Modeling the friction effects of eelgrass on the tidal flow in Great Bay, New Hampshire

Safak Nur Erturk
University of New Hampshire, Durham

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MODELING THE FRICTION EFFECTS OF EELGRASS

ON THE TIDAL FLOW IN GREAT BAY, NH

by

ŞAFAK NUR ERTÜRK

B.S. Istanbul Technical University, 1993
M.S. Istanbul Technical University, 1995

DISSERTATION

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This dissertation has been examined and approved.

Barbaros Celikkol  
Dissertation Director, Dr. Barbaros Celikkol,  
Professor of Mechanical Engineering and Ocean Engineering.

Kenneth Baldwin, Associate Professor of  
Mechanical Engineering and Ocean Engineering,  
Director, Jere A. Chase Ocean Engineering Laboratory.

Frederick T. Short, Research Professor of  
Natural Resources and Marine Science.

M. Robinson Swift, Professor of Mechanical  
Engineering and Ocean Engineering

May 17, 2000
Date
to my dad ....
PREFACE

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NOMENCLATURE

\( \varepsilon \) : porosity
\( \phi_j \) : basis functions in Weighted Residual Methods
\( \xi \) : sea surface elevation [m]
\( \mu \) : dynamic viscosity of a fluid [kg/ms]
\( \theta \) : numerical implicity
\( \rho \) : density of a fluid [kg/m³]
\( C_d \) : drag coefficient
d : diameter of a sphere in porous medium [m]
D : diffusion coefficient [m²/s]
g : gravitational acceleration of earth [m/s²]
g_x : x-component of gravitational acceleration [m/s²]
h : bathymetric depth [m]
h_o : porous layer thickness [m]
H : total depth of water column [m]
k : hydrolic conductivity [m/s]
K : permeability in a porous medium [m²]
N : number of basis functions in Weighted Residual Methods
P : pressure [N/m²]
q : total transport [m²/s]
q_o : transport in the open channel [m²/s]
q_p : porous medium transport [m²/s]
QUE : x-component of horizontal transport at each element center [m²/s]
QVE : y-component of horizontal transport at each element center [m²/s]
R : residual in Weighted Residual Methods
T : tidal periodicity [hr]
u : x-component of velocity [m/s]
$u_i$ : coefficients of basis functions in Weighted Residual Methods
$U$ : x-component of vertically averaged velocity [m/s]
$\text{UOC}$ : x-component of horizontal velocity in the open channel at each element center [m/s]
$v$ : y-component of velocity [m/s]
$v_0$ : y-component of open channel velocity [m/s]
$v_p$ : y-component of porus medium velocity [m/s]
$V$ : y-component of vertically averaged velocity [m/s]
$\text{VOC}$ : y-component of horizontal velocity in the open channel at each element center [m/s]
$W_i$ : weighting functions in Weighted Residual Methods
$ZN$ : surface elevation value at each node [m]
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ABSTRACT

MODELING THE FRICTION EFFECTS OF EELGRASS ON THE TIDAL FLOW IN GREAT BAY, NH

by

Safak Nur Erturk

University of New Hampshire, May, 2000

In this study the frictional effects of eelgrass \(Zostera marina\) on the tidal flow in Great Bay, NH is modeled using a bottom friction coefficient adjustment approach. A two-dimensional, non-linear, time stepping, finite element model, ADAM is used. The ADAM model incorporates two-dimensional wave physics, with a porous medium beneath the sediment surface to simulate wetting and drying process on the tidal flats. The effectiveness of ADAM model in simulating the tidal flow in Great Bay with wetting and drying on the tidal flats is verified by comparing the model results with the observational data. The model is calibrated by adjusting the bottom friction coefficient for the \(M_2\), \(M_2S_2\) and \(M_2S_2N_2\) tidal forcing, respectively. Eelgrass beds are treated as extra dampers and increased bottom friction coefficient values are used over the eelgrass beds. The flow field with eelgrass is compared to the flow field without eelgrass. Addition of eelgrass to the area reduced the velocities over the eelgrass beds, increased the velocities in the channels, increased the water surface area at low water by holding more water.
CHAPTER 1
INTRODUCTION

1.1. Motivation

Tidal currents and surface elevation changes dominate the physics of shallow estuaries. In cases where tidal range is on the order of the mean depth, the physics is non-linear. As the offshore tide propagates into the estuaries, it can become distorted because of the non-linear processes. The interaction between estuarine geometry and tidal forcing produces the asymmetries between flood and ebb currents. Prediction of flow field is difficult in estuaries due to these distortions introduced by hydrodynamic non-linearities. Kreiss (1957) observed the asymmetry between flood and ebb currents in tidal rivers. He found out that the flood current is stronger in speed but shorter in duration than the ebb flow.

The primary force balance is between friction and the pressure gradient in most shallow tidal embayments (Friedrichs et al., 1992). Swift and Brown (1983) verified this balance observationally throughout the Great Bay Estuary system. Friction can have a major influence on the tide primarily because of the low frequencies and thus long wavelengths involved. Frictional effects increase with decreased depth, increased tidal amplitude, or decreased tidal frequency. The major effect of linear friction on a tidal wave is to reduce its amplitude, shorten its wavelength, and slow it down. Higher frequency
tidal constituents are damped more, but the waves representing the lower constituents are slowed more. Pingree and Griffiths (1987) and Amin (1985) have shown that the influence of the bottom friction is such that the damping is proportionally large with small amplitude constituents and small with large amplitude constituents.

In a shallow estuary, there is a frictional effect of one tidal constituent on another. Although M_2 (principle lunar tide with a period of 12.42 hr), greatly dominates over all other constituents, the cumulative effect of these other constituents has a significant effect on M_2. Therefore, the ideal calibration would have the model forced by all-important constituents.

It is difficult to include large number of constituents in the model because long simulations are required for harmonic analysis of results. Most of the tidal constituents such as M_2, S_2 (principle solar tide with a period of 12.0 hr), and N_2 (larger lunar elliptic tide with a period of 12.66 hr) can be investigated in isolation using numerical models. Previous research suggests that some additional changes in the parameters are essential when the model is driven with an individual constituent.

The bottom friction coefficient can be calculated by fitting a model to amplitude and phase data from an estuary of interest. Model calibration as reported in the literature usually involves adjustment of the friction coefficient at various grid points until the model-produced data matches some measured data from the estuary being modeled.

The increase required in the bottom friction coefficient is very large when a small constituent is considered alone. The cumulative non-linear frictional effect of the tidal constituents left out will increase the frictional momentum loss from M_2 and will reduce its amplitude. Without these other constituents included in the model forcing, the bottom

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friction values are made too large in order to account for this additional $M_2$ amplitude reduction (Parker, 1984).

1.2. Great Bay Estuary, NH

The Great Bay Estuary System, shown in Figure 1-1, is located in the New Hampshire seacoast region. The geomorphology of the estuary is complex. Portsmouth Harbor at the mouth of the estuary and the lower Piscataqua River can be modeled as a channel. The tidal prism in this section of the estuary is the smallest in the system, but the section is dominated by the tidal flow of the entire system (Short, 1992).

The upper Piscataqua River is formed by the convergence of the Cocheco and Salmon Falls Rivers in Dover. In that section, the tidal currents are weaker than the lower Piscataqua. Little Bay is an L-shaped section of the estuary joining the Piscataqua River at Dover Point, to Great Bay at Adams Point. A central deep channel characterizes Little Bay with tidal flats on both sides. Little Bay turns sharply at Fox Point, creating complex flow patterns and a great deal of turbulence. Little Bay is dominated by tidal flow including up-bay effects from Great Bay. The Great Bay is a wide, shallow bay, characterized by tidal flats, a deep main channel and a network of drainage channels. The water surface of Great Bay covers 23km$^2$ at mean high water (MHW) and 11km$^2$ at mean low water (MLW) (Short, 1992). More than 50% of the surface area of Great Bay is exposed as mud flats or eelgrass flats at low tide. River flow varies seasonally with a maximum in spring. Tides dominate over freshwater input throughout the year. Reichard and Celikkol (1978) showed that the average fresh water input from rivers is around 2% of the tidal prism and there is an approximate equal ground water flow (personal
communications with Dr. Thomas Ballestero from UNH Civil Engineering Department).

As the average freshwater input is low in the Great Bay Estuary, tidal currents are more important than density-driven circulation (Swift and Brown, 1983).

![Great Bay Estuary System, NH (Short, 1992)](image)

**Figure 1-1.** Great Bay Estuary System, NH (Short, 1992)

In considering tidal flow dynamics, the Great Bay Estuary can be divided into two regimes: the Piscataqua and the Little Bay/Great Bay section. The tidal flow down bay from the narrow channel at Dover Point is more dissipative with a progressive tidal wave...
character. The flow in the Little Bay/Great Bay section is less dissipative and has a standing wave character (Swift and Brown, 1983).

At the mouth of the estuary near Portsmouth the average tidal range is 2.7m decreasing to 2.0m at Dover Point, increasing slightly to 2.1m at the mouth of Squamscott River (Short, 1992). The phase of the tide lags inward from the ocean. At Dover Point, the tide is 1.3 hours behind Portsmouth Harbor, at Adams Point it is 2.25 hours later and in the Lower Squamscott River it is 2.4 hours behind (Swift and Brown, 1983).

In 1975, National Oceanographic Survey (NOS) measured currents at various stations in the estuary. Maximum current speeds were 0.5m/s in Little Bay/Great Bay section, and were between 0.5m/s and 2.0m/s at stations in the Piscataqua River. Swift and Brown (1983) found that the current speeds were inversely proportional with the channel cross-sectional area.

1.3. Objectives

There has been a lack in simulating the tidal flow in Great Bay Estuary including wetting/drying phenomenon on the tidal flats in Great Bay section of the estuary. The tidal flats cover over 50% of the surface area in Great Bay. In this study, in order to resolve the wetting and drying on the tidal flats, the ADAM model (Ip et al., 1998) is chosen, which combines the two-dimensional wave physics with a porous medium beneath the sediment surface to simulate the wetting/drying process of the tidal flats on a fixed, high-resolution mesh.

The objectives of this study are:
• To investigate the effectiveness of ADAM model in simulating the tidal flow in Great Bay with wetting and drying on the tidal flats.

• To calibrate ADAM model by adjusting the bottom friction coefficient for, $M_2$, $M_2S_2$, and $M_2S_2N_2$ tidal forcing, respectively.

• To explore the frictional effects of eelgrass distribution on the flow regime in Great Bay.

1.4. Numerical Methods

The Finite Element Method (FEM) has been used to solve the primitive shallow water equations since the early 1970's. A significant advantage of the FEM over the Finite Difference Method (FDM) has always been the flexibility provided by the discretization of the domain under study using unstructured polygons, especially when triangles are used. This enables spatial detail to be adjusted according to variations in topographical features or the structure of the computed variables.

In this study, a 2-D, non-linear, time stepping, finite element model, ADAM, was used. ADAM model was developed at Dartmouth College by Dr. Daniel R. Lynch and Dr. Justin T. Ip (see Ip et al. 1998). The ADAM model combines the two-dimensional kinematic wave physics, with a porous medium beneath the sediment surface. The model is sensitive to the bottom friction coefficient distribution.
1.5. Approach

The Great Bay system is forced with three different tidal forcing, $M_2$, $M_2S_2$, and $M_2S_2N_2$ at Little Bay. A depth-related bottom friction coefficient is defined as:

$$C_d = A - B \times h$$

Where $h$ is the bathymetric depth, $A$ and $B$ are constant coefficients. The bottom friction coefficient increases to its maximum value as depth approaches zero. The bottom friction coefficient distribution is adjusted for each tidal forcing (such as $M_2$, $M_2S_2$, and $M_2S_2N_2$) until the model produced data matched the predicted data from Swift and Brown (1983).

Eelgrass leaves form a three-dimensional baffle in water acting as dampers and reduce water motion. Therefore, eelgrass beds are treated as extra dampers: the bottom friction coefficient over the eelgrass beds is increased to a maximum value of 0.1. This value is then checked with the friction values found from flume tank experiments (Kopp, 1999).

The change in water surface area and the average depth; changes in surface elevation amplitude and phase distributions and the changes in current speed and direction in Great Bay due to the frictional effects of eelgrass are explored.

The details of the steps taken in this study are given in Figure 1-2 with a flow chart.
Figure 1-2. Flow chart for the calibration of the ADAM model with the bottom friction coefficient.
1.6. Overview of Thesis

The thesis is organized as follows:

Chapter 2 explains the historical development of finite element modeling concept. In this chapter, the basics of finite element methods are given. The mesh generation technique and the numeric and geomorphologic properties of the generated meshes are described.

Chapter 3 views the hydrodynamic modeling efforts for the Great Bay Estuary system. The ADAM model is described in detail and the reasons in choosing the ADAM model are given. The governing equations for the kinematic, 2-D, non-linear, ADAM model and the assumptions made in this study are included in this chapter. Details about the porous medium approach are also given.

Chapter 4 introduces one of the most important ecological components in Great Bay, *Zostera* marina, L. or eelgrass as commonly known. This chapter gives a general idea about seagrasses and their effects on the water quality, sediment movement and the hydrodynamics in shallow embayments. The disturbance sources of seagrasses and the recovery efforts for the eelgrass habitats are also introduced.

Chapter 5 gives information about the field program performed in the summer of 1975 by the University of New Hampshire in cooperation with the National Ocean Survey (NOS). In this chapter, locations of moored current meters and sea level measurement stations are given. Model-produced data is compared with the predictions at these stations in Chapters 6, 7, 8 and 9.

Chapter 6 explains the approach in the adjustment of bottom friction coefficient in a systematic fashion. The gbgs16 mesh is introduced and the boundary forcing time
series for the $M_2$, $M_2S_2$ and $M_2S_2N_2$ tides are predicted for the gbes16 mesh in this chapter.

In Chapter 7, the $M_2$ tidal flow in Great Bay is explored. The gbes16 mesh introduced in Chapter 6 is used with the September 1990 eelgrass distribution in Great Bay. The change in the surface area and the average-depth, changes in surface elevation amplitude and phase distributions and the changes in current speed and direction in Great Bay due to the frictional effects of eelgrass are discussed in detail in this chapter.

Chapter 8 gives the simulation results for $M_2S_2$ tidal forcing. The effect of eelgrass distribution on the $M_2S_2$ flow in Great Bay is explored.

Chapter 9 gives the simulation results for $M_2S_2N_2$ tidal forcing.

Chapter 10 initiates a discussion on the results.

Appendix A describes the Darcian Flow for porous medium.

Appendix B contains information regarding the use of Galerkin method.
CHAPTER 2

FINITE ELEMENT METHOD AND MESH GENERATION

The ideas that gave birth to the Finite Element Methods (FEM) evolved gradually from the independent contributions of many people in the fields of engineering, applied mathematics, and physics.

Hrenikoff (1941) found out that the elastic behavior of a physically continuous plate would be similar, under certain loading conditions, to a framework of physically separate one-dimensional rods and beams, connected together as discrete points. The problem then handled for trusses and frameworks with similar computational methods.

Courant’s (1943) paper is a classic for finite element methods. To solve the torsion problem in elasticity, he defined piecewise linear polynomials over a triangularized region. Schoenberg’s (1946) paper gave birth to the theory of splines, recommending the use of piecewise polynomials for approximation and interpolation. Synge (1957) used piecewise linear functions defined over triangularized region with a Reitz variational procedure.

With the introduction of high-speed digital computers, Langefors (1952) and Argyris (1954) took the framework analysis procedures and reformulated them into a matrix format suited for efficient automatic computation. McMahon (1953) solved a three-dimensional electrostatic problem using tetrahedral elements and linear trial
functions. Polya (1954), Hersh (1955), and Weinberger (1956) used ideas similar to Courant's to estimate bounds for eigenvalues.

