Simulation of Hydrodynamics and Sediment Transport Patterns in Delaware Bay

A Thesis
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of
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Dedications

This work is dedicated to my son, whose heart will beat in a brave new world.
Acknowledgements

This thesis is a result of four years of work, during which I have been inspired by many people. I would like to take this opportunity to express my gratitude to them.

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This research seeks to increase understanding of hydrodynamic processes influencing the salinity intrusion and sediment transport patterns by simulating the complex flows in Delaware Estuary. For this purpose, a three-dimensional numerical model is developed for the tidal portion of the Delaware Estuary using the UnTRIM hydrodynamic kernel. The model extends from Trenton, NJ south past the inlet at Cape May, NJ and incorporates a large portion of the continental shelf.

The simulation efforts are focused on summer 2003. A variable, harmonically decomposed, water level boundary condition of three diurnal (K₁, Q₁, O₁) and four semi-diurnal (K₂, S₂, N₂, M₂) components are used to regenerate the observed tidal signals in the bay. The effect of forcing by the Chesapeake Bay through the Chesapeake-Delaware canal is also modeled. The major forcings such as inflow and wind is used to better reproduce the observed characteristics.

Various turbulence closure models are compared for use in Delaware Estuary to best represent the salinity intrusion patterns. In particular, seven different turbulence closures, five of which are two-equation closure models, are used for comparison. Four of these models are implemented in the UnTRIM hydrodynamic code using Generic Length Scale
(GLS) approach that mimics the models through its parameter combinations. The original Yamada Mellor level 2.5 code is used as the fifth one.

The water levels are compared with data available from National Oceanic and Atmospheric Administration observation stations. Harmonic analysis to observations and simulations are performed. All turbulence models perform similar in performance representing the tidal conditions.

Salinity time series data is available at Ship John Shoal Light Station for the 62 day simulation period. In addition to the time series data, a survey performed by University of Delaware along the main shipping channel in June 2003 is available. Simulation with different turbulence closures yielded substantially different results. Among the seven closures compared, the $k-\varepsilon$ parameterization of GLS is found to best represent the observed salinity characteristics.

The $k-\varepsilon$ model is used in the sediment transport modeling. The model results are compared to the available sediment data from a survey performed in spring 2003. The location of turbidity maximum is accurately identified by $k-\varepsilon$ model.
CHAPTER 1: INTRODUCTION

1.1. Background

The Delaware Estuary is located in the Mid-Atlantic region of the United States, surrounded by portions of Pennsylvania, New Jersey and Delaware. An estuary is where fresh water from a river mixes with salt water from an ocean or bay. The Delaware Estuary stretches approximately 210 km (Sharp, 1984), from the falls of the Delaware River between Trenton, New Jersey, and Morrisville, Pennsylvania, south to the mouth of the Delaware Bay between Cape May, New Jersey, and Cape Henlopen, Delaware.

Delaware Estuary is one of the most heavily used estuary systems in the U.S. The Estuary supports one of the world’s greatest concentrations of heavy industry, the world’s largest freshwater port, and the second largest refining petrochemical center in the U.S.; 70% of the oil shipped to the East Coast of the United States passes through the Delaware Estuary (Santoro, 2004). The port system generates $19 billion in annual revenue. The annual harvest of Eastern oysters from the Estuary exceeds $1.5 million in market value. The Delaware River and Estuary system provides drinking water to over 9 million people (Sutton, 1996). The Estuary also receives wastewater discharges from 162 industries and municipalities and approximately 300 combined sewer overflows.

The estuary is also an important ecosystem to numerous species. It is an important resting and feeding area for millions of migrating birds. Rare and endangered species also rely
on the Estuary. It is known for its wetlands, commercial fisheries, and horseshoe crab spawning. It is a region of overlapping habitat types and high biodiversity.

The importance of the estuary to both human life and ecology brings its own problems with it. The shipping supplies a lot of economic benefits, but it requires dredging of bottom sediments in order to maintain the navigation channel. The discharge of wastewater from industries and municipalities has caused severe contamination. Even though regulatory and cleanup efforts over the past decades have helped the environment; access to clean fresh water, altered sedimentary system, spreading of toxic contaminants, major oil spills, disturbed biogeochemical cycles, coastal erosion, fisheries and habitat loss are still some of the important environmental issues in Delaware River Estuary.

The past and current concerns in the estuary led to the continuous monitoring of hydrodynamic and environmental properties of Delaware Estuary by several organizations. Unites States Geological Survey (USGS), National Oceanographic and Atmospheric Administration (NOAA), Delaware Bay River Commission (DRBC) and Partnership for Delaware Estuary are some of them.

USGS and NOAA are the organizations that supply observational information regarding river discharges, sediment inputs, tidal amplitudes, currents, wind fields, and salinity at observation stations throughout the estuary. They not only provide data related to past events, but they also perform real time observations which are crucial for transportation and fishing industries. These real time data are also helpful during extreme conditions such as a storm event. Although these point measurements at stations are effective in
regulating transportation and fishery, they can not provide information related to the impact of the tides and currents on the general dynamics of the bay.

Water quality issues are also an important concern, especially for DRBC, because the estuary is used for water supply purposes and also as a waste effluent recipient. For example, the contamination of the water and sediments with harmful PCBs and metals has received much attention in recent years and is being addressed in a Total Maximum Daily Load (TMDL) development and implementation. Accordingly, it is necessary to understand the sediment dynamics of the estuary.

Taking all the above facts into consideration, it can be said that Delaware Estuary is crucial both ecologically and economically, providing so many benefits to the life of human and other species. Given the benefits obtained from the estuary, it is very important to be able to observe what is happening in the estuary, from both a hydrodynamic and environmental point of view. Several past observational and numerical studies of the Delaware Estuary are described below.

1.2. Previous Studies

The estuary can be classified into three major ecological zones distinguished by differences in salinity, turbidity, and biological productivity. The upper estuary is tidal freshwater and extends from Trenton to Marcus Hook, New Jersey. The middle estuary, from Marcus Hook to Artificial Island, has a wide salinity range (0-15 parts per thousand) and is characterized by high turbidity and low biological productivity (Santoro, 2004). The lower estuary is open bay (the reference to Delaware Bay in the following text
refers this region) and extends to the ocean. It has higher salinity and broad areas of fairly shallow water (approximately 5m). This zone has the highest primary biological production (Pennock and Sharp, 1986) throughout the estuary.

The hydrodynamics of the estuary are influenced by freshwater flow, tidal circulation, and wind. About 60% of the freshwater flow into the Estuary is from the non-tidal Delaware River, about 10% is from the Schuylkill River, and the remainder is from the Chesapeake and Delaware Canal, small rivers, and non-point source runoff (Sharp et al., 1986; Marino et al., 1991). This fresh water mixes with saline water from the ocean, creating the variable salinity distribution found in the lower estuary.

The Delaware Estuary is unique among large U.S. estuaries because it has a substantial freshwater tidal region, and thus is considered one of the largest of its kind in the world. The main mixing zone between seawater and freshwater occurs in the middle of the Estuary. The upstream intrusion of saline waters has also increased during the last 50 years (Smullen et al., 1984), as a result of a combination of sea level rise, channel deepening, and upstream removal of freshwater. The migration could be having ecological effects. Increasing water withdrawals for municipal use and cooling plants also increase salt water intrusion into aquifers which supply drinking water. An excessive level of salt in drinking water is a well known risk to public health. This raises one of the most important questions regarding the location of salinity front, which needs to be predicted and controlled for the regulation of the drinking water supply. The effect of upstream discharge (which is controlled by the dam at Trenton) and its relation to salinity intrusion must be well understood.
Shipping is important to the economy of the estuary region. To support port operations and accommodate increasingly larger ships, government-authorized dredging has been conducted in the Delaware Estuary since the latter part of the 19th century. The ship channel today is 13 meters deep. To maintain this depth, about 5.5 million cubic yards of sediment are dredged on an annual basis (Kim and Johnson, 1998). The dredged sediment was historically deposited largely on estuary shores and marshes, creating areas that were later developed for industry. Other key questions rise to understand and predict how and where these sediments fill the navigation channel, what is the source of these sediment, where the dredged sediments should be deposited, and what is the impact of dredging on the estuarine ecology?

Dredging has resulted in increased tidal range (DiLorenzo et al., 1992) and increased shoreline erosion caused by ship wakes. These factors have resulted in decreased intertidal vegetation in the upper and middle of the estuary (Ferren and Schuyler, 1980). Sommerfield and Madsen (2003) discovered that the seafloor itself is a major source of sediment, contributing over a million ton a year on average, due to widespread bottom erosion by tidal currents. They developed an interpretable map of bottom sediment types of the estuary between Burlington, New Jersey, and New Castle, Delaware. There is ongoing work at University of Delaware to extend the project area to cover a wider part of the estuary. Cook (2004) showed the location of the turbidity maximum. From an ecological point of view, deposition rates of sediments may have detrimental effects on
stream ecology. A field study by Miller et al. (2002) pointed out that the impact of exceeding natural sedimentation rates due to improper placement of dredge materials may cause total loss of certain communities and subsequent colonization by pioneer species. Another study showed that the sediments in the Delaware, Schuylkill, and Salem rivers of the upper Delaware Estuary contained the greatest concentrations of metals and organic contaminants of the mid-Atlantic region (Kiddon et al. 2003). All of these studies provide evidence for the importance of sediment transport modeling in Delaware Estuary, and point out needs to be addressed.

The Delaware Estuary still has one of the highest nutrient inputs of any major estuary in North America; urban wastewater is the major source of both nitrogen and phosphorus in the estuarine system. Sharp (1994) has shown that, total phosphorus dropped dramatically in the early 1970s. High nutrient levels usually provide ideal conditions for eutrophication, causing massive blooms dominated by cyanobacteria and diatoms (planktonic algae), but these do not usually occur in the Delaware Estuary. Rather, there are usually healthy populations of diatoms in both the tidal river and in the lower estuary; the middle estuary has low productivity because of high turbidity and less light penetration. Within the Delaware Estuary there are two primary nursery areas: wetlands, including the shallow marsh fringe areas and mudflats, and the low salinity areas at the head of the estuary. This low salinity open-water portion is a region of exceptional value to fish. This region receives fish eggs, larvae, and young from freshwater spawners, and even some larvae spawned in the lower estuary and ocean. The distribution of juvenile fishes within primary nursery areas is related to a variety of factors, including
temperature, salinity, turbidity, food availability, and predation pressure (O’Herron et al, 1994). So, the question regarding the knowledge of hydrodynamics, salinity and turbidity in the system needs to be answered.

The problems are clear, but what are the efforts that address these problems? How do the available studies address the concerns? From a hydrodynamic point of view, there are several numerical studies in the literature related to Delaware Estuary that address some of these problems.

One of the first numerical studies (Galperin and Mellor, 1990), introduces the estuary and shelf as a coupled system, with a complex turbulence closure (Mellor, 1982) stressing the importance of turbulence closure to the salinity intrusion and provides comparison of the currents, salinities and temperatures from the model with observations, but, the model lacks in the required resolution to solve the phenomenon and indicates that an extensive database for the boundaries is necessary.

Another model by Walters (1997) addresses the higher resolution issue but does not incorporate the continental shelf and complex turbulence closure in his model, mainly because of the computational cost. These models, complex in nature, explain and resolve some of the phenomena, and they are among the first models that use complicated 3-dimensional modeling in the estuary. On the other hand, local management organizations like DRBC, still uses one-dimensional models such as DYNHYD5, which supplies necessary hydrodynamic data for several environmental programs, but lacks an ability to
capture the lateral and vertical variability of the dynamics. This issue was addressed by another computational work which employs a three dimensional program, ECOM (HydroQual, Inc., 1998), but it only covers the upper and middle estuary (up to Liston point, downstream of Chesapeake & Delaware canal) and is one-dimensional (one element per width) at the upper estuary.

There is clear lack of numerical models which resolve both lateral and vertical variability in the estuary. This can only be resolved by a 3-dimensional model of sufficient resolution, covering the estuary and continental shelf, employing complex forcings and boundary conditions and resolving the mixing characteristics with proper turbulence closures. Moreover, no model exist that supplies information for both hydrodynamics and sediments for Delaware Estuary.

1.3. Specific needs for Delaware Estuary

In early 2005, the Partnership for the Delaware Estuary (PDE) convened a two-part science and management conference to bring researchers, resource managers and other interested parties together to summarize the current state of science and identify and prioritize science and management needs for the Delaware Estuary.

Recently, in 2006, a white paper was published (Kreeger et.al., 2006) by Partnership for the Delaware Estuary that summarized key points and science needs that were reported at the science conference and subsequent related meetings.
The following top ten technical needs were identified in this report: 1) contaminants (e.g., forms, sources, fates & effects of different classes); 2) tidal wetlands (e.g., status and trends of different types); 3) ecologically significant species and critical habitats (e.g., benthos, reefs, horseshoe crabs); 4) ecological flows (e.g., effects of freshwater inflow on salt balance and biota); 5) physical-chemical-biological linkages (e.g., effects of sediment budget on toxics and biota); 6) food web dynamics (e.g. identification and quantification of dominant trophic interactions); 7) nutrients (e.g., forms, concentrations and relative balance); 8) ecosystem functions (e.g. economic valuation of ecosystem services); 9) habitat restoration and enhancement; and 10) invasive species (e.g., monitoring and control).

The white paper specifically highlights the need for an updated hydrodynamic model for the entire estuary, including the lower zones, and requiring additional information on salinity, temperature and flow while explaining the need for modeling of tidal currents for shipping and the need to understand water mixing.

Furthermore, they recommend studies regarding some aspects of residual currents (e.g., buoyancy-driven and wind-driven factors) that are not well modeled, to obtain a more complete understanding of these components for modeling material transport (sediment, contaminant, nutrient etc.).

Questions were raised in the paper regarding the reduced flows to the estuary, which in turn could affect key habitats and biota in the tidal regions (for example, impact of
reduced flow on oysters -*Crassostrea virginica*-, which are impaired by saltier waters because of increased prevalence of disease agents and native plants living in freshwater tidal marshes such as wild rice, *Zizania aquatica* which were identified as at risk). These habitats are particularly at risk if the prevailing salt line advances up the estuary, making the precise knowledge of the location of salinity front utmost important.

Finally, the paper identifies high turbidity, greater average depths, and other factors, to be the reason for lower primary production (e.g., submerged aquatic vegetation, seagrass, macroalgae) in benthic communities of the Delaware Estuary, and directs scientists to research these effects.

The available numerical models do not take into consideration of some basic needs of the community. A summary of these problems are listed below:

1. The usage of one or two-dimensional methods to explain the three-dimensional nature of the phenomena.
2. The lack of sufficient resolution of the models to capture the related dynamics.
3. The effect continental shelf to the dynamics inside the estuary.
4. The lack of proper and sufficient representation of all the driving mechanisms, such as all components of tides, river discharge, wind, and aspects of residual currents (e.g., buoyancy-driven and wind-driven factors).
5. Proper representation of turbulence in 3-dimensional modeling to resolve mixing characteristics.
6. Identifying the exact location of salinity front.
7. Unavailability of numerical sediment transport models to explain the dynamics of sediments in the estuary.

The motivation of this work is to offer a way to answer to some of these needs.

1.4. Objectives of the Study

In order to address some of the explicit needs of the community, which is explained above; the objectives of this study are as follows:

1. Building a 3-dimensional hydrodynamic model of the Delaware Estuary, including the effect of all forcings (inflows, tides and wind etc.) and incorporating the whole estuary and continental shelf. This will address the specific need for the hydrodynamic model mentioned by the community.

2. Explaining the behavior of salinity intrusion and its dependence on proper turbulence closure by modeling and comparing the turbulence parameters, and generating a model capable of replicating the salinity fields in the estuary, by resolving the lateral and vertical nature of the phenomenon. This will contribute a numerical model that will make the necessary information available for mixing and accurately predict estuarine salinity gradients.
3. Modeling sediment transport in the bay in order to assess the transport of sediments, and determine the erosional and depositional patterns of sediments in the estuary, emphasizing the location and migration of the turbidity maxima.

No three-dimensional numerical models exist for Delaware Estuary for the simulation of both hydrodynamics and sediment transport. Therefore, this study will fill this gap and will produce a basis for future studies, for example, the effects of freshwater inflow and salt balance on ecologically significant species, on attaining and maintaining the applicable water quality standards for the estuary, understanding the deposition and re-suspension patterns of sediments in the estuary and understanding effects of deposition of contaminants on stream ecology.

1.5. Research Plan

In order to achieve the above objectives, the proper tools need to be employed. The first step is to determine the proper 3-D numerical model which varies greatly because of the underlying difference in discretization and the physics resolved. This step should answer the problem posed before: the usage of one or two-dimensional methods to explain the three-dimensional nature of the phenomenon. Each model is suitable for a different modeling situation and a decision should be made according to modeling needs. The proper model should resolve the phenomena while maintaining accuracy and efficiency. Many academic and commercial codes exist in literature such as MIKE-3, CH3D-WES, POM and ECOM-si, DELFT-3D, TELEMAC-3D, ROMS-TOMS, GOTM, ELCIRC and TRIM-UnTRIM family (details of these models are given in Chapter 2). Most of these
models use curvilinear grids in the horizontal direction, which is difficult to fit to complex geometries such as Delaware Estuary, and some of them have strict stability requirements (CH3D-WES, POM, ROMS, Delft3D, GOTM are among these codes). Moreover, they are not as efficient as the codes ELCIRC and TRIM-UnTRIM family of models. The ELCIRC model was formulated a few years after the UnTRIM, but was discontinued, and evolved to a new model SELFE in 2006. It was not as efficient as UnTRIM, and was not available at the start of this research. Consequently, the numerical Kernel UnTRIM (Casulli and Walters 2000) was chosen for the modeling of the Delaware Estuary because it is understood that the key at this step was to allow the necessary resolution in three dimensions without sacrificing the accuracy and efficiency for the numerical model. UnTRIM has all of these capabilities.

The second step is that the requirements of the numerical model UnTRIM must be fulfilled. A high resolution unstructured grid is generated using grid generator Janet to resolve the underlying physics, which covers the domain from the upstream boundary at Trenton to the downstream boundary at the continental shelf. The numerical model is forced at the boundaries with proper boundary conditions for tides, discharge, salinity and winds. These steps aimed to respond to the problems posed such as the lack of sufficient resolution of the models to capture the related dynamics, the effect continental shelf to the dynamics inside the estuary and the lack of proper and sufficient representation of all the driving mechanisms, including components of tides, river discharge, wind, etc.
Moreover, a turbulence closure model is needed to explain the mixing characteristics. While turbulent mixing occurs in all three directions, horizontal mixing terms are at least two orders of magnitude smaller than the substantial derivative of the horizontal velocity components. In circulation models, these terms are not resolved due to large grid spacing thus parameterizations can be used (Burchard, 2002). Consequently, the focus is on the vertical mixing for which a closure model must be found. Typically, it is not known a priori what level of complexity is necessary to adequately represent vertical turbulence closure. Choices range from a simple constant eddy viscosity/diffusivity, to an algebraic model, to a number of more sophisticated two-equation models with an increasing demand on effort and computational resources The proper choice of a turbulence model is of significant importance if one is to succeed in modeling the fate and transport of dissolved or particulate constituents correctly. So the questions a modeler typically faces and must answer are what level complexity is needed? Is a constant eddy viscosity approach sufficient or does one need to deploy a two-equation closure model? If the latter is true then: is there a two-equation model that performs best or do they all perform at the same level and does it not matter which turbulence closure model to use? These questions are answered by testing several turbulence closures. To achieve this, a turbulence model capable of replicating any two-equation closure is implemented into the UnTRIM kernel, and different turbulence models are tested in order to best represent the salinity intrusion and mixing characteristics in the Estuary. This test is completed for a low flow period of two months that is identified (July-August, 2003) and the salinity intrusion in the Estuary is modeled and replicated.
As a last step, with the proper hydrodynamic modeling of the Delaware Estuary, a sediment transport model is developed to assess the transport of sediments and determine the erosional and depositional patterns of sediments in the estuary, emphasizing the location of the turbidity maxima, and how it migrates.

1.6. Organization of the thesis

The details of each work are explained in Chapters 2 through 4. The thesis is organized as follows:

Chapter 2 presents the available hydrodynamic models, how the UnTRIM model is selected, the governing equations and their discretization and implementation.

Chapter 3 explains in detail how the hydrodynamic model is built, starting from the grid generation step, boundary forcings and how they built to different turbulence closures, presenting the simulation results including tides and salinity and gives details about important findings.

Chapter 4 formulates the sediment transport model and explains, in detail, the dynamics of the suspended sediments, turbidity maximum and erosional and depositional patterns in the Delaware Estuary.

Chapter 5 presents the conclusions, explains the contribution of this thesis and suggests future extensions to the current work.
CHAPERT 2: NUMERICAL MODEL

2.1. Aspects of 3-D modeling

3-D numerical models vary greatly because of the underlying difference in discretization and the physics resolved. Each model is suitable for a different modeling situation and decisions should be made according to modeling needs. The proper model should resolve the phenomena while maintaining accuracy and efficiency. In order to decide which model is suitable for the Delaware Estuary domain, these differences are explained below.

2.1.1. Grids and Discretization in Vertical

In order to numerically solve the partial differential equations (PDE), approximations are introduced. These approximations are algebraic equations that are solved at discrete points or cells. This means that the domain of interest should be represented as a grid. If the computational domain is selected to be rectangular in shape and the interior points are distributed along the orderly defined gridlines, this type of grid is known as Structured Grid. If the grid points can not be associated with orderly defined gridlines, this type of grid is known as Unstructured Grid.

