Intertidal hydrodynamics and basin-scale sediment dynamics in the Minas Basin, Bay of Fundy, and implications for change due to tidal power extraction

By

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Abstract

Minas Basin in the Bay of Fundy has the world’s largest tidal range and exchanges approximately 110 billion tonnes of water twice a day with tidal currents up to 5 ms\(^{-1}\) through Minas Passage, making it an ideal site for tidal power extraction. In this thesis a multi-domain high-resolution hydrodynamic model of Minas Basin is implemented and used to investigate: a) the relative influence of vegetation on flow routing in a macrotidal estuary to develop an understanding of the intertidal hydrodynamics in the natural system; and b) the implications of tidal energy extraction on basin-scale suspended sediment concentrations by simulating in-stream turbines.

The vegetation model incorporates the effects of vegetation on the flow (parameterized by the stem height, diameter and plant density) and is compared to field observations of water levels and current velocities over 6 tidal cycles at spring tide collected at closely-spaced sites in areas of different roughness types. Differences in flow resistance between vegetated and un-vegetated areas result in faster flows over un-vegetated areas, with vegetated areas having flow routing near-perpendicular to the vegetation edge. The results indicate that including salt marsh vegetation in a numerical model is crucial in controlling the hydrodynamic conditions both over the vegetated platforms and in the un-vegetated channels in a macrotidal estuary.

A coupled hydrodynamic-sediment-wave model was validated with field observations to examine the horizontal, vertical and temporal variability in tidal circulation and suspended sediment transport in the Minas Basin. The sediment transport is initialized using a bi-modal sediment distribution map and the model simulates both cohesive and non-cohesive sediments in the Minas Basin. The implications of constructing a large-scale turbine farm within the Minas
Channel and the impacts on suspended sediment within the Minas Basin are investigated. The turbine farm is simulated by semi-permeable structures that dissipate energy in the hydrodynamic model. The results emphasize the sensitivity of the system to changes in flow and suggest that a large scale tidal energy farm could reduce SSC by up to 37% on average across the basin.
Acknowledgements:

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<th>Symbol</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>A</td>
<td>Flow-through area (m²)</td>
</tr>
<tr>
<td>A_p(z)</td>
<td>Cross-sectional area of the vegetation across a horizontal plane b(z) × d(z)(m²)</td>
</tr>
<tr>
<td>C</td>
<td>Chézy friction coefficient (m⁻¹/₂ s⁻¹)</td>
</tr>
<tr>
<td>C_f, C_l</td>
<td>Friction and lift drag coefficients for friction and lift respectively</td>
</tr>
<tr>
<td>D_H, D_V</td>
<td>Horizontal and vertical diffusion coefficient (m²/s)</td>
</tr>
<tr>
<td>D'</td>
<td>Sediment deposition rate of sediment fraction l</td>
</tr>
<tr>
<td>E'</td>
<td>Sediment erosion rate of sediment fraction l</td>
</tr>
<tr>
<td>E</td>
<td>Elastic moduli of the plant stem</td>
</tr>
<tr>
<td>F(z)</td>
<td>Resistance imposed on the flow according to drag force (N)</td>
</tr>
<tr>
<td>F_x, F_z</td>
<td>Internal force components of the plant stems</td>
</tr>
<tr>
<td>H</td>
<td>Total water depth (m)</td>
</tr>
<tr>
<td>I</td>
<td>Moment of inertia of the plant stem (m⁴)</td>
</tr>
<tr>
<td>M_x, M_y</td>
<td>External sources or sinks of momentum</td>
</tr>
<tr>
<td>Q</td>
<td>Flow rate (m³/s)</td>
</tr>
<tr>
<td>S</td>
<td>Source and sink terms per unit area</td>
</tr>
<tr>
<td>U, V</td>
<td>Generalized Lagrangian Mean (GLM) velocity components (m/s) for simulations including waves (U = u + u_s and V = v + v_s)</td>
</tr>
<tr>
<td>U̅, V̅</td>
<td>Depth-averaged GLM velocity components (m/s)</td>
</tr>
<tr>
<td>U_v, U_w</td>
<td>Velocity vectors of water and vegetation (m/s)</td>
</tr>
<tr>
<td>a</td>
<td>Solidity of the plant stem (m²)</td>
</tr>
<tr>
<td>b</td>
<td>Width of plant stem</td>
</tr>
<tr>
<td>c</td>
<td>Mass concentration (kg/m³) of constituent</td>
</tr>
<tr>
<td>c_loss</td>
<td>Dimensionless loss coefficient</td>
</tr>
<tr>
<td>d</td>
<td>Thickness of plant stem</td>
</tr>
<tr>
<td>f</td>
<td>Coriolis coefficient (s⁻¹)</td>
</tr>
<tr>
<td>g</td>
<td>Gravitational acceleration (m/s²)</td>
</tr>
<tr>
<td>h</td>
<td>Water depth (m)</td>
</tr>
<tr>
<td>l</td>
<td>Sediment fraction (cohesive or non-cohesive)</td>
</tr>
<tr>
<td>n</td>
<td>Manning Coefficient n (s m⁻¹/³)</td>
</tr>
<tr>
<td>n(z)</td>
<td>Plant stems per unit area in the horizontal plane</td>
</tr>
<tr>
<td>q_s, q_n</td>
<td>Force components (friction and lift) to the plant stem</td>
</tr>
<tr>
<td>u(z)</td>
<td>Pore velocity (m/s)</td>
</tr>
<tr>
<td>u, v, w</td>
<td>Horizontal and vertical Eulerian velocity components (m/s) in Cartesian coordinates</td>
</tr>
<tr>
<td>w_s'</td>
<td>Sediment settling velocity of sediment fraction l [m/s]</td>
</tr>
<tr>
<td>Δx, Δy</td>
<td>Grid cell lengths</td>
</tr>
<tr>
<td>β</td>
<td>Van Rijn factor</td>
</tr>
<tr>
<td>ε'_s, ε'_s_x, ε'_s_y, ε'_s_z</td>
<td>Eddy diffusivities of sediment fraction l [m².s⁻¹]</td>
</tr>
<tr>
<td>ε'_s</td>
<td>Vertical sediment mixing coefficient for the sediment fraction l</td>
</tr>
<tr>
<td>ε_f</td>
<td>Vertical fluid mixing coefficient</td>
</tr>
<tr>
<td>ζ_u</td>
<td>Upstream water levels (m)</td>
</tr>
<tr>
<td>ζ_d</td>
<td>Downstream water levels (m)</td>
</tr>
<tr>
<td>η</td>
<td>Water surface elevation above reference datum (m)</td>
</tr>
<tr>
<td>θ</td>
<td>Angle of plant stem orientation</td>
</tr>
<tr>
<td>μ</td>
<td>Contraction coefficient</td>
</tr>
</tbody>
</table>
| ν_H, ν_V | Horizontal and vertical kinematic viscosity (m²/s); For the k-ε model the eddy viscosity is modeled as ν_V = c_μ' L √k with c_μ' and c_d calibration constants, k the
turbulent kinetic energy, and the mixing length, $L = C_D \frac{k\sqrt{\kappa}}{\varepsilon}$