Turner *et al.* (1956) modeled the odd-shaped wing panels of high-speed aircraft as an assemblage of smaller panels of simple triangular shape. This was a breakthrough as it made it possible to model two- or three-dimensional structures as assemblages of similar two- or three-dimensional pieces rather than of one-dimensional bars. Greenstadt (1959) divided a domain into cells, assigned a different function to each cell, and applied a variational principle. White (1962) and Friedrichs (1962) used triangular elements to develop difference equations from variational principles. The name of the method, "*finite elements*", first appeared in Clough’s (1960) paper. Melosh (1963), Besseling (1963), Jones (1964), and Fraeijs de Veubeke (1964) showed that the FEM could be identified as a form of the Ritz variational method using piecewise-defined trial functions. Zienkiewicz & Cheung (1965) showed that FEM is applicable to all field problems that could be placed in variational form.

In order to better conform to curve boundaries, curved finite elements have been widely used in recent years (Ertürk, 1995). Such elements are called the "isoparametric" elements (Zienkiewicz, 1971). Irregular computational grids have become increasingly popular for a wide variety of numerical modeling applications as they allow points to be situated on curved boundaries of irregularly shaped domains.

### 2.1. Basics of Finite Element Methods

FEM is a numerical technique for finding an approximate numerical solution to the governing equations of a problem. FEM is applicable to solid mechanics, heat transfer, fluid flow, etc.
transfer, fluid mechanics, acoustics, electro-magnetism and quantum mechanics problems. Those problems can be described by differential, integral or variational equations; they can be boundary-value, eigen-value or initial-value problems. The domain of the problem may be a complicated or a simple geometry. Physical properties (density, conductivity, etc.) may vary throughout the domain. Boundary conditions or initial conditions can be given in many different forms (Burnett, 1987).

For most practical problems, it is impossible to find an explicit expression for the unknown, in terms of known functions, which \textit{exactly} satisfies the governing equations and the boundary conditions. The purpose of the FEM is to find an explicit expression for the unknown, in terms of known functions, which \textit{approximately} satisfies the governing equations and the boundary conditions (the approximate solution may satisfy some of the boundary conditions exactly).

FEM uses a trial-solution approach in order to obtain an approximate solution. The trial-solution approach has three major steps:

- Start with an approximate solution for the unknown
- Apply an optimizing criterion to the approximate solution
- Estimate the accuracy of the approximate solution

There are two major types of optimizing criteria, which can be applied to the approximate solution:

- Methods of Weighted Residuals (MWR), which is used when the governing equations are differential equations (Canuto \textit{et al.}, 1988).
• Ritz Variational Method (RVM), which is used when governing equations are variational (integral) equations (Krasnov et al., 1975 and Mura and Koya, 1992).

MWR criteria try to minimize an expression of error in the differential equation, while RVM try to minimize some physical quantity, such as energy. Some of the most popular MWR criteria are collocation method, sub-domain method, least-squares method and Galerkin Method. The FE model adopted in this study, ADAM model (see Chapter 3), uses the Galerkin method as an optimizing criterion.

Accuracy can be defined as the closeness of the approximate solution to the exact solution. If the estimate of accuracy is not in an acceptable range then the trial solution will be constructed again and the same procedure will be applied until an acceptable accuracy is reached.

First step in applying FEM to a system is to divide the domain into rectangular or triangular elements. In the next section, the procedure adopted in this study for generating a mesh in the Great Bay Estuary is explained.

2.2. Mesh Generation in the Great Bay Estuary System

In order to use ADAM model (see next chapter for detail), a mesh defining the system of interest with triangular elements is needed. A public domain search for mesh generation software uncovers two results:

• MESHTOOLS developed for MATLAB by Tom Gross from Skidaway Institute of Oceanography, Savannah, Georgia and
• TRIANGLE developed by Jonathan Richard Shewchuk from the Carnegie Mellon University, Pittsburgh, Pennsylvania as a part of the parallel FEM tools generation project Archimedes.

License and version problems in MATLAB and lack of documentation for MESHTOOLS directed us to use TRIANGLE for the present purpose. TRIANGLE is well documented, capable of doing all the calculations and refinements needed for mesh generation and is proven to work correctly. All the meshes generated in this study were created using TRIANGLE (see http://www.cs.cmu.edu/~quake/triangle.html).

2.2.1. FE Mesh Generation Tool, TRIANGLE

Basic finite element mesh generation is almost a standard procedure. It consists of a Delaunay triangulation routine complemented with refinement and interpolation routines. A Delaunay triangulation of a point set is a triangulation of the point set with the property that no point in the point set falls in the interior of the circumcircle (circle that passes through all three vertices) of any triangle in the triangulation (Figure 2-1). The circumcircle of a triangle is the unique circle that passes through all three vertices of the triangle (Shewchuk, 1996).

A triangle is said to be bad if it has an angle too small or an area too large to satisfy the user’s constraints. A bad triangle is split by inserting a vertex at its circumcenter (the center of its circumcircle); the Delaunay property guarantees that the bad triangle is eliminated.
Figure 2-1. Each bad triangle is split by inserting a vertex at its circumcenter and maintaining the Delaunay property (Shewchuk, 1996).

TRIANGLE can generate meshes in two different ways. The first one is by reading a PSLG file with an extension (.poly), which can specify points, segments (shorelines), holes (islands), and regional attributes and area constraints. A Planar Straight Line Graph (PSLG) is a collection of points and segments. Segments are simply edges whose endpoints are points in the PSLG. The second way is by reading a standard node and an element connectivity file. The node files have an extension (.node) and the element files have an extension (.ele). In this study, a PSLG file was used to generate the initial mesh. TRIANGLE generates exact Delaunay triangulations, constrained Delaunay triangulations and conforming Delaunay triangulations.

A constrained Delaunay triangulation of a PSLG is similar to a Delaunay triangulation but each PSLG segment is present as a single edge in the triangulation. A conforming Delaunay triangulation of a PSLG is a true Delaunay triangulation in which each PSLG segment may have been subdivided into several edges by the insertion of additional points. These inserted points are necessary to allow the segments to exist in the mesh while maintaining the Delaunay property.

Conforming Delaunay triangulation of a PSLG can be generated with no small angles and are thus suitable for finite element analysis. TRIANGLE is capable of refining
already existing meshes by imposing maximum triangle areas or by defining minimum element angles. In this way, attributes belonging to each node are also interpolated.

2.2.2. Extracting Data for the Mesh Generation

The first step in creating a FE mesh for Great Bay Estuary system is to define the shoreline boundary. The mean high water (MHW) level as it appears on USGS 1:25000 metric 7.5-minute topographic charts is used for this purpose. Second step is to identify the open boundaries at the mouth of the estuary and at the upriver ends of the rivers that empty into the Great Bay. A straight line going from Kittery Point to the Odiornes Point on Newcastle Island is used as the open boundary. The dams on the rivers as identified on the USGS charts are used as upper open boundaries. Third step is to identify all the island MHW shorelines in the estuary system. They are input as holes into the mesh generation program, TRIANGLE. Then some of the islands are regrouped and/or eliminated. The very small islands are eliminated, while some very close ones are connected together. After this procedure, the number of islands is decreased from 62 to 21. It is presumed that these improvements will have no significant effect on the results since they are not to interfere with the main estuary circulation at a high rate.

The coordinates of all the boundaries are extracted from UNH Jere A. Chase Ocean Engineering Laboratory archives, which are in Arc/Info GIS (Geographical Information System) format. The NAD83 (North American 1983 Datum) is used to convert these coordinates to New Hampshire State Plane Coordinate System, which has its origin at Universal Transverse Mercator, Zone 19. This conversion from latitude longitude format to meters is necessary for finite element modeling purposes. The finite
element nodes with known depths are entered into the improved Arc/Info maps by
digitizing them from NOAA nautical charts. The NOAA charts are mainly prepared for
navigational purposes and give the depths in feet at mean lower low water.

Bathymetry resolution is the main problem. The bathymetric depths have to be
interpolated from the data that is available. There is a lack of detail in depth readings
especially between Piscataqua River Bridge and the Railroad Bridge in Piscataqua River.
At a later stage, more bathymetry data is taken throughout the Great Bay Estuary by Ata Bilgili (graduate student at Jere A. Chase OEL) and is blended with the existing data.

2.2.3. Preliminary Meshes for the Great Bay Estuary System

The extracted boundary and node coordinates are converted to a format that can
be used with TRIANGLE. The mesh is improved by refining the boundaries where large
amounts of very small elements are clustered. The mesh is refined using TRIANGLE
with a minimum angle of 30° restriction in order to avoid possible numerical instabilities
with any finite element model in the future. The “GBEST1” mesh is created to model the
whole estuary system with our best available bathymetric data. GBEST1 mesh has 26455
nodes and 46740 elements. Since it exceeds the computational limitation in the beginning,
the "divide and conquer" strategy is adopted.

Considerable effort is put in modeling the entire Great Bay Estuary System with
ADAM model. The mesh is subdivided into small enough sections to simulate individual
rivers and smaller regions of interest, with the final goal of simulating the whole Great
Bay Estuary System including only the essential components in order to fit the
computational limitation. This strategy enables us to gain valuable experience on the
limitation of ADAM software in modeling the realistic features and processes occurring in the domain, and the importance of each sub-domain contribution to the entire estuary system. Detailed simulation results of each component of the estuary system and a vast combination of the important components are obtained. Results include mass conservation, residual current, transports, bottom stress, and sediment transport at dynamical equilibrium, time series of the non-linear asymmetric flood and ebb cycle as M2 tidal forcing is applied at the appropriate open boundaries with predicted elevation data from Swift and Brown (1983). Most of the simulation results are presented at:

http://nemo.unh.edu/safak/introduction.html

The sub-domains include the following meshes (see Table 2-1.):

- **BR5**: models the Bellamy River.
- **YR5**: models the Oyster River.
- **port3**: models the waterway between the Portsmouth Harbor and the Lower Piscataqua River.
- **gbay6**: models the Great Bay area including the Great Bay, the Little Bay, the Squamscott River, the Winnicut River, and the Lamprey River.
- **pby**: models the Bellamy, the Piscataqua and the Oyster Rivers.
- **pr6**: models the Lower and the Upper Piscataqua River.
- **gbriv**: models the Great Bay, the Little Bay with the Oyster and the Bellamy Rivers.
- **phriv**: models the Portsmouth Harbor section and the Lower and the Upper Piscataqua Rivers.
Table 2- 1. Numeric and geomorphologic properties of the preliminary meshes used during the modeling efforts for the Great Bay Estuary system. All the coordinates are given in New Hampshire State Plane coordinate system (NAD83).

<table>
<thead>
<tr>
<th>Mesh Name</th>
<th>Number of nodes (NN)</th>
<th>Number of Elements (NE)</th>
<th>Band width (BW)</th>
<th>Horizontal coordinate (m)</th>
<th>Bathymetry Range (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BR5</td>
<td>1054</td>
<td>1828</td>
<td>49</td>
<td>$365106 \leq x \leq 367128$</td>
<td>$70202.4 \leq y \leq 75121.8$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$0 \leq h \leq 7.1$</td>
<td></td>
</tr>
<tr>
<td>YR5</td>
<td>1409</td>
<td>2415</td>
<td>63</td>
<td>$360905 \leq x \leq 365071$</td>
<td>$69128.7 \leq y \leq 71114.7$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$0 \leq h \leq 8.79$</td>
<td></td>
</tr>
<tr>
<td>port3</td>
<td>8577</td>
<td>14974</td>
<td>243</td>
<td>$372036 \leq x \leq 380827$</td>
<td>$60711.9 \leq y \leq 68562.7$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$0 \leq h \leq 25.4$</td>
<td></td>
</tr>
<tr>
<td>gbay6</td>
<td>10439</td>
<td>18526</td>
<td>211</td>
<td>$358339 \leq x \leq 367989$</td>
<td>$54003.1 \leq y \leq 69333.8$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$0 \leq h \leq 21.8$</td>
<td></td>
</tr>
<tr>
<td>pby</td>
<td>8621</td>
<td>15404</td>
<td>173</td>
<td>$360905 \leq x \leq 372255$</td>
<td>$66089.1 \leq y \leq 79516$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$0 \leq h \leq 23.0$</td>
<td></td>
</tr>
<tr>
<td>pr6</td>
<td>3417</td>
<td>6043</td>
<td>79</td>
<td>$365955 \leq x \leq 372244$</td>
<td>$66835.2 \leq y \leq 79516$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$0 \leq h \leq 18.93$</td>
<td></td>
</tr>
<tr>
<td>gbriv</td>
<td>10223</td>
<td>18710</td>
<td>199</td>
<td>$360905 \leq x \leq 368805$</td>
<td>$61030.5 \leq y \leq 75121.8$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$0 \leq h \leq 23.0$</td>
<td></td>
</tr>
<tr>
<td>phriv</td>
<td>12113</td>
<td>21235</td>
<td>243</td>
<td>$365955 \leq x \leq 380827$</td>
<td>$60711.9 \leq y \leq 79516$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$0 \leq h \leq 25.4$</td>
<td></td>
</tr>
</tbody>
</table>
Figure 2-2. Bellamy River (BR5) mesh has 1054 nodes and 1828 triangular elements. Maximum depth value in this section is 7.1m.
Figure 2-3. Oyster River (YR5) mesh has 1409 nodes and 2415 elements. Maximum depth value in this section is 8.79m.
Figure 2-4. Portsmouth Harbor (port3) mesh has 8577 nodes and 14974 elements. Maximum depth value in this section is 25.4m.
Figure 2-5. Great Bay (gbay6) mesh has 10439 nodes and 18526 elements. Maximum depth value in this section is 21.8m.
Figure 2-6. Three River (pby) mesh has 8621 nodes and 15404 elements. Maximum depth value in this section is 23.0m.
Figure 2-7. Piscataqua River (pr6) mesh 3417 nodes and 6043 elements. Maximum depth value in this section is 18.93m.
Figure 2-8. Great Bay (gbriv) mesh with the Oyster and Bellamy rivers has 10223 nodes and 18710 elements. Maximum depth value in this section is 23.0m.
Figure 2-9. Portsmouth Harbor and Piscataqua River (phriv) mesh has 12113 nodes and 21235 elements. Maximum depth value in this section is 25.4m.
All the above-mentioned meshes are then merged and some small tributaries are cut and the GBES4 mesh is obtained. GBES4 is the master mesh, which is used for simulating the whole estuary. The master mesh is cut into pieces when needed for individual purposes.

The bathymetry in the channels in Great Bay area is then fine-tuned with the data obtained through personal communications with Dr. Fred Short at Jackson Estuarine Laboratory. The mesh with the detailed bathymetry in the Great Bay section is called the "gbay18" mesh. The details of this mesh with the bathymetry contours are shown in Figure 2-10.
Figure 2-10. Bathymetry contours and the final mesh detail of the gbes18 mesh.
CHAPTER 3

HYDRODYNAMIC MODEL, ADAM

Shallow, small-scale estuaries are non-linear. The hydrodynamics in these estuaries are well described by the classic two-dimensional shallow water equations. However, small length scales, combined with near-critical flow conditions as the depth approaches zero, makes the control of advection the dominant computational theme, even when other processes are physically dominant.

3.1. Modeling Efforts in the Great Bay Estuary

Great Bay Estuary is a complex, small-scale, well-mixed estuary. There has been several hydrodynamic modeling and field measurement efforts in the Great Bay Estuary system.