All methods, and consequently grid types have their own advantages and disadvantages. There is no unique way to decide which method is better, but for a certain given geometry one method has more advantages than the other. A grid selection should be made according to the problem of interest.
If a domain is rectangular, finite difference equations are most efficiently solved with equal grid spacing. In reality, it is usually impossible to have rectangular domains. Thus, it is necessary to transform the nonrectangular physical domain into rectangular computational domain where grid points are equally spaced. This type of transformation is known as the coordinate transformation. It is important to note that the computational domain is obtained by deforming and stretching the physical domain.

On the other hand, if the domain is highly irregular, unstructured grids are better suited to map out the irregularities, like bays and tributaries. Finite volume and finite element methods are generally used with unstructured grids. For a 2-D grid generation, triangular elements are generally used. The triangular elements are most flexible in shape to fit any type of boundary. The most popular methods that generate such grids are the Advancing Front methods (Lo, 1985) and the Delaunay methods (Weatherill, 1988).

For hydrodynamic modeling, two different vertical discretization exists; “z” and “σ”. While “z” discretization divides the domain using equal spacing between each layer, the σ levels are used to follow bathymetry and divide the domain into pre-specified number of layers. Because of the nature of σ discretization, the thickness of each layer changes with time and space.

2.1.2. Efficiency, Accuracy and Stability

Efficiency, accuracy and stability of codes differ depending on time and space discretization techniques. The codes may be implicit or explicit in nature and may be first
or second order accurate. All these parameters depend on the specific techniques that are used to discretize the code and cannot be generalized.

2.2. Choice of Appropriate Code

Many academic and commercial codes exist in literature such as; MIKE-3, CH3D-WES, POM and ECOM-si, DELFT-3D, TELEMAC-3D, ROMS-TOMS, GOTM, ELCIRC and TRIM-UnTRIM family, to name just a few of the most widely used.

CH3D-WES was developed by the US Army Corps of Engineers (USACE) Waterways Experiment Station (WES), Coastal and Hydraulics Laboratory (CHL). The basic code was developed by Sheng (1986) and deploys a time-varying three-dimensional hydrodynamic and transport model based on a boundary-fitted curvilinear numerical grid. In this model the closure of vertical momentum is achieved by the use of a \( k-\varepsilon \) model. For horizontal mixing, the Smagorinsky model is applied.

The Princeton Ocean Model (POM) is a sigma coordinate, free surface, primitive equation ocean model, which includes a turbulence sub-model. It was developed by Blumberg and Mellor (1987) and has been widely used by a significant user community. The code incorporates the well-known (Mellor, 1982) turbulence closure. ECOM-si is similar to the POM described in Blumberg and Mellor (1987) but incorporates an implicit scheme developed by Casulli (1990) for solving the gravity wave so the need for separate barotropic and baroclinic time steps is eliminated.
The Regional Ocean Model System (ROMS) is a free-surface, hydrostatic, primitive equation ocean model that uses stretched, terrain-following coordinates in the vertical and orthogonal curvilinear coordinates in the horizontal. Initially, it was based on the S-coordinate Rutgers University Model (SCRUM) described by Song and Haidvogel (1994). ROMS was completely rewritten to improve both its numerical characteristics and efficiency in single and multi-threaded computer architectures. It was also expanded to include a variety of new features including high-order advection schemes; accurate pressure gradient algorithms; several subgrid-scale parameterizations; atmospheric, oceanic, and benthic boundary layers; biological modules; radiation boundary conditions; and data assimilation. This model is mostly used for coastal and oceanographic simulations.

The Delft3D is a commercial 3D hydrodynamic (and transport) simulation program which calculates non-steady flow and transport phenomena resulting from tidal and meteorological forcing on a curvilinear, boundary fitted grid (Postma et al., 2003). Other commercial programs include Mike-3, MIKE11 and MIKE21 (Warren and Bach, 1992), which is a software package for three-dimensional free-surface flows developed by Danish Hydraulic Institute (DHI), and TELEMAC, (Hervouet and Bates, 2000) which is a 3-D finite element based modeling code.

GOTM has been developed and is supported by a core team of ocean modelers at the Baltic Sea Research Institute (Umlauf, 2003). GOTM aims at simulating vertical exchange processes accurately in the marine environment where mixing is known to play
a key role. It has been designed such that it can easily be coupled to 3-D circulation models, and used as a module for the computation of vertical turbulent mixing. The core of the model computes solutions for the one-dimensional versions of the transport equations of momentum, salt and heat.

Most of these models (CH3D-WES, Delft3D, ROMS etc.) use curvilinear grids in the horizontal direction which is difficult to fit to complex geometries and some of them have strict stability requirements. These codes are not as efficient as the codes ELCIRC and TRIM-UnTRIM family of codes.

The Eulerian-Lagrangian Circulation model (ELCIRC) is an unstructured-grid model designed for the effective simulation of 3D baroclinic circulation across river-to-ocean scales (Zhang et al., 2004). It uses a finite-volume/finite-difference Eulerian-Lagrangian algorithm to solve the shallow water equations, and is written to address a wide range of physical processes and of atmospheric, ocean and river forcings. The numerical algorithm is of low-order accuracy, but volume conservative, stable and computationally efficient. It also naturally incorporates wetting and drying of tidal flats. The model uses the same formulation as the UnTRIM model and was developed a few years after the UnTRIM code, but was discontinued, and evolved to a new model “SELFE” in 2006. It is not as efficient as UnTRIM, and was not available at the start of this research.

The Unstructured Tidal Residual Inter Mudflat model (UnTRIM) is a semi-implicit scheme for solving the hydrodynamic equations on specially arranged unstructured grids
and shares the same philosophy with the family of TRIM models (Casulli, 1990; Casulli and Cheng, 1992; Cheng et. al., 1993). The hydro-system, being so complex, requires a stable and efficient way of solving the governing equations. The numerical model UnTRIM (Casulli and Zanolli, 2002; Casulli and Walters, 2000) is capable of solving Reynolds Averaged Navier-Stokes equations (RANS) together with salinity and temperature (scalar transport) on unstructured grids. The numerical approach uses a semi-implicit method which incorporates an Eulerian-Lagrangian approximation for the advective terms, making the method unconditionally stable for barotropic flows (Casulli and Cheng, 1992). The numerical scheme is subject to a weak Courant-Friedrichs-Lewy (CFL) stability condition for baroclinic flows. This property allows the modeler to use high time step values in simulations, and as a consequence, UnTRIM can be very efficiently used for long term and forecast simulations. The unique way of building the finite difference expressions on an orthogonal unstructured grid produces a system of equations which can be solved efficiently by a preconditioned conjugate gradient method. Moreover, the model allows wetting and drying of elements that is crucial to the different simulation scenarios. The flexibility of using triangular, quadrilaterals (and theoretically penta and hexa node) elements and the resulting ability to very accurately map the complex domain in addition to the possibility of running this code on a single Intel processor machine coupled with the fact that it shows by far superior execution time and CPU characteristics made it the code of choice for this research.
2.3. Governing Equations

2.3.1. Mass and Momentum Conservation

The governing three-dimensional equations describing free-surface flows can be derived from the Navier-Stokes equations after averaging over turbulent time-scales. Such equations express the physical principle of conservation of volume, mass, and momentum. The momentum equations for an incompressible fluid have the following form:

\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} - f v = - \frac{\partial p}{\partial x} + \nu^h \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) + \frac{\partial}{\partial z} \left( \nu^v \frac{\partial u}{\partial z} \right)
\] (1)

\[
\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} + f u = - \frac{\partial p}{\partial y} + \nu^h \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) + \frac{\partial}{\partial z} \left( \nu^v \frac{\partial v}{\partial z} \right)
\] (2)

\[
\frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} = - \frac{\partial p}{\partial z} + \nu^h \left( \frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} \right) + \frac{\partial}{\partial z} \left( \nu^v \frac{\partial w}{\partial z} \right) - \frac{\rho}{\rho_0} g
\] (3)

Here \( f \) is the Coriolis parameter, and \( \nu^h \) and \( \nu^v \) are the coefficients of horizontal and vertical eddy viscosity, respectively.

The incompressible continuity equation is given by:

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0
\] (4)
Integrating the continuity equation over the depth and using a kinematic condition at the free surface leads to a free surface equation:

\[
\frac{\partial \eta}{\partial t} + \frac{\partial}{\partial x} \left[ \int_{-h}^{0} udz \right] + \frac{\partial}{\partial y} \left[ \int_{-h}^{0} vdz \right] = 0
\]  

(5)

in which \( \eta \) is the free surface elevation.

### 2.3.2. Transport of Species

The mass conservation of any scalar variable is expressed by:

\[
\frac{\partial C}{\partial t} + \frac{\partial (uC)}{\partial x} + \frac{\partial (vC)}{\partial y} + \frac{\partial \left[(w-w^s)C\right]}{\partial z} = \frac{\partial}{\partial x} \left( K^h \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial y} \left( K^v \frac{\partial C}{\partial y} \right) + \frac{\partial}{\partial z} \left( K^z \frac{\partial C}{\partial z} \right) + \text{source}
\]  

(6)

where \( C \) denotes the concentration of any scalar transported species such as salinity, temperature, sediment etc. \( w^s \) is the settling velocity when \( C \) is the sediment concentration. \( K^h \) and \( K^v \) are the horizontal and vertical diffusivity coefficients, respectively. The system is closed by an equation of state:

\[
\rho = \rho(C)
\]

where \( \rho \) is the fluid density that depends on concentration. The numerical model integrates the governing equations in a finite volume sense on specially arranged grids.
called unstructured orthogonal grids. The numerical discretization of the momentum equations are explained in detail in Casulli and Walters (2000) whereas the numerical discretization of the transport equation is explained in detail in Casulli and Zanolli (2002).

2.4. Unstructured Orthogonal Grid

The use of unstructured grids offers great flexibility in developing areas with potentially vastly different resolution characteristics. This not only increases the accuracy but also fortifies the model efficiency by using the computational resources mostly on the areas of interest. The UnTRIM model uses a special version of an unstructured grid: the orthogonal unstructured grid. An orthogonal unstructured grid is obtained by covering the domain with convex polygons. The element or polygon center coincides with the center of the circum-circle of the element, which is not necessarily the geometric center. Connecting each polygon center, the line joining the center of each adjacent polygon is orthogonal to the shared side of these two polygons (Figure 2.1), which is the main idea behind the orthogonal grid configuration.
The orthogonal unstructured grids can be obtained efficiently and qualitatively by Delaunay triangulation (Spragle et al., 1991). In this method, the domain is decomposed into polygons where each polygon is linked with a single point (marked by black squares in Figure 2.2) which is called the “generating point”. A domain can be decomposed into polygons where any point inside the polygon is closer to its own generating point than the generating point of any other polygon. The polygons generated are referred as Dirichlet tessellation or Voronoi tessellation (Weatherill 1988). The boundaries of polygons are perpendicular bisectors of the lines joining the neighboring generating points which form a perfect unstructured orthogonal grid (Figure 2.2).

2.4.1. Requirements for a Good Grid

The accuracy of the numerical model depends on the perpendicularity of the segment joining the centers to the shared face. Also, the centers of the adjacent elements must be
as equal in distance as possible from the shared face to increase accuracy. The special cases of unstructured orthogonal grids, obtained by squares and equilateral triangles where the polygon centers coincide with the geometric center, produce a perfectly second order accurate spatial discretization of the governing equations. On the other hand, the convergence rate depends on the diagonal dominancy of the coefficient matrix for the preconditioned conjugate gradient solver. An increase in diagonal dominance in the coefficient matrix can be obtained by either increasing the grid size or by decreasing the time step. While the former decreases spatial accuracy, the latter increases the computational execution time. The modeler must seriously consider these constraints and reach a trade-off between these two parameters for the study.

Figure 2.2 Delaunay triangulation with Voronoi tessellation.
2.5. Turbulence Closure

The momentum and transport equations require knowledge of turbulent eddy viscosity ($\nu$) and eddy diffusivity ($K$) of the hydrodynamic system. These flow properties can be obtained by turbulence modeling. Although there is no turbulence model incorporated within the UnTRIM code, it is adoptable to any turbulence model with the use of “get” and “set” functions that extract and insert parameter values into the numerical kernel thus allowing any type of turbulence closure to be adapted to the kernel.

Turbulence is a natural phenomenon in fluids that occurs when the velocity gradients are high, resulting in disturbances in the flow domain as a function of space and time. Turbulence arises near walls or between two neighboring layers with different velocities. It results from unstable waves generated from laminar flows as the Reynolds number increases. With increasing velocity gradients, the flow becomes rotational, leading to a stretching of vortex lines, which can not be supported in two dimensions. Thus the turbulent flow is always physically three-dimensional typical random fluctuations.

The majority of flows begin as orderly fluid motion (laminar flow). As the Reynolds number is increased, instabilities within the boundary layer are generated. Subsequently these instabilities will lead the flow to transition from laminar to the random fluid motion of turbulence. Several factors may affect these processes such as surface roughness, heat transfer, pressure gradient, buoyancy and free stream turbulence.
For developing a turbulence model, the physical processes involved must be identified and included in the model description. The processes defining the turbulence are:

- Production (turbulence is produced by different processes depending on the physics of the problem in which small eddies become larger ones, e.g., boundary layer, pressure gradient, buoyancy)
- Convection and Diffusion (The transport of the fluid property from one region to another)
- Dissipation (Where small eddies become self destructive due to the molecular viscosity)

In turbulent flows, large and small scales of the continuous energy spectrum, which are proportional to the size of eddy motions, are mixed. Here eddies are overlapping in space, with large ones carrying small ones. In this process, the turbulent kinetic energy transfers from larger eddies to smaller ones, then the smallest eddies eventually dissipate their energy into heat through molecular viscosity.

The turbulent flow can be analyzed by either deterministic or statistical methods. In the direct numerical simulation (DNS) (Lele, 1989; Liu, et. al., 1997), which is deterministic, a refined mesh is used so that all of these scales, large and small, are resolved. Application of this method is restricted to a small group of problems since the computational cost for real systems is prohibitive due to necessary fine grid resolution
(centimeters or millimeters). In statistical approaches, time averaging of variables separates the mean quantities from fluctuations. This results in new unknown variables appearing in the governing equations. Thus, additional equations are introduced to close the system which is known as turbulence modeling or Reynolds averaged Navier-Stokes (RANS) methods. A compromise between DNS and RANS is the large eddy simulation (LES) (Leonard, 1974; Germano et. al., 1991) which has become popular in recent years. Here, large-scale eddies are computed and small scales are modeled. Small-scale eddies are associated with the dissipation range of isotropic turbulence, in which modeling is simpler than RANS.

Although the LES and DNS are very powerful tools for turbulence modeling, their use is nearly impossible for large hydrodynamic systems. Some current work has been carried out on small hydrodynamic flow problems such as flow past a cylinder (Nakayama and Vengadesan 2002), flow over a weir (Sarker and Rhodes 2004) contracting and expanding channels sections etc. for best hydraulic performance. However, most of the commercial and academic 3-D hydrodynamic codes are based on RANS turbulence modeling.

In turbulence modeling, all large and small scales of turbulence are modeled so that mesh refinements needed for DNS are not required. As previously mentioned, flow fields can be calculated by time or space averaging the flow variables which results in additional unknowns in the governing equations. Additional equations are provided by the closure process or the turbulence modeling.
2.5.1. Review of Zero, One and Two Equation Turbulence Models

Zero-equation (algebraic) models: The purpose of these models is to close the system without providing an extra differential equation. This may be achieved by the classical method of Prandtl mixing length or more recent models by Cebeci (1974) or Luyten et. al. (1996). These models provide Reynolds stresses in terms of eddy viscosity.

One-equation models: In the one equation models, a term $k$ known as the turbulent kinetic energy is related to eddy viscosity. A transport equation for the turbulent kinetic energy $k$ is added to the system and solved simultaneously with the Navier-Stokes equations.

Two-equation models: In complex flows, the lower order turbulence models, that is zero or one–equation models become very complicated and often ambiguous. Two-equation models were developed to better represent the physics of turbulence.

A class of two-equation models for turbulence closure has been extensively applied to estuarine simulation. The most successful ones are the Mellor and Yamada (Mellor 1982), modeling the turbulent kinetic energy ($k$) and the length scale ($l$); the $k$-$\varepsilon$ model of Rodi (1987), modeling the turbulent kinetic energy ($k$) and its dissipation rate ($\varepsilon$) and the $k$-$\omega$ model of Wilcox (1988).
In a recent study, the Mellor-Yamada level 2.5 closure (MY2.5) has been compared to data collected at northern San Francisco Bay where the model tends to underestimate turbulent kinetic energy in regions of strong stratification and to overestimate turbulent kinetic energy in weakly stratified regions (Stacey et al. 1999).

Burchard et al. (1998) compared $k$-$\varepsilon$ and Mellor-Yamada two-equation turbulence models. They showed that the choice of the stability functions, which are used as proportionality factors for calculating the eddy viscosity and diffusivity, has a stronger influence on the performance of the turbulence model than does the choice of length scale related equation. Burchard and Bolding (2001) have compared several second-moment turbulence closure models with different length scale-related parameter transport equations. They showed the influence of different stability functions on the performance of the turbulence models where they showed that the second-moment closure by Canuto et al. (2001) is superior to others.

2.6. Generic Length Scale Model

Recently Umlauf and Burchard (2003) proposed a generic length-scale equation that can represent the transport of $l$, $\varepsilon$ and $\omega$ by a single equation. Application of this method enables the user to choose a variety of two-equation methods by solving an equation for turbulent kinetic energy and an equation for generic length scale parameter. The ability to execute a code using the various closure methods prompted the use of the GLS because it permits a straightforward comparison between the closure approaches.
The GLS model solves a transport equation for turbulent kinetic energy ($k$) and a transport equation for a generic parameter ($\Psi$). The generic parameter is defined by:

$$\Psi = (c^0_p \cdot k^m \cdot \mu^n)$$  \hspace{1cm} (7)

Depending on the value of $p$, $m$ and $n$, the parameter takes the form of different turbulent closure parameters like $\varepsilon, \omega, kl$. The transport equation for ($k$) in a Cartesian coordinate system is given by:

$$\frac{\partial k}{\partial t} + u \frac{\partial k}{\partial x} + v \frac{\partial k}{\partial y} + w \frac{\partial k}{\partial z} = \frac{\partial}{\partial z} \left( \frac{K_M}{\sigma_k} \frac{\partial k}{\partial z} \right) + P + B - \varepsilon$$  \hspace{1cm} (8)

where, $P$ is the shear production $B$ is the buoyancy and $\varepsilon$ is the dissipation rate.

Similarly the transport equation for the generic parameter ($\Psi$) is given by:

$$\frac{\partial \Psi}{\partial t} + u \frac{\partial \Psi}{\partial x} + v \frac{\partial \Psi}{\partial y} + w \frac{\partial \Psi}{\partial z} = \frac{\partial}{\partial z} \left( \frac{K_M}{\sigma_\Psi} \frac{\partial \Psi}{\partial z} \right) + \frac{\Psi}{k} \left( c_1 P + c_3 B - c_2 \varepsilon F_{\text{wall}} \right)$$  \hspace{1cm} (9)

The production ($P$) and buoyancy ($B$) of turbulent kinetic energy are calculated by:

$$P = K_M \cdot \left[ \left( \frac{\partial U}{\partial z} \right)^2 + \left( \frac{\partial V}{\partial z} \right)^2 \right]$$  \hspace{1cm} (10)
\[ B = -K_H \cdot N^2 \]  \hspace{1cm} (11)

where \( N^2 = \frac{-g}{\rho_0} \frac{\partial \rho}{\partial z} \) and the dissipation rate (\( \varepsilon \)) is:

\[ \varepsilon = \left( c^0_\mu \right)^{3a(p/n)} \cdot k^{(1/2)(m/n)} \cdot \Psi^{-1/n} \]  \hspace{1cm} (12)

After the solution of turbulent kinetic energy (\( k \)) and generic parameter (\( \Psi \)), the eddy viscosity (\( K_M \)) and diffusivity (\( K_H \)) values are calculated using:

\[ K_M = c \cdot \sqrt{2k} \cdot l \cdot S_M + \nu \]  \hspace{1cm} (13)

\[ K_H = c \cdot \sqrt{2k} \cdot l \cdot S_H + \nu_0 \]  \hspace{1cm} (14)

\( S_M \) and \( S_H \) are the Kanta-Clayson type stability functions. \( \nu \) and \( \nu_0 \) are the molecular viscosity and diffusivities respectively.

The GLS method for turbulence closure is implemented in two steps. First a separate code is developed for testing the code then the code is inserted into the UnTRIM engine. The solution procedure for the first code in the above equations is fractional step method. In this method, the horizontal advection terms are time stepped using a finite volume discretization then the remaining terms are calculated with a finite difference formulation in the z-direction.
The advection part for \((k^*)\) is calculated for each polygon by:

\[
P_i \cdot \Delta z_{i,k} \cdot \frac{k_i^* - k_i^{n}}{\Delta t} = -\sum \text{sign}_{i,j} \cdot u_j \cdot k_i \cdot \lambda_j \cdot \Delta z_{j,k} + (w_{i+z+1} k_{i+z+1} - w_{i} k_{i}) \cdot P_i
\]

(15)

to obtain the \((k^*)\) values. Here \(P_i\) represent the area of the \(i^{th}\) polygon for the computational domain and \(\sum \text{sign}_{i,j} \cdot u_j \cdot k_i \cdot \lambda_j \cdot \Delta z_{j,k}\) represents the sumo of advective fluxes in horizontal direction. \((w_{i+z+1} k_{i+z+1} - w_{i} k_{i}) \cdot P_i\) represents the advective flux in vertical direction.