$\nu_T(z)$ Eddy viscosity (m\(^2\) s\(^{-1}\))

$\rho$ Fluid density (kg m\(^{-3}\))

$\rho_0$ Reference density of water (kg m\(^{-3}\))

$\rho_t$ Combined total density of the plant stem and surrounding virtual water mass

$\rho_w$ Fluid density (kg m\(^{-3}\))

$\sigma$ Vertical coordinate (m)

$\phi(z)$ Average plant stem diameter
Chapter 1: General Introduction

1.1 Upper Bay of Fundy

The Bay of Fundy is located on the Eastern seaboard of Canada between Nova Scotia and New Brunswick and is connected to the Gulf of Maine in the North Atlantic Ocean. The upper Bay of Fundy is divided into two basins called Minas Basin and Chignecto Bay. The Minas Basin system, the site investigated in this thesis, is a semi-enclosed, macrotidal embayment that is divided into four main regions: Minas Channel, Minas Passage, Minas Basin and Cobequid Bay (Figure 1). Minas Channel narrows eastwards to a 5 km wide channel called Minas Passage, which connects to Minas Basin. Minas Passage is the conduit for tidal flows into and out of Minas Basin with fast (up to 5 ms\(^{-1}\)) currents (Amos, 1980; Li et al., 2013; Todd et al., 2014) and high turbulence. It has been scoured of sediment and a deep feature called the “Minas Passage Scour Trench” with a maximum depth of 170 m which exists just north of Cape Split (Swift and Borns 1967; Shaw et al., 2010). Due to the high currents in Minas Passage, it has been investigated as a potential site for generating tidal power since the 1960’s (Li et al., 2013). The amplification of tidal elevations in the Bay of Fundy is caused by a near resonant condition due to the geometry of the basin which has a natural period of 13.3 hr (Garrett, 1972) that is close to the 12.42 hr M\(_2\) Lunar tidal period.
The area of the tidal flats in Minas Basin is about 360 km², with almost half in Cobequid Bay in the eastern end of the Minas Basin. Due to its shallow bathymetry and the large tidal amplitude, approximately two thirds of the bay is exposed at low tide, revealing a wide expanse elongate sand bars and sand flats (Amos and Joice, 1977; Dalrymple et al., 1975). Surface waves in the Minas Basin are locally generated by wind because the region is sheltered by cliffs and from the larger swell and storm waves in the Bay of Fundy (Fader et al., 1977; Amos, 1980). The cliffs are variable in composition, but mainly consist of Triassic sandstone, Paleozoic rocks and glacial material (Amos, 1980). Other morphologic features in the Minas Basin include migrating sand wave fields (Klein, 1970; Dalrymple, 1984; Shaw et al., 2010; Li et al., 2013), gravel and cobble stone beaches (Ownes, 1977), pocket beaches, and mudflats and salt marshes (Grant, 1970; Gordon et al., 1985; Davidson-Arnott et al., 2000). Salt marshes occur in many areas and are extensive in the southwest part of Minas Basin surrounding the Southern Bight (Figure 1), with the total marsh area estimated to be on the order of 395 km² over four
centuries ago (prior to European settlement) (Shaw et al., 2010; Davidson-Arnott et al., 2002). It has suggested that the modern marsh area has been reduced to 65km² and the marsh area available for deposition has been reduced by approximately 70% (Amos and Tee, 1989; Gordon and Cranford, 1995; Davidson-Arnott et al., 2002).