National Ocean Survey (NOS) and UNH carried out a cooperative field program in the Great Bay Estuary during the summer of 1975. Swenson et al. (1977) summarized the current and sea level data from the NOS/UNH program.

Reichard (1976) applied Connor and Wang’s (1973) 2-D finite element model to Portsmouth Harbor, Piscataqua River, Little Bay and Great Bay segments of the estuary. This model was not capable of handling mud flats, and these areas were neglected.

The temperature, salinity, and density distribution in the Great Bay Estuary was given in Silver and Brown (1979). These results verify that most of the estuary is well
mixed. Brown and Arellano (1979) applied a tidal prism model to the Great Bay Estuary and assessed its performance by comparing salinity predictions with the observations.

Brown and Trask (1980) obtained cross-sectional distributions of longitudinal current for two transects bracketing a bottom mounted current meter.

Schmidt (1980) used a dye tracer in the Lower Piscataqua to provide data for calibrating a finite element dispersion model.

In 1981, an oil spill trajectory model (SLICK) was developed for the Great Bay and the Piscataqua River by the Department of Mechanical Engineering at the University of New Hampshire in cooperation with the Normandeau Associates, Inc. SLICK was an interactive program.

Swift and Brown (1983) used harmonic data analysis to compute tidal constituents for the current and sea level values at specified stations.

In 1989, the Piscataqua Oil Spill Trajectory and Response (PROSTAR) program was developed at UNH and was used by McDonald (1992) to determine the course of an oil spill and likely points of contact with the shoreline.

Clere (1993) measured velocities and water levels and calibrated the two-dimensional model, RMA-2V (hydrodynamic model of TABS-2), in order to determine the water levels and current speeds and directions for the nodes of the mesh network.

Chadwick (1993) and Pavlos (1994) used DYNHYD3, the hydrodynamic section of WASP3 model. This model was a one-dimensional box model developed by the Environmental Protection Agency (EPA), designed to predict the velocities in a river or an estuary. It was based on the one-dimensional forms of continuity and momentum equations and an explicit finite difference approach.
The hydrodynamic models used so far were not capable of handling the wetting/drying processes on the tidal flats in Great Bay, which cover over 50% of the surface area. In this study, a two-dimensional, non-linear, time stepping finite element model, which can handle wetting/drying by a porous medium approach is adopted.

3.2. **ADAM Model**

ADAM model was originally developed at Dartmouth College by Dr. Daniel R. Lynch and Dr. Justin T. Ip (Ip et al., 1998). ADAM model incorporates two-dimensional wave physics, with a porous medium beneath the sediment surface to simulate wetting and drying process of tidal flats on a fixed, high-resolution mesh.

The objective of this study is to investigate the friction effects of eelgrass on the tidal flow in Great Bay. The area of interest, particularly the Great Bay and the Little Bay section, is characterized by a network of channels with tidal flats on the sides. The primary reason in choosing ADAM model was the importance of the wetting/drying process on the tidal flats. The following reasons are also taken into account:

- The Great Bay Estuary is small enough to neglect Coriolis accelerations, and it is vertically mixed. ADAM model is a depth-integrated (two-dimensional) model, which may adequately treat the dynamics in the Great Bay Estuary system.

- The primary force balance is between friction and the pressure gradient in most shallow tidal embayments (Friedrichs et al., 1992). Swift and Brown (1983) verified this balance observationally throughout the Great Bay Estuary system. In ADAM model, the acceleration terms in the momentum equation are neglected and the force balance is
reduced to its simplest form, which is the balance between the bottom friction and the pressure gradient.

- The representation of the flow regime at very low water levels has been a problem. In some models, the elements are entirely deactivated when they are sufficiently dry. However, this approach causes some numerical instabilities as the depth goes to zero. Operational simplicity demands a fixed-grid approach, variable local resolution, and an algorithm, which is not dominated by numerical control of advection in situations where it is unimportant. In the ADAM model, a heterogeneous porous medium underlying the water column is used to represent the continuous, slow drainage. Flow in the porous medium is described by Darcy's law (see Appendix A).

- In time stepping models, the governing equations are discretized in time using a finite difference strategy. The main advantage of time stepping models is their ability to incorporate all the non-linearities. The most significant disadvantages are issues regarding proper specification of time dependent boundary conditions and forcing, the large size of output data sets, and the computational time required (on the order of days in this case). In the ADAM model, the non-linear diffusion equation is discretized with linear finite elements by the Galerkin method (see Appendix B) in space and solved implicitly by iteration in time. The time dependent boundary conditions and forcing is easy to specify. The priority is to resolve the non-linearities. In order to resolve the non-linearities, the computational time and the storage space are sacrificed.
3.3. **Governing Equations**

The governing equations are the non-linear, two-dimensional shallow water equations. Vertically averaged horizontal velocities \( \bar{u} \) and \( \bar{v} \) are

\[
\bar{u} = \frac{1}{h + \xi} \int_{-h}^{h} u \, dz, \quad \bar{v} = \frac{1}{h + \xi} \int_{-h}^{h} v \, dz
\]

The continuity equation is:

\[
\frac{\partial [u(h + \xi)]}{\partial x} + \frac{\partial [v(h + \xi)]}{\partial y} + \frac{\partial (h + \xi)}{\partial t} = 0
\]

in a more compact form the continuity equation is

\[
\frac{\partial H}{\partial t} + \nabla.HV = 0 \quad (3.1)
\]

The horizontal momentum equation is:

\[
\frac{\partial V}{\partial t} + V \cdot \nabla V + g \nabla \zeta + \frac{C_d}{H} |V|V = 0 \quad (3.2)
\]

Symbol definitions:

- \( g \) gravitational acceleration
- \( h \) bathymetric depth
- \( \xi \) surface elevation
- \( H \) total depth of water column
- \( C_d \) bottom friction coefficient
- \( \bar{u}, \bar{v} \) Cartesian components of vertically averaged horizontal fluid velocity
- \( u, v \) Cartesian components of horizontal fluid velocity
- \( V \) vertically averaged fluid velocity with Cartesian components \( (\bar{u}, \bar{v}) \)
- \( x, y \) Cartesian coordinates, positive eastward and northward
- \( t \) time

As the primary force balance is between the bottom friction and the pressure gradient in shallow tidal embayments (Swift and Brown, 1983), the acceleration terms are negligible and the momentum balance becomes
\[ g \nabla \xi + \frac{C_d}{H} \nabla |V|V = 0 \]  \hspace{1cm} (3.3)

Then

\[ V = -\sqrt{\frac{g \nabla \xi H}{C_d}} \]  \hspace{1cm} (3.4)

Defining transport \( q \) as \( q = HV \) and substituting Eq.(3.4)

\[ q = -\sqrt{\frac{gH^3}{C_d \nabla \xi}} \nabla \xi \]  \hspace{1cm} (3.5)

Eq.(3.5) is then substituted into the continuity equation, Eq.(3.1), to obtain the so-called “kinematic” equation:

\[ \frac{\partial \xi}{\partial t} - \nabla \cdot D \nabla \xi = 0 \]  \hspace{1cm} (3.6)

with non-linear diffusion coefficient \( D \):

\[ D = H \sqrt{\frac{gH}{C_d \nabla \xi}} \]  \hspace{1cm} (3.7)

3.4. Handling The Porous Medium

Adding a porous layer beneath the sediment surface allows a natural transition, as the water level is lowered, from pure open-channel flow to a Darcian flow (Appendix A). To achieve this transition, the variation of the porosity and conductivity of the medium is specified as a function of depth. As a result, “dry” areas continue to participate hydraulically in the overall system, and the free surface is allowed to fall below the usual bathymetric depth, providing increased stability to the numerical solutions.
Figure 3-1. Schematic geometry of the porous medium beneath the sediment surface in ADAM model (Ip et al., 1998).

The combined open channel and porous medium system is described by

\[ q = q_0 + q_p = -DV_\xi \]  \hspace{1cm} (3.8)

\[ S \frac{\partial \xi}{\partial t} - \nabla D \nabla \xi = 0 \]  \hspace{1cm} (3.9)

where \( q_0 \) is the transport in the open channel; \( q_p \) is the porous medium transport; \( S \) is the storage coefficient specified as a function of \( \xi \). And \( z \) (\( S=1 \) in open channel and \( S=\varepsilon \), porosity, in porous medium). The non-linear diffusion equation, Eq.(3.9), is discretized with linear finite elements by the Galerkin method in space (Appendix B) as

\[ S^{m+\theta} \left[ \frac{\xi^{m+1} - \xi^m}{\Delta t} \right] - \nabla D^{m+\theta} \nabla \left[ \theta \xi^{m+1} + (1-\theta)\xi^m \right] = 0 \]  \hspace{1cm} (3.10)

where \( \theta \) is the numerical implicity. The solution to the above equation is obtained iteratively in each time step.
3.4.1. **Equations in the Wet (saturated) region where $H > h_0$:**

The total transport in the wet region is:

$$q = q_p + q_0 = -D \nabla \xi$$

$$q_p = -K h_0 \nabla \xi \quad \text{and} \quad q_0 = -\sqrt{\frac{g(H - h_0)^3}{C_d|\nabla \xi|}} \nabla \xi$$

$$q = -K h_0 \nabla \xi - \sqrt{\frac{g(H - h_0)^3}{C_d|\nabla \xi|}} \nabla \xi$$

with the diffusion coefficient

$$D = K h_0 + \sqrt{\frac{g(H - h_0)^3}{C_d|\nabla \xi|}}$$

and the velocity

$$v = v_o + v_p$$

where $v_o = \frac{q_0}{H - h_0}$ and $v_p = \frac{q_p}{h_0 \varepsilon}$

3.4.2. **Equations in the Dry (unsaturated) region where $H < h_0$:**

The transport in the dry region is:

$$q = q_p + q_0 = -D \nabla \xi$$

$$q_p = -K H \nabla \xi \quad \text{and} \quad q_0 = 0$$

with the diffusion coefficient

$$D = KH$$

and the velocity is

$$v = v_o + v_p$$

where $v_o = 0$ and $v_p = \frac{q_p}{H \varepsilon}$
3.5. **Parameters Used in the ADAM Model Simulations**

**Porous Layer Thickness**: A heterogeneous porous medium underlying the water column is used. Porous layer thickness is taken 1m, which is approximately half of the tidal range in order to handle the drying process on the tidal flats in Great Bay.

**Porosity and Hydraulic Conductivity**: For porosity value, $\varepsilon$, 0.35 is used which is roughly between the porosity value for sand ($\varepsilon=0.25$) and clay ($\varepsilon=0.50$) and the hydraulic conductivity is set to $3.162\times10^{-4}$ everywhere in the estuary.

**Time Step Size**: At the beginning 400 time steps per tidal $M_2$ cycle (12.42 hr) is used. After performing a convergence study on the time step size, it is found that the reduction on the number of time steps from 400 to 300 does not have a significant effect on the model results.

**Length of Simulation**: The length of simulations are dependent on the boundary forcing. A minimum number of tidal cycles necessary to resolve the boundary forcing time series is used (see Chapter 6).

3.6. **The Program Structure**

**Main Program and Fixed Subroutines**: ADAM2_v3.f is the core program, which performs all finite element assembly and solution operations with the backing of the fixed subroutines. ADAM2_v3.f reads formatted input files and writes a formatted echo file, the latter containing a summary of the input files and run data.
**User Subroutine:** A user-built subroutine must be linked to ADAM2_v3.f to specify the boundary forcing and the format in which the results are to be output.

**Include File:** The include file ADAM.DIM assigns values to parameters required for dimensioning purposes.

**Input Files:** The horizontal coordinates of each node in the mesh are given in a node file with the name ‘meshname’.nod. The bathymetry values of each node in the mesh are given in a bathymetry file named ‘meshname’.bat. The order of elements as they appear in the mesh is given in an element file named ‘meshname’.ele. The boundary node numbers where the tidal elevation forcing is applied are given in an elevation file.
named 'meshname'.elv. The initial surface elevation and initial bottom friction coefficient at each node are given in two separate files named 'meshname'/zinit.s2r and 'meshname'/simulation-name'.s2r, respectively.

All the files are in ASCII format. The input file formats are used without any change in the MATLAB routines, which were generated for post-processing purposes.

3.6.1. **Standard Output Files**

'meshname'.echo : This file contains useful information regarding the size of dimensional arrays, and the names of the input files.

'meshname'.log : If the run is terminated due to dimensioning or boundary condition problems, log file gives a message describing the error.

v.v2r_e: This file is a 2-D, real valued, vertically-averaged horizontal velocity field. There are two header lines:

- line 1: the geometric meshname
- line 2: reserved for the user's description of the file

Following these lines, there are NE lines of the form:

1  UOC(I)  VOC(I)

Where: (UOC,VOC) are the (x, y) components of horizontal velocity in the open channel (MKS).

The loop is over the elements: I=1,NE and NE is the number of elements in the 2-D mesh.
q.v2r_e: A 2-D real valued vertically-averaged transport field. There are two header lines:

line 1: the geometric meshname

line 2: reserved for the user's description of the file.

Following these lines, there are NE lines of the form

I QUE(I) QVE(I)

Where: (QUE, QVE) are the (x, y) components of horizontal transport (MKS).

The loop is over the elements: I=1,NE and NE is the number of elements in the 2-D mesh.

z.s2r: A 2-D real valued scalar field (tidal elevations). There are two header lines:

line 1: the geometric meshname

line 2: reserved for the user's description of the file

Following these lines, there are NN lines of the form

I ZN(I)

Where: ZN(I) is the scalar value at node I (MKS).

The loop is over the nodes: I=1,NN and NN is the number nodes in the 2-D mesh.

Any other output format is dependent on the user's treatment of the User Subroutines. Residual velocity, residual transport and residual bottom stress at the end of each tidal cycle can be output in ASCII format.

The output files that are used in the MATLAB routines are created for visualization purposes. It is possible to create animation files with the output data in order to visualize the wetting/drying process in detail.
CHAPTER 4

EELGRASS (ZOSTERA MARINA, L.)

4.1. Functions of Eelgrass in an Estuary

Eelgrass (Zostera marina L.) is a submerged plant that grows exclusively in estuaries and in shallow coastal areas with moderate currents and soft beds. Eelgrass has leaves, stems, and roots. Eelgrass is the most common temperate seagrass species in the North Atlantic. Tremendous variation in size in the length of eelgrass blades can be found from 6 cm to over 300 cm long. The blades connect to the rhizome at the sediment surface with roots extending into the substrate of each rhizome node. A terminal mature shoot occurs at the end of each rhizome, with the young shoots occurring as lateral branches. A sheath at the base of the blade encompasses 3-5 strap-like leaves.

Figure 4-1. Eelgrass, Zostera marina L. (Fonseca et al., 1998).
Greenish female flowers at the ends of long stems float on the surface of water. The male flowers are clustered on short stems near the base of the plant. As the male flowers grow, they detach from the stem and rise to the surface of water. They release pollen into the water. When the pollen and the female flower meet, they fertilize and produce seeds (Compton, 1999).