Here the transported terms are calculated at the prism centers. Since the turbulent quantities are required at the top face of each cell, these values will be interpolated to the top faces of all prisms. The same type of equation is also solved to obtain generic parameter \((\Psi^*)\) at * time step and interpolated.

The remaining terms in the kinetic energy equation are discretized by a finite difference formulation. The equation is written for each column produced by the prisms of same polygon.

\[
\frac{k_i^{n+1} - k_i^*}{\Delta t} = \left( \frac{K_M}{\sigma_z} \right)_{(i+1)_{i+1}} \cdot \frac{k_i^{n+1} - k_i^{n}}{\Delta z_{i+1}} - \left( \frac{K_M}{\sigma_z} \right)_{(i)_{i+1}} \cdot \frac{k_i^{n+1} - k_i^{n}}{\Delta z_{i}} + P + B - \varepsilon
\]

(16)
The system can be solved with a tridiagonal matrix algorithm. The boundary conditions of the system are given by:

Dirichlet:

\[ \psi_{\text{top, bottom}} = \left( c_\mu^0 \right)^p \cdot k^n \cdot k^m \cdot \left( z_{\text{top, bottom}} \right)^n \]

\[ k_{\text{top, bottom}} = \frac{U_*^2}{\left( c_\mu^0 \right)^2} \]

where \( U_* \) is the friction velocity at the free surface and bottom.

Neumann:

\[ \frac{K_M}{\sigma_\psi} \frac{\partial \psi}{\partial z}_{\text{top, bottom}} = -n \cdot \frac{K_M}{\sigma_\psi} \cdot \left( c_\mu^0 \right)^p \cdot k^m \cdot \left( z_{\text{top, bottom}} \right)^{n-1} \]

\[ \frac{K_M}{\sigma_k} \frac{\partial k}{\partial z}_{\text{top, bottom}} = 0 \]

The coefficient arrays for the tridiagonal matrix solver, representing sub-diagonal \( (C) \), diagonal \( (B) \), super-diagonal \( (A) \) and the right hand side of tridiagonal system \( (D) \), are then calculated as:
\[ C_i \cdot k_{i+1}^{n+1} = \frac{1.0}{\Delta z_i} \cdot \Delta t \cdot \left( \frac{K_M}{\sigma_z} \right)_{(i)_{\text{half}}} \cdot \frac{1}{(\Delta z_{i+1} + \Delta z_i) / 2} \cdot k_{i+1}^{n+1} \]

\[ B_i \cdot k_i^{n+1} = -1 + \Delta t \cdot \left( \frac{w_i \cdot (1 - \gamma)}{\Delta z_{i+1}} - \frac{w_i \cdot \gamma}{\Delta z_i} + \frac{\frac{1.0}{\Delta z_{i+1}} - \frac{K_M}{\sigma_z} \cdot \frac{1.0}{\Delta z_i}}{\frac{1}{(\Delta z_{i+1} + \Delta z_i) / 2} - \frac{K_{nw}}{k_i^*}} \right) \cdot k_i^{n+1} \]

\[ A_i \cdot k_{i+1}^{n+1} = \frac{1.0}{\Delta z_i} \cdot \Delta t \cdot \left( \frac{K_M}{\sigma_z} \right)_{(i)_{\text{half}}} \cdot k_{i+1}^{n+1} \]

\[ D_i = -k_i^* - K_{pi} \cdot \Delta t \]

**Equation for generic parameter (Ψ)**

Following a similar format we obtain:

\[ \frac{\psi_i^{n+1} - \psi_i^n}{\Delta t} = -w_i \cdot (1 - \gamma) \cdot \frac{\psi_{i+1}^{n+1} - \psi_i^{n+1}}{\Delta z_{i+1}} - w_i \cdot \gamma \cdot \frac{\psi_i^{n+1} - \psi_{i-1}^{n+1}}{\Delta z_i} \]

\[ + \frac{\left( \frac{K_M}{\sigma_{\psi}} \right)_{(i+1)_{\text{half}}} \cdot \psi_{i+1}^{n+1} - \psi_i^{n+1}}{\Delta z_{i+1}} - \frac{\left( \frac{K_M}{\sigma_{\psi}} \right)_{(i)_{\text{half}}} \cdot \psi_i^{n+1} - \psi_{i-1}^{n+1}}{\Delta z_i} \]

\[ + \frac{\left( \frac{K_M}{\sigma_{\psi}} \right) \cdot \psi_i^{n+1} - \psi_{i-1}^{n+1}}{\Delta z_i} \]

\[ + \frac{\psi_i^{n+1}}{k_i^n} \left( c_i P + c_i B - c \varepsilon F_{\text{wall}} \right) \]

Again the system is solved for TDMA and the boundary conditions are given by:
The coefficient arrays are then calculated as:

\[ A_i \cdot \psi_{i-1}^{n+1} = \frac{1.0}{\Delta z_i} \cdot \Delta t \cdot \left( w_i \cdot \gamma + \frac{\left( K_M \right)}{\sigma_z} \cdot (\Delta z_{i+1} + \Delta z_i) / 2 \right) \cdot \psi_{i-1}^{n+1} \]

\[ B_i \cdot \psi_{i}^{n+1} = \left( -1 + \Delta t \cdot \frac{w_i \cdot (1 - \gamma)}{\Delta z_{i+1}} - \frac{w_i \cdot \gamma}{\Delta z_i} \right) + \frac{\left( K_M \right)}{\sigma_z} \cdot (\Delta z_{i+1} + \Delta z_i) / 2 \cdot \left( \frac{1.0}{\Delta z_{i+1}} - \frac{1.0}{\Delta z_i} \right) + \left( c_i P + c_B - c_F \cdot F_{wall} \right) \cdot \frac{k^*}{k_i} \cdot \psi_{i}^{n+1} \]

\[ C_i \cdot \psi_{i+1}^{n+1} = \frac{1.0}{\Delta z_{i+1}} \cdot \Delta t \cdot \left( -w_i \cdot (1 - \gamma) + \frac{\left( K_M \right)}{\sigma_z} \cdot (\Delta z_{i+1} + \Delta z_i) / 2 \right) \cdot \psi_{i+1}^{n+1} \]

\[ D_i = -\psi_i^* \]

**Table 2-1 Values of Constants for Generic Length Scale Model**

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<thead>
<tr>
<th></th>
<th>(k - kl)</th>
<th>(k - \epsilon)</th>
<th>(k - \omega)</th>
<th>(k - ge)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(p)</td>
<td>0.0</td>
<td>3.0</td>
<td>-1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>(m)</td>
<td>1.0</td>
<td>1.5</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>(n)</td>
<td>1.0</td>
<td>-1.0</td>
<td>-1.0</td>
<td>-0.67</td>
</tr>
<tr>
<td>(\sigma_k)</td>
<td>2.44</td>
<td>1.0</td>
<td>2.0</td>
<td>0.8</td>
</tr>
</tbody>
</table>
The implementation closely follows the work of Warner et. al. (2005) and the same values for model constants is used in this work (Table 2-1).

### Step By Step Algorithmic Implementation:

- Solve the advection equation for turbulent kinetic energy ($k$)
- Interpolate the values to the top of prisms
- Solve the advection equation for generic parameter ($\Psi$)
- Interpolate the values to the top of prisms
- Calculate $P + B - \varepsilon$ using previous time step values
- Solve the tridiagonal system for turbulent kinetic energy ($k$)
- Solve the tridiagonal system for generic parameter ($\Psi$)
- Limit minimum values for ($k$) and ($\Psi$)
- Calculate length scale ($l$)
- Calculate stability functions $S_M$ and $S_H$
• Calculate eddy viscosity $K_M$ and eddy diffusivity $K_H$

After the code is tested, it is implemented into the UnTRIM engine using its transport code. The advective and diffusive transport of turbulent kinetic energy ($k$) and generic parameter ($\Psi$) are calculated using the UnTRIM engine, then, the values are interpolated into cell faces. The minimum values of $k$ and $\Psi$ are set. The values of velocity gradient ($M$) and buoyancy frequency ($N^2$) are calculated using:

$$M^2 = \left[ \left( \frac{\partial U}{\partial z} \right)^2 + \left( \frac{\partial V}{\partial z} \right)^2 \right]$$  \hspace{1cm} (17)

$$N^2 = -\frac{g}{\rho_0} \frac{\partial \rho}{\partial z}$$  \hspace{1cm} (18)

An upper or lower limit, depending on the value of $n$, is imposed on $\Psi$

$$\Psi^{1/n} \leq \sqrt{0.56 \left( \frac{c^0_\mu}{n} \right)^{m/n} k^{m/n+1/2} N^{-1}}$$  \hspace{1cm} (19)

Next, the length scale is calculated using:

$$l = \left( \frac{c^0_\mu}{n} \right)^{-p/n} k^{-m/n} \Psi^{p/n}$$  \hspace{1cm} (20)

The eddy viscosity ($K_M$) and diffusivity ($K_H$) values are calculated using Kantha and Clayson (1994) type stability functions $S_M$ and $S_H$:
\[ S_H = \frac{a_2 \left( 1 - 6 a_i/b_i \right)}{1 - 3 a_2 G_h \left( 6 a_i + b_2 \left( 1 - c_3 \right) \right)} \]  

(21)

\[ S_M = \frac{b_i^{-1/3} + \left( 18 a_i a_i + 9 a_i a_i \left( 1 - c_2 \right) \right) S_H G_h}{1 - 9 a_i a_i G_h} \]  

(22)

Where \( G_h = -\frac{N^2 l^2}{2k} \) and an upper limit is imposed as

\[ G_h^{\text{max}} = \frac{1}{a_2 \left( b_1 + 12.0 a_i + 3 b_2 \left( 1 - c_3 \right) \right)} \]  

(23)

Then

\[ K_M = c \cdot \sqrt{2k} \cdot l \cdot S_M + \nu \]  

(24)

\[ K_H = c \cdot \sqrt{2k} \cdot l \cdot S_H + \nu_\theta \]  

(25)

where \( \nu \) and \( \nu_\theta \) are the molecular viscosity and diffusivity, respectively. The value of \( c \) is 1.0. In the next step, the production \( P \) and buoyancy \( B \) of turbulent kinetic energy are calculated by:

\[ P = K_M \cdot M^2 \quad \text{where } M \text{ is given in (17)} \]

\[ B = -K_H \cdot N^2 \quad \text{where } N \text{ is given in (18)} \]
And the dissipation rate ($\varepsilon$) is calculated from:

$$
\varepsilon = \left(c_\mu^0\right)^{3+(p/n)} \cdot k^{(3/2)+(m/n)} \cdot \Psi^{-(1/\alpha)}
$$

(26)

The turbulent kinetic energy $k$ and length scale parameter $\Psi$ are then updated using the fractional step method:

$$
\frac{k^{\text{new}} - k^{\text{UnTRIM}}}{\Delta t} = P + B - \varepsilon
$$

(27)

and

$$
\frac{\Psi^{\text{new}} - \Psi^{\text{UnTRIM}}}{\Delta t} = \frac{\Psi^{\text{UnTRIM}}}{k^{\text{UnTRIM}}} \left(c_1 P + c_3 B - c_2 \varepsilon F_{\text{wall}}\right)
$$

(28)
CHAPTER 3: HYDRODYNAMIC MODELING

3.1. Introduction

As explained in the first chapter, the aim of the study is to simulate the circulation patterns and understand the behavior of salinity intrusion to the Delaware Estuary by comparing the effects of turbulence closure. In order to properly model the hydrodynamics of the Estuary, it is necessary to understand the physics of the system to apply the proper modeling tools. These steps are explained in detail in the following sections.

3.2. Characteristics of the Estuary

In this section, characteristics of Delaware Estuary including physical and economical properties will be explained in detail.

3.2.1. Physical Properties

The non-tidal part of Delaware River system is the longest un-dammed river east of the Mississippi River. The system is fed by 216 tributaries, the largest being the Schuylkill and Lehigh Rivers in Pennsylvania. It serves as a major source of water for big cities such as Philadelphia and heavy industry, yet supports a world-class trout fishery. Nearly 15 million people rely on the Delaware River Basin for water, but the river itself is small, draining only four-tenths of one percent of the total continental U.S. land area. The Delaware River was included in the National Wild and Scenic Rivers System. The actions taken after this, resulted in the remarkable improvement of its water quality. The
river system can be identified by two regions: tidal region (estuary) (Figure 3.1, from delawareestuary.org) and non-tidal region (river).

![Figure 3.1 Tidal Delaware River Basin](image)

The tidal part of the Delaware System, Delaware Estuary, stretches from Trenton, New Jersey and Morrisville, Pennsylvania, south to Cape May, New Jersey and Cape Henlopen, Delaware. It includes portions of Pennsylvania, New Jersey and Delaware. Supplying water for more than 7 million people in the Philadelphia Metropolitan area, the Delaware Estuary plays a crucial role for drinking water supply and as a recipient of industrial and municipal wastewater effluent.
The Estuary is comprised of three different regions: 1) the outer Bay, which is characterized by large and relatively shallow areas and adjacent marshes, 2) lower estuary, a middle section that provides the narrowing-down segments from a large bay to the narrow riverine section, and 3) upper estuary, the narrow channel that reaches upstream to the head of tide at a dam in Trenton. The latter is largely comprised of a deep navigation channel that needs to be dredged in order to permit 40ft draft vessels to reach the upstream port facilities.

Because of the funneling effect of the midsection, the velocities in the narrow channel are substantially higher than the outer regions and the tidal signal is magnified due the preservation of the tidal wave energy (minus attenuation) leading to a fundamentally different flow regime than in the outer bay.

Hence, clear simulation depends on both the proper overall representation of the domain hydrodynamics and the need to map sub-region flow effects such as counter flow circulations behind bars and islands, local eddies at pier heads, confluences, behind jutting land masses.

3.2.2. Economical Properties

As a result of clean-up efforts in the Delaware estuary, shad and other fish species are increasing in number. A record number of juvenile shad were netted in the Delaware during 1996, a strong indication of exceptionally good spawning runs when these fish return to the river as adults. A recent study of Delaware Bay shad fishing placed a $3.2
million annual value on this fishery alone (DRBC, 2004). Another important resource is the American or Eastern oyster which yielded a value of $2.2 million in the 1997 season.

There are other economic benefits derived from the river. The Delaware River Port Complex, including docking facilities in Pennsylvania, New Jersey, and Delaware, is the largest freshwater port in the world. The Port of Philadelphia generated $335 million in business revenue in 1997 according to the Philadelphia Regional Port Authority. State and local taxes from port transactions that year totaled $13 million. There were 3,622 jobs directly stemming from port activities.

3.3. Review of Previous Studies

Delaware Estuary has been subject to several numerical and observational studies in the past. The Delaware Estuary is approximately 210 km in length and has a navigation channel of 40 ft deep throughout its extent. The navigation channel covers most of the width in the upper estuary portion where the estuary is narrow. On the other hand, the lower estuary is wide and shallow with a maximum width of 42 km (Galperin and Mellor 1990a). The Delaware River is the main source of discharge for the estuary, where the upstream flow from Delaware River is maintained with a minimum flow of 85 m³/s. There are several tributaries flowing into the Delaware Estuary; such as Schuylkill River, Christina River, Rancocas River; the largest of which is the Schuylkill River.

In a recent study (Schwartz 2003), a submarine groundwater discharge zone has been identified in the Delaware River and Estuary. This zone is located approximately 82 km
upstream from the mouth of the Delaware Bay. The calculated submarine groundwater discharge flux of 14–29 m$^3$/s in that zone is approximately equivalent to the surface water discharge of the second and third largest tributary rivers of the Delaware Estuary. This discharge is not included in the current work but it should be accounted in the future studies as it provides a substantial contribution to estuary fresh water influx.

The Delaware Estuary is a weakly stratified estuary (Garvine et al. 1992) because the ratio of the tidal volume to the freshwater inflow is large. The subtidal$^1$ fluctuations in salinity in the middle reach of Delaware are dominated by pronounced seasonal cycle and the interannual variation$^2$ in the seasonal cycle (Wong 1995). The salinity in the river is closely related to the freshwater inflow, which in turn, is strongly influenced by the rainfall patterns. These patterns are associated with large scale storm events which produce large seasonal and interannual variations in salinity. Wong (1995) suggested that the axial variation in response of the vertical salinity structure to the change in river discharge can be explained by density induced gravitational circulation.

The predominant constituent of the tidal signal is the principal lunar semi-diurnal (M$^2$). The effect of other astronomical tides such as O$_1$, K$_1$, N$_2$, S$_2$ and the effect of overtide$^3$ M$_4$ are small compared to that of M$^2$. The mean tidal range of the M$^2$ constituent at the mouth of Delaware Estuary is 1.3 m, increasing to 2.7 m at the head of the tides at Trenton (Parker, 1991). The combined effects of these tidal constituents generate tidal

$^1$ Long term, tide filtered  
$^2$ Variations within the year  
$^3$ Shallow water tides that are generated by friction or morphology.
currents with a typical speed of 1.0 m/s at the mouth of the Bay and 1.5 m/s in narrow segments of upper estuary.

There is a combined effect of forcing by the Chesapeake Bay through the C&D canal and open boundary in Delaware Bay. At semidiurnal tidal frequency, the barotropic\(^4\) response of the Delaware estuary is predominantly driven by the forcing from the ocean through the mouth of the estuary. However, the volume exchange is strongly influenced by the Chesapeake Bay via the C&D canal at subtidal frequencies (Wong 1991). This influence changes not only the volumetric flow through the bay but also the response of the bay to the forcing at the mouth of the bay.

Numerical modeling of the Estuary is limited to a few studies. A coupled three-dimensional hydrodynamic and transport model that simulated the Delaware Bay, is explained in a series of two papers (Galperin and Mellor, 1990a) and (Galperin and Mellor, 1990b). The first paper provides a description of the numerical model, specifications of various forcing and boundary conditions whereas the second one concentrates on the comparison of the currents, salinities and temperatures from the model with observations. The study is one of the first studies that have been applied to estuaries and shelf as a coupled system. The horizontal grid covers the lower part of the Delaware estuary and C&D canal with a grid spacing of 1x1 km, the shelf with a grid spacing of 5x4 km. The vertical grid is a sigma (\(\sigma\)) grid. The grid size leads to a 2d grid in the narrow river segment of the bay. The model uses a level 2.5 turbulence closure

\(^4\) A state in a water mass, in which, the surfaces of constant pressure are parallel to the surfaces of constant density.
with modifications for stratification (Mellor, 1982). Free surface elevation at the ocean boundary is calculated by a trial and error procedure due to unavailability of data at the shelf. Other forcing includes inflow, surface wind stress, surface heat flux and temperature and salinity at the boundaries. Galperin and Mellor (1990b) conclude that higher resolution is required to improve the results especially in the vicinity of the navigation channel. They further indicate that an extensive database for the boundaries is necessary. Although the three-dimensional, time-dependent model applies a complex turbulence closure submodel that generates the diffusivities, the salinity response to discharge changes is much higher than what is observed (e.g., Garvine et al., 1992) mainly because of insufficient resolution (Walters, 1997).

In more recent studies, Garvine (1999) and Whitney (2003) use an extended version of the same model to simulate the coastal discharge penetration into the continental shelf and plume dynamics. Effects of wind stress on plume dynamics and mixing are addressed in observational studies (Houghton et al. 2004) and (Sanders and Garvine 2001). Munchow and Garvine (1993) observed buoyancy driven currents in the Delaware coastal flows and compared their observations with the results of Galperin and Mellor (1990b). They found that a coastal current is trapped near the shore and the buoyant plume of water is independent of wind direction which the numerical model failed to simulate. They speculated that the model application failed because it contained a grid matching algorithm for 1x1 km grid and 5x4 km grid at the mouth of the bay. They further stated that the model is too sensitive to wind forcing.
Another model study of tidal residual flow in Delaware Bay and River (Walters 1997) uses finite element discretization in space and a harmonic representation in time. A grid containing 12,264 nodes and 23,390 triangular elements covers the horizontal plane with 25 nodes in vertical spaced logarithmically along \( \sigma \) coordinates. The grid starts at the mouth of the estuary with a resolution of 500 m and decreasing to 100 m at the start of the narrowing section and 25 m at the head of the tide. In this study, temperature effects on density were neglected. The study uses a zero order closure of dispersion coefficients and the effect of wind stress is not included. Walters (1997) observed that the tidal wave enters from the ocean and undergoes local amplification at the head and east side of the estuary. According to his results, the amplitude at the bay mouth is controlled by local frictional effects, whereas the amplitude at Trenton is determined by a standing wave. The amplitude of this wave is sensitive to the amplitude at the mouth of the narrowing section. The results also show the important effects of stratification even for a seemingly well mixed estuary.

3.4. Grid Generation with JANET

3.4.1. Decision on Grid Size

Grid resolution is determined by the general hydrodynamics but should also resolve the disturbances like counter flow circulations behind bars and islands, and local eddies at pier heads, with local refinements. Because of the importance of sediment dynamics, the grid development is also based on the need to capture these dynamics. This means that regions of deposition and re-suspension must be represented in detail even though they
may not necessarily play an important role in computing the hydrodynamics because mass and momentum exchange takes place predominantly in the deeper section of the channel.