1.2 Geologic History

The general physiography of the Bay of Fundy region was documented by early researchers including Goldthwait (1924), Crosby (1962), Fader et al. (1977), and Stephens (1977). The Bay of Fundy originated during the Appalachian orogeny 286-660 million years ago (Swift and Lyall, 1968) and opened to the present-day Atlantic Ocean by plate tectonics (Wade et al., 1996). Sedimentary infilling began 200 million years ago followed by dominantly clastic sediment deposition (King and Maclen, 1976; Stevens, 1977; Mossman and Grantam, 1996), and then by folding and uplifting (Desplanque and Mossman, 2001).

The Bay of Fundy was significantly altered during the glaciation period, with sea level changes causing early glacial emergence, and present and continuing submergence. The Laurentide ice sheet covered most of Canada including the Gulf or Maine 18,000 years ago, leaving in its wake of glaciomarine sediments (i.e., glacial outwash, moraines and large drumlin fields) (Swift and Borns, 1967; Wightman, 1970; Desplanque and Mossman, 2001; Todd et al., 2014). As the glacier was receding 14,000 years ago, the Bay of Fundy elevation changed due to land surface rebound and sea level rise. Approximately 7000 years ago the Minas Basin became tidally dominated and the tidal range has been increasing at an approximately linear rate of 0.15 m per century since that time (Amos, 1980; Amos, 1987, Shaw et al., 2010). Over the past 4000 years, strong currents up to 5 ms⁻¹ have been transporting water through Minas Passage with every tidal cycle (Li et al., 2013).
The tidal range in the Bay of Fundy varies from 2.4 m at the bay mouth to 16.3 m at the head of Minas Basin (Greenberg, 1977) as indicated in Figure 2. The tides are dominated by the principal lunar semi-diurnal constituent M\textsubscript{2}, with a period of 12.42 hr. While the M\textsubscript{2} tide dominates the sea level variability, the N\textsubscript{2} and S\textsubscript{2} constituents add a considerable variability with amplitudes on the order of 1 m (Dupont, 2005). Relatively small differences exist between the diurnal tides, with up to an absolute value of 1 m at spring tide (Amos, 1980). Strong tidal currents are generated in many parts of the bay, most notably in the Minas Passage where currents reach up to 5 m s\textsuperscript{-1}. The Bay of Fundy exchanges about 110 billion tonnes of water nearly twice a day out of the 255 km long bay (Greenberg, 1979). This volume is the same as the estimated to be approximately equal to the cumulative total daily volume of all the world’s rivers discharged into the oceans (Desplanque and Mossman, 2001).

![Figure 2: Spatial variation in tidal range in the Bay of Fundy: a) at the mouth (Yarmouth), b) and in Minas Basin (Burntcoat Head) with some of the highest tidal elevations in the world from May 14 (YD 134) to June 24 (YD 175), 2013 (where YD is the day of the year and Jan 1 is YD 1) The first grey period indicates time of the salt marsh field experiment discussed in Chapter 2 and the second grey period indicates the time of the basin sediment field experiment discussed in Chapter 3.](image-url)
1.3 Sediments

The seabed of Minas Basin is highly variable in composition and is covered by postglacial deposits or bedrock. The bed surface deposits are predominately gravels, pebbles, and cobbles in the sub-tidal region and sand and mud in the intertidal region (Amos 1980). Exposed bedrock is located where scouring dominates and consists of Paleozoic sandstones, siltstones and shales (Amos et al., 1980; Shaw et al., 2010). Sediments in the Minas Basin are derived from four main areas: eroding cliffs, the rivers draining into the system, sediments in suspension entering via Minas Passage and seabed reworking, particularly intertidal areas (Fader et al., 1977; Amos, 1980).

Evidence of sedimentation and sediment movement is abundant as intertidal sandflats and sand dune wave fields are visible at low tide. The high concentrations of suspended sediment at the sea surface are due to the re-suspension of mud from intertidal mudflats by wave and current activity (Dalrymple et al., 1991). Saltmarshes occupy large portions of high intertidal zones in temperate and high latitude regions, where energy conditions are sufficiently low for sediment deposition and establishment of salt-tolerant grasses. (Allen and Pye, 1992; Friedrichs and Perry, 2001). Salt marsh geomorphology is shaped heavily by the stabilizing and retarding effect of vegetation (Fagherazzi and Sun, 2004; Baptist, 2005; Bouma et al., 2007; Temmerman et al., 2007; Fagherazzi et al., 2008; Davis et al., 2011; Schwarz et al., 2014). Because of this, the Minas Basin has received considerable attention from researchers interested in the behaviour of sediments as they could be strongly influenced by changes in the system from tidal power development (Wu et al., 2011; Mulligan et al., 2012; Li et al., 2013;).
1.4 Previous Numerical Modelling Studies

Numerical studies can be used to simulate various fundamental physical conditions of the coastal environment such as water level elevations, currents and sediment processes. These studies began in the 1970’s, when Garrett (1974) investigated the frequencies of the system using a normal mode approach and estimated changes to the tides by tidal dam construction. Tee (1976) modelled the spatial distribution of tidal currents and identified that the currents are controlled by the geometry of the basin. Greenberg (1977, 1979) modelled the M\textsubscript{2} tide in the Minas Basin using a series of four nested meshes and incorporated friction by use of a quadratic bottom stress to simulate existing and post tidal-barrage tides. Due to computational limitations and course grids (1.6 km), the errors in tidal phases and amplitudes were large by today’s standards where such grid cells are either made with a triangular mesh or grid cells two order of magnitude lower for the Bay of Fundy system. Another tidal power development study by Sucsy et al. (1991) implemented the first three-dimensional model in the Bay of Fundy, but was less accurate than the results of Greenberg (1979), due to a uniform coarser model grid resolution of 5 km.