Eelgrass habitats are one of the most productive ecosystems. Eelgrass plays several important roles in its environment. Some of them are as follows:

- Eelgrass forms the base of food chain (Botos, 1999)
- Eelgrass grows easily and provides oxygen for the animals in the ecosystem.
- When eelgrass dies, the dead leaves increase the organic matter in water providing valuable food for water birds, such as ducks and geese.
- Eelgrass beds serve as shelter for many marine and estuarine creatures. They attract large predatory fish for feeding (Short, 1992).
- Eelgrass meadows act as a filter of estuarine waters, removing both suspended sediments and dissolved nutrients (Short and Short, 1984)
- Eelgrass beds prevent erosion and maintain sediment stability by trapping sediment with its rhizomes (Ward et al., 1998).
- Eelgrass leaves form a three-dimensional baffle in the water, they act as dampers and reduce water motion, alter the current circulation and flow patterns (Grizzle et al., 1996).
4.2. **Effects of Eelgrass on Current Flow**

Eelgrass strongly affects local current flow and sediment dynamics and reduces current flow within the eelgrass meadow. The momentum extracted by exposed shoots significantly reduces current speeds within the meadow (Harlin *et al.*, 1982, Madsen & Warncke, 1983, Peterson *et al.*, 1984 and Fonseca *et al.*, 1983). The perturbations in flow and sediment transport caused by sea grass meadows may significantly affect the ecology of the resident community. Eckman (1987) suggested that:

- Current flux through the meadow depends directly on the density of eelgrass shoots,

- Rates of recruitment of bivalves onto eelgrass blades vary directly with the shoot density dependent current flux,

- Subsequent growth rates and survival of suspension feeding bivalves vary directly with the shoot density dependent flux of seawater through the meadow.

Fonseca and Kenworthy (1987), in preliminary laboratory studies, suggest that currents affect leaf production of eelgrass. Current velocity, together with wave action, creates hydraulic regimes that influence eelgrass and seedling distribution, which in turn affects the flow field. Thus, when models of are constructed for eelgrass-dominated estuaries, consideration of frictional drag due to the eelgrass may have a significant impact on the model predictions.
4.3. Disturbance Sources of Eelgrass

Eelgrass meadows require high light levels for their growth, which restricts them to shallow coastal areas where they are susceptible to human disturbances that may damage or kill them. The disturbance sources of eelgrass can be listed as follows:

1. Human Related Disturbance Sources
   - Dredging and filling
   - Mooring scars
   - Propeller scars
   - Jet skis
   - Vessel wakes
   - Reduction in water quality (including water clarity)

2. Natural Disturbance Sources:
   - Diseases
   - Physical disruptions from storms and shifting channels redefine bed distribution and composition.
   - Seasonal disturbances (low tides which expose and desiccate beds)
   - Catastrophic events like hurricanes
   - Biological disturbance
   - Ice scour, extreme cold
   - Thermal effluents from electric power plants

4.3.1. Wasting Disease (Bridges and Phillips, 1999)

In 1931, the Wasting Disease is first observed in areas along the northeast coast of North America. The signs were blackish-brown discolorations, loss of leaves and finally the death of the eelgrass. Later, the Wasting Disease was observed in Europe. By 1933,
almost all eelgrass in the North Atlantic was affected. All of the eelgrass in most areas of
the Atlantic coast disappeared in one year.

Finding some organisms in the dying eelgrass beds lead scientists to assume that
the eelgrass destruction was caused by an infection of an epidemic organism. However,
later they observed that in Mediterranean and the Pacific coast of North America the
eelgrass was unaffected. Some scientists proposed that there was a correlation between
shifting periods of droughts and above-average precipitation with the disease.

Another theory is that of increased water temperature. Rasmussen (1977) collected records of water temperature and showed that temperatures in the early 1930’s
did not increase on the Pacific coast of North America and in the Mediterranean, while it
increased significantly in the North Atlantic. High temperatures weakened plants that then
became exposed to a variety of biological organisms.

Several scientists have theorized that in the early 1950s when eelgrass, particularly in the western Atlantic, began to reestablish themselves in suitable estuarine
areas, the colonizing plants were hardier and more resistant strain.

4.4. Restoration and Mitigation Efforts of Seagrass Habitats

Loss of eelgrass habitat leads to several undesirable and difficult-to-reverse
conditions. Shoreline erosion and water column turbidity increase. All important,
associated habitat functions are eliminated (Kikuchi, 1980 and Peterson, 1982). When
eelgrass dies, the sediments it helped to stabilize will resuspend into the water column.
Resuspended sediment lowers light levels that may not allow future eelgrass to recover
unless the water clarity is improved.
Disturbances rapidly kill seagrass while recovery is very slow. The critical role that seagrasses play in many coastal environments, coupled with their extensive losses, have created widespread support for their conservation and restoration. As the human population grows, loss of the seagrass communities continues. When protection programs fail, active planting seems to be the only option to avoid a permanent loss of these habitats. At present, there have been two types of planting processes going on in order to preserve the present habitats (Fonseca et al., 1998):

- **Restoration**: In the restoration process, the habitats are being returned to their pre-existing condition.
- **Mitigation**: In the mitigation process, the functionally equivalent areas are being restored or created to compensate for permitted habitat losses.

Seagrass restoration has been conducted on an experimental scale along all coasts and within all coastal regions of the U.S. However, the mitigation of impacts resulting from permitted activities has been relatively small. The greatest efforts have been in the National Marine Fisheries Service (NMFS) Southeast and Southwest regions. While permits have been reviewed which deal with seagrass habitat, few actions are taken. Site selection and test planting for a 3-acre mitigation in the Piscataqua River (NH) has been the first permit-related mitigation, which NMFS has been involved in making recommendations. This has included not only transplanting but also consideration of alteration of bottom topography to achieve appropriate planting depths for eelgrass (Fonseca et al., 1998).

Eelgrass and the ecosystem it fosters are an important component of the Great Bay Estuary. Short (1992) documented the importance of eelgrass in the Great Bay ecosystem.
Eelgrass covers big areas, especially in the Great Bay region. The eelgrass distribution changes seasonally. In Chapters 7, 8 and 9, the frictional effects of eelgrass on the tidal flow in Great Bay will be explored in detail.
CHAPTER 5

TIDES AND TIDAL FORCING

Gravitational attraction of the sun and the moon are responsible for the tidal motions on the earth. Tides are caused by the movement of the sun and the moon relative to points on the earth’s surface. Gravitational force is proportional to the product of the masses of the two objects and inversely proportional to the square of the distance between them. The mass of the sun is about $2.5 \times 10^7$ times that of the moon. The distance between the sun and the earth is 400 times longer than the distance between the moon and the earth. Thus, tidal forces produced by the moon are slightly more than twice those of the sun (Knauss, 1997).

The tides in the global oceans cause the rhythmic rise and fall of sea level along the world’s coastlines. In some places, the sea level rises and falls with a period of about half a day (these are called semi-diurnal tides), whereas in other places the period is more like a day (called diurnal tides). In some places, the tides are mixed, with changing periods during the year, when the sun and the moon line up with the Earth.

To model tidal motions, it is necessary to prescribe the astronomical forcing. The tidal forcing term in the equations of motion can be expressed as a Fourier series, with each term representing a tidal constituent. There are many tidal constituents. Most of the tidal constituents are given in Table 5-1.
In order to make tidal predictions at a location, one must have tidal records at that location. Harmonic analysis helps to determine the role of tidal constituents at the given location. Using astronomical tables, future ocean tides can be predicted at a given location.
5.1. **Boundary Conditions**

Three different types of boundary conditions can be specified for FE model simulations:

- **Essential Boundary Condition**: An equation relating the unknown value and/or of its derivatives up to order m-1, at the points on the boundary.

- **Natural Boundary Condition**: An equation relating the values of any of the derivatives of the unknown value from order m to 2m-1, at points on the boundary.

- **Mixed Boundary Condition**: A mix of the first two, containing the unknown and/or any of its derivatives up to order 2m-1.

Essential boundary conditions involve the lower-order derivatives and are sometimes referred to as Dirichlet boundary conditions. Natural boundary conditions involve the higher-order derivatives and sometimes referred to as Neumann boundary conditions. The mixed boundary conditions also referred as Robin boundary condition (Burnett, 1987).

\( M_2, S_2 \) and \( N_2 \) are the most dominant constituents in the Great Bay estuary system (Swift and Brown, 1983). Throughout this study, a harmonic analysis program TIDHAR was used to make predictions for the boundary forcing at the open boundaries of each mesh. For that purpose, 1975 observational data that we had in our archives was used.
5.2. Observational Data

During the summer of 1975, the University of New Hampshire (UNH) in cooperation with the National Ocean Survey (NOS) performed a comprehensive field program, designed to measure the tidal elevations and currents within the Great Bay Estuary.

UNH investigated the vertical and horizontal variability of estuarine currents and water properties at selected locations in the estuary. The purpose of the NOS survey was to update tidal elevation and current prediction data, redefine and update tidal datum planes for land movement and shoreline determination, and acquire water circulation data to be used for future ecological studies of the area.

The NOS deployed a number automatic digital recording (ADR) tidal gauges and current meters at stations shown in Figure 5-1. The ADR tide gauges recorded six-minute values of the sea level, as measured by a float in the standard NOS tidal well to a precision of better than 3 cm resolution.
Figure 5-1. Location map of the summer 1975, NOS/UNH sea level stations (•). The transects are the ones through which Swift and Brown (1983) estimated cross-section averaged currents.
5.3. **Sea Level Observations**

A harmonic analysis of the sea level records showed that the dominant $M_2$ semi-diurnal constituent amplitude decreases from 1.29m at open ocean station T-5 to 0.83m at station T-16 at the mouth of Bellamy River and increases throughout Little and Great Bays to the head of the inner estuary at station T-19 (Swift and Brown, 1983). The 70° phase lag of the sea level at station T-19 relative to the sea level at station T-5 explains most of the corresponding 2.5-hour time lag of total sea level.

<table>
<thead>
<tr>
<th>Station I.D</th>
<th>Tide Gage Type</th>
<th>Station Latitude (North)</th>
<th>Station Longitude (West)</th>
<th>Start Date</th>
<th>Start Time</th>
<th>End Date</th>
<th>End Time</th>
<th>No. of Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-5</td>
<td>ADR</td>
<td>43°04’25”</td>
<td>70°43’07”</td>
<td>06-24-75</td>
<td>00:00</td>
<td>09-29-75</td>
<td>23:00</td>
<td>97</td>
</tr>
<tr>
<td>Seavey</td>
<td>ADR</td>
<td>43°04’45”</td>
<td>70°44’30”</td>
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<td>00:00</td>
<td>12-31-75</td>
<td>23:00</td>
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<tr>
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<td>43°05’25”</td>
<td>70°45’50”</td>
<td>07-01-75</td>
<td>00:00</td>
<td>09-30-75</td>
<td>23:00</td>
<td>91</td>
</tr>
<tr>
<td>T-12</td>
<td>ADR</td>
<td>43°05’49”</td>
<td>70°47’00”</td>
<td>09-05-75</td>
<td>00:00</td>
<td>09-30-75</td>
<td>23:00</td>
<td>25</td>
</tr>
<tr>
<td>T-13</td>
<td>ADR</td>
<td>43°06’10”</td>
<td>70°47’40”</td>
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<td>00:00</td>
<td>09-30-75</td>
<td>23:00</td>
<td>29</td>
</tr>
<tr>
<td>T-14A</td>
<td>ADR</td>
<td>43°07’00”</td>
<td>70°48’45”</td>
<td>09-03-75</td>
<td>00:00</td>
<td>11-13-75</td>
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</tr>
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<td>00:00</td>
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</tr>
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<td>ADR</td>
<td>43°07’45”</td>
<td>70°50’50”</td>
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<td>00:00</td>
<td>08-11-75</td>
<td>23:00</td>
<td>21</td>
</tr>
<tr>
<td>UNH Resis.</td>
<td>ADR</td>
<td>43°05’25”</td>
<td>70°51’55”</td>
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<td>00:00</td>
<td>07-31-75</td>
<td>23:00</td>
<td>30</td>
</tr>
</tbody>
</table>
5.4. Current Observations

The NOS current time series are measured at the locations given in Table 5-3 and shown in Figure 5-1. A typical mooring consists of an anchored surface buoy, from which a string of Savonius rotor current meters were suspended and a heavy weight was added to minimize the current-induced tilt of the array. The nominal depths of the current measurements used are 4.6m and 9.2m, respectively. Any data pair whose direction falls outside ±15° of the mean direction is discarded. The remaining speeds and directions are averaged. The estimated precision of the measured current speed and direction are 2.6 cm/sec and ±2.5°, respectively, for zero tilt and speeds less than 52 cm/sec. The estimated precision of speeds greater than 52 cm/sec is about ±5.0 cm/sec (Swenson et al., 1977).

Swift and Brown (1983) describe how currents and sea levels were aggregated to form estuarine cross-section averaged longitudinal current time series at the above-mentioned locations. Observed cross-section averaged current is based on vertically averaged current measurements made at a single mooring at each cross-section. Two multipliers are applied to the axial component of the vertically averaged, station time series: one for the flood and one for the ebb. The multipliers are determined such that the net transport over the particular phase (flood or ebb) agrees with the cumulative tidal prism inland of the cross-section. Prism is estimated using nautical charts and average tidal ranges. The harmonic constants for the astronomical $M_2$, $S_2$, $N_2$, $K_1$, and $O_1$, tidal constituents, as well as the nonlinear shallow water constituents of $M_4$ and $M_6$ are determined by a harmonic analysis of these cross-section averaged current time series. The estimated uncertainty of the cross-section averaged currents is ±10%.
<table>
<thead>
<tr>
<th>Station I.D</th>
<th>Current Meter Type</th>
<th>Station Latitude (North)</th>
<th>Station Longitude (West)</th>
<th>Start Date</th>
<th>Start Time</th>
<th>End Date</th>
<th>End Time</th>
<th>No. of Days</th>
</tr>
</thead>
<tbody>
<tr>
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<td>A, B</td>
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<td>70°43'01&quot;</td>
<td>07-09-75</td>
<td>19:49</td>
<td>11-02-75</td>
<td>18:13</td>
<td>115</td>
</tr>
<tr>
<td>C-119</td>
<td>A, B</td>
<td>43°05'27&quot;</td>
<td>70°45'38&quot;</td>
<td>07-10-75</td>
<td>19:27</td>
<td>09-26-75</td>
<td>19:15</td>
<td>78</td>
</tr>
<tr>
<td>C-124</td>
<td>A</td>
<td>43°07'00&quot;</td>
<td>70°49'44&quot;</td>
<td>07-09-75</td>
<td>23:36</td>
<td>09-26-75</td>
<td>15:12</td>
<td>79</td>
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<tr>
<td>C-131</td>
<td>A, B</td>
<td>43°06'00&quot;</td>
<td>70°51'40&quot;</td>
<td>08-28-75</td>
<td>16:00</td>
<td>08-05-75</td>
<td>16:00</td>
<td>8</td>
</tr>
<tr>
<td>C-133</td>
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<td>43°04'55&quot;</td>
<td>70°52'06&quot;</td>
<td>08-11-75</td>
<td>16:00</td>
<td>08-23-75</td>
<td>16:00</td>
<td>12</td>
</tr>
</tbody>
</table>
CHAPTER 6

MODELING THE M\(_2\) TIDAL FLOW

FOR THE ENTIRE GREAT BAY ESTUARY

The principal lunar tide M\(_2\), with a period of 12.42 hours, has important influences on the regional currents. Therefore, the initial focus was centered on the M\(_2\) harmonic constituent and its biharmonics (such as M\(_4\) and M\(_6\)). The numerical ADAM model was tested for its ability to compute M\(_2\) tidal dynamics in the Great Bay Estuary. The database of M\(_2\) tidal elevations and currents from Swift and Brown (1983), were used in verification of the model and to test the assumptions made in the simulations.

In this chapter, the bottom friction coefficient is fine-tuned for the M\(_2\) tidal constituent until the model produced data that matched closely to the tidal analysis predicted for amplitude and phase data from Swift and Brown (1983).