While the above mentioned aspects determine the necessary grid refinements in specific regions, numerical aspects determine shape, alignment, and the up and down-sizing of grid elements when transitioning from fine to coarser regions of the grid. These aspects are the direct result of how the governing equations are solved and cannot be viewed independently of grid development. In fact, the spatial and temporal accuracy of the numerical integration technique for the governing equations depends directly on the element shape and how neighboring elements connect to each other. Therefore, close attention must be paid during the grid development to satisfy not only the requirements necessitated by the physics, but also the requirements imposed by the numerical solution technique to maintain a degree of accuracy as high as possible.

3.4.2. Generation of Delaware Grid

The applicability of different grid generation techniques was also outlined by Cheng and Casulli (2001). As they stated, the grids generated for finite element methods can be used for UnTRIM applications. However, there is no guarantee that the generated mesh is orthogonal because finite element type solution methods do not require orthogonality. The two common schemes for generating unstructured grids are the Advancing Front method and the Delaunay method. While the former lacks in supplying orthogonality,
mentioned properties of the second scheme can be used to produce an orthogonal mesh for UnTRIM.

The grid for Delaware Estuary is generated by a commercial program called JANET (JAva NET generator). Since the program is written in the Java programming language, it is platform independent and runs on any operating system. The grid generator not only generates UnTRIM-conforming grids by Delaunay triangulation but also reads and writes the grid file that satisfies the input/output requirements of UnTRIM (Celebioglu and Piasecki, 2004).

As a first step, a horizontal boundary, which is 2.0 m above the mean lower low water (MLLW), is selected with all the tributaries included. Then major tributaries and point sources are identified to produce the computational domain while minor tributaries were removed because their inclusion in the modeling domain will have no discernable effect on the hydrodynamic simulations. Next, 1.25 million values are extracted from National Ocean Service (NOS) GEODAS-CD to extract the depth soundings. These points were then triangulated to generate a digital terrain model (DTM) (Figure 3.2; Figure 3.3).
Figure 3.2 Bathymetry (DTM) of the domain.

The DTM is required by the grid generator to calculate depth values for grid points that do not coincide with a sounding point. In addition, JANET needs the DTM to execute
criteria based grid generation, like the automatic inclusion of a finer grid resolution in regions of steep bathymetric gradients. The next step is to generate an initial grid. JANET provides a number of powerful tools that help in generating a “good” orthogonal grid. For example, it can restrict the maximum permissible inside angle, and minimum and maximum areas an element can have. It also has a number of smoothing functions. In addition, working polygons can be set along with pre-specified nodes to permit the control element size, important for the gradual increase or decrease edge lengths of elements. Finally, the layer structure of JANET allows one to isolate certain areas within the grid where separate refining or coarsening routines can be applied. Grid generation itself can be carried out sequentially, i.e. the domain can be divided into several sub domains and then later be linked to form the final mesh. For this work, a grid is generated containing 47,464 elements in the horizontal direction using triangular and quadrilateral elements.

The domain is split into four sub-domains (Figure 3.3) starting from the upstream boundary Trenton and extending to the downstream boundary at Atlantic Ocean. A grid for each sub-domain is generated using different criteria and the generated grids for each sub-domain are merged to form the grid for the whole domain (Figure 3.4).

In the top two sub-domains, the estuary, most of which is covered by navigation channel, is narrow. These sub-domains also include treatment plants, fresh water intakes and man-made structures that complicate the flow field. Maximum area and maximum edge length criteria are used for these domains to achieve a high degree of resolution.
In the lower parts where the estuary is wider, Equilateral elements with refinements following bathymetry changes are used. Also, limiting the minimum angle in triangles produces high quality spatial discretization. A special technique, which searches for bathymetry gradients, forces refinement of elements at sharp gradients (user specified) of bathymetry in order to have smaller element sizes that captures these gradient changes.

The minimum angle criterion forces the minimum angle of elements to be higher than a specified value. This produces triangles that are closer to equilateral triangles and increases accuracy. The first criterion is mostly applied at the bay entrance while the second is applied inside the bay where its width has a maximum value in the lowest sub-domain.
Figure 3.4 Merged Grid
The Delaware River is heavily used by maritime transportation for which a navigation channel of 40 feet is maintained. As a consequence most of the flow passes through the deep navigation channels. Aligning the sides of elements to these channels not only prevents unrealistic fluxes out of the channel but also decreases the numerical diffusion. The alignment is made by building construction polygons which follow the navigation channel so that the element sides can be aligned to these polygons (Figure 3.5).

Figure 3.5 Alignment of elements to the navigation channel near Rancocas Creek.
The grid was generated so the element size is smallest (on average) in the upper half of the estuary, i.e. the region containing the most confluences, intakes and outfalls, side bays, shallow areas, and sections with very rapid changes in bathymetry due to the navigation channel. The average grid size in this area is approximately 40 meters, with some of the elements being larger. The smallest size is approximately 12 meters. The grid size gradually increases to 1.5 – 2.0 km in the outer bay and approximately 3 km at the open boundary.

Second order accuracy in spatial discretization is achieved if the polygon centers are equally distant from the shared side. Thus the gradual change in grid size keeps the center of polygons nearly the same distance from the shared side and minimizes the deviation from second order accuracy. This is achieved by forcing a gradual change of element size at the boundary by applying the mask options that permit the gradual transition from fine to coarse and from coarse to fine grid sizes. An example is shown in Figure 3.6.
Figure 3.6 Gradual change in grid size near Lewes.

Although JANET generates high quality grids, some of the elements may be of poor quality. The grid generator marks non-orthogonal elements for visual inspection and subsequently allows the user to fix them by moving and adjusting the location of element nodes. Typically, poor quality is a result of the location of the polygon centers and not so much the result of a violation of the orthogonality constraint. Element centers, close to the shared edge, results in a decrease of accuracy in the spatial discretization. To alleviate this problem, JANET permits the conversion of two adjacent triangles into a single
quadrilateral. The fourth corner of the generated quadrilateral may not coincide with the circum-circle, resulting in a deviation from orthogonality. As a result, the demand for orthogonality may need to be relaxed in those cases. Figure 3.7 shows an example quadrilateral element and the amount of deviation from orthogonality (degrees) for each side of the element.

![Figure 3.7](image)

**Figure 3.7 Level of deviation from orthogonality for a quadrilateral element.**

The grid, shown in Figure 3.4, is used for tidal simulation and has a very fine resolution at the upper part of the domain. Early simulations showed that the tidal boundary conditions applied at the circular open boundary did not produce the tidal signals correctly at stations within the Estuary. To overcome this, the boundary was extended to the continental shelf (up to the 50 meter isobath). Thus, the processes of the continental shelf and their relation and impact on the bay dynamics were captured. The total number of elements in the extended grid is 49215 in the horizontal direction with 34 layers.
(Figure 3.8). The boundary conditions for the extended grid were extracted from East Coast tidal database. They reproduced tidal conditions in the Estuary.

During this research, a new version of the grid generator software became available with an option to permit automatic generation of quadrilateral elements in open and well defined sub-regions with regular boundaries that could then be nested with triangular grids. So another grid, mostly quadrilateral with coarser resolution was prepared to improve computational efficiency. The availability of quadrilateral grid generation enabled long elements to be used with smaller width in the along channel direction. Thus, a grid 200 m long and 40 m wide covers the same area as ten equilateral triangles 40 m on a side. This change decreases the execution time.
A horizontal grid of 7445 quadrilateral and 2635 triangular elements was generated (Figure 3.9). The size of the elements ranges from 40 m at the upstream boundary at Trenton to 2,500 m at the continental shelf.

![Mixed quadrilateral and triangular grid](image)

**Figure 3.9 Mixed quadrilateral and triangular grid**

This grid is designed by gradually changing the grid size and keeping the center of polygons nearly the same distance from the shared side, thus, minimizing the deviation from second order accuracy.

The quadrilateral elements are generated by aligning the elements by either side of a construction curve which follows the curvature of the channel (Figure 3.10). The
construction curves are generated as Bezier curves, a high order mathematical curve fitting technique to points, in order to achieve smooth transition and orthogonal quadrilateral elements (Figure 3.10).

![Figure 3.10 Construction polygons](image)

The use of quadrilateral elements allowed the grid to be perfectly aligned to the along-channel flow direction and increased the accuracy of numerical model. Parts of the domain that cannot be generated by quadrilateral elements are covered by triangular elements. These areas are generated separately and then nested into the quadrilaterals (Figure 3.9 and Figure 3.11).
Once grid generation is completed, the vertical datum must be modified. Bathymetry is referenced to mean-lower-low-water (MLLW) level while the tidal boundary conditions are referenced to mean sea level (MSL). The transformation from MLLW to MSL is done with the VDatum software tool (Hess 2002; Parker et al. 2003). The software is designed to transform coastal elevations between 28 different vertical datums consisting of tidal, orthometric, and ellipsoidal datums. Although the Vdatum domain covers most of the Delaware Estuary (Figure 3.12), extrapolations are made using NOAA’s tidal stations for the parts that are not covered.
3.5. Model Setup

3.5.1. Simulation Period

A simulation period of two months (July - August 2003) was selected to capture varying flow conditions over medium-size duration. The simulation period represents a low flow summer condition in Delaware Estuary where the salinity intrusion is higher compared to high inflow periods such as spring conditions. The selection was made based on the best available coverage of discharge, tidal, and salinity observations in the Estuary.

3.5.2. Available Data

Different types of data are available through various sources. The following data is available for the simulation period in Delaware Estuary:
• River discharge: Several gauging stations are available from United States Geological Survey (USGS) which measures the flow passing through and the Delaware River and its tributaries (Figure 3.13).

• Wind field: Wind speeds and directions are available from the National Data Buoy Center of NOAA (Buoy 44009).

• Water surface elevations: Data available from National Oceanic and Atmospheric Administration (NOAA) observation stations of Physical Oceanographic Real-Time System (PORTS) for several stations within the bay (Figure 3.18 and Figure 3.23).

• Salinity time series: Available at Ship John Shoal Light station of PORTS system.

• Salinity profile: A salinity profile along the main navigation channel is available from a survey completed by University of Delaware (Cook, 2004; Cook et. al., 2006). The survey was performed in June, 2003 two months prior to the simulation period.

3.5.3. Boundary Conditions

Inflow Boundary Conditions

Inflow boundary conditions were extracted from United States Geological Survey (USGS) stations. Major Tributaries such as the Schuylkill River, Rancocas River and Christina River were considered in addition to the main source of discharge, the Delaware River. The total inflow value can be as high as 1200 (m³/s) as shown in Figure 3.14.
The USGS stations shown in Table 3-1 are used for building the hydrographs in Figure 3.14.
Table 3-1 USGS Station Names and Numbers

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<th>STATION NAME</th>
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<tbody>
<tr>
<td>1463500</td>
<td>DELAWARE RIVER AT TRENTON NJ</td>
</tr>
<tr>
<td>1478000</td>
<td>CHRISTINA RIVER AT COOCHS BRIDGE, DE</td>
</tr>
<tr>
<td>1478245</td>
<td>WHITE CLAY CREEK NEAR STRICKERSVILLE, PA</td>
</tr>
<tr>
<td>1478650</td>
<td>WHITE CLAY CREEK AT NEWARK, DE</td>
</tr>
<tr>
<td>1479000</td>
<td>WHITE CLAY CREEK NEAR NEWARK, DE</td>
</tr>
<tr>
<td>1479820</td>
<td>RED CLAY CREEK NEAR KENNETT SQUARE, PA</td>
</tr>
<tr>
<td>1480015</td>
<td>RED CLAY CREEK NEAR STANTON, DE</td>
</tr>
<tr>
<td>1481000</td>
<td>BRANDYWINE CREEK AT CHADDS FORD, PA</td>
</tr>
<tr>
<td>1481500</td>
<td>BRANDYWINE CREEK AT WILMINGTON, DE</td>
</tr>
<tr>
<td>1483700</td>
<td>ST JONES RIVER AT DOVER, DE</td>
</tr>
<tr>
<td>1474500</td>
<td>SCHUYKILL RIVER AT PHILADELPHIA, PA</td>
</tr>
</tbody>
</table>

Tidal Boundary Conditions

Tidal boundary conditions are supplied at the 85 boundary elements of the extended grid at the ocean boundary. The effect of tides by the Chesapeake Bay is forced at the end of C&D canal.

The predominant constituent of the tidal signal is the M2. While the other tidal constituents such as O1, K1, N2, S2 and the effect of over tide M4 are small compared to the M2 component, the decision was made to include them into the boundary forcing with the aim to eliminate a potential source for inaccuracy when computing surface
elevations, velocities, and salinity profiles. In order to simulate these effects, a variable, harmonically decomposed, water level boundary condition of three diurnal (K1, Q1, O1) and four semi-diurnal (K2, S2, N2, M2) components in both space and time was extracted from the East Coast Tidal Database (Mukai et al. 2001). Through the East Coast Database of tidal elevations, elevations and currents in open waters within the Western North Atlantic Tidal (WNAT) domain (Figure 3.15) are available.

The WNAT domain encompasses the Western North Atlantic Ocean, the Gulf of Mexico and the Caribbean Sea. The database defines the computed elevation and velocity amplitude and phase for the O1, K1, Q1, M2, S2, N2, and K2 tidal constituents as well as the steady, M4 and M6 overtones.
A computer program is used to produce an output of each harmonic constituent elevation amplitude and phase at the 85 boundary element centers where the open boundary conditions are applied. The time history of water surface elevations at each of these boundary elements are computed from:
\[
\eta(t) = \sum A_i \cdot f_i(t_0) \cdot \cos \left[ \frac{2\pi}{T_i} (t - t_0) + V_i(t_0) - \Phi_i \right]
\]  

(29)

where \( \eta \) represents the free surface elevation and \( A_i \) and \( \Phi_i \) are the amplitude and phase of the \( i \)\textsuperscript{th} constituent, respectively. The nodal factor \( f_i(t_0) \) and the equilibrium argument \( V_i(t_0) \) with reference to Greenwich Meridian Time are computed using another computer program for each constituent for reference time \( t_0 \) and is shown in Table 3-2. \( T_i \) is the period of each constituent and is given in Table 3-3. A sample plot of combination of 5 constituents for a single boundary element is shown in Figure 3.16.

![Tidal Height vs Time](image)

**Figure 3.16** Tidal forcing for an element at the continental shelf boundary
Table 3-2 Nodal Factor and Equilibrium Argument of Tidal Constituents

<table>
<thead>
<tr>
<th>CONSTITUENT</th>
<th>NODE FACTOR</th>
<th>EQ. ARG. (ref. GM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>K1</td>
<td>1.07334</td>
<td>2.42</td>
</tr>
<tr>
<td>O1</td>
<td>1.11852</td>
<td>307.69</td>
</tr>
<tr>
<td>P1</td>
<td>1</td>
<td>350.86</td>
</tr>
<tr>
<td>Q1</td>
<td>1.11852</td>
<td>48.72</td>
</tr>
<tr>
<td>N2</td>
<td>0.97928</td>
<td>48.34</td>
</tr>
<tr>
<td>M2</td>
<td>0.97928</td>
<td>307.31</td>
</tr>
<tr>
<td>S2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>K2</td>
<td>1.18333</td>
<td>184.25</td>
</tr>
</tbody>
</table>

Table 3-3 Frequency and Period of Each Tidal Constituent

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Frequency(Radians/Second)</th>
<th>Period(Hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>K1</td>
<td>0.000072921158360</td>
<td>23.934469660</td>
</tr>
<tr>
<td>O1</td>
<td>0.000067597744150</td>
<td>25.819341670</td>
</tr>
<tr>
<td>M2</td>
<td>0.000140518902510</td>
<td>12.420601220</td>
</tr>
<tr>
<td>S2</td>
<td>0.000145444104330</td>
<td>12.000000000</td>
</tr>
<tr>
<td>N2</td>
<td>0.000137879699490</td>
<td>12.658348260</td>
</tr>
<tr>
<td>K2</td>
<td>0.000145842317200</td>
<td>11.967234790</td>
</tr>
<tr>
<td>Q1</td>
<td>0.000064958541130</td>
<td>26.868356680</td>
</tr>
<tr>
<td>M4</td>
<td>0.000281037805020</td>
<td>6.210300610</td>
</tr>
<tr>
<td>M6</td>
<td>0.000421556707530</td>
<td>4.140200408</td>
</tr>
</tbody>
</table>
It is assumed that the extracted components generate adequate open boundary conditions at the continental shelf boundary and that the nonlinear components are generated by the numerical model within the domain. The water level at the Chesapeake Bay end of C&D canal are calculated using the K1, Q1, O1, K2, S2, N2, M2, and SA components from the NOAA/NOS station (ID: 8573927) at Chesapeake City, MD.

**Wind Fields**

For the simulation period, uniform wind forcing over the entire domain was applied using the National Ocean Service (NOS) buoy data (Figure 3.17). South south-west winds were dominant except during certain periods of time when strong north-east wind events were observed.

![Figure 3.17 Along and across-shelf wind forcing](image)
Even though recent studies seem to indicate that local wind fields do have an impact on the circulation patterns, this study applied a global wind field due to the lack of data for local fields.

**Bottom and Surface Friction**

A quadratic drag law is used at both the bottom and free surface boundaries. The x and y components of the bottom shear stress are calculated from:

\[
\tau_b^x = \rho_0 r_b \sqrt{u^2 + v^2} u
\]  
\[
\tau_b^y = \rho_0 r_b \sqrt{u^2 + v^2} v
\]

where \( \rho_0 \) is the fluid density, \( r_b \) is the bottom drag coefficient, and \( u \) and \( v \) are the velocities in x and y directions respectively. The bottom drag coefficient between 0.0025 and 0.0045 were used in order to best match the observed tidal characteristics.

Similarly, wind friction is calculated from:

\[
\tau_i^x = \rho_o r_i \sqrt{(u_a - u)^2 + (v_a - v)^2} (u_a - u)
\]

\[
\tau_i^y = \rho_o r_i \sqrt{(u_a - u)^2 + (v_a - v)^2} (v_a - v)
\]
where \( u_a \) and \( v_a \) are the components of the wind velocity shown in Figure 3.17. A constant drag coefficient \( (r_f) \) of \( 1.75 \times 10^{-6} \) is used for the surface layer.

**Equation of State**

The density term is assumed to depend only on the concentration of salinity. Temperature is not taken into account because previous studies in the Delaware Bay have shown that the temperature effect is small compared to salinity. A linearized form of equation of state is used.

\[
\frac{\rho}{\rho_0} = 1.0 + 7.8 \times 10^{-4} \cdot C_s
\]

(34)

where \( C_s \) is the salinity concentration in practical salinity unit (PSU)

**Time step**

An estimate for time step based on the maximum internal wave speed can be calculated. Salinity difference of 30 PSU yields:

\[
\frac{\rho}{\rho_0} = 1.0 + 7.8 \times 10^{-4} \cdot (30) \approx 1.021
\]

which introduces 21 kg/m\(^3\) difference in density and a grid size of 300 m yields:
A time step of 150 seconds was used in the simulations.

3.6. Results and Discussion

For the two-month period of July and August, 2003, continuity and momentum equations are solved together with four scalar transport constituents, i.e. salinity, turbulent kinetic energy, turbulent length scale, and sediment concentration. A total of seven different simulations were performed to compare and select a proper turbulence closure model for the Delaware Estuary.

The seven different turbulence closures are used and simulation results were compared with data to capture varying flow conditions over the 62 day simulation period. These models are: a constant eddy viscosity, mixing length theory with Richardson number modification, GLS formulation with $k - \varepsilon$, $k - \omega$, $k - kl$ and $k - ge$ parameterization and the original Mellor-Yamada level 2.5 (MY25) closures. The effect of vertical viscosity is compared and the best performing model ($k - \varepsilon$) is used in sediment transport simulations.

The simulation period included a combined river discharge forcing of selected tributaries (Figure 3.14) where two significant peak flows occurred. The first one occurred on July
23\textsuperscript{rd} with a peak discharge of 900 m\textsuperscript{3}/s (total inflow from all sources), and the other one was on August 7\textsuperscript{th} with a peak discharge of 1200 m\textsuperscript{3}/s. Tidal currents periodically accelerate and slow the current in the Estuary. The total effect of different tidal constituents is imposed at the ocean boundary and at the C&D canal. The average tidal range for the duration of the simulation is around 1.2 m at the ocean boundary (50 m isobath), reaching 2.0 m at the bay entrance, and up to 2.8 m mid-estuary.

3.6.1. Free Surface Elevation

The water surface elevation within the Delaware Estuary is influenced by the estuarine geometry, bathymetry and bottom friction. Tides approach the bay in the across-shelf direction. Free surface elevation is mostly effected by the tidal boundary conditions.
The seven major tidal constituents used to reproduce water surface elevations are sufficient to represent the amplitude and phase of tidal signals at Cape May (A), Lewes (B), Brandywine Shoal Light (C), and Ship John Shoal Light (D), shown in Figure 3.18 (figure generated using Google Earth).

As shown in Figure 3.19 and Figure 3.20, the simulations, performed using five turbulence closure models, all capture the amplitude and phase of the tidal signal accurately at the mouth of the bay. The tidal signal reaches to the Cape May and Lewes stations almost simultaneously. The Mellor Yamada 2.5, GLS $k-kl$ and $k-\omega$ slightly overestimates amplitudes, whereas the $k-ge$ method underestimates them.
Further upstream at the stations Brandywine Shoal Light and Ship John Shoal Light (Figure 3.21 and Figure 3.22), the tidal wave becomes steeper. The GLS formulation with $k-\varepsilon$ and $k^{-ge}$ parameterizations underestimate amplitudes compared to the other models. The $k^{-ge}$ model underestimates the most among the other models at the upstream station Ship John Shoal light with a difference in amplitude of 23 cm.