Scott and Greenberg (1983) modeled changes in tidal range in the Bay of Fundy and demonstrated that tidal amplitudes in the Bay of Fundy increased more rapidly from 7000 to 4000 years ago than from 4000 years ago to the present due to a decrease in the global rate of sea-level rise, by altering bathymetry in the model to compensate for postglacial sea-level changes. Greenberg and Amos (1983) examined the transport of suspended sediments using a numerical model, and considered the effects of the construction of a tidal barrage on sediment transport. The model by Greenberg was then extended by DeWolfe (1986) to include other tidal constituents (N\textsubscript{2}, S\textsubscript{2}, O\textsubscript{1}, K\textsubscript{1}). This work focused on the potential impacts of tidal power development and a detailed comparison with observations was not reported. Sankaranarayanan and McCay (2003) and Dupont (2002, 2005) modelled five tidal constituents (M\textsubscript{2}, N\textsubscript{2}, S\textsubscript{2}, O\textsubscript{1}, K\textsubscript{1}) in the Bay of Fundy and achieved errors of less than 0.2 m in amplitude and 7° in phase for M\textsubscript{2}, but had higher errors in the Minas Basin (root-mean-squared error of 0.3-0.5 m) with an overall accuracy within ~10%.
Recently there has been renewed attention to the application of numerical models to predict tidal currents and sediment transport patterns in the Bay of Fundy to investigate the potential impacts of tidal power extraction. Karsten et al. (2008) examined the maximum power production over a tidal cycle from in-stream turbines placed in Minas Passage using the FVCOM model, where it was found that a maximum power extraction of 7 GW would lead to a 36% reduction in tidal amplitude in the Minas Basin. Hasegawa (2011) used the POM model to study far-field energy extraction effects using quadratic friction in the momentum equations on tidal amplitudes in the Bay of Fundy. Wu et al. (2011) used the FVCOM model to determine the sediment transport in Minas Basin, including bed load and suspended particulate load, and evaluated the model against independent remote sensing images. Li et al. (2013) and Todd et al. (2014) used the Wu et al. (2011) results to quantify the relationship between bedform fields and model-predicted tidal current and sediment transport patterns in the Minas Channel and Passage. In comparison with acoustic current meter data (Mulligan et al., 2013) and satellite colour data (Tao et al., 2014), the Delft3D model has been used to investigate tidal energy and suspended sediment processes in Minas Basin.

1.5 Delft3D Hydrodynamic Model

Delft3D, developed by Deltares and Delft University of Technology, is a modelling system that solves the unsteady shallow-water equations in three dimensions (3D). The system of equations consists of the horizontal momentum equations (Eq. 2-3), a vertical momentum equation that is equal to the hydrostatic pressure relation since vertical accelerations are assumed to be small compared to gravitational acceleration (Eq. 4), the continuity equation (Eq.5), the transport equation (Eq. 6), and k-ε turbulence closure model (Lesser et al., 2004). The horizontal friction terms (Reynold’s stresses) $F_x$ and $F_y$, are determined using the eddy viscosity concept described by Rodi (1984). The momentum equations are given by:
\[
\frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} + \omega \frac{\partial U}{h \partial \sigma} - fV = - \left( g \frac{\partial \eta}{\partial x} + g \frac{h}{\rho_0} \int_0^\sigma \left( \frac{\partial \rho}{\partial x} + \frac{\partial \sigma'}{\partial x} \frac{\partial \rho}{\partial \sigma'} \right) \partial \sigma' \right) \\
+ v_H \left( \frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2} \right) + M_x + \frac{1}{h^2} \frac{\partial}{\partial \sigma} \left( \nu_V \frac{\partial U}{\partial \sigma} \right)
\]

(1)

\[
\frac{\partial V}{\partial t} + U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} + \omega \frac{\partial V}{h \partial \sigma} - fU = - \left( g \frac{\partial \eta}{\partial y} + g \frac{h}{\rho_0} \int_0^\sigma \left( \frac{\partial \rho}{\partial y} + \frac{\partial \sigma'}{\partial y} \frac{\partial \rho}{\partial \sigma'} \right) \partial \sigma' \right) + \\
v_H \left( \frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} \right) + M_y + \frac{1}{h^2} \frac{\partial}{\partial \sigma} \left( \nu_V \frac{\partial V}{\partial \sigma} \right)
\]

(2)

\[
\frac{\partial P}{\partial \sigma} = -g \rho H
\]