6.1. Computational Setup

The gbes4 mesh with 39617 linear triangular elements and 22140 nodes is used for these simulations. Bathymetry values are given at the corner nodes of each element. Boundary tidal forcing is applied at fifty-eight (58) nodes at the mouth of Portsmouth Harbor. M\(_2\) tidal forcing with a period of 12.42 hrs is used at the Portsmouth Harbor open boundary. Four hundred (400) time steps are used per tidal cycle. The simulations are
started with fluid at rest and are terminated after six $M_2$ tidal cycles at dynamic equilibrium. The simulation parameters are given in Table 6-1.

Table 6-1. Parameters used in ADAM model simulation of the Great Bay Estuary.

<table>
<thead>
<tr>
<th>Description</th>
<th>Parameters</th>
</tr>
</thead>
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<tr>
<td>Mesh name</td>
<td>gbcs4</td>
</tr>
<tr>
<td>Bathymetry range</td>
<td>$0 \leq h \leq 25.40m$</td>
</tr>
<tr>
<td>Porous layer thickness</td>
<td>$h_0 = 1.00m$</td>
</tr>
<tr>
<td>Hydraulic conductivity</td>
<td>$k = 0.0003162$</td>
</tr>
<tr>
<td>Bottom friction coefficient</td>
<td>See Figure 6-1</td>
</tr>
<tr>
<td>Time increment</td>
<td>$\Delta t = 111.78sec$</td>
</tr>
<tr>
<td>Time steps per tidal period</td>
<td>400</td>
</tr>
<tr>
<td>Tidal periodicity</td>
<td>$T = 12.42 \text{ hrs}$</td>
</tr>
<tr>
<td>Length of simulation</td>
<td>$0 \leq t \leq 6T$</td>
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<tr>
<td>Numerical implicitity</td>
<td>$\theta = 1$</td>
</tr>
<tr>
<td>Number of nonlinear iterations</td>
<td>4</td>
</tr>
</tbody>
</table>

6.2. **Tidal Boundary Forcing at Portsmouth Harbor**

$M_2$ tidal forcing is specified as the Dirichlet elevation boundary condition across the open ocean boundary extending from Gerrish Island in the north, to Odiorne Point in the southeast (see Figure 5-1). The elevation boundary condition used to force the model at the open ocean boundary is predicted using the harmonic constant derived from two offshore stations near Cape Porpoise Harbor (43.383° N, 70.432° W) and Hampton Harbor, NH (42.54° N, 70.49° W). Interpolated amplitude and phase for $M_2$ tidal forcing time series is 1.30m and 321.1°K, respectively.
The predicted time series starts five \( M_2 \) tidal cycles before September 1, 1975. The length of the \( M_2 \) forcing time series is six (6) \( M_2 \) tidal cycles (74.52 hrs.). It starts on August 29, 1975 9:54 (663201.9 in Julian hours) and ends on September 1, 1975 12:25:12 (663276.42 in Julian hours).

6.3. **Bottom Friction Coefficient Adjustment for the Great Bay Estuary**

In this chapter, a space-variable, depth-dependent bottom friction coefficient distribution is adjusted for the \( M_2 \) tidal forcing until the model results fitted closely to the predicted surface elevation amplitude and phase and cross-section averaged velocity data from Swift and Brown (1983). In all the test simulations, the simulation parameters given in Table 6-1 are used. The bottom friction coefficient distributions for different simulations are shown in Figure 6-1.

![Figure 6-1. Space-variable, depth-dependent bottom friction coefficient distribution for simulations A, B and C.](image)
6.4. **Statistical Analysis Methods**

In order to compare the model results with the predicted time series some statistical analysis has to be performed. Definitions of some statistical analysis tools that were used for comparative purposes are given below:

**Correlation Coefficient:**

The correlation coefficient is a measure of the strength of the relationship between the model output and the predicted data. While variables having a high correlation coefficient do not guarantee a cause and effect relationship between the pair, having a high correlation is a necessary condition for such a relationship. Correlation coefficient is calculated as follows:

$$ R(\text{model, predicted}) = \frac{C(\text{model, predicted})}{\sqrt{C(\text{model, model})C(\text{predicted, predicted})}} $$

where $C$ is the covariance matrix.

**Normalized RMS (Root Mean Square) of Error:**

The Root Mean Square error is a measure of the deviation of the model output value from the predicted value. In Root Mean Square error, the deviations are summed and then divided by the number of time periods in the time series. Finally, the square root of this quantity is evaluated. The Root Mean Square is used to quantitatively measure how closely the model output variable tracks the predicted data. The magnitude of the Root Mean Square error can be evaluated only by comparing it to the mean of the time series.
\[ \text{RMS}_N = \frac{\sqrt{\text{mean}(\text{model} - \text{predicted})^2}}{\text{std (predicted)}} \] where std is the standard deviation.

**Skill**

Skill is defined as:

\[ S = 1 - \frac{\text{mean}(\text{model} - \text{predicted})^2}{\text{mean(predicted)}^2} \]

### 6.5. Results for M₂ Forcing

Nine tidal stations, Seavey, T-11, T-12, T-13, T14A, T-14, T-16, T-UNH, and T-19 are used to make the surface elevation comparisons between model results and the predicted data from Swift and Brown (1983). Four stations, C-104, C-119, C124 and C-131 are used to make the cross-section averaged velocity comparisons between the model results and the predicted data from Swift and Brown (1983). The results from the simulations A, B, and C are compared with the predicted data from Swift and Brown (1983). Each simulation result is given below.

#### 6.5.1. Simulation A

This simulation is the starting point to find out the proper bottom friction coefficient distribution. First, a constant value bottom friction coefficient was used throughout the Great Bay Estuary to find the order of magnitude for the bottom friction coefficient.
Figure 6-2. Simulation A: Surface elevation comparisons between the model-produced data and the tidal analysis predicted data. The tidal analysis predicted data are shown in solid red lines and model-produced data is shown in dashed blue lines.

The constant bottom friction works well in representing the flow between stations Seavey and T-14. In that region, the amplitudes and phases of the model predicted data matches with the tidal analysis predicted data. After station T-14, the elevations are not adequately damped to match the tidal analysis predictions and the model predicted data precedes the tidal analysis predicted data starting from station T-16.
The comparison of the model-produced, cross-section averaged velocities with the predicted data in Figure 6-3 shows that the model overpredicts the velocities with the specified bottom friction distribution.

**Figure 6-3.** Simulation A: Comparison of cross-section averaged velocity values with tidal analysis predicted data. Solid red lines indicate tidal analysis predicted data and dashed blue lines indicate model-produced data.
6.5.2. **Simulation B**

The results from the previous simulation indicate that the bottom friction coefficient values should be increased in order to decrease the velocities, which in turn will help to correct the phase differences. In this simulation, the bottom friction coefficient is increased and changed linearly with depth. The range for the friction coefficient is 0.005 and 0.02, the latter corresponding to the minimum depth.

**Surface Elevation Comparisons for Simulation B**

- **Station Seavey**
- **Station T-11**
- **Station T-12**
- **Station T-13**
- **Station T-14A**
- **Station T-14**
- **Station T-16**
- **Station T-UNH**
- **Station T-19**

*Figure 6-4. Simulation B: Surface elevation comparisons between the model-produced data and the tidal analysis predicted data. The tidal analysis predicted data are shown with solid lines and model-produced data is shown with dashed blue lines.*

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The bottom friction found is too high. Thus, the model predicted surface elevation amplitudes (beginning from station T-12) start damping too early. However, the cross-section averaged velocity comparison in Figure 6-5 shows that the model-produced values at C-104 and C-131 compare well with the predicted data, but the model produced values at C-119 and C-124 do not match with the predicted data.

**Cross-sectionally Averaged Velocity Comparisons for Simulation B**

![Cross-sectionally Averaged Velocity Comparisons for Simulation B](image)

**Figure 6-5.** Simulation B: Comparison of cross-section averaged velocity values with tidal analysis predicted data. Solid lines indicate tidal analysis predicted data and dashed lines indicate model-produced data.
6.5.3. **Simulation C**

In this simulation, the bottom friction coefficient is decreased in the deep channels in order to prevent early damping in the surface elevation amplitudes. The range for the friction coefficient is 0.005 and 0.01, the latter corresponding to the minimum depth. The maximum value for the bottom friction is reduced by half compared with simulation B.

**Surface Elevation Comparisons for Simulation C**

![Graphs showing surface elevation comparisons for Simulation C](image)

**Figure 6-6.** Simulation C: Surface elevation comparisons between the model-produced data and the tidal analysis predicted data. The tidal analysis predicted data are shown with solid red lines and model-produced data is shown with dashed blue lines.
The model predictions match with the tidal analysis predictions better than the previous two simulation results. However, there is still a phase difference between the model results and the tidal analysis predicted data. The model-produced data precedes the tidal analysis predictions starting from station T-16. The amplitudes on the other hand, are not damped too much and match closely with the tidal analysis predictions.

The comparison for the cross-section averaged velocity values is shown in Figure 6-7. The model produced data matches the predicted data closely at stations C-104, C-124 and C-131. However, C-119 is a problem station.

![Cross-sectionally Averaged Velocity Comparisons for Simulation C](image)

**Figure 6-7.** Simulation C: Comparison of cross-section averaged velocity values with tidal analysis predicted data. Solid red lines indicate tidal analysis predicted data and dashed blue lines indicate model-produced data.
Comparison of different simulation results shows that when the phase of the model produced surface elevation time series agrees with the phase of the tidal analysis predicted surface elevation time series, the amplitudes of the model produced surface elevations time series do not agree with the amplitudes of the tidal analysis predicted surface elevation time series.

Statistical analysis results, including the correlation coefficient and the normalized Root Mean Square (RMS) values for each station, for simulations A, B and C are given in the following tables (Table 6-2 – Table 6-5).

Table 6-2. Correlation coefficient values at the current-meter stations.

<table>
<thead>
<tr>
<th>Station</th>
<th>Simulations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
</tr>
<tr>
<td>C-104</td>
<td>0.93</td>
</tr>
<tr>
<td>C-119</td>
<td>0.95</td>
</tr>
<tr>
<td>C-124</td>
<td>0.91</td>
</tr>
<tr>
<td>C-131</td>
<td>0.90</td>
</tr>
</tbody>
</table>
Table 6-3. Correlation coefficient values at the surface elevation stations.

<table>
<thead>
<tr>
<th>Station</th>
<th>Simulations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
</tr>
<tr>
<td>T-5</td>
<td>1.00</td>
</tr>
<tr>
<td>Seavey</td>
<td>0.99</td>
</tr>
<tr>
<td>T-11</td>
<td>1.00</td>
</tr>
<tr>
<td>T-12</td>
<td>1.00</td>
</tr>
<tr>
<td>T-13</td>
<td>1.00</td>
</tr>
<tr>
<td>T-14A</td>
<td>1.00</td>
</tr>
<tr>
<td>T-14</td>
<td>0.99</td>
</tr>
<tr>
<td>T-16</td>
<td>0.94</td>
</tr>
<tr>
<td>T-UNH</td>
<td>0.94</td>
</tr>
<tr>
<td>T-19</td>
<td>0.91</td>
</tr>
</tbody>
</table>

Table 6-4. Normalized Root Mean Square (RMS) values at the current-meter stations.

<table>
<thead>
<tr>
<th>Station</th>
<th>Simulations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
</tr>
<tr>
<td>C-104</td>
<td>0.49</td>
</tr>
<tr>
<td>C-119</td>
<td>0.86</td>
</tr>
<tr>
<td>C-124</td>
<td>0.52</td>
</tr>
<tr>
<td>C-131</td>
<td>0.71</td>
</tr>
</tbody>
</table>
Table 6-5. Normalized Root Mean Square (RMS) values at the surface elevation stations.

<table>
<thead>
<tr>
<th>Station</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-5</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Seavey</td>
<td>0.12</td>
<td>0.12</td>
<td>0.12</td>
</tr>
<tr>
<td>T-11</td>
<td>0.06</td>
<td>0.07</td>
<td>0.05</td>
</tr>
<tr>
<td>T-12</td>
<td>0.05</td>
<td>0.18</td>
<td>0.09</td>
</tr>
<tr>
<td>T-13</td>
<td>0.10</td>
<td>0.16</td>
<td>0.07</td>
</tr>
<tr>
<td>T-14A</td>
<td>0.09</td>
<td>0.19</td>
<td>0.09</td>
</tr>
<tr>
<td>T-14</td>
<td>0.12</td>
<td>0.25</td>
<td>0.11</td>
</tr>
<tr>
<td>T-16</td>
<td>0.39</td>
<td>0.22</td>
<td>0.21</td>
</tr>
<tr>
<td>T-UNH</td>
<td>0.38</td>
<td>0.27</td>
<td>0.21</td>
</tr>
<tr>
<td>T-19</td>
<td>0.43</td>
<td>0.31</td>
<td>0.27</td>
</tr>
</tbody>
</table>

6.6. *The gbes16 Mesh*

The Great Bay section of the estuary, where the eelgrass distribution is most extensive, is the area of interest for exploring the frictional effects of eelgrass on the tidal flow. However, in the above simulations, the model produced flow was either damped too much or preceded the tidal analysis predicted data before reaching the Great Bay. At this stage, a strategic step was taken; the research was focused only on the tidal flow in the Great Bay section.

In order to resolve the flow in the Great Bay, the mesh is cut at Little Bay and a new boundary forcing is applied at the open boundary of the new mesh (see Figure 6-8).
The boundary forcing is obtained by interpolating tidal analysis predicted amplitude and phase values at various stations in the estuary. The number of nodes is reduced from 22140 to 5657 and the number of elements is reduced from 39617 to 10526. Number of time steps per tidal cycles is reduced from 400 to 300. All these reductions help to reduce the computing time by 83%. In the new mesh, called the gbes16 mesh, the maximum element area is 8389.1m$^2$ and the minimum element area is 39.85m$^2$.

6.7. **Boundary Forcing for the gbes16 Mesh**

The elevation time series used to force the model at the open boundary for the gbes16 mesh simulations is predicted using the harmonic constituents from Swift and Brown (1983). First, the amplitude and phase values at all the stations (see Table 6-6) are interpolated to obtain the amplitude and phase values at the open boundary in Little Bay for each constituent. The amplitude and phase values found for the $M_2$ constituent are 0.85m and 27°K, respectively. For the $S_2$ constituent the amplitude is 0.09m and the phase is 63°K. For the $N_2$ constituent the amplitude is 0.18m and the phase is 347°K.
The interpolated amplitude and phase values at the open boundary are used as input data together with the location west longitude (70.85) for the program TIDHAR. TIDHAR is a program that predicts the tidal forcing time series at a given location. The predicted boundary forcing time series for $M_2$, $M_2S_2$ and $M_2S_2N_2$ are shown in Figure 6-9. The time series length depends on the boundary forcing used. For the $M_2$ forcing six tidal cycles were enough to resolve the character of the time series. However for the $M_2S_2$ forcing we had to use at least 36 tidal cycles in order to resolve the Spring and the Neap.
tide. For the $M_2S_2N_2$ forcing 108 tidal cycles were used to resolve the Spring and the Neap tide.

Table 6-6. Amplitude and phase values for the significant sea level harmonic constituents at sea level stations (Swift and Brown, 1983). K is the local epoch.