In to better quantify the degree of matching or deviance a harmonic analysis was performed using the tidal analysis package of Foreman (1977). Hourly observation and simulation values are extracted from time series for the 62 day simulation and analyses was performed for all 36 possible components. The results for the most significant components, M2, N2, S2, K2, K1, O1, P1, and M4, are presented on Table 3-4 through Table 3-11. Other components are negligible in amplitude or not captured by the analysis because the 62 day data is not long enough.

The models, overall, predicted the amplitudes accurately but the most accurate model varies from station to station. Since the most dominant component of the tidal signal is the M2 tide, it is clear that the differences in the observed and simulated water levels largely originate from this component. The errors in amplitudes for other components N2, S2, K2, K1, O1, P1, and M4 are mostly within 1 cm in all stations. The Cape May and Lewes stations (both are close to the bay mouth and are located on the two opposing sides of the mouth, see also Figure 3.18), receive the M2 tidal signals almost simultaneously (3 degree difference); but the amplitudes vary from model to model. The
$k - \omega$ model best matches the observations at Cape May (Table 3-4) while the $k - \varepsilon$ and MY25 best matches the observation at Lewes (Table 3-5). The $k - ge$ model underestimates the amplitudes at both of these stations. The phase of M2 tide is captured within 5 degrees for all models at all stations. The $k - \varepsilon$ model best captured the phase at Ship John Shoal Light station (Table 3-11) while the $k - \omega$ model the worst and the opposite is true for Lewes station (Table 3-9). Further upstream at Brandywine Station $k - \omega$ and $k - kl$ models are the most accurate models (Table 3-6). All models except $k - \omega$ underestimate the M2 amplitudes at Ship John Shoal Light Station, $k - ge$ being the least accurate one.

While all of the models use the same bottom friction coefficients, it is important to note that the friction coefficients have not been calibrated for a specific model to better fit the tidal amplitudes. The models represented the time series of water levels accurately. This suggests that water surface elevations are controlled mainly by boundary conditions and geometry rather than the internal mixing. The choice of turbulence closure plays a small role in determining the tidal heights for the stations at the bay mouth.
Figure 3.19 Measured and simulated water levels with different turbulence closures at Cape May Station
Figure 3.20 Measured and simulated water levels with different turbulent closures at Lewes Station
Figure 3.21 Measured and simulated water levels with different closures at Brandywine Shoal Light Station
Figure 3.22 Measured and simulated water levels with different turbulent closures at Ship John Shoal Light Station
### Table 3-4 Harmonic Analysis Results for Cape May Station

| Observation | $k-\omega$ | $k-\epsilon$ | $k-kl$ | Const. | Amp. (m) | Amp. (m) | Err (m) | Amp. (m) | Amp. (m) | Err (m) | Amp. (m) | Amp. (m) | Err (m) | Amp. (m) | Amp. (m) | Err (m) |
|-------------|------------|--------------|--------|--------|---------|---------|--------|---------|---------|--------|---------|---------|--------|---------|---------|
| M2          | 0.728      | 0.728        | -0.001 | 0.671  | 0.714   | 0.695   | -0.033 | 0.631   | 0.097   |
| N2          | 0.133      | 0.140        | 0.008  | 0.127  | 0.134   | 0.128   | -0.004 | 0.119   | -0.014  |
| S2          | 0.122      | 0.138        | 0.015  | 0.128  | 0.136   | 0.130   | 0.008  | 0.119   | -0.003  |
| K1          | 0.109      | 0.086        | -0.023 | 0.084  | 0.084   | 0.084   | -0.025 | 0.082   | -0.027  |
| O1          | 0.085      | 0.078        | -0.007 | 0.076  | 0.077   | 0.077   | -0.009 | 0.075   | -0.011  |
| P1          | 0.036      | 0.029        | -0.008 | 0.028  | 0.028   | 0.028   | -0.008 | 0.027   | -0.009  |
| K2          | 0.033      | 0.037        | 0.004  | 0.035  | 0.037   | 0.035   | 0.002  | 0.032   | -0.001  |
| M4          | 0.013      | 0.018        | 0.006  | 0.009  | 0.011   | 0.008   | -0.005 | 0.006   | -0.007  |

### Table 3-5 Harmonic Analysis Results for Lewes Station

| Observation | $k-\omega$ | $k-\epsilon$ | $k-kl$ | Const. | Amp. (m) | Amp. (m) | Err (m) | Amp. (m) | Amp. (m) | Err (m) | Amp. (m) | Amp. (m) | Err (m) | Amp. (m) | Amp. (m) | Err (m) |
|-------------|------------|--------------|--------|--------|---------|---------|--------|---------|---------|--------|---------|---------|--------|---------|---------|
| M2          | 0.600      | 0.612        | 0.013  | 0.594  | 0.614   | 0.602   | 0.002  | 0.570   | -0.030  |
| N2          | 0.115      | 0.120        | 0.005  | 0.117  | 0.121   | 0.118   | 0.003  | 0.113   | -0.002  |
| S2          | 0.108      | 0.118        | 0.010  | 0.116  | 0.120   | 0.117   | 0.008  | 0.111   | 0.003   |
| K1          | 0.103      | 0.085        | -0.018 | 0.083  | 0.084   | 0.083   | -0.020 | 0.082   | -0.021  |
| O1          | 0.084      | 0.076        | -0.008 | 0.075  | 0.075   | 0.075   | -0.009 | 0.074   | -0.010  |
| P1          | 0.034      | 0.028        | -0.006 | 0.028  | 0.028   | 0.028   | -0.006 | 0.027   | -0.007  |
| K2          | 0.029      | 0.032        | 0.003  | 0.032  | 0.033   | 0.032   | 0.002  | 0.030   | 0.001   |
| M4          | 0.011      | 0.022        | 0.010  | 0.013  | 0.015   | 0.013   | 0.002  | 0.010   | -0.002  |
### Table 3-6 Harmonic Analysis Results for Brandywine Shoal Light Station

<table>
<thead>
<tr>
<th>Observation</th>
<th>$k-\omega$</th>
<th>$k-\epsilon$</th>
<th>$k-kl$</th>
<th>MY-25</th>
<th>$k-ge$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Const.</td>
<td>Amp. (m)</td>
<td>Amp. (m)</td>
<td>Err (m)</td>
<td>Amp. (m)</td>
<td>Amp. (m)</td>
</tr>
<tr>
<td>M2</td>
<td>0.740</td>
<td>0.746</td>
<td>0.006</td>
<td>0.679</td>
<td>-0.061</td>
</tr>
<tr>
<td>N2</td>
<td>0.133</td>
<td>0.144</td>
<td>0.011</td>
<td>0.126</td>
<td>-0.007</td>
</tr>
<tr>
<td>S2</td>
<td>0.120</td>
<td>0.139</td>
<td>0.020</td>
<td>0.127</td>
<td>0.007</td>
</tr>
<tr>
<td>K1</td>
<td>0.114</td>
<td>0.088</td>
<td>0.026</td>
<td>0.083</td>
<td>-0.031</td>
</tr>
<tr>
<td>O1</td>
<td>0.085</td>
<td>0.080</td>
<td>0.006</td>
<td>0.077</td>
<td>-0.009</td>
</tr>
<tr>
<td>P1</td>
<td>0.038</td>
<td>0.029</td>
<td>0.009</td>
<td>0.028</td>
<td>-0.010</td>
</tr>
<tr>
<td>K2</td>
<td>0.033</td>
<td>0.038</td>
<td>0.005</td>
<td>0.034</td>
<td>0.002</td>
</tr>
<tr>
<td>M4</td>
<td>0.010</td>
<td>0.018</td>
<td>0.008</td>
<td>0.008</td>
<td>-0.002</td>
</tr>
</tbody>
</table>

### Table 3-7 Harmonic Analysis Results for Ship John Shoal Light Station

<table>
<thead>
<tr>
<th>Observation</th>
<th>$k-\omega$</th>
<th>$k-\epsilon$</th>
<th>$k-kl$</th>
<th>MY-25</th>
<th>$k-ge$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Const.</td>
<td>Amp. (m)</td>
<td>Amp. (m)</td>
<td>Err (m)</td>
<td>Amp. (m)</td>
<td>Amp. (m)</td>
</tr>
<tr>
<td>M2</td>
<td>0.878</td>
<td>0.950</td>
<td>0.071</td>
<td>0.728</td>
<td>-0.150</td>
</tr>
<tr>
<td>N2</td>
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<td>0.177</td>
<td>0.042</td>
<td>0.118</td>
<td>-0.017</td>
</tr>
<tr>
<td>S2</td>
<td>0.129</td>
<td>0.172</td>
<td>0.044</td>
<td>0.124</td>
<td>-0.005</td>
</tr>
<tr>
<td>K1</td>
<td>0.121</td>
<td>0.088</td>
<td>0.033</td>
<td>0.073</td>
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</tr>
<tr>
<td>O1</td>
<td>0.088</td>
<td>0.086</td>
<td>0.003</td>
<td>0.075</td>
<td>-0.014</td>
</tr>
<tr>
<td>P1</td>
<td>0.040</td>
<td>0.029</td>
<td>0.011</td>
<td>0.024</td>
<td>-0.016</td>
</tr>
<tr>
<td>K2</td>
<td>0.035</td>
<td>0.047</td>
<td>0.012</td>
<td>0.034</td>
<td>-0.001</td>
</tr>
<tr>
<td>M4</td>
<td>0.037</td>
<td>0.044</td>
<td>0.007</td>
<td>0.033</td>
<td>-0.004</td>
</tr>
</tbody>
</table>
Table 3-8 Phase of Each Tidal Constituent at Cape May Station

<table>
<thead>
<tr>
<th>Observation</th>
<th>Const.</th>
<th>Phase (deg)</th>
<th>Err (deg)</th>
<th>Phase (deg)</th>
<th>Err (deg)</th>
<th>Phase (deg)</th>
<th>Err (deg)</th>
<th>Phase (deg)</th>
<th>Err (deg)</th>
<th>Phase (deg)</th>
<th>Err (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M2</td>
<td>55.3</td>
<td>53.6</td>
<td>-1.7</td>
<td>52.9</td>
<td>-2.4</td>
<td>51.9</td>
<td>-3.4</td>
<td>53.4</td>
<td>-1.9</td>
<td>53.6</td>
</tr>
<tr>
<td></td>
<td>N2</td>
<td>34.0</td>
<td>40.4</td>
<td>6.4</td>
<td>35.3</td>
<td>1.3</td>
<td>35.0</td>
<td>0.9</td>
<td>36.3</td>
<td>2.2</td>
<td>36.4</td>
</tr>
<tr>
<td></td>
<td>S2</td>
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<td>80.3</td>
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<td>79.5</td>
<td>-6.2</td>
<td>79.7</td>
<td>-6.0</td>
<td>81.2</td>
<td>-4.5</td>
<td>80.4</td>
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<td>189.3</td>
<td>-24.1</td>
<td>188.1</td>
<td>-25.3</td>
<td>188.8</td>
<td>-24.6</td>
<td>191.1</td>
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<td>O1</td>
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<td>-199.2</td>
<td>209.0</td>
<td>9.6</td>
<td>211.3</td>
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<td>196.4</td>
<td>-24.1</td>
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<td>K2</td>
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<td>-9.2</td>
<td>102.1</td>
<td>-8.9</td>
<td>103.6</td>
<td>-7.4</td>
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<td>M4</td>
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<td>188.3</td>
<td>1.0</td>
<td>211.6</td>
<td>64.4</td>
<td>200.2</td>
<td>53.0</td>
<td>218.4</td>
<td>71.2</td>
<td>217.2</td>
</tr>
</tbody>
</table>

Table 3-9 Phase of Each Tidal Constituent at Lewes Station

<table>
<thead>
<tr>
<th>Observation</th>
<th>Const.</th>
<th>Phase (deg)</th>
<th>Err (deg)</th>
<th>Phase (deg)</th>
<th>Err (deg)</th>
<th>Phase (deg)</th>
<th>Err (deg)</th>
<th>Phase (deg)</th>
<th>Err (deg)</th>
</tr>
</thead>
<tbody>
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<td></td>
<td>M2</td>
<td>58.1</td>
<td>56.7</td>
<td>-1.4</td>
<td>53.1</td>
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<td>N2</td>
<td>33.8</td>
<td>41.6</td>
<td>7.8</td>
<td>34.0</td>
<td>0.2</td>
<td>35.3</td>
<td>1.5</td>
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</tr>
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<td></td>
<td>S2</td>
<td>87.8</td>
<td>81.4</td>
<td>-6.3</td>
<td>77.6</td>
<td>-10.2</td>
<td>79.5</td>
<td>-8.3</td>
<td>79.0</td>
</tr>
<tr>
<td></td>
<td>K1</td>
<td>214.6</td>
<td>191.2</td>
<td>-23.4</td>
<td>190.8</td>
<td>-23.8</td>
<td>190.7</td>
<td>-23.8</td>
<td>191.1</td>
</tr>
<tr>
<td></td>
<td>O1</td>
<td>201.2</td>
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<td>9.1</td>
<td>210.6</td>
<td>9.4</td>
<td>0.1</td>
<td>-201.1</td>
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<td>P1</td>
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<td>197.9</td>
<td>-23.8</td>
<td>197.8</td>
<td>-23.8</td>
<td>198.1</td>
</tr>
<tr>
<td></td>
<td>K2</td>
<td>110.2</td>
<td>103.8</td>
<td>-6.3</td>
<td>100.0</td>
<td>-10.2</td>
<td>101.9</td>
<td>-8.3</td>
<td>101.4</td>
</tr>
<tr>
<td></td>
<td>M4</td>
<td>226.4</td>
<td>199.8</td>
<td>-26.7</td>
<td>213.7</td>
<td>-12.7</td>
<td>207.2</td>
<td>-19.3</td>
<td>217.1</td>
</tr>
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</table>
Table 3-10 Phase of Each Tidal Constituent at Brandywine Shoal Light Station

<table>
<thead>
<tr>
<th>Observation</th>
<th>$k-\omega$</th>
<th>$k-\epsilon$</th>
<th>$k-k_t$</th>
<th>MY-25</th>
<th>$k$-ge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Const.</td>
<td>Phase (deg)</td>
<td>Phase (deg)</td>
<td>Err (deg)</td>
<td>Phase (deg)</td>
<td>Err (deg)</td>
</tr>
<tr>
<td>M2</td>
<td>63.4</td>
<td>62.3</td>
<td>-1.1</td>
<td>60.8</td>
<td>-2.6</td>
</tr>
<tr>
<td>N2</td>
<td>41.3</td>
<td>50.1</td>
<td>8.9</td>
<td>43.3</td>
<td>2.0</td>
</tr>
<tr>
<td>S2</td>
<td>93.4</td>
<td>89.7</td>
<td>-3.7</td>
<td>88.0</td>
<td>-5.4</td>
</tr>
<tr>
<td>K1</td>
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<td>-23.8</td>
<td>193.3</td>
<td>-21.2</td>
</tr>
<tr>
<td>O1</td>
<td>203.1</td>
<td>210.0</td>
<td>6.8</td>
<td>212.9</td>
<td>9.7</td>
</tr>
<tr>
<td>P1</td>
<td>221.6</td>
<td>197.8</td>
<td>-23.8</td>
<td>200.4</td>
<td>-21.2</td>
</tr>
<tr>
<td>K2</td>
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<td>112.1</td>
<td>-3.7</td>
<td>110.4</td>
<td>-5.4</td>
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<tr>
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<td>187.8</td>
<td>199.4</td>
<td>11.6</td>
<td>213.1</td>
<td>25.3</td>
</tr>
</tbody>
</table>

Table 3-11 Phase of Each Tidal Constituent at Ship John Shoal Light Station

<table>
<thead>
<tr>
<th>Observation</th>
<th>$k-\omega$</th>
<th>$k-\epsilon$</th>
<th>$k-k_t$</th>
<th>MY-25</th>
<th>$k$-ge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Const.</td>
<td>Phase (deg)</td>
<td>Phase (deg)</td>
<td>Err (deg)</td>
<td>Phase (deg)</td>
<td>Err (deg)</td>
</tr>
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<td>M2</td>
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<td>93.0</td>
<td>-4.0</td>
<td>98.6</td>
<td>1.6</td>
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<td>N2</td>
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<td>83.3</td>
<td>4.7</td>
<td>88.0</td>
<td>9.5</td>
</tr>
<tr>
<td>S2</td>
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<td>128.9</td>
<td>-5.4</td>
<td>135.2</td>
<td>0.8</td>
</tr>
<tr>
<td>K1</td>
<td>231.5</td>
<td>203.4</td>
<td>-28.1</td>
<td>213.8</td>
<td>-17.7</td>
</tr>
<tr>
<td>O1</td>
<td>222.3</td>
<td>222.0</td>
<td>-0.3</td>
<td>231.8</td>
<td>9.5</td>
</tr>
<tr>
<td>P1</td>
<td>238.6</td>
<td>210.5</td>
<td>-28.1</td>
<td>220.8</td>
<td>-17.7</td>
</tr>
<tr>
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<td>151.3</td>
<td>-5.4</td>
<td>157.6</td>
<td>0.8</td>
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<tr>
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<td>81.9</td>
<td>109.4</td>
<td>27.4</td>
<td>139.7</td>
<td>57.7</td>
</tr>
</tbody>
</table>
While this work is focused on the mixing characteristics of the lower estuary and bay the model domain also includes the sections leading up to the head of tide at Trenton. Because there are several additional stations in the upper reaches of the Delaware Estuary, i.e. Marcus Hook (E), Philadelphia (F), Burlington (G) and Newbold (H); shown in Figure 3.23, they lend themselves for additional comparisons that actually test the ability of the model to properly transmit the tidal signal through the narrow and deep sections of the estuary, typically considered a litmus test for the accuracy of hydrodynamic simulations. Water surface elevations and simulation results using the algebraic closure model are shown in Figure 3.24. The results show similar behavior compared to two equation models at stations, Cape May, Brandywine Shoal Light, and Ship John Shoal Light. The
amplitudes are underestimated for upstream stations. The difference in observed and simulated amplitudes increases moving upstream, and phase difference between the observed and simulated results become significant especially for the Burlington and Newbold stations (Figure 3.24). While the increasing deviation is no surprise as one moves further upstream (errors further downstream propagate upstream), the reason can be twofold. Firstly, it should be mentioned that this phenomenon can actually be caused by grid characteristics rather than physical processes (or the inaccurate modeling them). The grid generation can cause artifacts in the depth allocation by creating almost invisible bottom walls that compartmentalize the bottom elements in effect creating enormous flow resistance. The use of JANET allowed the removal of these artificial walls at the bottom to create a smooth bottom and side wall geometry. Hence, the deviations in the upstream stations are in all likelihood due to improperly assigned bottom friction coefficients requiring additional fine tuning in future modeling efforts.
Figure 3.24 Water surface elevations for algebraic model
3.6.2. Salinity

Unfortunately, salinity time series data was only available at a single station for the simulation period (the other stations showed “no value”, indicating a malfunction of the sensor), i.e. at Ship John station. The comparison of salinity data at the Ship John station to simulation results is shown in Figure 3.25. The variations in salinity amplitude are not simulated well by the algebraic closure or the constant viscosity approach. It appears that an approach more complex than the low order closures is needed to characterize the turbulent mixing. For the simulation period, the $k - \varepsilon$ model best reproduced the salinity. The MY25 closure and its representation $k - kl$ in GLS present similar values for salinities. This means that the GLS $k - kl$ model replicated the original MY25 closure results. Although the same wall proximity functions are used in the models, minor differences in amplitudes are observed. The reason for these minor differences arises from the additional limitations implemented in GLS model (see eqn. 19). In the $k - \omega$ model, the amplitudes of fluctuations are overestimated. In addition, the $k - \omega$ model predicts more salinity intrusion than the other models. Consequently, the mean salinity values at the Ship John Station deviate significantly from the data. The response to the wind events of July 23rd present similar increasing and decreasing trends in the $k - \omega$, $k - kl$ and MY25 models (Figure 3.25). The amplitudes of salinity during this event decrease in all models except the $k - ge$ model and $k - ge$ model shows a shift in magnitudes. The strong short duration wind event at July 9th has the highest impact on $k - \omega$, $k - kl$ and MY25 models.
Figure 3.25 Measured and simulated salinity values at Ship John station
A better measure for the accuracy of the salinity time series is the use of the root mean square error (RMSE). For the salinity time series shown in Figure 3.25, the RMSE is calculated using:

\[
RMSE = \sqrt{\frac{\sum_{i=1}^{n}(C_s - C_m)^2}{n}}
\]

where \( n \) is the number of measurements, \( C_s \) is the simulated salinity concentration, \( C_m \) is the measured salinity concentration. The \( k-\varepsilon \) model has the least amount of error followed by the MY25 and \( k-ge \) models, respectively (Table 3-12). Although the variations in salinity due to tides are captured better with \( k-\omega \) model, the error is higher than any other model including the constant eddy viscosity and the algebraic closure.