(3)

where \( u, v, w \) are the horizontal and vertical Eulerian velocity components (ms\(^{-1}\)) in Cartesian coordinates, \( \eta \) is the water surface elevation above the reference datum (m), \( \rho \) is the fluid density (kg\( m^{-3} \)), \( \rho_0 \) is the reference density of water, taken as 1030 (kg\( m^{-3} \)), \( x, y, \sigma \) are the horizontal and vertical coordinates (m), \( g \) is gravitational acceleration (ms\(^{-2}\)), \( h \) is the water depth (m), \( v_H \) and \( \nu_V \) are the horizontal and vertical viscosity, \( f \) is the Coriolis coefficient (s\(^{-1}\)), \( H \) is the total water depth (\( h + \eta \)) (m), and \( P \) is the pressure (pa), and \( M_x \) and \( M_y \) represent external sources or sinks of momentum (Lesser et al., 2004). The depth averaged continuity equation is given by:

\[
\frac{\partial \eta}{\partial t} + \frac{\partial [hU]}{\partial x} + \frac{\partial [hV]}{\partial y} = S
\]

(4)
where \( S \) represents the contributions per unit area due to the discharge or withdrawal of water, \( \bar{U}, \bar{V} \) are the Generalized Lagrangian Mean (GLM) velocity components (ms\(^{-1}\)) for simulations including waves (\( U = u + u_s \) and \( V = v + v_s \)), \( u_s, v_s \) are the Stokes’ drift components, evaporation and precipitation. The advection–diffusion equation is given by:

\[
\frac{\partial [hc]}{\partial t} + \frac{\partial [hUc]}{\partial x} + \frac{\partial [hVc]}{\partial y} + \frac{\partial [\omega c]}{\partial z} = h \left[ \frac{\partial}{\partial x} \left( D_H \frac{\partial c}{\partial x} \right) + \frac{\partial}{\partial y} \left( D_H \frac{\partial c}{\partial y} \right) \right] \\
+ \frac{1}{h} \frac{\partial}{\partial \sigma} \left[ D_V \frac{\partial c}{\partial \sigma} \right] + hS
\]  

(5)

where \( S \) represents source and sink terms per unit area, and \( D_H \) and \( D_V \) are horizontal and vertical and diffusivities, \( c \) is the mass concentration (kg\(^1\)m\(^{-3}\)) of constituent (salinity, sediment). A \( \sigma \)-coordinate approach is used for the vertical grid where the number of layers is constant over the horizontal computational area according to:

\[
\sigma = \frac{z - \eta}{h}
\]  

(6)

The flow domain of a 3D shallow water model consists of a number of vertical layers, with the layer interfaces following planes of constant \( \sigma \). This makes the Delft3D model suitable for predicting the flow in shallow coastal areas and places with large tidal ranges since a large vertical range of water depths can be modelled with higher vertical resolution in shallower areas. The model also incorporates the processes for drying and flooding of model cells necessary for simulating intertidal flats. The model can be coupled with SWAN, a third-generation spectral wind wave model that simulates the evolution of surface waves (Booij et al., 1999). A vegetation module that is integrated in Delft3D can be used to simulate the three-dimensional effects of salt marsh grasses on the flow. The model consists of a one-dimensional turbulence model combined with a model that simulates the bending of plant stems based on a force balance that accounts for vegetation position and buoyancy (Dijkstra and Uittenbogaard, 2010).
1.6 Objectives of the Present Study

The objectives of this thesis are to implement a multi-domain high-resolution hydrodynamic model Delft3D, to investigate: a) the relative influence of vegetation on flow routing in a macrotidal estuary and develop a framework for future modeling of tidal energy extraction effects; and b) the implications of tidal energy extraction on suspended sediments in the Minas Basin by simulating in-stream turbines. These objectives are examined by:

a. Simulating tidal currents and water levels, calibrated using acoustic observations across a change in vegetation type in the intertidal zone, using a system of three interconnected model domains at increasing resolution toward the intertidal zone to achieve high resolution of the salt marsh and drainage channels;

b. Implementing a flexible plant-flow vegetation module to simulate the impact of vegetation on flow patterns in a natural macrotidal marsh in the Bay of Fundy;

c. Validating a high resolution coupled hydrodynamic-sediment-wave model with field observations to examine the horizontal, vertical and temporal variability in tidal circulation and suspended sediment transport in the Minas Basin; and

d. Assessing the implications of in stream tidal energy extraction devices on suspended sediments in the Minas Basin by simulating in-stream turbines in the Minas Channel.