<table>
<thead>
<tr>
<th>Station</th>
<th>$M_2$ Amplitude (m)</th>
<th>Phase K (deg)</th>
<th>$S_2$ Amplitude (m)</th>
<th>Phase K (deg)</th>
<th>$N_2$ Amplitude (m)</th>
<th>Phase K (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-5</td>
<td>1.29</td>
<td>325</td>
<td>0.19</td>
<td>359</td>
<td>0.30</td>
<td>297</td>
</tr>
<tr>
<td>Seavey</td>
<td>1.20</td>
<td>333</td>
<td>0.17</td>
<td>8</td>
<td>0.28</td>
<td>306</td>
</tr>
<tr>
<td>T-11</td>
<td>1.12</td>
<td>336</td>
<td>0.15</td>
<td>10</td>
<td>0.25</td>
<td>308</td>
</tr>
<tr>
<td>T-12</td>
<td>1.00</td>
<td>346</td>
<td>0.15</td>
<td>29</td>
<td>0.23</td>
<td>318</td>
</tr>
<tr>
<td>T-13</td>
<td>0.95</td>
<td>352</td>
<td>0.14</td>
<td>32</td>
<td>0.22</td>
<td>322</td>
</tr>
<tr>
<td>T-14A</td>
<td>0.93</td>
<td>358</td>
<td>0.12</td>
<td>43</td>
<td>0.21</td>
<td>326</td>
</tr>
<tr>
<td>T-14</td>
<td>0.94</td>
<td>3</td>
<td>0.12</td>
<td>38</td>
<td>0.21</td>
<td>335</td>
</tr>
<tr>
<td>T-16</td>
<td>0.83</td>
<td>24</td>
<td>0.07</td>
<td>51</td>
<td>0.18</td>
<td>344</td>
</tr>
<tr>
<td>T-UNH</td>
<td>0.87</td>
<td>29</td>
<td>0.13</td>
<td>80</td>
<td>0.19</td>
<td>342</td>
</tr>
<tr>
<td>T-19</td>
<td>0.92</td>
<td>34</td>
<td>0.10</td>
<td>83</td>
<td>0.18</td>
<td>371</td>
</tr>
</tbody>
</table>

The predicted time series starts five $M_2$ tidal cycles before September 1, 1975. The length of $M_2$ forcing time series is six (6) $M_2$ tidal cycles (74.52 hrs.). It starts on August 29, 1975 at 9:54 am (663201.9 in Julian hours) and ends on September 1, 1975 at 12:25:12 pm (663276.42 in Julian hours).

The length of $M_2S_2$ is 36 $M_2$ tidal cycles (447.12 hours). It starts on August 29, 1975 at 9:54:00 am (663201.9 in Julian hours) and ends on September 17, 1975 at 1:02:24 pm (663649.04 in Julian hours).
The length of $M_2S_2N_2$ time series is $108 M_2$ tidal cycles (1341.36 hours). It starts on August 29, 1975 at 9:54 am (663201.9 in Julian hours) and ends on October 24, 1975 at 7:19:29 am (664543.325 in Julian hours).

![Graphs of $M_2$, $M_2S_2$, and $M_2S_2N_2$ forcing](image)

**Figure 6-9.** Time series of the boundary forcing for the gbes16 mesh. $M_2$ forcing is six $M_2$ tidal cycles (74.52 hrs) long whereas $M_2S_2$ forcing is 36 $M_2$ tidal cycles (447.12 hrs) and $M_2S_2N_2$ forcing is 108 $M_2$ tidal cycles (1341.36 hrs) long.

The Great Bay system is forced with the above-mentioned boundary forcing time series for the $M_2$, $M_2S_2$ and $M_2S_2N_2$ tidal forcing in the following chapters.
CHAPTER 7

MODELING THE M2 TIDAL FLOW IN GREAT BAY

In this chapter, the M2 tidal flow in the Great Bay and Little Bay section is explored. The Great Bay system, defined by the gbes16 mesh, is forced with the M2 tidal elevation time series predicted in Chapter 6. The simulation parameters are shown in Table 7-1. A space-variable bottom friction coefficient $C_d$ that decreases with increasing depth is used (see simulation C in chapter 6). The relationship between the bottom friction coefficient and depth is given in equation 7.1.

$$C_d = A - B \times h$$  \hspace{1cm} (7.1)

In the above equation, $A = 1 \times 10^{-2}$ and $B = 1.97 \times 10^{-4}$ [1/m] for the $0m < h < 18.47m$ depth range for the M2 tidal forcing.

Tidal flat areas cover a large portion of Great Bay. Those tidal flats are exposed during low water. For that reason, it is important to calculate the bottom friction coefficient distribution at each time step for the new depth value. The bottom friction calculation scheme is added in one of the FORTRAN source codes.
Table 7-1. Simulation parameters for the ADAM model in Great Bay.

<table>
<thead>
<tr>
<th>Description</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bathymetry range</td>
<td>0 ≤ h ≤ 18.47m</td>
</tr>
<tr>
<td>Porous layer thickness</td>
<td>h₀ = 1.00m</td>
</tr>
<tr>
<td>Hydraulic conductivity</td>
<td>k = 0.0003162</td>
</tr>
<tr>
<td>Bottom friction coefficient</td>
<td>Simulation C</td>
</tr>
<tr>
<td>Time increment</td>
<td>Δt = 149.047 sec</td>
</tr>
<tr>
<td>Time steps per tidal period</td>
<td>300</td>
</tr>
<tr>
<td>Tidal periodicity</td>
<td>T = 12.42 hrs</td>
</tr>
<tr>
<td>Length of simulation</td>
<td>0 ≤ t ≤ 6T</td>
</tr>
<tr>
<td>Numerical implicitity</td>
<td>θ = 1</td>
</tr>
<tr>
<td>Number of nonlinear iterations</td>
<td>4</td>
</tr>
</tbody>
</table>

7.1. **Results for the M₂ Tidal Forcing without Eelgrass**

The system established a dynamic equilibrium rapidly and mass conservation is maintained after the third tidal cycle after a ramp up. Figure 7-1 shows the time history of the total fluid volume across the open boundary transect.

![Mass balance at the open boundary transect in Little Bay](image_url)

*Figure 7-1. Time series of the total fluid volume across the open boundary transect in Little Bay. The total volume includes the 1.0m deep porous medium.*

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The water surface of Great Bay (gbes16 mesh) covers 19.02km² (corresponding to 9676 elements in the gbes16 mesh) at mean high water and 10.63km² (corresponding to 4892 elements in the gbes16 mesh) at mean low water. Thus, 44% of surface area in Great Bay drains at low M₂ tide. The high water and low water boundaries for M₂ tide are shown in Figure 7-2.

Figure 7-2. High water and low water boundaries for the M₂ tide.
The calculated average depth is 2.62m for mean high water and 1.97m for mean low water. Those results show that ADAM model is capable of treating the wetting/drying process in the Great Bay section of the estuary.

The model results at specified stations are compared with the tidal analysis predicted time series. Figure 7-3 shows the comparison of surface elevation and cross-section averaged velocity values at stations T-UNH, T-19 and C-131. The model predicted surface elevation time series at station T-UNH and station T-19 and cross-section averaged velocity time series at station C-131 compare well with the tidal analysis predicted data at those locations for the M\textsubscript{2} tidal forcing. The statistical analysis of those comparisons is given in Table 7-2. The details of statistical analysis methods can be found in Chapter 6.

| Table 7-2. Statistical analysis results for M\textsubscript{2} forcing in Great Bay. |
|-----------------------------------------------|----------------|----------------|
| Correlation Coef. | STATION T-UNH | Station T-19 | Station C-131 |
| Skill | 0.99 | 0.99 | 0.90 |
| RMS\textsubscript{N} | 0.08 | 0.12 | 0.31 |
Figure 7-3. $M_2$ forcing: Comparison of model predicted time series and tidal analysis predicted data at stations T-UNH, T-19 and C-131. Top figure shows the comparison of surface elevation at station T-UNH. Second figure shows the comparison of surface elevation at station T-19. The bottom figure shows the comparison of cross-section averaged velocity at station C-131.

Figure 7-4 shows the surface elevation amplitude distribution in Great Bay. The $M_2$ surface elevation amplitude changes between 0.85m in the channels and 0.75m in the regions close to the shoreline. The $M_2$ surface elevation phase distribution in Great Bay...
is shown in Figure 7-5. The $M_2$ surface elevation phase increases $10^\circ$ between the open boundary in Little Bay and the station T-19. This phase difference corresponds to a lag of 20 minutes between the two locations.

The change in phase is consistent with the value given in Swift and Brown (1983). However, the model-predicted surface elevation amplitude does not increase from station T-UNH to station T-19 as given in Swift and Brown (1983).

![Figure 7-4. The model predicted $M_2$ tide surface elevation amplitude distribution in Great Bay. The amplitudes are in meters.](image-url)
M2 Constituent Surface Elevation Phase Contours in Great Bay

Figure 7-5. The model predicted M2 tide surface elevation phase distribution in Great Bay. The phases are in Greenwich epoch.

The highest velocities are observed in the Furber Strait, where the cross-sectional area of the channel is the minimum. The highest velocity value in the Furber Strait is 1.29m/s for the maximum ebb stage and 1.35m/s for the maximum flood stage. The velocities decrease to 0.4m/s - 0.5 m/s in the channels in south–east and south-west Great Bay.
Figure 7-6. Model predicted maximum flood velocities in Great Bay for the M$_2$ tidal forcing. The zoom windows show some important areas. The highest velocity vector is shown in green.
Figure 7-7. Model predicted maximum ebb velocities in Great Bay for the M2 tidal forcing. The zoom windows show some important areas. The highest velocity vector is shown in green.
In the Great Bay section of the estuary the deep channels are surrounded by tidal flats and there is a transition from ebb dominance in the channels to flood dominance in the shallow tidal flats. The model results show the transition perfectly. This transition is shown in Figure 7-8.

In overall system, the average depth is the shallowest around high water. As the friction is inversely proportional to the depth, there is more frictional loss at high tide than at low tide in the channels. High friction slows down the propagation of high tide in the channels. The low tide propagates faster than the high tide in the channels, giving way to ebb dominance in those regions. On the other hand, the average depths on the tidal flats are the shallowest around low water. High tide propagates faster than the low tide on the tidal flats making the tidal flats locally flood-dominant areas.

Residual velocities are the time averaged velocities over one tidal cycle. In Figure 7-8, in windows #1 and #2, the ebb-dominant residual velocities in the channels are shown. Window #4 is an example to the flood-dominance on the tidal flats. In windows #3 and #5, once again a flood dominance on the tidal flats and ebb-dominance in the channels are observed. Those two insets are also interesting because of the large-scale gyres, which are generated due to the exchange between the flood dominant and ebb dominant sections.
Figure 7-8. Residual velocities in Great Bay for the M$_2$ tidal forcing. Ebb dominance in the channels is shown in windows #1 and #2. Flood dominance on the tidal flats is shown in window #4. Windows #3 and #5 show the gyres which are generated by the exchange between ebb dominant and flood dominant sections.
7.2. **Eelgrass Effects on the M$_2$ Tidal Flow in Great Bay**

In this section, the 1990 eelgrass distribution data in Great Bay, shown in Figure 7-9 is used. The eelgrass distribution data is obtained through personal communications with Dr. Fred Short from UNH Jackson Estuarine Laboratory.

![Eelgrass Distribution in Great Bay](image)

**Figure 7-9.** Map of eelgrass distribution in Great Bay, 1990. Eelgrass is shown in green, with the selected stations numbered from 1-27 for sampling hydrodynamic results from the model.
The bottom friction coefficient distribution found for $M_2$ tidal forcing in the previous sections is used with an adjustment at the eelgrass beds. Eelgrass blocks the water flow, thus eelgrass beds are treated as extra dampers. The bottom friction coefficient values are increased over the eelgrass beds to a value of 0.1, which is 10 times higher than the maximum bottom friction coefficient value used in the previous sections. This value is later checked through personal communications with Blaine Kopp from Maine Maritime Academy who has done a flume tank experiment on eelgrass and found some bottom friction coefficient values for various eelgrass densities (Kopp, 1999). Twenty-seven (27) stations are selected in Great Bay to observe the frictional effects of eelgrass on the tidal flow. Those control stations are shown in Figure 7-9.

The surface area for the mean high water and the mean low water is calculated again for the simulation with eelgrass. The water surface of Great Bay (gbes16 mesh) covers 19.02km² (9675 elements in the gbes16 mesh) at mean high water and 12.20km² (55780 elements in the gbes16 mesh) at mean low water. The calculated average depth is 2.62m for mean high water and 1.73m for mean low water. The average depth at mean low water with eelgrass is 24cm lower than the average depth at mean low water without any eelgrass. Also the surface area at mean low water with eelgrass is 1.57km² (688 elements in the gbes16 mesh) larger than the surface area at mean low water without eelgrass. No significant change is observed in the surface area and the average depth.
values at mean high water. Those results show that, due to the high friction values, eelgrass holds water at low water and keeps greater surface area wet.

Figure 7-10. High water and low water boundaries for the $M_2$ tide with eelgrass. The high water boundary is shown in green and the low water boundary is shown in red.
The eelgrass distribution affects the surface elevation phase about $2^\circ$ (see Figure 7-12) corresponding to a 4 min lag on the big tidal flats in south-east and south-west Great Bay. However, the change in the total tidal volume due to the friction effects of eelgrass is negligible (0.5%).

![M2 Constituent Surface Elevation Amplitude Contours in Great Bay](image)

**Figure 7-11.** The model predicted $M_2$ tide surface elevation amplitude distribution in Great Bay with eelgrass. The amplitudes are in meters.
Figure 7-12. The model predicted $M_2$ tide surface elevation phase distribution in Great Bay with eelgrass. The phases are in Greenwich epoch.

The velocities are damped over the eelgrass beds due to the friction effects of eelgrass. The flow over the tidal flats is directed into the deep channels and the velocities in those deep channels are increased. Those changes are shown Figures 7-13 through 7-15 for the selected sites in Great Bay over one tidal cycle of the simulations.
Figure 7-13. $M_2$ Forcing: Comparison between the model-predicted velocity vectors with eelgrass and the model-predicted velocity vectors without eelgrass at stations 1-9. Eelgrass simulation results are shown with blue vectors.

Stations 1 through 13 and station 26 are all on tidal flats. The velocities at those stations were decreased and change direction towards the deep channel when there is eelgrass on the tidal flats.
Figure 7-14. M2 Forcing: Comparison between the model-predicted velocity vectors with eelgrass and the model-predicted velocity vectors without eelgrass at stations 10-18. Eelgrass simulation results are shown with blue vectors.

Station 15 is far away from eelgrass effects and no velocity change due to eelgrass observed at this station. At all other stations, which are in deep channels between the eelgrass beds, the velocities are increased due to the friction effects of eelgrass.
Figure 7-15. M$_2$ Forcing: Comparison between the model-predicted velocity vectors with eelgrass and the model-predicted velocity vectors without eelgrass at stations 19-27. Eelgrass simulation results are shown with blue vectors.

The velocity vectors were examined at the maximum ebb and maximum flood stages with and without eelgrass. The difference observed in velocity magnitudes and directions on the tidal flats and the deep channels are shown in Figure 7-16 through Figure 7-18. The velocity distribution at maximum ebb on a tidal flat in east Great Bay is shown in Figure 7-16. The velocities are slowed down over the tidal flats when there is
eelgrass. Also, there is a visible change in the direction of the flow over the tidal flat. On the other hand, the velocities are increased in the deep channel next to the tidal flat.

![Figure 7-16. M2 Forcing: Velocity Vector Difference at Maximum Ebb](image)

Figure 7-16. M2 Forcing: Difference in current vectors at maximum ebb in east Great Bay. Velocities without eelgrass distribution are shown with black vectors. White vectors indicate the velocities when there is eelgrass. The eelgrass bed is surrounded by a green contour.
The velocity distribution in south Great Bay is shown in Figure 7-17. There are channels on both the east and the west side of the tidal flat. The velocity vectors on the tidal flat are decreased and directed towards the nearest channel when there is eelgrass. On the other hand, the velocities in the channels are increased.

