	1 45	"	"	2.8
Hyannisport	high 1 00 *after*, low 0 30	"	"	3.1
Cotuit	" 1 15 " " 0 45	"	"	2.5
Succonnesset	0 50	"	"	1.9
Falmouth Inner Harbor	same as		"	1.5
Nantucket Island				
Siasconset	0 15	*after*	BOSTON	1.2
Great Point	high 0 40 *after*, low 0 25	"	"	3.1
Nantucket	1 00	"	"	3.0
Tuckernuck Island	high0 45 *after*, low 0 25	"	"	2.6
Muskeget Island, North side	0 20	"	"	2.0

BOSTON Tables, p. 12-17

When a high tide exceeds av. ht., the *following* low tide will be lower than av.

	H.M.			Rise in feet
Martha's Vineyard				
Cape Pogue	high 0 45 *after*, low same as		BOSTON	2.2
Edgartown	high 1 00 *after*, low 0 15	*after*	"	2.(
Oak Bluffs	high 0 30 *after*, low 0 15	*before*	"	1.
East Chop	high 0 25 *after*, low 0 15	"	"	1.
Vineyard Haven	high 0 25 *after*, low 0 05	"	"	1.
West Chop	high 0 15 *after*, low 0 30	"	"	1.
Lake Tashmoo (inside)	2 30	*before*	"	2.
Cedar Tree Neck	high 0 15 *after*, low 1 35	*after*	NEWPORT	2.
Menemsha	high 0 05 *after*, low 0 40	"	"	2.
Gay Head	high same as, low 0 50	"	"	3.
Squibnocket Point	high 0 40 *before*, low 0 05	"	"	2.
Wasque Point	high 2 05 *after*, low 3 25	"	"	1.
Nomans Island	high 0 15 *before*, low 0 25	"	"	3.
Vineyard Sound North Side				
Little Hbr., Wds.Hole	high 0 35 *after*, low 2 25	*after*	NEWPORT	1
Oceanographic Inst.	high 0 27 *after*, low 2 00	"	"	2
Tarpaulin Cove	high 0 15 *after*, low 1 30	"	"	1
Quicks's Hole, S.side	high 0 10 *before*, low 0 15	"	"	2
Buzzards Bay				
Cuttyhunk, Pond Entrance	same as		NEWPORT	3
Penikese Island	0 15	*before*	"	3
W. Falmouth Harbor	0 25	*after*	"	4
Monument Beach	0 25	"	"	4
Pocasset Harbor	0 25	"	"	4
Wareham	0 25	"	"	4
Bird Island	0 10	"	"	4
Marion	0 10	"	"	4
Mattapoisett	0 15	"	"	[illegible]
New Bedford	0 10	"	"	[illegible]
South Dartmouth	0 30	"	"	[illegible]
Dumpling Rocks	same as		"	[illegible]
Westport Harbor	high 0 10 *after*, low 0 40	"	"	[illegible]

RHODE ISLAND & MASS. Narragansett Bay

	H.M.			Rise in feet
Sakonnet	0 10	*before*	NEWPORT	[illegible]
Tiverton	0 20	*after*	"	
Beavertail	same as		"	
Prudence Island	0 10	*after*	"	
Bristol Point	0 20	"	"	
Fall River	0 30	"	"	
Taunton	high 1 10 *after*, low 2 25	*after*	"	
Warren	0 15	"	"	
Providence	0 10	"	"	
Pawtucket	0 20	"	"	
East Greenwich	0 15	"	"	
Wickford	0 10	"	"	
Narragansett Pier	0 10	*before*		

RHODE ISLAND, Outer Coast

	H.M.			Rise in feet
Pt. Judith Harbor	high 0 05 *before*, low 0 20	*after*	NEWPORT	
Great Salt Pond, Block Is.	same as		"	
Watch Hill	high 0 45 *after*, low 1 20	"	"	

BOSTON Tables, p. 12-17
NEWPORT Tables, p. 64-69

When a high tide exceeds av. ht., the *following* low tide will be lower than av.

ENDNOTES

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8. Richard G. Lewis II, Pamet River Study, (Massachusetts: 1989), p. 8.

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15. Richard G. Lewis II, p. 9.

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19. Random House Dictionary , p. 937.

20. David G. Aubrey, Carl T. Friedrichs, Graham S. Giese, and Richard G. Lewis II, Application and Assessment of a Shallow-Water Tide Model to the Pamet River, Truro, Massachusetts, (Massachusetts: 1989), p. 6.

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