Chapter 2 provides an overview of the salt marsh site and field observations, and describes the hydrodynamic model and plant-flow vegetation module, with model results and comparisons with observations. The implication of the vegetation on the flow routing over a tidal marsh are discussed, and conclusions and recommendations are presented. Chapter 3 provides an overview of the basin-wide field observations, and describes the sediment model and forcing conditions. Model results are compared with observations and a discussion on the implications of a turbine array on suspended sediment dynamics is presented. Chapter 4 summarizes the main findings of this thesis, and the overall conclusions, and recommendations for future research.
Chapter 2: Hydrodynamics in a macrotidal estuary and the influence of vegetation on flow over a salt marsh platform

Abstract:

A three-dimensional hydrodynamic model was used to study the relative impact of salt marsh vegetation in a macrotidal estuary using a system of three connected grids that resolve flows in tidal drainage channels incised in the marsh platform. The model incorporates the flexible effects of vegetation on the flow drag, parameterized by the stem height, diameter and plant density. Field observations of water levels and current velocities over 6 tidal cycles at spring tide were collected in areas of different roughness corresponding to high marsh *Spartina patens*, low marsh *Spartina alterniflora*, and a muddy tidal channel bed. High resolution airborne LIDAR and existing multibeam bathymetry data were used to define the water depths and the spatially-variable vegetation maps in the multi-domain model. Model results indicate that the vegetation plays a major role in controlling flow speed and drainage patterns, especially over the marsh platform in a macrotidal environment. Differences in flow resistance between vegetated and un-vegetated areas result in faster flows over un-vegetated areas, with vegetated areas having flow routing near-perpendicular to the vegetation edge. Water level elevations well above the vegetation canopy height results in sheet flow over both vegetated and un-vegetated areas. The results indicate that including salt marsh vegetation with flexible stems in a numerical model is crucial in controlling the hydrodynamic conditions in a macrotidal estuary both over the vegetated platforms and in the un-vegetated channels.
2.1 Introduction

The Bay of Fundy is a macrotidal environment located on the Atlantic Coast of North America, between the provinces of Nova Scotia (NS) and New Brunswick (NB) in Eastern Canada. It is renowned for its large tidal amplitudes (e.g., 16.2 m at Burntcoat head, NS) and is distinguished as ‘hypertidal’ (Allen, 2000; Davidson-Arnott et al., 2002). The geometry and bathymetry of the Bay of Fundy results in a natural period that is close to the $M_2$ lunar semidiurnal tidal period of 12.42 hours, causing a near-resonant condition (Garrett, 1972). The large amplitude of the tide in the Bay of Fundy produces a wide range of geomorphic conditions and sediment types, including an extensive intertidal area consisting of mud flats and salt marshes, due to the high spatial variability in tidal current velocity and bed shear stress, and to the pre-existing geomorphology.

Salt marshes form in the upper intertidal zone of coastal regions in mid and high latitudes and are found in areas that are sheltered from high wave action which permits both the deposition of fine sediments and the establishment of vegetation (Kusters et al., 2003; Boorman, 1999; Craft et al., 2009). They provide a valuable ecological environment and function as critical habitat in biological production (Reed et al., 1999; Donnelly and Bertness, 2001; Mitsch and Gosselink, 2000) and are typically bordered by a variety of herbs, grasses or low shrubs and adhere to sharp boundaries defined by tolerance to stressors, such as large changes in salinity (Adam, 1990; Bertness, 1991). The topography of tidal marshes typically consists of a vegetated marsh platform, dissected by dense networks of un-vegetated tidal channels or creeks, sometimes with levee-basin micro-topography between the drainage channels (Orme, 1990; Pethick, 1992; Allen, 2000).

Tidal channels have been the focus of many studies on flow and sediment transport (e.g. Bayliss-Smith et al., 1979; French and Stoddart, 1992; Reed et al., 1985; van Proodij et al., 2006; Bouma et al., 2005a; O’Laughlin and van Proosdij, 2012), but not all of the hydrodynamics takes place in tidal channels, as a
portion of the water that floods and ebbs from the system with the tides is transported as sheet flow over the marsh platform (French and Stoddart, 1992; Davidson-Arnott et al., 2002; Temmerman et al., 2005). Vegetation such as marsh grasses reduces tidal flow velocity and turbulence (Leonard and Luther, 1995; Leonard and Croft, 2006; Temmerman et al., 2005; Kusters et al., 2003; Baptist et al., 2007), dampen wave activity (Moller, 2002; Augustin et al 2009; Mariotti and Farherazzi, 2013; Duarte et al., 2014; Moeller et al 2014) and influence geomorphology (Fagherazzi and Sun, 2004; Baptist, 2005; Bouma et al., 2007; Temmerman et al., 2007; Fagherazzi et al., 2008; Schwarz et al., 2014). The vertical profile of horizontal flow above the marsh platform is strongly affected by the marsh vegetation (Leonard and Luther 1995; Shi et al., 1995; Bouma et al., 2005). Factors that control salt marsh and tidal creek hydrodynamics are driven by the local topography, tidal prism, tidal amplitude and vegetation (Temmerman et al., 2005). Consequently flow paths over tidal marshes are complex and have high spatial variability (Wang et al., 1993; Leonard, 1997; Christiansen et al., 2000; Davidson-Arnott et al., 2002; Temmerman et al., 2005, Townend et al., 2011). Typically field observation of flows in tidal marshes are limited to measurements in un-vegetated areas or above the vegetation elevation. Most of the previous modeling studies of the spatial flow patterns in tidal marshes are idealized and use a one- or two-dimensional approach by assuming a flat surface and not accounting for the influence of vegetation on flow (Allen, 1994; Fagherazzi and Sun 2004; Lawrence et al., 2004; Marani et al., 2003; Mudd et al., 2004; Rinaldo et al., 1999, Woolnough et al., 1995, Holland et al., 2010). Recent modelling studies on three-dimensional salt marsh hydrodynamics have modelled vegetation as rigid cylinders in mesotidal environments, but these studies don’t take into account the flexible bending of plant stems (Kusters et al., 2003; Temmerman et al., 2005; Bouma et al., 2007; Temmerman et al., 2007; Schwarz et al., 2014). By implementing a flexible plant-flow vegetation module, a better approximation can be used to determine how vegetation routes flow in macrotidal saltmarsh environments.
In this study a high-resolution three-dimensional hydrodynamic model (Delft3D) with a flexible plant-flow vegetation module is applied to better simulate the impact of vegetation on flow patterns in a natural macrotidal marsh in the Bay of Fundy. This paper is organized as follows: Section 2.2 provides an overview of the study site and field observations, Section 2.3 describes the hydrodynamic model and plant-flow vegetation module, and Section 2.4 provides the model results and comparisons with observations. Section 2.5 discusses the implication of the vegetation on the flow routing over a tidal marsh, and conclusions and recommendations are presented in Section 2.6.