<table>
<thead>
<tr>
<th></th>
<th>( k-\varepsilon )</th>
<th>MY25</th>
<th>( k-ge )</th>
<th>( k-kl )</th>
<th>( k-\omega )</th>
<th>Algebraic</th>
<th>Constant</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMSE</td>
<td>1.394</td>
<td>1.408</td>
<td>1.568</td>
<td>1.797</td>
<td>5.525</td>
<td>2.462</td>
<td>3.911</td>
</tr>
</tbody>
</table>

The tidally averaged salinity time series are plotted for the two best models \( k-\varepsilon \) and MY25 and compared to the tidally averaged time series observed at Ship John Shoal Light Station (Figure 3.26). Both models show similar trends while the response of MY25 model is stronger to the strong wind events on July 10th and July 26th.
Figure 3.26 Tidal averaged salinity profiles

Figure 3.27 Main Channel
In order to better demonstrate the differences in salinity stratification, a longitudinal cross-section along the main navigation channel (Figure 3.27) is identified. Snapshots of vertical profiles along the main channel are plotted for flood (Figure 3.28) and ebb tides (Figure 3.29).

Figure 3.28 and Figure 3.29 both show the salinity observations (starting from the river km 22 along the main channel) for a survey performed by university of Delaware on June 2003 (Cook et. al. 2006, Cook, 2004). The $k - \varepsilon$ and $k - ge$ models have a well mixed bottom layer and then show a moderate degree of stratification towards the surface layers suggesting larger vertical mixing coefficients. This is also supported by the fact that the tidal variations of salinity amplitudes of $k - \varepsilon$ and $k - ge$ are smaller than that of the other models (Figure 3.25), implying added viscosity and internal friction. The salinity front (2 PSU) for $k - \varepsilon$ is located at kilometer 78 during flood tide and the variation between the flood and ebb tide is 6 km which closely follows the survey completed in June 2003.

The $k - \omega$ model shows the highest level of stratification around 10 PSU (Figure 3.28 and Figure 3.29) and the salinity front is located between kilometers 94-98 for ebb and flood tides, respectively. Comparing the $k - kl$ (GLS representation of Mellor-Yamada) and the separate MY25 model, the salt front of the $k - kl$ model migrates 2 - 4 km further upstream than that of the MY25. The behavior of both models is similar for ebb and flood tides. This is also observed in the measurements of Ship John Station (Figure 3.25). Upwelling events are observed in the MY25 formulation at the deep channel mouth.
Although the models predicted the surface salinity values accurately, both show a high degree of stratification and the salinity front migrates 16 to 19 km further upstream which is not supported by the observations. All models show the salinity front between 75 km and 100 km, similar to what was found by Cook et. al. (2006) except the $k - ge$ model, which is at 71 km for the ebb tide. $k - \varepsilon$ and $k - ge$ models both capture the salinity front accurately when the fronts are compared to the survey data.

The measured salinity profile shows a local trapping around river kilometer 50 which is not captured by any of the models. The reason for this trapping can be the observed high inflow values during the spring conditions. The two month time difference between the survey and simulations can also be the reason in not capturing the local trapping in all of the closure models although the $k - \varepsilon$ and $k - ge$ models captures the general behavior (20 PSU and 24 PSU fronts).
Figure 3.28 Along channel salinity profile for a flood tide
Figure 3.29 Along channel salinity profile for ebb tide
In order to elucidate the specific behavior of shear and buoyancy production, and dissipation terms of the various turbulence closure models during a tidal cycle, a single tidal cycle on July 16th was selected (Figure 3.30). During this cycle the salinity amplitudes are closely followed by all GLS closures except the $k-\omega$ model at Ship John Shoal Light station. The ebb and flood tide velocities are plotted for the same tidal cycle in Figure 3.31. The difference in shear and buoyancy production of turbulent kinetic energy, its dissipation rate and the eddy viscosity values are investigated to understand the underlying differences in turbulence closure models. Five points, corresponding to high and low tide values and in-between those, are selected and marked on the tidal signal (WSE) with black dots (Figure 3.30).

The buoyancy production (see eqn 12) is dominant compared to shear production (eqn. 10) values during high and low tide values. However, in-between high and low tides shear production is an order of magnitude larger than the buoyancy production suggesting a flow similar to channel flow. The dissipation rates (eqn 12) for 2nd and 4th column (in between high and low tides) is one order of magnitude higher than the others and the scales in Figure 3.30 are different for visualization purposes.

An interesting phenomenon is that all models show very little mixing on the top half of the water column compared to the bottom half for the ebb tide. This suggests the mixing is small close to the surface and it is a clear sign of stratification observed in Figure 3.28 and Figure 3.29. The buoyancy production for all models is small during ebb tide, showing a partial stratification that depends on tides (Garvine 1992 and Wong 1995). The
The $k-\omega$ model shows smaller shear production and dissipation values compared to other models. All the models show the peak eddy viscosity around 0.02 m²/s, typical for estuarine dynamics.

Figure 3.30 Turbulence parameters for GLS closures at Ship John Shoal Light.
Figure 3.31 Maximum velocity profiles for flood and ebb tides for Ship John Shoal Light station

Figure 3.31 shows the maximum velocities for different turbulence closures during flood and ebb tides. MY25, $k-$ $\omega$ and $k-$ $kl$ show the highest velocities; whereas the
velocities are smaller for $k-\varepsilon$ and $k-ge$. This shows that the underestimation of M2 tidal amplitude has effect on the average velocity and consequently the underestimation $k-\varepsilon$ and $k-ge$ models caused lower velocities at this station. In addition, ebb velocities are higher than flood velocities. This is an expected result since the superposition of outgoing tide and the river inflow is higher than the difference of incoming tide and river inflow. More over the depths associated with ebb tides are lower than the depths associated with flood tides, causing higher velocities. Similar velocity profiles are observed at Tinicum Island and New Castle (Cook et. al., 2006)
4.1. Introduction

Knowledge of estuarine hydrodynamics is a key component for evaluating the transport of sediments. For this reason several turbulence closure models were compared in Chapter 3. The best performing model \( (k-\varepsilon) \) from these tests is used in the sediment transport modeling. The objective for the sediment transport modeling of this work is to assess the transport of sediments and determine the erosion and deposition patterns of sediments in the estuary. In order to achieve this, sediment characteristics in the estuary need to be identified and a proper numerical model should be built. These steps are outlined in the following sections.

4.2. Sediment Surveys and Literature

Delaware Estuary was subject to several studies. Main tributaries supply most of the suspended sediment load to the estuary. To be specific, the Delaware River at Trenton supplies 56 percent of the load, while the Schuylkill River contributes about 20 percent, and the Christina River about 9 percent (Mansue and Comings, 1974; Santoro, 2004). The sediments undergo many re-suspension and deposition cycles where sediment may be initially deposited in the channel and on the banks of the Delaware Estuary, get reworked by the tides, and eventually slowly moving down stream where they usually end up in salt marshes or in the estuarine turbidity maximum zone. During an average year, 1.4 million metric tons of suspended sediments are delivered to the Delaware
Estuary from its tributaries and more than 50 percent of the load is supplied during the high flow seasons of March and April (Cook et. al., 2006; Santoro, 2004).

Every year, on average, 3.1 million metric tons of sediment is dredged from the shipping channel between Philadelphia and Wilmington by the U.S. Army Corps of Engineers. Sommerfield and Madsen (2003) discovered that the seafloor itself is a major source of sediment, contributing over a million ton a year on average, due to widespread bottom erosion by tidal currents. Their findings stress the dynamic nature of sediments in Delaware Estuary.

An often observed phenomenon in turbid estuaries such as the Delaware Estuary is the estuarine turbidity maximum (ETM). Many studies have focused on the ETM on estuaries such as the Chesapeake Bay (Sanford et al. 2001) and the Hudson River (Geyer et al. 2001). The ETM in the Delaware Estuary extends from 50 to 120 km from the bay mouth (Biggs et. al., 1983). The particle characteristics within the ETM vary. The mean size of suspended particles is bigger in the ETM zone than the lower bay and the upper estuary (Gibbs et. al., 1983). Migration of ETM during typical spring time events is described by Cook et. al. (2006). Two surveys performed on March and June 2003 showed the axial salinity and suspended sediment concentration distribution along the shipping channel of Delaware Estuary (Cook et. al., 2006).
Sommerfield and Madsen (2003) developed an interpretable map of bottom sediment types of the estuary between Burlington, New Jersey, and New Castle, Delaware. They also quantified recent sedimentation rates using the chronologies developed from profiles of radioisotopes $^{137}$Cs and $^{210}$Pb. They classified the main channel bottom composition into fine deposition, no deposition and mixed grain reworking areas. This means that the channel bottom is composed of patchy areas of gravel, sand, and mud. The authors showed many locations where the bedrock is exposed or close to the surface. The project area covers upper and some part of lower estuary and there is an ongoing work at University of Delaware to extend the project area to cover Bay Area.

Two surveys performed on March and June 2003 showed the axial salinity and suspended sediment concentration distribution along the shipping channel of Delaware Estuary (Cook et. al., 2006; Cook, 2004). Cook reported on sedimentary conditions throughout the Delaware Estuary, the research concentrated at Tinicum Island and New Castle, Delaware where observations supplied the data such as critical shear stress for erosion and settling velocity. The estimated critical shear stress for the sediments varied between 1 to 3 dynes/cm$^2$ in these observations. Cook also showed that the turbidity maximum is located 75 to 120 km from the Estuary entrance. He observed considerable variation in the location and intensity of turbidity maximum. This subtidal variability in the location of ETM is caused mostly by the change in the fresh water inflow. His findings showed significant sediment storage within the system, but he argued that this may be a short term phenomenon.
The uSSEABED database (Reid et al., 2005) for the Atlantic coast of the United States became available for use from USGS in early 2006. This database incorporates a wide variety of information about: seafloor sediment texture, composition, and color, biota and biological effects on the seafloor, rocky areas and seafloor hardness, seafloor features, such as ripples, sea floor acoustic properties, sediment geochemical analyses, and sediment geotechnical analyses. This dataset will provide information for different sediment types and will be used in the future studies.

From an ecological point of view, deposition rates of sediments may have detrimental effects on stream ecology. A field study by Miller et al. (2002) pointed that the impact of exceeding natural sedimentation rates due to improper dredge materials placement may cause total loss of certain communities and subsequent colonization by pioneer species. Another study showed that the sediments in the Delaware, Schuylkill, and Salem rivers of the upper Delaware Estuary contained the greatest concentrations of metals and organic contaminants of the mid-Atlantic region (Kiddon et al. 2003).

All of these studies are evidences for the importance of sediment transport modeling in Delaware Estuary. From a modeling point of view, the physical properties of sediments, such as size, shape and composition, and the flow properties such as currents, turbulence and water density determine the transport of sediments. The flow properties should be sufficiently resolved in order to simulate the transport of sediments.
4.3. Theory of Models

With the help of accurate turbulence closure models, suspended sediment transport can be determined by numerical models. Bed load transport, on the other hand, is difficult to model because it requires a very fine grid resolution in the vicinity of the bed. Usually the thickness of the bed load transport layer is a few diameters of the sediments. This leads to a dual approach, whereby the suspended load is calculated by numerical models and the bed load is calculated by semi-empirical formulations. Then, the total load is the sum of the suspended load and the bed load where the depositional flux $D_b$ and the entrainment rate $E_b$ are supplied as boundary conditions to the numerical model (Figure 4.1).

![Figure 4.1 Configuration of sediment transport model](image-url)
4.3.1. Suspended Load Transport

The distribution of the suspended sediment concentration is governed by the advection diffusion equation:

$$\frac{\partial C}{\partial t} + \frac{\partial}{\partial x}(uC) + \frac{\partial}{\partial y}(vC) + \frac{\partial}{\partial z}((w-w_s)C) = \frac{\partial}{\partial x}\left(K_h \frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_h \frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_v \frac{\partial C}{\partial z}\right)$$  \hspace{1cm} (36)  

where \( C \) is the local sediment concentration, \( w \) is the vertical flow velocity, \( w_s \) is the settling velocity of the sediment, \( K_h \) and \( K_v \) are the horizontal and vertical diffusivity coefficients. The diffusivity coefficients and the velocity profiles are computed by the numerical model and fed into the sediment transport equation.

The only parameter that needs to be modeled in equation (36) is the settling velocity \( w_s \).

As seen in Figure 4.1, boundary conditions should be supplied to the governing equation. At the top boundary, which is the free surface, the vertical sediment flux is zero leading to the following flux boundary condition:

$$-K_v \frac{\partial C}{\partial z} + (w-w_s)C = 0$$  \hspace{1cm} (37)  

At the lower boundary, which is the interface between the bed load layer, the net flux should be specified as a boundary condition. The net flux is the difference of the
depositional flux $D_b$ and the entrainment rate $E_b$. The deposition rate at the bottom is calculated from the settling velocity:

$$D_b = w_s \cdot C_b$$  \hspace{1cm} (38)

where, $C_b$ is the bottom concentration. It is assumed that the entrainment rate $E_b$ is equal to the one in equilibrium condition. That is,

$$E_b = M \cdot f\left(\tau_b, \tau_c\right)$$  \hspace{1cm} (39)

where, $M$ is the erosion rate and $f$ is a function which depend on the bottom shear stress, $\tau_b$ is the shear stress applied by the fluid to the sediments, $\tau_c$ is the critical shear stress at which the sediments starts to erode (Winterwerp and Van Kesteren, 2004).

### 4.3.2. Bed Load Transport

Due to the lack of adequate data this study omitted the inclusion of a bed load transport formulation into the numerical model, but several different bed load formulations were compared for completeness sake and are presented and discussed in detail in Appendix B.
4.4. Model Setup

The modeling approach used to investigate the suspended sediment concentrations and locate the estuarine turbidity maximum consisted of hydrodynamic simulations in three dimensions together with the selection of the best turbulence closure model from chapter 3.

The sediment transport calculations are completed with $k-\varepsilon$ turbulence closure, which is found the best performing model for salinity transport. Due to the difficulty of identifying the initial sediment distribution and associated erodible thickness of the layer, this work used an initial 10mm erodible bed for the whole domain. While this is not a realistic initiation of the erodible sediments (the total mass of erodible material is in all likelihood much higher than reality and as such will lead to elevated concentrations) it serves a reasonable base to initiate the motion of sediments and force a sufficient amount of material into the water column. While concentrations may not match, it is expected that the location of the turbidity maximum and also the curvature and location of iso lines can be computed with reasonable accuracy.

Suspended sediment concentrations and erodible bed thickness are examined and compared with the survey findings (Cook et.al., 2006; Cook, 2004). A single class of sediment is used in the simulations. Erosional and depositional fluxes are used as boundary conditions as shown in Figure 4.1.
4.4.1. Simulation Period

The simulation are performed for the period of two months (July - August 2003), with turbulence model, $k-\varepsilon$, and along channel suspended sediment concentrations are compared to the observations in March and June 2003 (Cook et al., 2006).

4.4.2. Boundary Conditions

As explained in the previous sections, the numerical model requires flux boundary condition for the top and bottom boundaries. No flux boundary condition is applied for the free surface (Eqn. 37), while at the bottom boundary:

\[-K_v \frac{\partial C}{\partial z} + (w - w_s) C = \alpha_b + \beta_b (C_b - C) \quad (40)\]

where $\alpha_b$ is the erosional flux given by:

\[\alpha_b = \frac{E}{\rho_s} = \frac{M}{\rho_s} \left( \frac{\tau_b - \tau_c}{\tau_c} \right) \quad \text{for} \quad \tau_b > \tau_c \quad (41)\]

and

\[\alpha_b = 0 \quad \text{for} \quad \tau_b < \tau_c \quad (42)\]

The typical critical shear stress values in literature (Winterwerp and van Kesteren, 2004, p. 348) are between 0.1 Pa and 5 Pa. The survey findings show the critical shear stress at New Castle and Tinicum Island observation stations is between 0.1 and 0.3 Pa. The average value of 0.2 Pa is used as critical shear stress throughout the simulations.
If we define \( \theta = \frac{\tau_b}{\tau_c} \) and a step function \( S(x) = \begin{cases} x & \text{if } x > 0 \\ 0 & \text{if } x \leq 0 \end{cases} \) then \( \alpha_B \) becomes

\[
\alpha_B = \frac{M}{\rho_s} S(\theta - 1)
\] (43)

And the depositional flux is supplied with using:

\[
\beta_B = w_x \\
C_B = 0
\] (44)

\( M \) is the erosion parameter in erosion law of Partheniades in \( \left( \frac{kg}{m^2 s} \right) \), \( E \) is the erosion rate in \( \left( \frac{kg}{m^2 s} \right) \), \( \alpha_B \) is bottom erosional flux in \( (m/s) \), \( \beta_B \) is bottom depositional flux in \( (m/s) \), and \( C, C_B \) are the volumetric concentration of sediments \((-\)).

Depending on the value of \( \alpha_B, \beta_B \) and actual concentration \( C \) near the bottom, the total flux can be positive or negative showing net erosion or deposition of sediments. In order to calculate the erosional flux, the erosion parameter \( (M) \) is required by the numerical model. Although the erosion parameter varies with time and depth in sediment column, it is usually taken constant with typical values between \( 1.0 \times 10^{-5} \) and \( 5.0 \times 10^{-4} \) (kg/m\(^2\)/s) (Winterwerp and van Kesteren, 2004).
The survey findings (Cook, 2004) show considerable scatter in data to estimate the erosion parameter. The data changes with different tidal cycles but it is consistent within a single tidal cycle. A value of M around 9.0x10^{-5} (kg/m^2/s) is found for a single tidal cycle in that work. Various different erosion parameters are employed in simulations and the results are plotted for an erosion parameter of 6.0x10^{-4} (kg/m^2/s).

The effective settling velocity can be calculated by (Scott 1984):

\[ w_s = W_{S,r} (1 - k\phi_s)^n \quad k \approx 1 \quad \text{and} \quad 2.5 < n < 5.5 \]  

(45)

depending on the particle Reynolds number. The observations in Delaware estuary suggest that the maximum concentration is around 1000 (mg/l) = 1 (kg/m^3). Assuming the sediment density is 2650 kg/m^3:

\[ \phi_s = \frac{M_s/V_r}{\rho_s} = \frac{1}{2650} \approx 0.0004 \]

we can deduce that:

\[ w_s \approx W_{S,r} \]

Within a single class of sediments, the median settling velocity of sediment is dependent on the suspended sediment concentration. The settling velocity increases with increasing
suspended sediment concentration. An Owen Tube experiment conducted by HR Wallingford in eight European estuaries (Whitehouse et.al. 2000) suggested an empirical form of equation where the mean settling velocity for a single mean grain size depends on the concentration for a suspended sediment concentration range of 0.1 \( kg/m^3 \) -10.0 \( kg/m^3 \) and is given by:

\[
w_s = 0.001 \cdot (C_m)^{1.0}
\]  

(46)

where \( w_s \) is in (\( m/s \)) and \( C_m \) is the mass concentration in (\( kg/m^3 \)). The settling velocity depending on the sediment concentration is used for the simulations. On the other hand, the bulk settling velocity measured at two stations New Castle and Tinicum Island (Cook et. al., 2006) shows settling velocities of 0.004 m/s and 0.0018 m/s, respectively.

*Inflow Boundary conditions:*

The sediment inflow from Delaware River is calculated from curve fitting to the available data from USGS during the simulation year. The available data for suspended sediment (mg/l) and the corresponding discharge (m\(^3\)/s) is shown in Table 4-1. The discharge varies between 85 m\(^3\)/s and 1000 m\(^3\)/s, and an exponential curve is fitted to the available data for that year and is shown in Figure 4.2. A similar plot and the corresponding data set for Schuylkill River are shown in Figure 4.3 and Table 4-2.
The numerical model forced with the boundary conditions is compared with the observations in the Estuary to locate the estuarine turbidity maximum and determine the behavior of suspended sediment during the two month simulation period.
Table 4-1 Delaware River Suspended Sediment Load

<table>
<thead>
<tr>
<th>Date</th>
<th>SSC (mg/l)</th>
<th>Discharge (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>01/08/2003</td>
<td>3</td>
<td>556.3</td>
</tr>
<tr>
<td>03/06/2003</td>
<td>13</td>
<td>498.4</td>
</tr>
<tr>
<td>04/10/2003</td>
<td>5</td>
<td>688.1</td>
</tr>
<tr>
<td>05/08/2003</td>
<td>6</td>
<td>334.1</td>
</tr>
<tr>
<td>06/04/2003</td>
<td>205</td>
<td>1237.4</td>
</tr>
<tr>
<td>06/05/2003</td>
<td>37</td>
<td>1112.9</td>
</tr>
<tr>
<td>06/21/2003</td>
<td>278</td>
<td>1279.9</td>
</tr>
<tr>
<td>07/02/2003</td>
<td>6</td>
<td>376.6</td>
</tr>
<tr>
<td>09/04/2003</td>
<td>63</td>
<td>954.3</td>
</tr>
<tr>
<td>11/06/2003</td>
<td>8</td>
<td>716.4</td>
</tr>
</tbody>
</table>

Figure 4.2 Suspended sediment load for Delaware River
### Table 4-2 Schuylkill River Suspended Sediment Load

<table>
<thead>
<tr>
<th>Date</th>
<th>SSC (mg/l)</th>
<th>Discharge (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>01/16/2003</td>
<td>3</td>
<td>73.3</td>
</tr>
<tr>
<td>03/12/2003</td>
<td>8</td>
<td>138.5</td>
</tr>
<tr>
<td>04/09/2003</td>
<td>23</td>
<td>127.7</td>
</tr>
<tr>
<td>05/15/2003</td>
<td>10</td>
<td>41.9</td>
</tr>
<tr>
<td>06/04/2003</td>
<td>180</td>
<td>543.7</td>
</tr>
<tr>
<td>06/05/2003</td>
<td>107</td>
<td>498.4</td>
</tr>
<tr>
<td>06/20/2003</td>
<td>59</td>
<td>277.8</td>
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<td>07/15/2003</td>
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<td>07/22/2003</td>
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<td>150.4</td>
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<td>09/03/2003</td>
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<td>101.1</td>
</tr>
<tr>
<td>11/19/2003</td>
<td>7</td>
<td>97.1</td>
</tr>
</tbody>
</table>

![Figure 4.3 Suspended sediment load for Schuylkill River](image-url)
4.4.3. A Big Storm Event

In addition to simulations for this two month period, a fictional storm with a hundred year recurrence interval is simulated to observe the impact of big storm events on the suspended sediment dynamics. The hundred year discharge value for Delaware River at Trenton is 6000 (m$^3$/s) whereas it is 1300 (m$^3$/s) in Schuylkill river (Figure 4.4). The storm takes place at the 52nd day of the simulation. It causes a storm surge of 30cm at the ocean boundary and it lasts for three days. The estuarine turbidity maximum and suspended sediment concentrations are examined for the last 10 days of the simulation.