Figure 7-17. M2 Forcing: Difference in current vectors at maximum ebb in south Great Bay. Velocities without eelgrass distribution are shown with black vectors. White vectors indicate the velocities when there is eelgrass. The eelgrass bed is surrounded by a green contour.

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The velocity distribution in mid Great Bay is shown in Figure 7-18. There is a smaller channel on the west side of the main channel. The velocity vectors on the tidal flat in between the two channels are directed towards the deepest channel. When there is eelgrass, the velocity values over the eelgrass bed are decreased while the velocity values in the channels are increased.

Figure 7-18. M2 Forcing: Difference in current vectors at maximum ebb in mid Great Bay. Velocities without eelgrass distribution are shown with black vectors. White vectors indicate the velocities when there is eelgrass. The eelgrass bed is surrounded by a green contour.
The velocity distribution in southwest Great Bay is shown in Figure 7-19. The velocity vectors on the tidal flat outside the eelgrass bed are directed around the eelgrass bed towards the deep channel in the west. When there is eelgrass, the velocity values over the eelgrass bed are decreased while the velocity vectors are increased in the channels.

Figure 7-19. M2 Forcing: Difference in current vectors at maximum ebb in southeast Great Bay. Velocities without eelgrass distribution are shown with black vectors. White vectors indicate the velocities when there is eelgrass. The eelgrass bed is surrounded by a green contour.
Eelgrass, due to the high bottom friction values, decreases the velocities and holds the water for a longer time increasing the pressure gradient. The increase in the pressure gradient causes the water to flow from the tidal flats to the channels, thus the velocities in the channels are increased.
CHAPTER 8

MODELING THE $M_2S_2$ TIDAL FLOW IN GREAT BAY

In this chapter, the Great Bay system is forced with an $M_2S_2$ tidal elevation time series at the boundary transect in Little Bay. In order to resolve the spring and neap tides in $M_2S_2$ tidal forcing, the simulation is run for 36 $M_2$ tidal cycles, which corresponds to 447.12 hrs. The details of the boundary forcing time series is given in Chapter 6. The space-variable, depth dependent bottom friction coefficient distribution used in the $M_2$ simulation is modified for the $M_2S_2$ simulation. The modification is done by decreasing the bottom friction coefficient values by 5% at each node. The simulation parameters are given in Table 8-1.

Table 8-1. Simulation parameters for the $M_2S_2$ forcing in Great Bay.

<table>
<thead>
<tr>
<th>Description</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bathymetry range</td>
<td>$0 \leq h \leq 18.47m$</td>
</tr>
<tr>
<td>Porous layer thickness</td>
<td>$h_0 = 1.00m$</td>
</tr>
<tr>
<td>Hydraulic conductivity</td>
<td>$k = 0.0003162$</td>
</tr>
<tr>
<td>Bottom friction coefficient</td>
<td>See Simulation C</td>
</tr>
<tr>
<td>Time increment</td>
<td>$\Delta t = 149.047$ sec</td>
</tr>
<tr>
<td>Time steps per tidal period</td>
<td>300</td>
</tr>
<tr>
<td>Tidal periodicity</td>
<td>$T = 12.42$ hrs ($M_2$)</td>
</tr>
<tr>
<td>Length of simulation</td>
<td>$0 \leq t \leq 36T$ (447.12 hrs)</td>
</tr>
<tr>
<td>Numerical implicitity</td>
<td>$\theta = 1$</td>
</tr>
<tr>
<td>Number of nonlinear iterations</td>
<td>4</td>
</tr>
</tbody>
</table>

100
8.1. **Results for the M₂S₂ Forcing without Eelgrass**

The simulation results are examined in two parts: the Spring tide and the Neap tide. For this purpose, two windows are chosen on the M₂S₂ tidal forcing time series. The time steps between 4800-5100 correspond to the Spring tide window and the time steps between 9300-9600 correspond to the Neap tide window.

- **During the Spring tide**, the water surface area of Great Bay is 19.19 km² (9852 elements) at high water with an average depth of 2.68m and 9.64 km² (4394 elements) at low water with an average depth of 2.08m. Thus, during the Spring tide, 50% of the surface area in Great Bay dries at low water and 31319092 m³ water is discharged during that drying process.

- **During the Neap tide**, the water surface area in Great Bay is 18.99 km² (9694 elements) at high water with an average depth of 2.53m and is 11.41 km² (5206 elements) at low water with an average depth of 1.92m. During the Neap tide, 40% of the surface area dries at low water.

The high water and low water boundaries for the M₂S₂ tide during the Spring and the Neap tides are shown in Figure 8-1.
Figure 8-1. High water and low water boundaries for the $M_2S_2$ tide. The high water boundary is shown in green and the low water boundary is shown in red for the spring tide. The high water boundary is shown in pink and the low water boundary is shown in blue for the neap tide.

The model results at specified stations are compared with the tidal analysis predicted time series. Figure 8-2 shows the comparison of the surface elevation time series at stations T-UNH and T-19 and the comparison of cross-section averaged velocity time series at station C-131, respectively. The model predictions compare well.
with the tidal analysis predicted data at those stations. The statistical analysis of those comparisons are given in Table 8-2.

<table>
<thead>
<tr>
<th>Station</th>
<th>Time (hrs)</th>
<th>Predicted data</th>
<th>Model results</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-UNH</td>
<td>12.42</td>
<td>-1.5</td>
<td>12.42</td>
</tr>
<tr>
<td></td>
<td>99.36</td>
<td>99.36</td>
<td>99.36</td>
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<tr>
<td></td>
<td>186.3</td>
<td>186.3</td>
<td>186.3</td>
</tr>
<tr>
<td></td>
<td>273.24</td>
<td>273.24</td>
<td>273.24</td>
</tr>
<tr>
<td></td>
<td>360.16</td>
<td>360.16</td>
<td>360.16</td>
</tr>
<tr>
<td></td>
<td>447.12</td>
<td>447.12</td>
<td>447.12</td>
</tr>
</tbody>
</table>

Figure 8-2. $M_2S_2$ forcing: Comparison of model predicted time series and tidal analysis predicted data at stations T-UNH, T-19 and C-131. Top figure shows the comparison of the surface elevation time series at station T-UNH. Second figure shows the comparison of the surface elevation time series at station T-19. The bottom figure shows the comparison of cross-section averaged velocity time series at station C-131.
Table 8-2. Statistical analysis results for the $M_2S_2$ forcing in Great Bay.

<table>
<thead>
<tr>
<th></th>
<th>STATION T-UNH</th>
<th>Station T-19</th>
<th>Station C-131</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correlation Coef.</td>
<td>0.98</td>
<td>0.98</td>
<td>0.96</td>
</tr>
<tr>
<td>Skill</td>
<td>0.96</td>
<td>0.95</td>
<td>0.92</td>
</tr>
<tr>
<td>$RMS_N$</td>
<td>0.20</td>
<td>0.22</td>
<td>0.28</td>
</tr>
</tbody>
</table>

8.2. **Eelgrass Effects on the $M_2S_2$ Tidal Flow in Great Bay**

The same 1990 eelgrass distribution explained in Chapter 7 is used for the $M_2S_2$ simulation. The effects observed are as follows:

- During the spring tide, the water surface of Great Bay covers 19.19 km$^2$ (9852 elements) at high water and 10.03 km$^2$ (4602 elements) at low water. The average depth is 2.68m for high water and 2.01m for low water. The average depth at low water with eelgrass is 7cm lower than the average depth at low water without any eelgrass. Also the water surface area at low water with eelgrass is 0.4 km$^2$ (208 elements) larger than the water surface area at low water without eelgrass. There was no significant change in the surface area and the average depth values at high water.

- During the neap tide, the water surface of Great Bay covers 18.99 km$^2$ (9694 elements) at high water and 12.37 km$^2$ (5612 elements) at low water. The average depth is 2.53m for high water and 1.77m for low water.
water. The average depth at low water with eelgrass is 15cm lower than average depth at low water without any eelgrass. Also the water surface area at low water with eelgrass is 0.96 km² (410 elements) larger than the water surface area at low water without eelgrass. There was no significant change in the surface area and the average depth values at high water.

Figure 8-3. High water and low water boundaries for the $M_2S_2$ tide with eelgrass. The high water boundary is shown in green and the low water boundary is shown in red for the spring tide. The high water boundary is shown in pink and the low water boundary is shown in blue for the neap tide.
The difference in the water volume time series between the simulation without eelgrass and the simulation with eelgrass is shown in Figure 8-4.

Figure 8-4. The difference in water volume time series between the simulation with eelgrass and the simulation without eelgrass for the M2S2 tide. Flood is in the negative direction.

When there is no eelgrass distribution, 590000 m$^3$ more water enters and 650000 m$^3$ more water exits the system at spring tide. This means that eelgrass blocks the water entering the system, and once the high water stage is reached eelgrass holds the water and blocks it from exiting the system.
8.2.1. **Eelgrass Effects on the M₂S₂ Tidal Flow at Spring Tide**

The previous twenty-seven (27) arbitrary stations in Great Bay are used in order to observe the frictional effects of eelgrass on the M₂S₂ tidal flow during the Spring tide. The changes in velocity magnitudes and directions are shown in Figure 8-5 through Figure 8-7 over the Spring cycle.

![M₂S₂ Forcing - Spring Cycle: Change In Velocity Vector Directions in One Tidal Cycle](image)

**Figure 8-5.** M₂S₂ forcing: Comparison between model-predicted velocity vectors with eelgrass and the model-predicted velocity vectors without eelgrass at stations 1-9 for the spring tide. Eelgrass simulation results are shown with blue vectors.

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Stations 1-13 and station 26 are all on the tidal flats. The velocities at those stations are decreased and changed direction towards the deep channels when there is eelgrass on the tidal flats. Station 15 is in the Furber Strait far from the eelgrass effects and no velocity change due to eelgrass is observed at this station. The velocities at stations 16-27, except station 26, are increased as they are located in the channels.

Figure 8-6. M₂S₂ forcing: Comparison between model-predicted velocity vectors with eelgrass and the model-predicted velocity vectors without eelgrass at stations 10-18 for the spring tide. Eelgrass simulation results are shown with blue vectors.
Figure 8-7. $M_{2}S_{2}$ forcing: Comparison between model-predicted velocity vectors with eelgrass and the model-predicted velocity vectors without eelgrass at stations 19-27 for the spring tide. Eelgrass simulation results are shown with blue vectors.

The velocity vectors were explored at the maximum ebb and maximum flood stages with and without eelgrass. The changes observed in velocity magnitudes and directions on the tidal flats and the deep channels are shown in Figure 8-8 and Figure 8-9.
The velocity distribution in the south east Great Bay around an eelgrass bed is shown in Figure 8-8. The velocity vectors on the tidal flat outside the eelgrass bed are directed around the eelgrass bed towards the channel in the west. When there is eelgrass, the velocity values over the eelgrass bed are decreased while the velocity vectors are increased in between the eelgrass beds.

**Figure 8-8.** $M_2 S_2$ forcing: Difference in current vectors at maximum ebb in the south east Great Bay around an eelgrass bed. Velocities calculated without eelgrass distribution are shown with black vectors. White vectors indicate the velocities when there is eelgrass. The eelgrass bed is surrounded by a green contour.
The velocity distribution around an eelgrass bed in the west Great Bay is shown in Figure 8-9. When there is eelgrass, the velocity values over the eelgrass bed are decreased and directed towards the nearest channel while the velocity vectors are increased in the channel.

**Figure 8-9.** $M_2S_2$ forcing: Velocity Vector Difference at Maximum Ebb

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8.2.2. **Eelgrass Effects on the $M_2S_2$ Tidal Flow at Neap Tide**

The same twenty-seven (27) arbitrary stations in Great Bay are used in order to observe the frictional effects of eelgrass on the $M_2S_2$ tidal flow during the Neap tide. The changes in velocity magnitudes and directions are shown in Figure 8-10 through Figure 8-12 over the Neap cycle.

![Graph showing changes in velocity vector directions](image)

**Figure 8-10. $M_2S_2$ forcing: Comparison between model-predicted velocity vectors with eelgrass and the model-predicted velocity vectors without eelgrass at stations 1-9 for the neap tide. Eelgrass simulation results are shown with blue vectors.**
Stations 1-13 and station 26 are all on the tidal flats. The velocities at those stations are decreased and changed direction towards the deep channels when there is eelgrass on the tidal flats. Station 15 is in the Furber Strait far from the eelgrass effects and no velocity change due to eelgrass is observed at this station. The velocities at stations 16-27, except station 26, are increased as they are located in the channels.

Figure 8-11. $M_2S_2$ forcing: Comparison between model-predicted velocity vectors with eelgrass and the model-predicted velocity vectors without eelgrass at stations 10-18 for the neap tide. Eelgrass simulation results are shown with blue vectors.
M2S2 Forcing – Neap Cycle: Change in Velocity Vector Directions in One Tidal Cycle

Figure 8-12. M$_2$S$_2$ forcing: Comparison between model-predicted velocity vectors with eelgrass and the model-predicted velocity vectors without eelgrass at stations 19-27 for the neap tide. Eelgrass simulation results are shown with blue vectors.

The results for the Spring and the Neap tides show that the frictional effects of eelgrass on the tidal flow is consistent. In the next chapter, the M$_2$S$_2$N$_2$ tidal flow will be examined with the eelgrass effects.
CHAPTER 9

MODELING THE M₂S₂N₂ TIDAL FLOW IN GREAT BAY

In this chapter, the Great Bay system is forced with an M₂S₂N₂ tidal elevation time series at the boundary transect in Little Bay. In order to resolve the spring and neap tides in M₂S₂N₂ tidal forcing, the simulation is run for 108 M₂ tidal cycles, which corresponds to 1341.36 hrs. The details of the boundary forcing time series is given in Chapter 6. The space-variable, depth dependent bottom friction coefficient distribution used in the M₂ simulation is modified for the M₂S₂N₂ simulation. The modification was done by decreasing the bottom friction coefficient values by 7% at each node. The simulation parameters are given in Table 9-1.

<table>
<thead>
<tr>
<th>Description</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bathymetry range</td>
<td>0 ≤ h ≤ 18.47m</td>
</tr>
<tr>
<td>Porous layer thickness</td>
<td>h₀ = 1.00m</td>
</tr>
<tr>
<td>Hydraulic conductivity</td>
<td>k = 0.0003162</td>
</tr>
<tr>
<td>Bottom friction coefficient</td>
<td>See Simulation C</td>
</tr>
<tr>
<td>Time increment</td>
<td>Δt = 149.047 sec</td>
</tr>
<tr>
<td>Time steps per tidal period</td>
<td>300</td>
</tr>
<tr>
<td>Tidal periodicity</td>
<td>T = 12.42 hrs</td>
</tr>
<tr>
<td>Length of simulation</td>
<td>0 ≤ t ≤ 108T (1341.36 hrs)</td>
</tr>
<tr>
<td>Numerical implicitity</td>
<td>θ = 1</td>
</tr>
<tr>
<td>Number of nonlinear iterations</td>
<td>4</td>
</tr>
</tbody>
</table>
9.1. **Results for the M$_2$S$_2$N$_2$ Forcing without Eelgrass**

The simulation results are examined in two parts: Spring tide Neap tide. For this purpose, two windows are chosen on the M$_2$S$_2$N$_2$ tidal forcing time series. The time steps between 17100-17400 correspond to the Neap tide and the time steps between 22500-22800 correspond to the Spring tide.

- **During Spring tide,** the water surface area of Great Bay is 19.70 km$^2$ (10336 elements) at high water with an average depth of 2.80m and 8.16 km$^2$ (3755 elements) at low water with an average depth of 2.27m. Thus, during Spring tide, 59% of the surface area in Great Bay dries at low water and 36586227 m$^3$ water is discharged during that drying process.