2.2 Study Area and Field Observations

The Minas Basin in the upper Bay of Fundy is a 124 km long by 30 km wide tidal bay shown in Figure 3. The Basin has a mean depth of 19 m, with deep areas in Minas Channel reported up to 170 m and 360 km² of intertidal flats around the basin, especially in the eastern (Cobequid Bay) and southwestern (Southern Bight) regions. The field site is the Kingsport saltmarsh and mudflat system, which is located within the Cornwallis Estuary, north of Wolfville, NS (Figure 3c). An array of four hydrodynamic instruments were deployed in a 2nd order stream tidal creek, as defined by Strahler (1952). The stream serves as a major conduit of water and suspended material through the marsh system. The 2nd-order creek forms another seaward connection during inundation cycles before the high marsh is flooded creating a ‘loop’ that has two open seaward connections. The Kingsport marsh system is exposed to waves from the Cornwallis estuary and when inundated is influenced by tidal currents.
Figure 3: Model grids, boundaries and bathymetry: a) Minas Basin (outer grid 200 m), b) Cornwallis Estuary (middle grid, 33 m), c) Kingsport Marsh (inner grid 8 m) and d) instrument locations for three velocimeters’ (M1-M3) and one Aquadopp (C4). Model boundaries are indicated by magenta lines; bathymetry for each grid cell ranging a) to 100 m; b-c) to 10 m; and d) to 2 m. Black lines indicate contour depths at intervals of: a) 20 m, b) 7 m, c) 5 m and d) 1.5 m.
Data were collected over 4 days of spring tides from May 25-28, 2013, with maximum tidal amplitudes from 12.8 to 15.0 m, resulting in water depths of 6.3 to 8.3 m in the tidal creek. The instruments, which include an acoustic Doppler profiler (Nortek Aquadopp) at C4 and three acoustic Doppler velocimeters (Nortek Vectors) at sites M1, M2, M3 (Figure 3) were oriented 72.4° from North to be aligned with the channel. This resulted in observations of along-channel ($u_{\text{along}}$) and across-channel ($u_{\text{across}}$) velocity components (Figure 4b). The bottom-mounted, upward-facing acoustic Doppler profiler was deployed near the creek thalweg and sampled at a rate of 1 Hz using 18 vertical bins spaced at 50 cm that span a range of over 9 m over the full water column.

Figure 4: Tidal variability over four days from May 24-28, 2013: a) predicted water levels from the tidal prediction model that define the hydrodynamic model boundary condition (blue), with observed water levels in a tidal channel at C4 (black); b) along- and cross-channel depth-averaged velocity components at C4. Where $\eta$ is the water level and $u$ is the flow velocity.

The macrotidal marsh is deeply incised by tidal creek networks system. The majority of the marsh platform vegetation is dominated by the high marsh species *Spartina patens* while lower elevations grading into creeks and mudflats are dominated by the low marsh species *Spartina alterniflora* (O’Laughlin and van Proosdij, 2012). The three Nortek vector instruments were deployed along a transect
that extended from the creek into the high marsh (Figure 3d). Station M3 was deployed on the creek bank within *Spartina alterniflora* and M2 was situated within 2 m of the creek bank on the boundary between *Spartina alterniflora* and *Spartina patens*. M1 was positioned furthest from the creek and at the highest elevation on the marsh surface, approximately 10 m from station M2 and was surrounded by *Spartina patens*. Each of the three marsh instruments (M1, M2, and M3) operated at 6 MHz and sampled at 16 Hz in 5 minute bursts every 10 minutes. Mean current velocity were estimated by time-averaging over the 5-min measurement bursts (Figure 5). The sampling volume for all marsh instruments was located 15 cm above the marsh surface. Data from all instruments were downloaded in the field at low tide for every tidal cycle due to the high resolution temporal sampling scheme.

Figure 5: Water levels (blue), along-channel (red) and cross-channel (green) velocity components on May 25, 2013, at four sites indicated on Fig. 3d: a) M1, b) M2, c) M3, and d) C4.