![Figure 4.4 Inflow values during the storm](image)

4.5. Results and Discussions

Tidally averaged suspended sediment concentrations of simulations (mg/l) together with the survey data (Cook et. al., 2006) for the cross section of main channel are plotted in
Figure 4.5. The simulation and observations reveal significant spatial variability in suspended sediment concentrations both vertically and along the estuary (Figure 4.5).

Simulation results agree with the observations, where the turbid zone is observed between river kilometers 50 and 120 of the estuary. The simulation results are close to observations where the tidally averaged simulations also show the turbidity zone between...
50 and 120 river kilometers, reaching its maximum between kilometers 80 and 90. The observations show concentrations ranging from 0 to 40 mg/l near the entrance of the Estuary, and increasing upstream, reaching the peak between river kilometers 80 to 100. Near the Estuary entrance the simulations show higher concentration levels for suspended sediments (40-70 mg/l).

Within the turbidity maximum suspended sediment concentration reaches up to 150 mg/l for the March survey and up to 1000 mg/l for June survey. The tidally averaged results indicate a maximum concentration of 350 mg/l but reaching up to 650 mg/l within the tidal cycle (Figure 4.7 and Figure 4.8). While the location and extent of the ETM is fairly well captured, it is also apparent that there is too much sediment in the water column at ETM compared to the observations. This is, as mentioned above, due to the initial 10mm erodible layer distributed across the entire estuary bottom. Future work will need to address this issue by attempting to run the model for a sufficiently long time until a quasi equilibrium is reached, i.e. the right amount of material is in the system before a simulation leading up to the specified time frame can be initiated.

To better understand the difference between the observations and simulations, the logarithm of normalized settling velocity \( \log\left(\frac{w_s}{w_{smin}}\right) \) is plotted in Figure 4.6. It is clearly seen that the settling velocities are very small for the concentration ranges 0-100 mg/l. The settling formulation used in simulations is valid within the range 0.1-10 kg/m³ (100-10000 mg/l). Since the maximum observed values during the survey and the simulations are well within this range no hindered settling occurs, that is, the settling is in
the linear range and the linear formula is valid. But the formula yields substantially small settling velocities for values smaller than 100 mg/l. The simulated low settling velocities are at the entrance region of the estuary as shown in Figure 4.6.

![Figure 4.6 Normalized settling velocity along shipping channel](image)

It is believed that the reason for higher sediment concentrations near the entrance region is caused by small settling velocities, and there is a need for empirical settling velocities for the sediments with concentrations below 100 mg/l for Delaware Estuary.

Sediment concentrations vary within a single tidal cycle which causes the location and intensity of the turbidity maximum to change considerably. River inflow and wind events also have the potential to influence the turbidity maximum. As turbulence field varies over tidal cycle, the concentration varies as expected. The snapshots of suspended sediment concentration at 1 hour intervals are plotted for a flood tide in Figure 4.7 and for an ebb tide in Figure 4.8. As the flood tide moves in (Figure 4.7) the turbidity zone moves upstream, while the maximum sediment concentrations decrease because of lower velocities associated with flood tides (Figure 3.31) and consequently, lower shear stress values. A narrowing in the turbid region is also observed during the flood tide.
Figure 4.7 Sediment concentrations (mg/l) along shipping channel for a flood tide
Figure 4.8 Sediment concentrations (mg/l) along shipping channel for an ebb tide
Salinity simulations suggest that there is a stratification associated with tidal variations. This behavior is evident when the flood tide moves in and the turbid zone is pushed upstream at depths more than 5 meters; whereas the upper few meters move downstream. This is the time when the collapse of mixing capacity at the upper part (very small eddy viscosity) for stratified condition is observed as shown in the third column of Figure 3.30.

As the ebb tide moves in, the stratification slowly disappears, leaving itself to a well mixed estuary. The velocities are higher compared to that of flood tide (Figure 3.31) resulting in much higher sediment concentrations (650 mg/l). There is a small second peak of turbidity maximum for ebb tide between river kilometers 120 and 130 which is also observed during June survey. The observations show a higher degree of stratification which should be observed for ebb tides but a very small amount of stratification is present during ebb tides.

The results also show strong correlation between the turbidity maximum and salinity where the turbidity maximum is located between 2 psu and 0.1 psu lines. The $k-\varepsilon$ model shows the 2 psu line between river km 78 and 84, while the turbidity maximum moves between 75 km and 90 km.

Simulations suggest that the tidally averaged intensities and the instantaneous values vary considerably, where the instantaneous concentrations exceed double the tidally averaged
values at times. Comparison of the March and June 2003 sediment concentrations also indicates that the suspended sediment concentrations vary considerably, not only within a tidal cycle but also within the spring season as a result of different river inflow and wind forcing. The main source of sediment is the Estuary itself throughout the simulation eroding and settling within and in between the tidal cycles continuously, which is responsible for the pattern and continuation of the turbidity maximum. The higher concentrations may be a direct result of initiating the system with 10mm erodible bed, producing too much erodible sediment within the estuary.

A report for sedimentological and geophysical survey of upper Delaware estuary by Sommerfield and Madsen (2003) shows bottom sediment types and erosional, depositional parts in the tidal river and upper estuary area as shown in Figure 4.9. A high resolution image is available at http://www.state.nj.us/drbc/UDelsurvey/index.htm. The plot allows a visual summary where the areas with fine deposition are marked with pink and non deposition areas are marked with yellow.
At the start of the simulation, an erodible thickness of 10 mm is assigned uniformly to the Estuary and the system is left alone to reach equilibrium. No further eroding is allowed once the 10 mm is fully eroded until further settling occurs. A similar plot is obtained for the upper estuary at the end of the 62 day simulation as shown in Figure 4.10. The pink represents the parts where the sediments are deposited (total erodible depth is more than 10 mm), and the yellow represents erosion (erodible depth between 0 and 10mm). Figure 4.9 and Figure 4.10 are plotted on top of each other on Figure 4.11 in order to understand how the model predicts the survey results. The survey does not cover the whole width of estuary; whereas the simulation results are plotted for the whole width.
The simulation results show erosion downstream of Tinicum Island between Crum Creek and Marcus Hook where similar observations appear in the survey (yellow on top of yellow). Similarly, between Raccoon Creek and Oldmans Creek, both model and the survey show depositional patterns. The numerical model shows deposition close to channel boundaries where depths are smaller compared to main navigation channel. Patches of depositional areas and erosional areas mostly coincide but it should be kept in mind that the simulations are initiated with 10 mm erodible bed which is not the case in reality.
In order to test the effect of initiating the system with uniform erodible bed, the depths are set to zero at the 47th day of simulation and allowed to freely erode. The development of erosional and depositional areas is observed for the last 15 days. It is assumed that the bed materials erode and deposit in patterns and come to a balance during these 47 days and the last 15 days show the locations for erosion and deposition.

Snapshots of erosion and deposition at 3 day intervals are plotted for 15 days in Figure 4.12. Clear patches of erosion are observed at the estuary entrance and deposition is
mostly observed at the shallower sections close to the boundaries. The bed slowly erodes on certain locations and keeps eroding throughout the 15 days however it is not known whether the part eroded in these 15 days are erodible or not. Further information is required for the erodibility of the bed material between upper estuary and bay entrance to initiate the simulations with realistic initial conditions. In the last 15 days, the depths are much less than 10mm, suggesting that the initiating the system with 10 mm erodible bed supplies too much erodible material and causing higher suspended sediment concentrations within the water column.
Figure 4.12 Snapshots of erosion and deposition for the last 15 days of simulation
The numerical test storm results revealed significant findings. The suspended sediment concentrations after the storm (between 52\textsuperscript{nd} and 62\textsuperscript{nd} days) are plotted on Figure 4.13, Figure 4.14 and Figure 4.15. Each figure shows a total of 3 days with 12 hour intervals within each profile starting. Figure 4.13 shows the duration of the storm (3 days), where the high suspended sediment concentrations begin to feed from upstream at the second day, slowly moving downstream and increasing the concentrations up to 1400 (mg/l) between river kilometers 120 and 140.

After the 3\textsuperscript{rd} day the storm ends but the effect of the high discharge from the tributaries and the corresponding high sediment concentrations is experienced with delay. As the turbid water propagates downstream, it meets with the turbidity front at river kilometer 80 and slowly pushes the turbidity front downstream between the 3\textsuperscript{rd} and 6\textsuperscript{th} days (Figure 4.14). During this time the bottom sediments also contribute to the suspended sediment concentrations especially between river kilometers 20 and 30. The highest sediment concentrations reach 1800 (mg/l) at certain spots.

At the beginning of the 6\textsuperscript{th} day the upstream feeding of suspended sediments decreases while the accumulation of the sediments continues to increase at the turbidity maximum (Figure 4.15). The maximum suspended sediment concentrations (2800 mg/l) are observed at the 7\textsuperscript{th} day while the turbid water continues to move downstream finally covering a range between river kilometers 15 and 140. The turbidity maximum is observed between river kilometers 60 and 70 during this time.
Figure 4.13 Suspended sediment concentrations (mg/l) for the test case (0-3 days)
Figure 4.14 Suspended sediment concentrations (mg/l) for the test case (3-6 days)
Figure 4.15 Suspended sediment concentrations (mg/l) for the test case (6-9 days)
The numerical experiment with the hundred year storm showed that the maximum suspended sediment concentrations reach as high as 2800 (mg/l) compared to 650 (mg/l) without the storm. While the turbidity range expands, the turbidity maximum is observed around river kilometer 60 and 70.

If the erosion depths are compared to the case without the storm, the regions of erosion and deposition change significantly. In Figure 4.16, the erosion depths in mm at the end of the simulation, with (right panel) and without (left panel) the storm is plotted. The storm increased the depositional areas, moreover the amount of deposition increases, filling most of the areas showing erosional patterns for the case without the storm. Large patches of erosional areas are also observed which were not present when there were no storms. One of the important findings of this numerical experiment is that the significant storms change the distribution of bottom sediments drastically. It is understood that tides regulate the distribution of bottom sediments, whereas the impact of storms are significant enough to change the overall distribution process and should be taken into consideration.

![Figure 4.16 Erosion depths (mm) for bottom sediments with and without storm](image)
The suspended sediment transport simulations were not successful in a sense because the simulations created higher suspended sediment concentrations within the water column. There may be several reasons for this.

It is shown in Figure 4.12 that the erosional depths do not change more than a few millimeters after the 45th day of simulation. So, initiating the system with 10 mm erodible bed supplies too much material to the water column and may result in the computed higher concentrations.

The high concentrations at the bay mouth can be caused by low settling velocities. Although the settling velocity formula (Eqn 46) is calibrated at eight different European estuaries, it may not be suitable for Delaware Bay. Instead, constant velocities can be used. An average of the two observed values at New Castle and Tinicum Island can be used for the entire domain, but a more realistic approach would be dividing the domain into several sub-domains according to sediment types and setting different settling velocities for different sub-domains, and if possible supplying data from observational studies for these settling velocity values.

The model was successful in a sense that the turbid zone is identified between 50 - 120 km from the bay mouth similar to literature (Biggs et.al, 1983; Cook et. al ,2006) and the turbidity maximum is identified between river kilometers 75 and 90 and shows strong correlation to salinity front which is also observed by Cook et. al. (2006).
CHAPTER 5: CONCLUSIONS

5.1. Summary and Conclusions

Simulations were conducted for a period of two months in July-August, 2003 over the model domain from the head of the tidal region at Trenton to the continental shelf (50m isobath). River discharge from selected tributaries such as Delaware River, Schuylkill River, Christina River and Rancocas River, a variable, harmonically decomposed, water level boundary condition from three diurnal (K1, Q1, O1) and four semi-diurnal (K2, S2, N2, M2) tidal components, and winds form the forcing. In order to test whether the choice of turbulence closure makes a difference or not, several different turbulence closures were implemented and compared in their performance.

Seven different turbulence closures; a constant eddy viscosity, mixing length theory with Richardson number modification, GLS formulation with $k-\varepsilon$, $k-\omega$, $k-kl$ and $k-ge$ parameterization and the original Mellor-Yamada level 2.5 (MY25) closures were used and compared with data.

The generic length scale turbulence closure was implemented into the UnTRIM numerical model. The generality of the GLS model essentially allows for an infinite number of parameter combinations as selection of which could be tested as well. All simulations were performed with identical boundary conditions. The available data was based on a salinity time series available at a single station and a survey performed in June.
2003. Performances of the models were evaluated relative to the available water level and salinity data. There are several outcomes.

All of the models simulated the water surface elevations with reasonable accuracy, some more closely \((k-\omega, \ k-kl, \ MY25)\) others a little less accurate \((k-\varepsilon, k-ge)\). This indicates that the effect of vertical mixing on water surface elevation is smaller compared to the tidal forcing. UnTRIM model accurately simulated the hydrodynamic system with specified boundary conditions from the tidal database and inflow values. The results granted the accuracy of tidal database, and encourage modelers to employ in Delaware Estuary.

Low order turbulence closures such as constant viscosity approach and mixing length theory do not produce satisfactory results for salt transport, i.e. they show significant deviations from the measured salinity data. The mean amplitudes also deviate from the available data for these models. This suggests that the use of more complex approaches than low order closures are needed to better characterize the nature of turbulence.

Among the two equation closures, the \(k-\omega\) model showed the furthest salinity intrusion and also did not match the available data. The \(k-ge\) model followed the salinity values very closely except for the strong, long duration wind event at July 23rd. The \(k-ge\) model also showed the smallest degree of upstream salinity migration. The \(k-kl\) closure reproduced the results of the Mellor-Yamada level 2.5 model within reasonable accuracy and can be considered equivalent in their level of performance. Both methods performed
better than the $k-\omega$ and $k-g\varepsilon$ approach, closely following the rising and falling trends in the mean salinity even though the mean values are slightly overestimated. The $k-\varepsilon$ model matched the available sensor data best for the Delaware Estuary while capturing the salinity front from the observations.

It is concluded that: i) the lower order turbulence models do not perform adequately (though not terribly wrong) in the Delaware Estuary which suggests that a 2-equation closure approach should be used ii) that the GLS ($k-\varepsilon$) approach appeared to best match the available salinity data, even though performing slightly less accurate when predicting water level elevations, and iii) that various closure models yield substantially different results. When compared to the other three two-equation models, the difference is significant enough to warrant an educated selection, rather than randomly choosing any of the models. In this case the GLS ($k-\varepsilon$) approach appears to work best, even though it is difficult to discern general rules for the selection of an appropriate or the best model for other modeling domains.

There is a good chance that any of the closure models might work better for a different estuary, which would suggest that any modeler might want to consider a test-scenario with which to test and compare different closure models first, before settling on one. For the Delaware Estuary, the circulation patterns are successfully simulated and the salinity intrusion into the Estuary is explained and simulated by comparing the effects of turbulence closure.
In order to assess the transport of sediments and determine the erosional and depositional patterns of sediments in the estuary, a decoupled sediment transport model was produced and coded using OpenMP in Fortran programming language for parallel processing. This approach did not produce satisfactory results. There are two main reasons for this: i) The use of unstructured grid required random access to the memory and reading and writing the hydrodynamic results consumed so much computation time and memory, as a result, the transport code did not generate the intended scalability for higher number of CPU’s. ii) The twelve node computational cluster available in Drexel University became very slow compared to the new computers and discontinued in the last year of this research. The details of the work are explained in Appendix A

The second approach for determining the sediment transport patterns in the estuary was to use the hydrodynamic code itself to calculate the transport of sediments as it is done in turbulence closure. The simulated hydrodynamics supplied the necessary data and using the best performing turbulence closure ($k-\varepsilon$), and the simulations for the suspended sediment transport are performed.

The system was initiated with uniform erodible bed. Suspended sediment concentrations and erodible bed thickness are examined and compared with the survey findings. Effects of erosion parameter, settling velocity and shear stress are modeled with the help of the available data and various simulation trials. Further information is needed for the erodibility of the bed material, and settling velocity. Results closely follow the observations and they reveal significant variability in suspended sediment concentration.
Strong tidal forces push salinity up-estuary beneath the river water. The turbulence caused by these tidal forces results in re-suspension of sediment. The dissolved material in the river water flocculates at the same time when it comes into contact with the salt front pushing its way up-estuary. This process results in elevated levels of suspended particulate material, ETM and requires proper modeling of turbulence.

The turbidity zone and the turbidity maximum are identified. The effects of turbulence mixing and partial stratification depending on tides are observed throughout the simulations. Strong correlation between the salinity front and turbidity maximum is identified by modeling turbulence closure accurately.

The numerical experiment of suspended sediments also showed the importance of storms and exposed the significant changes caused by storms in the estuary.

Within the framework of this research, a numerical model for the Delaware Estuary is developed. Hydrodynamics, salinity transport, turbulence parameters and suspended sediment transport is modeled, simulated, and compared with data. Although this research has focused on Delaware Estuary the methodology can be extended to any domain easily. The application of time and space dependent forcing such as tides, river discharges, wind fields and sediment loads makes the model suitable for simulating any other time frame and domain easily without changing the structure of the model.
5.2. Future Outlook

The model proved its capabilities in terms of modeling hydrodynamics and sediment transport. A more detailed application will provide more insight to the sediment transport processes in Delaware Estuary. Future enhancements to the model can be made by:

- Simulating a real storm event comparing the hydrodynamics and sediment transport with the available data and examining the effect of the storm and analyzing the ability of the model to replicate the big events.
- Increasing the capabilities of the sediment model by adding the information for bottom sediments and mapping them to a database, adding a bed load model which will run simultaneously with suspended sediment model, and capability of running the model with different class of sediments if data becomes available.
- A morphological model can be integrated if the updated version of the hydrodynamic code is acquired, allowing to change the bathymetric depths during the simulations.
- As the computers advance, it may be possible to use the high resolution grid both for hydrodynamics and sediment transport processes which will bring detailed information about the dynamic system.
LIST OF REFERENCES


APPENDIX A: AN OPENMP IMPLEMENTATION FOR A DECOUPLED GENERIC TRANSPORT EQUATION

A.01 Transport equation

Equations for passive tracers, such as salinity and temperature, are needed to calculate the density ($\rho$). A conservative form of transport equation for salinity can be written as:

$$\frac{\partial S}{\partial t} + \frac{\partial}{\partial x}(uS) + \frac{\partial}{\partial y}(vS) + \frac{\partial}{\partial z}(wS) = \frac{\partial}{\partial x} \left( K_h \frac{\partial S}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_h \frac{\partial S}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_v \frac{\partial S}{\partial z} \right)$$

where; $S$ is the concentration of salinity, $K_h$ and $K_v$ are the horizontal and vertical diffusivity coefficient and $u, v, w$ are the velocity components in $x, y, z$ directions, respectively.

A similar form of equations for Temperature ($T$) can also be written as:

$$\frac{\partial T}{\partial t} + \frac{\partial}{\partial x}(uT) + \frac{\partial}{\partial y}(vT) + \frac{\partial}{\partial z}(wT) = \frac{\partial}{\partial x} \left( K_h \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_h \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_v \frac{\partial T}{\partial z} \right)$$

A solar radiation term (source/sink) may be added to the temperature equation. The system of equations is closed with an equation of state of form:

$$\rho = \rho(T, S, P)$$
where; $P$ is the pressure.

Depending on the type of tracer, be it salinity, temperature, turbulence parameters or sediments, the only difference is the additional source and sink terms and the settling velocity in case it is sediments. So a general form of equation can be written as:

$$\frac{\partial C}{\partial t} + \frac{\partial}{\partial x}(uC) + \frac{\partial}{\partial y}(vC) + \frac{\partial}{\partial z}((w - w_s)C) = \frac{\partial}{\partial x} \left( K_h \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_h \frac{\partial C}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_v \frac{\partial C}{\partial z} \right) + \text{source}$$

where; $C$ is the parameter of interest.