- **During Neap tide,** the water surface area in Great Bay is 18.90 km$^2$ (9632 elements) at high water with an average depth of 2.50m and is 12.21 km$^2$ (5563 elements) at low water with an average depth of 1.82m. During Neap tide, 35% of the surface area dries at low water.

The high water and low water boundaries for the M$_2$S$_2$N$_2$ tide during the Spring and the Neap tides are shown in Figure 9-1.
Figure 9-1. High water and low water boundaries for the $M_2S_2N_2$ tide. The high water boundary is shown in green and the low water boundary is shown in red for the spring tide. The high water boundary is shown in pink and the low water boundary is shown in blue for the neap tide.

The model results at specified stations are compared with the tidal analysis predicted time series. The statistical analysis results for the comparison of the surface elevation time series at stations T-UNH and T-19 and the comparison of cross-section...
averaged velocity time series at station C-131 are given in Table 9-2. The model predictions compare well with the tidal analysis predicted data at those stations.

Table 9-2. Statistical analysis results for $M_2S_2N_2$ forcing in Great Bay.

<table>
<thead>
<tr>
<th></th>
<th>STATION T-UNH</th>
<th>Station T-19</th>
<th>Station C-131</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correlation Coef.</td>
<td>0.99</td>
<td>0.99</td>
<td>0.96</td>
</tr>
<tr>
<td>Skill</td>
<td>0.99</td>
<td>0.98</td>
<td>0.93</td>
</tr>
<tr>
<td>$\text{RMS}_N$</td>
<td>0.12</td>
<td>0.16</td>
<td>0.27</td>
</tr>
</tbody>
</table>

9.2. **Eelgrass Effects on the $M_2S_2N_2$ Tidal Flow in Great Bay**

The same 1990 eelgrass distribution explained in Chapter 7 is used for the $M_2S_2N_2$ simulation. The following effects are observed:

- During Spring tide, the water surface of Great Bay covers 19.70 km$^2$ (10336 elements) at high water and 8.62 km$^2$ (3988 elements) at low water. The average depth is 2.80 m for high water and 2.16 m for low water. The average depth at low water with eelgrass is 11 cm lower than the average depth at low water without any eelgrass. Also, the water surface area at low water with eelgrass is 0.45 km$^2$ (233 elements) larger than the water surface area at low water without eelgrass. There was no significant change in the surface area and the average depth values at high water.
Figure 9-2. High water and low water boundaries for the M2S2N2 tide with eelgrass. The high water boundary is shown in green and the low water boundary is shown in red for the spring tide. The high water boundary is shown in pink and the low water boundary is shown in blue for the neap tide.

- During Neap tide, the water surface of Great Bay covers 18.90 km² (9632 elements) at high water and 13.47 km² (6094 elements) at low water. The average depth is 2.50m for high water and 1.66m for low water. The average depth at low water with eelgrass is 16cm lower than the average depth at low water without any eelgrass. Also the water surface area at low water with eelgrass is 1.26 km² (531 elements) larger than the water

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surface area at low water without eelgrass. There was no significant change in the surface area and the average depth values at high water.

The difference in the water volume time series between the simulation without eelgrass and the simulation with eelgrass is shown in Figure 9-3.

![M2S2N2 Tide: Difference in Fluid Volume](image)

**Figure 9-3.** The difference in water volume time series between the simulation with eelgrass and the simulation without eelgrass for $M_2S_2N_2$ tide. Flood is in the negative direction.

When there is no eelgrass distribution, 820000 m$^3$ more water enters and 750000 m$^3$ more water exits the system at spring tide. This again shows that the eelgrass blocks the water entering the system, and once the high water stage is reached eelgrass holds the water and blocks it from exiting the system.
9.2.1. **Eelgrass Effects on the M$_2$S$_2$N$_2$ Tidal Flow at Spring Tide**

The previous twenty-seven (27) arbitrary stations in Great Bay are used in order to observe the frictional effects of eelgrass on the M$_2$S$_2$N$_2$ tidal flow during the spring tide. The changes in velocity magnitudes and directions are shown in Figure 9-4 through Figure 9-6 for the Spring cycle.

**Figure 9-4.** M$_2$S$_2$N$_2$ forcing: Comparison between model-predicted velocity vectors with eelgrass and the model-predicted velocity vectors without eelgrass at stations 1-9 for the spring tide. Eelgrasse simulation results are shown with blue vectors.
Stations 1-13 and station 26 are all on the tidal flats. The velocities at those stations are decreased and change direction towards the deep channels when there was eelgrass on the tidal flats. Station 15 is in the Furber Strait far from the eelgrass effects and no velocity change due to eelgrass is observed at this station. The velocities at stations 16-27, except station 26, are increased as they are located in the channels.

Figure 9-5. M2S2N2 forcing: Comparison between model-predicted velocity vectors with eelgrass and the model-predicted velocity vectors without eelgrass at stations 10-18 for the spring tide. Eelgrass simulation results are shown with blue vectors.
Figure 9-6. $M_2S_2N_2$ forcing: Comparison between model-predicted velocity vectors with eelgrass and the model-predicted velocity vectors without eelgrass at stations 19-27 for the spring tide. Eelgrass simulation results are shown with blue vectors.
9.2.2. **Eelgrass Effects on the M₂S₂N₂ Tidal Flow at Neap Tide**

The changes in velocity magnitudes and directions are shown in Figure 9-7 through Figure 9-9 for the Neap cycle.

![M₂S₂N₂ Forcing - Neap Cycle](image)

Figure 9-7. **M₂S₂N₂ forcing**: Comparison between model-predicted velocity vectors with eelgrass and the model-predicted velocity vectors without eelgrass at stations 1-9 for the neap tide. Eelgrass simulation results are shown with blue vectors.

Stations 1-13 and station 26 are on the tidal flats. The velocities at those stations are decreased directed towards the deep channels when there was eelgrass on the tidal
flats. Station 15 is in the Furber Strait far from the eelgrass effects and no velocity change due to eelgrass is observed at this station. The velocities at stations 16-27, except station 26, are increased as they are located in the channels.

Figure 9-8. M2S2N2 forcing: Comparison between model-predicted velocity vectors with eelgrass and the model-predicted velocity vectors without eelgrass at stations 10-18 for the neap tide. Eelgrass simulation results are shown with blue vectors.
Figure 9-9. M$_2$S$_2$N$_2$ forcing: Comparison between model-predicted velocity vectors with eelgrass and the model-predicted velocity vectors without eelgrass at stations 19-27 for the neap tide. Eelgrass simulation results are shown with blue vectors.
CHAPTER 10

CONCLUSIONS AND DISCUSSION

The objectives of this study are:

- To investigate the effectiveness of ADAM model in simulating the tidal flow in Great Bay with wetting and drying on the tidal flats.

- To calibrate ADAM model by adjusting the bottom friction coefficient for, $M_2$, $M_2S_2$, and $M_2S_2N_2$ tidal forcing, respectively.

- To explore the frictional effects of eelgrass distribution on the flow regime in Great Bay.

These goals are achieved. Simulation of Great Bay Estuary with ADAM model is good in general. ADAM model resolves the wetting/drying process on the tidal flats well. However, when the whole Great Bay Estuary system is modeled, some problems are observed in the upper estuary. Either the surface elevation amplitudes or the phase values did not compare well with the predictions from Swift and Brown (1983) data. This problem is solved by applying the model only to the Great Bay/Little Bay section in the upper estuary, which is the area of interest for exploring the eelgrass effects. Simulation of the Great Bay section works well. The Great Bay section is characterized by a network
of channels with tidal flats on the sides. A transition from ebb dominance in the channels to flood dominance in the shallow tidal flats, which is the real dynamics in that section, is obtained with ADAM model simulations. Thus, the assumptions made in ADAM model are verified.

The bottom friction coefficient distribution is adjusted for the $M_2$, $M_2S_2$ and $M_2S_2N_2$ tidal forcing. The results are compared with the predictions from Swift and Brown (1983) data where possible.

After a satisfactory bottom friction coefficient distribution is found for each tidal forcing, 1990 eelgrass distribution is added to the system. The eelgrass beds treated as extra dampers and the friction coefficients are increased at those locations. Addition of eelgrass causes the following changes in the model results:

- the velocity over the eelgrass beds are reduced,
- the velocity in the channels are increased,
- eelgrass blocks the water, lets less water enter the system during flood, and lets less water exit the system during ebb.
- eelgrass holds water and increases the water surface area, with a maximum increase at low water,
- eelgrass decreases the average depth at low water due to the increase in water surface area.

The change in water surface area and average depth caused by the eelgrass distribution is given in Table 10-1.

**Table 10-1. Water surface area and averaged depth values for various simulations.**

<table>
<thead>
<tr>
<th>Forcing Type</th>
<th>Tide Type</th>
<th>Dries %</th>
<th>Eelgrass Info.</th>
<th>High Water</th>
<th>Low Water</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Area (m²)</td>
<td>Depth (m)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Area (m²)</td>
<td>Depth (m)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( M_2 ) Forcing</td>
<td>44</td>
<td>No-eelgrass</td>
<td>19.02</td>
<td>2.62</td>
<td>10.63</td>
</tr>
<tr>
<td>( M_2S_2 ) Forcing</td>
<td>36</td>
<td>Eelgrass</td>
<td>19.02</td>
<td>2.62</td>
<td>12.20</td>
</tr>
<tr>
<td>( M_2S_2N_2 ) Forcing</td>
<td>50</td>
<td>No-eelgrass</td>
<td>19.19</td>
<td>2.68</td>
<td>9.64</td>
</tr>
<tr>
<td>( M_2S_2N_2 ) Forcing</td>
<td>48</td>
<td>Eelgrass</td>
<td>19.19</td>
<td>2.68</td>
<td>10.03</td>
</tr>
<tr>
<td>( M_2S_2N_2 ) Forcing</td>
<td>40</td>
<td>No-eelgrass</td>
<td>18.99</td>
<td>2.53</td>
<td>11.41</td>
</tr>
<tr>
<td>( M_2S_2N_2 ) Forcing</td>
<td>35</td>
<td>Eelgrass</td>
<td>18.99</td>
<td>2.53</td>
<td>12.37</td>
</tr>
<tr>
<td>( M_2S_2N_2 ) Forcing</td>
<td>59</td>
<td>No-eelgrass</td>
<td>19.70</td>
<td>2.80</td>
<td>8.16</td>
</tr>
<tr>
<td>( M_2S_2N_2 ) Forcing</td>
<td>56</td>
<td>Eelgrass</td>
<td>19.70</td>
<td>2.80</td>
<td>8.62</td>
</tr>
<tr>
<td>( M_2S_2N_2 ) Forcing</td>
<td>35</td>
<td>No-eelgrass</td>
<td>18.90</td>
<td>2.50</td>
<td>12.21</td>
</tr>
<tr>
<td>( M_2S_2N_2 ) Forcing</td>
<td>29</td>
<td>Eelgrass</td>
<td>18.90</td>
<td>2.50</td>
<td>13.47</td>
</tr>
</tbody>
</table>
The lack of detailed bathymetry information and velocity measurements in the Great Bay section makes the modeling efforts difficult. However, modeling the eelgrass effects on the tidal flow by increasing the bottom friction is a good approximation and gives physically realistic results.
LIST OF REFERENCES
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APPENDIX A

Darcian Flow:

In the fluid mechanics of porous media, the place of momentum equations of force balances is occupied by the numerous experimental observations summarized mathematically as the "Darcy Law". The observations were first reported by Darcy who, based on measurement alone, discovered that the area averaged fluid velocity through a column of porous material is proportional to the pressure gradient established along the column. Subsequent experiments proved that the area-averaged velocity is, in addition, inversely proportional to the viscosity ($\mu$) of the fluid seeping through the porous material.

So one can write:

$$u = \frac{K}{\mu} \left( -\frac{dP}{dx} \right)$$

(A-1)

where $K$ is an empirical constant called permeability. The dimensions of $K$ must be

$$[K] = \left[ \frac{\mu u}{dP} \right] = \text{(length)}^2$$

(A-2)

Darcy flow is the macroscopic manifestation of a highly viscous flow through the pores of the permeable structure, and $K^{1/2}$ is a length scale representative of the effective pore diameter. Ergun (1952) proposed

$$K = \frac{d^2 \varepsilon^3}{150(1-\varepsilon)^2}$$

(A-3)

as a correlation for the measured permeabilities of columns of packed spheres of diameter $d$ and porosity $\varepsilon$. 

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In the presence of a body force per unit volume \( \rho g_x \), the Darcy Law (A-1) becomes

\[
\mathbf{u} = \frac{K}{\mu} \left( -\frac{dP}{dx} + \rho g_x \right)
\]

(A-4)

acknowledging the fact that the flow through the porous column stops when the externally controlled pressure gradient \( dP/dx \) matches the hydrostatic gradient \( \rho g_x \).
APPENDIX B

The Galerkin Method:

For most practical problems, it is impossible to determine the exact solution to the
differential equations in terms of known functions, which exactly satisfies the governing
equations and the boundary conditions. As an alternative, the FEM seeks an approximate
solution; an explicit expression in terms of known functions, which only approximately
satisfies the governing equations and the boundary conditions.

The FEM obtains an approximate solution by using the classical trial-solution
procedure. The trial-solution procedure is composed of three principal operations,
respectively Burnett (1987):

- Construction of trial solution,
- Application of optimizing criterion,
- Estimation of the accuracy.

One has to determine an approximate solution \( \bar{u} \), which comes close to the
unknown true solution \( u \) for a given problem. The function \( \bar{u} \) will be defined everywhere
in terms of a finite set of mathematical basis functions \( \phi_j(x) \) whose properties are a
priori well known:

\[
    u(x) \approx \bar{u}(x) = \sum_{j=1}^{N} u_j \phi_j(x) \quad \text{(B-1)}
\]

The coefficients \( u_j \) are the primary unknowns of any problem once the basis has
been selected. In any practical problem, the basis in use will necessarily be finite and
incomplete - i.e. incapable except in lucky cases representing the exact solution perfectly.
Any numerical solution may be viewed as a two-step process. First, select a basis which
is likely to fit the unknown solution for the particular problem. Second, determine the coefficients $u_j$ in a reliable way.

Use of a finite or incomplete basis guarantees that in general a given differential equation cannot be satisfied everywhere, leaving an imbalance or residual, $R$, everywhere. Clearly, $R$ depends on the selection of both the basis $\phi_i$ and the coefficient $u_j$. Problem-dependent basis selection is the first step towards a small residual. Given a finite basis, one must then settle for making $R$ small in some average way by choosing the coefficients $u_j$.

In the Method of Weighted Residuals (MWR), in order to determine $u_j$, $R$ is required to vanish in a weighted integral sense. In Cartesian space we have

$$\iiint RW_i dx dy dz = 0$$

(B-2)

for a set of distinct weighting functions $W_i(x)$, $i = 1, N$, and the integration performed over the full domain in which the differential equation governs. We can use the inner product notation, $\langle , \rangle$, to indicate domain (volume) integration and the MWR is stated compactly:

$$\langle R, W_i \rangle = 0 \quad i = 1, N$$

(B-3)

Equivalently, “$R$ is orthogonal to $W_i$“ with $N$ basis functions $\phi_i$ selected a priori, a choice of $N$ independent weighting functions $W_i$ will determine the $N$ unknown $u_j$.

Galerkin Method is an MWR in which weighting functions are identical to the basis functions:

$$W_i = \phi_i$$

(B-4)

This is extensively used with finite elements.