### A.02 Scales of Motion

The scale of motions for the transport equation for an estuary can be given as:

- Horizontal length: $[x, y] \approx O \left(10^2 \right) m$
- Vertical length: $[z] \approx O \left(1 \right) m$
- Horizontal velocity: $[u, v] \approx O \left(1 \right) ms^{-1}$
- Vertical velocity: $[w] \approx O \left(10^{-4} \right) ms^{-1}$
- Horizontal diffusivity: $[K_h] \approx O \left(1 \right) m^2 s^{-1}$
- Vertical diffusivity: $[K_v] \approx O \left(10^{-2} \right) m^2 s^{-1}$

So the order of magnitude of each term can be given as:
When we look at the advective terms the horizontal advection is far more dominant than the vertical one. Also the vertical diffusion term is two orders of magnitude larger than the horizontal diffusion terms.

### A.03 Advection Discretization

If we compare the order of magnitude of each term in the transport equation we see that the advection terms are dominant. Using a mass conserving scheme or a scheme which is free of spurious oscillations will affect the results vastly (Gross et al. 1999). The test cases of diagonal advection of square and rotation of a Gaussian cone in the study of Gross et al. showed the success of total variation diminishing (TVD) schemes.

The comparison of a Lax-Wendroff type TVD method with superbee limiter and the quadratic upstream differencing method (QUICKEST) showed that the CPU time
required for the TVD method for pure 2D advection equation in a structured grid is less than that of the QUICKEST while it maintains the required properties like max-min and is stable.

TVD methods can be extended to unstructured grid while some difficulties may arise. These difficulties will be discussed in the next sections.

A.04 Flux-Corrected transport

Flux-corrected transport (FCT) is a way of approximating a conservation law with high order schemes where the solution is smooth while using a low-order monotone scheme where the solution is poorly resolved or discontinuous.

Consider the 1-D transport equation;

\[ \frac{\partial C}{\partial t} + \frac{\partial}{\partial x} (uC) = 0 \quad \text{or} \quad \frac{\partial C}{\partial t} + \frac{\partial}{\partial x} \left( f(C) \right) = 0 \]

A finite difference approximation to the formula can be written in conservation form:

\[ \frac{C_{i}^{n+1} - C_{i}^{n}}{\Delta t} + \left( \frac{F_{i+\frac{1}{2}}^{n} - F_{i-\frac{1}{2}}^{n}}{\Delta x} \right) \]

Where; \( F \) is a numerical approximation to \( f(C) \).
The calculation of the fluxes with a flux corrected transport algorithm is outlined by (Durran 1998). The method first calculates the fluxes using a low-order monotone scheme. Monotone schemes are free from oscillations and they don’t create new local extrema. Generally upwind scheme is used as a low-order scheme. Next, another set of fluxes is calculated using a high order scheme and the amount of *anti-diffusion* is calculated by subtracting the low order scheme from the high order one. Then, a monotone estimate of the solution is calculated using low-order fluxes. Then the *anti-diffusion* is limited using the previous time step values of neighboring cells in order not to generate new maxima or minima. As a last step the solution is anti-diffused using the calculated value. The method adds *anti-diffusion* to the low-order scheme which is known to be diffusive.

![Figure A. 1 An unstructured grid](image)
Consider the transport of scalar parameter $C$, on a finite volume form for the given grid in Figure A.1; the low order flux $F^{l}$ for face $j$ is given by:

$$F^{l} = qC_{c}$$

Similarly, a high order flux $F^{h}$ can be calculated using a central difference scheme:

$$F^{h} = (qC_{D} + qC_{C}) = q \left( \frac{C_{D} + C_{C}}{2} \right)$$

Then, the amount of anti-diffusion for the face $j$ is:

$$A = F^{h} - F^{l} = q \left( \frac{C_{D} - C_{C}}{2} \right)$$

Then for a flux corrected scheme a monotone estimate of the solution at cell center is calculated.

$$C^{\text{std}} = C^{n} - \frac{\Delta t}{V} \sum_{j \in \Omega_{n}} F^{l}_{j}$$
On the anti-diffusion step, we correct the $A$ so that the anti-diffusion step will not generate new maxima or minima.

\[ A^c = \Phi A \quad \text{where } \Phi \text{ is a limiter.} \]

Then the anti-diffusion step is calculated as:

\[ C^{n+1} = C^{id} - \frac{\Delta t}{\Delta x} \sum_{j \in \mathbb{R}_n} A^c_j \]

### A.05 Flux-Limiter Methods

This method is very similar to the FCT method in a sense that they both calculate a monotone first order scheme and a high order scheme. However the limiter used in this method does not require calculation of an intermediate solution. Instead it uses the local solution at previous time step in a manner guaranteeing that the scheme generates TVD approximations to 1D scalar conservation law.

So the method can be formulated as:

\[ F_j = F_j^l + \Phi \left( F_j^h - F_j^l \right) \]
A TVD scheme can be written as a sum of a diffusive first order upwind and an anti-diffusive second order upwind scheme as:

\[ F^i = qC_c \quad \text{and} \quad F^h = q \frac{(3C_c - C_U)}{2} \]

So that

\[ F_j = qC_c + \frac{1}{2} q\Phi(r_j)(C_D - C_c) \]

Where \( \Phi \) is a function of local solution and function of \( r_j \) which is given by:

\[ r_j = \frac{(C_c - C_U)}{(C_D - C_c)} \]

The main difficulty in implementing TVD schemes in unstructured grids lies in the need for defining the node “U”. A second order accuracy for \( r \) is achieved when the node “U” lies on the line joining the line “C” and “D” with “C” being at the center of the “UD” segment (Darwish and Moukalled 2003). But a more practical approach would be using the flux limiter function as a ratio of consecutive gradients for the sides supplying a positive flux to the element considered in a finite volume sense (Casulli and Zanolli 2002).
Then, the possible flux limiters can be given by:

Minmod limiter: \[ \Phi(r) = \max\left[0, \min(1, r)\right] \]

Superbee limiter: \[ \Phi(r) = \max\left[0, \min(1, 2r), \min(2, r)\right] \]

Van Leer limiter (MUSCL): \[ \Phi(r) = \frac{r + |r|}{1 + |r|} \]

MC limiter: \[ \Phi(r) = \max\left[0, \min\left(2r, \frac{1 + r}{2}, 2\right)\right] \]

Also depending on the value of \( \Phi \) other schemes can be obtained;

Downwind scheme: \[ \Phi(r) = 2 \]

Central difference scheme: \[ \Phi(r) = 1 \]

Second order upwind scheme: \[ \Phi(r) = r \]

A.06 A Finite Volume Discretization of Transport Equation

When we look at the advection terms, the stability criteria imposed by the vertical advection term is two orders of magnitude larger than the horizontal advection terms. Therefore, the vertical diffusive terms and the vertical advection are treated implicitly, while the horizontal diffusion and horizontal advection are treated explicitly.
Implicit

Using the formulation given for flux limiters a general finite volume form of discretization can be calculated as:

\[
P_i \sum_{j \in S_j'} \hat{\Phi}^{n+\theta}_{j,i,k} \rightangledown_{j,S_j} \Delta z_{i,k}^{n+\theta} \frac{C_{m(i,j),k}^n - C_{i,k}^n}{\delta_j} - \frac{\Delta t}{2} \sum_{j \in S_j'} \Phi_j^n \int_{j \in S_j'} \left[ C_{m(i,j),k}^n - C_{i,k}^n \right] \rightangledown_{j,S_j}
\]

The above equation produces a tridiagonal system and can be directly solved by Thomas algorithm.

### A.07 Parallel Processing

In order to understand how suspended sediments are transported, several classes of sediments will be used in the simulations. Each group of sediment will interact with each
other and form sources and sinks in the transport equation of corresponding size. These require solution of the generic transport equation several times at each time step. Moreover, the transport of sediments requires long term simulation periods and many simulations are necessary for what if scenarios. Because of these reasons, the simulations require high computational power. The required computer power can be obtained by parallel processing and the codes can be parallelized using Message Passing Interface (MPI) or OpenMP programming interfaces.

A.08 OpenMP

The OpenMP Application Program Interface (API) supports multi-platform shared-memory parallel programming in C/C++ and FORTRAN on all architectures, including UNIX platforms and Windows NT platforms. Jointly defined by a group of major computer hardware and software vendors, OpenMP is a portable, scalable model that gives shared-memory parallel programmers a simple and flexible interface for developing platforms ranging from the desktop to the supercomputer for developing parallel applications for platforms ranging from the desktop to the supercomputer.

The execution begins with a single process referred to as the master thread. Upon entering a parallel region the master thread creates a team of threads. Each of these threads will do the same computations unless otherwise specified. Upon exiting a parallel region, only the master thread continues. In an OpenMP model of parallel execution, all
the threads share a common address space. The execution of the OpenMP parallel program is outlined in Figure A. 2

OpenMP architecture is made up of:

1. Source code controls
2. Library routines
3. Runtime environment variables
which makes it easy to apply to codes. The code can be parallelized in stages and obtains modest scaling (4X-32X).

A.09 Computer Resources

The availability of computer resources limits the developer especially in parallel processing architectures. Currently, Drexel University has a parallel computing facility. The IBM RS/6000 S-80 was acquired by the College of Engineering in 2001 with funds received from a National Science Foundation Grant and an IBM SUR Grant by professors B. Farouk, R. Cairncross, C. Kastinins, A Zavaliangas, and A. Zerva.

The available programming languages and compilers are the IBM C/C++ for AIX, IBM XLFortran, IBM VisualAge for Java. Additional Libraries, that are available, are the IBM Engineering and Scientific Subroutine Library which includes highly optimized subroutines for mathematical, scientific and engineering requirements. Subroutines are optimized for use in parallel programming as well. IBM Parallel Operating Environment (POE) and IBM’s Message Passing Interface (MPI) implementation creates multiple processes and enables sharing of domain data across processes to parallelize execution of job. OpenMP allows creating parallel programs using multiple threads.

OpenMP, being a shared memory parallel programming model, can be effectively used in Drexel University’s computing facilities. Besides, OpenMP can be easily implemented in
FORTRAN and C codes. Therefore OpenMP is a selected for parallel programming purpose in Delaware Estuary.

A.10 Parallelization of Transport Equation using OpenMP

A parallel transport code is built for executing the transport in IBM machines in Drexel University. For that purpose the output files of numerical model UnTRIM is written in binary format. But the native machine language in a PC and IBM AIX is different. Regular PC’s use “Little Endian” whereas the AIX system uses “Big Endian”. So the output files are converted into the native machine language format of AIG using another code. Since the output routines of UnTRIM are not double precision some accuracy is lost during this writing and reading process.

After the code is completed, several simulations with different number of processors are tried and compared for efficiency reasons. The test is conducted on a triangular grid for a U-channel and the increase in speed is compared to number of processors as seen in Figure A. 3.

The program showed a small decrease in total CPU time for up to 4 processors then the CPU time increased rapidly. It is not fully understood whether the increase in CPU time is a result of the code or the platform it is running. In any case, the calculations for 4 CPU were running only 24% faster than a single CPU, making the code inefficient for running in parallel and the aimed scaling of up to 4X-8X is not observed.
In early 2006, the IBM computer platform became unavailable because of relative speed loss to new computers and the high cost of maintenance. When the speed of the separate code and the UnTRIM model is compared, the UnTRIM model runs 2.56 times faster than the parallel sediment transport code without reading and writing the data, and the ratio further increases when reading and writing the data is considered.

Although a lot of effort was put on generating a parallel sediment transport code, the results were not satisfactory and the work is discontinued.
A mass balance equation for the bed load layer can be written as:

\[(1 - p') \frac{\partial \delta_b}{\partial t} + \frac{\partial (\delta_b \bar{C}_b)}{\partial t} + D_b + E_b + \frac{\partial}{\partial x} (\alpha_x q_b) + \frac{\partial}{\partial y} (\alpha_y q_b) = 0\]

where, \(p'\) is the porosity of the bed material, \(\delta_b\) is the thickness of the bed load layer, and \(\bar{C}_b\) is the average concentration at the bed load layer. \(\alpha_x\) and \(\alpha_y\) are the directional cosines for calculation of the component of bed load in the corresponding direction. The only unknown in the above formulation \((q_b)\) can be calculated using various formulations. Some of the recent formulations are explained in detail below.

**Van Rijn’s Bed Load Transport Formula:**

Van Rijn developed a bed load (1984a) and a suspended load (1984b) formula. The bed load formula is uniform in nature in which the particles move primarily because of saltations and jumps. The formula can be used for sediments sizes ranging from 0.2-2mm (coarse sand). The dimensionless formula is given by:

\[
\frac{q_{sb}}{\sqrt{g \cdot (SG - 1) \cdot D_{50}^3}} = \phi_{sb} = \begin{cases} 
0.053 \cdot D_s^{-0.3} \cdot \left( \tau^* \right)^{2.1} & \tau^* < 3 \\
0.1 \cdot D_s^{-0.3} \cdot \left( \tau^* \right)^{1.5} & \tau^* \geq 3 
\end{cases}
\]

where, the dimensionless grain size and shear parameter are given by:
\[ D_s = D_{50} \cdot \left( \frac{(SG - 1) \cdot g}{\nu} \right)^{\frac{1}{3}} \text{ and } \tau^* = \frac{\mu \cdot \tau - \tau_{cr}}{\tau_{cr}} \]

\[ \tau_{cr} = (\rho_s - \rho) \cdot g \cdot D_{50} \cdot \theta_{cr} \]  where \( \theta_{cr} \) is the critical Shields parameter.

The parameter \( \mu \) represents the bed form factor and is calculated as the ratio of total Chezy’s factor to the grain related Chezy’s factor.

\[ \mu = \left( \frac{C}{C'} \right) \text{ and } C' = 18 \cdot \log \left( \frac{12 \cdot R_c}{3 \cdot D_{50}} \right) \text{ where } C' \text{ is in m}^{1/2}/s. \]

Van Rijn extended his formula for fractional transport and modified the transport formula as:

\[ \frac{q_{sb,i}}{\sqrt{g \cdot (SG - 1) \cdot D_i^3}} = \phi_{sb,i} = \begin{cases} p_i \cdot 0.053 \cdot D_i^{-0.3} \cdot (\tau^*)^{2.1} & \tau^* < 3 \\ p_i \cdot 0.1 \cdot D_i^{-0.3} \cdot (\tau^*)^{1.5} & \tau^* \geq 3 \end{cases} \]

where \( p_i \) is the probability of the \( i^{th} \) fraction corresponding to diameter \( D_i \) and replaced all \( D_{50} \)'s by \( D_i \).

**Parker’s Bed Load Transport Formula:**

Parker’s (1990) bed load transport formula is a fractional formula which is completely based on field data. The data used to derive the formula ranges from 18-30 mm size in \( D_{50} \) with an average \( \sigma_g \) of 6, which permits the determination of the transport of small
gravels. The transport formula includes a hiding-exposure factor. The formula is developed for a surface layer which has a thickness of $D_{90}$. The dimensionless formula is given by:

$$\frac{q_{sh,i} \cdot g \cdot (SG - 1)}{\left(\frac{\tau_b}{\rho}\right)^{3/2} \cdot F_i} = 0.0025 \cdot G(\phi)$$

where, $F_i$ is the volumetric fraction of the $i^{th}$ fraction, $SG$ is the specific gravity and $\tau_b$ is the total bed shear stress. Using the below expressions;

$$\phi_w = \frac{\tau_b}{0.0386 \cdot \rho \cdot (SG - 1) \cdot g \cdot D_m}$$

$$w = 1 + \frac{\sigma}{\sigma_0} \cdot (w_0 - 1)$$

$$g_0(\delta_i) = \left(\frac{D_i}{D_m}\right)^{-0.0951}$$

the variable $\phi$ and the function $G(\phi)$ can be calculated as:

$$\phi = \phi_w \cdot w \cdot g_0(\delta_i)$$

$$G(\phi) = \begin{cases} 
5474 \cdot \left(1 - \frac{0.853}{\phi}\right)^{4.5} & \text{for } 1.59 > \phi \\
& \text{for } 1 \leq \phi \leq 1.59 \\
\phi^{14.2} & \text{for } \phi < 1 
\end{cases}$$

Ribberink’s Bed Load Transport Formula:

Ribberink (1998) developed a uniform bed load formula that has been calibrated using both field data and experiments. The sediment size in this calibration ranged from 0.19-
3.8mm (sand and fine gravel). The formula uses $D_{50}$ as the representative grain size. The dimensionless transport parameter is determined by:

$$\frac{q_{sb}}{\sqrt{(SG-1) \cdot g \cdot D_{50}^3}} = 10.4 \left( \frac{\theta_{50} - \theta_{cr}}{\theta_{cr}} \right)^{1.67}$$

where $\theta_{50}'$ is the effective Shields parameter and calculated by:

$$\theta_{50}' = \frac{\tau'}{(\rho_s - \rho) \cdot g \cdot D_{50}}$$

$$\tau' = \rho \cdot g \cdot \frac{u^2}{C'}$$

and $C' = 18 \cdot \log\left( \frac{12 \cdot R_b}{k_s} \right)$ is the grain related Chezy’s factor

where $k_s = \max\left\{ 3 \cdot D_{90}, D_{50} \cdot \left( 1 + 6 \left( \frac{\theta_{50}'}{\theta_{cr}} - 1 \right) \right) \right\}$

**Wu’s Bed Load Formula:**

Wu et al. (2000) developed a fractional formula for bed load transport that has been calibrated using a wide range of field and experimental data. The fractional formula compares the grain size of a fraction to the grain sizes of other fractions and it is assumed that the particles are randomly distributed on the bed. The dimensionless transport parameter is calculated by:

$$\frac{q_{sb,i}}{\sqrt{(SG-1) \cdot g \cdot D_i^3}} = p_i \cdot 0.0053 \left[ \left( \frac{n'}{n} \right)^{3/2} \frac{\tau_i}{\tau_{cr,i}} - 1 \right]^{2.2}$$
where the critical stress for the \(i\)th fraction is given by:

\[
\tau_{cr,i} = (\rho_s - \rho) \cdot g \cdot D_i \cdot \theta_{cr} \cdot \zeta_i
\]

and

\[
\theta_{cr} = 0.03
\]

is the critical Shield’s parameter.

\[
\zeta_i = \left( \frac{p_{e,i}}{p_{h,i}} \right)^{-0.6}
\]

is the hiding exposure factor

\[
p_{e,i} = \sum_{j=1}^{N_i} p_j \frac{d_i}{d_i + d_j}
\]

is the probability of exposure

\[
p_{h,i} = \sum_{j=1}^{N_i} p_j \frac{d_j}{d_i + d_j}
\]

is the probability of hiding

\[
n' = \frac{6D_{50}}{20}
\]

is the Manning’s roughness related to grains and \(n\) is the Manning’s roughness coefficient.

**Wilcock’s Bed Load Transport Formula:**

Wilcock and Crowe (2003) developed a fractional transport formula that was calibrated using experiments only. The sediment ranges used in those experiments were from 4-10mm (small gravels). The dimensionless transport parameter of Wilcock and Crowe is given by:

\[
\frac{(SG-1) \cdot g \cdot q_{sh,i}}{p_i \cdot u^3} = \begin{cases} 
0.002 \cdot \phi^{7.5} & \phi < 1.35 \\
14 \cdot \left(1 - \frac{0.894}{\phi^{0.5}}\right) & \phi \geq 1.35
\end{cases}
\]

Where
\[ \phi = \frac{\tau_b}{\tau_{ri}} \]

\[ \frac{\tau_{ri}}{\tau_{rs50}} = \left( \frac{D_i}{D_{s50}} \right)^b \]

where \( \tau_{ri} \) is a reference shear stress value.

\[ b = \frac{0.69}{1 + e^{1.5 \left( \frac{D_i}{D_{s50}} \right)}} \]

\[ \frac{\tau_{rs50}}{(SG - 1) \cdot \rho \cdot g \cdot D_{s50}} = 0.021 + 0.013e^{(-14F_s)} \]

where the right hand side is an empirical fit to the experimental results. The parameter \( F_s \) denotes the sand fraction in the active layer.

*Formulation for Delaware Estuary sediments*

Investigating the calibration ranges of the formulas, it is important to note that the formulation of Wu et al. spans the widest range of application. Wilcock and Parker’s formulations can be used for gravel while Ribberink and van Rijn’s can be used for sands.
When we look at the type of the formulations, all of them are fractional except Ribberink’s formulation.

**Table B-1 Type of Bedload Formulations**

<table>
<thead>
<tr>
<th>Formulation</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Van Rijn (1984)</td>
<td>Uniform and Fractional</td>
</tr>
<tr>
<td>Parker (1990)</td>
<td>Fractional</td>
</tr>
<tr>
<td>Ribberink (1998)</td>
<td>Uniform</td>
</tr>
<tr>
<td>Wu (2000)</td>
<td>Fractional</td>
</tr>
<tr>
<td>Wilcock (2003)</td>
<td>Fractional</td>
</tr>
</tbody>
</table>
Sediments in the Delaware Estuary vary significantly. The bottom sediment sizes in the upper estuary area cover a range of grain sizes from silty clay to gravel, there is also an across-channel variation in sediment size. The sediments in middle portion of the estuary from Philadelphia to Salem River are mostly coarse-grained sand-gravel mixtures with a small percentage of clay in it (Sommerfield and Madsen 2003). Finer particles are easy to erode and usually have small settling velocities. On the other hand, coarser particles from fine-sands to gravel are difficult to erode and have high settling velocities. So the saltation and jump of particles (Bed Load) usually take place in this particle size range. Because of this, a bed load formula, calibrated for a range of sediments from fine-sands to gravels, is appropriate for Delaware Estuary. Figure B.1 indicates that the fractional formulation of Wu et al (2000) is covering the widest range and it is advised to be used in the simulation of bed load transport in Delaware Estuary.
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