Measurements of plant density and plant height were collected on the Kingsport marsh at instrument deployment sites M1, M2, and M3 during the selected model simulation period (where, methodology was
determined by O’Laughlin and van Proosdij, 2012). For each of the two species, the plant heights and number of plants stems per unit area were calculated by harvesting a representative area above ground plant material with a 20 cm diameter ring at each instrument location, which are located in both high marsh and low marsh (O’Laughlin and van Proosdij, 2012). The average height of vegetation at sites M1, M2, M3 are 0.40, 0.34, and 0.48 m respectively, monthly results for local observed plant height and density for each site are given in Appendix A (Tables A1 and A2). Typical *Spartina alterniflora* are on the order of 10 mm in diameter and 30-240 cm in height, and *Spartina patens* are on the order of 10 mm in diameter and 30-120 cm in height (Tiner, 1993; U.S. Department of Agriculture, 2008). Other dominant sea-bed types that exist in the Cornwallis Estuary are intertidal sand and intertidal mud (Figure 6).

![Figure 6: Photographs indicating the four dominant seabed types in the Cornwallis Estuary of Minas Basin: a) intertidal sand; b) intertidal mud; c) low marsh vegetation (*Spartina alterniflora*); and d) high marsh vegetation (*Spartina patens*).](image-url)
2.3 Numerical Model

2.3.1 Model Description

The Delft3D hydrodynamic model (Lesser et al., 2004) is a three-dimensional, structured grid ocean model that has been successfully applied to intertidal areas to understand the hydrodynamics within saltmarshes in micro- and mesotidal areas (Kusters et al., 2003; Temmerman et al., 2005; Temmerman et al., 2007; Baptist et al., 2007; van Leeuwen et al., 2010; Hu et al., 2011; Xing et al., 2013; Schwarz et al., 2014; Borsje et al., 2014, Schellingerhout et al., 2014). Delft3D uses a finite-difference scheme to solve the horizontal momentum equations, numerically simulating water levels and currents driven by boundary forcing (e.g., currents, tides, river flows). It uses topographically following σ-coordinates in the vertical dimension and calculates non-steady flow and transport phenomena, and uses a second order k-epsilon turbulence closure scheme (Uittenbogaard et al., 1992; Bijvelds, 2001). The model domain in the present study extends from Cape Chignecto, NS, to the eastern end of Cobequid Bay in Minas Basin, covering an area of about 110 km in the east-west direction by 80 km in the north-south direction (Figure 3). A 2-way nesting technique called domain decomposition is used to enhance the resolution of the Kingsport Marsh, using three separate but connected hydrodynamic grids. The coarse grid has a horizontal resolution of 200 m, and extends eastward from Cape Chignecto and encompasses all of Minas Basin. The middle grid has a resolution of 33 m and extends westward from the town of Kingsport into the Cornwallis Estuary. The fine grid has a resolution of 8 m and covers the tributary areas of the Kingsport Marsh. The threshold depth for the hydrodynamic calculations during flooding and drying of grid cells is defined at 0.01 m water depth.

The bathymetric grid for Minas Basin was constructed by combining existing hydrographic multi-beam bathymetry with high-resolution LIDAR data obtained in July 2011. The LIDAR data were based on a high-order active GPS benchmark in Dartmouth, NS, using dual-frequency GPS receivers. Once corrected
for laser reflection on the marsh, the data were used to determine the topography in the intertidal area of Kingsport Marsh with a resolution of 1 m over an 8 km by 8 km area. The bathymetric data sets were merged after being referenced to Canadian Geodetic Vertical Datum 28 (CGVD28). The bathymetry was then triangularly interpolated to each grid cell vertex, yielding a grid that resolves the intricate tidal marsh topography.

The three hydrodynamic model (coarse, middle and fine grids) use 3, 6 and 18 vertical layers with uniform distribution over the water column, representing 33%, 16.6% and 5.6% of the water depth respectively. After sensitivity analysis using a range of different number of layers in the model, this particular vertical structure was selected as it was practical for computational efficiency expected from a single desktop computer (Intel 2nd generation i7 processor) and exhibited little difference from results with a greater number of layers in the outer grids. The model uses a time step of 3 seconds to maintain a stable Courant condition for the highest resolution grid. The model is forced by tides at the entrance to the Minas Basin at Cape Chignetco (Figure 3a) and the boundary conditions are developed from the tidal prediction model Webtide (Dupont et al., 2005). Five main tidal constituents (M2, S2, N2, K1, and O1) are used to predict the tidal water level elevations on 5 minute intervals at the entrance to Minas Basin, which is used as input for the model (Figure 4a). A fluid density of 1030 kg m$^{-3}$, Chezy bottom drag coefficient of 50 m$^{1/2}$ s$^{-1}$, a minimum background horizontal eddy viscosity of $1 \times 10^2$ m$^2$s$^{-1}$ and minimum background vertical eddy viscosity of $1 \times 10^6$ m$^2$s$^{-1}$ are used over the entire domain. The simulation is run over a period of 8 days allowing 4 days of model spin-up prior to 4 days of comparison with measured data.
2.3.2 Bottom Roughness

Roughness coefficients represent the resistance to flow in channels and flood plains. The bottom drag coefficient is a key parameter in a hydrodynamic model since it has a significant influence on the calculation of velocity, shear stress, stratification in the near bottom layer, and thus the sediment transport properties (Wu et al., 2011). Bottom roughness in Delft3D can be computed according to the Manning formulation where a specified value is given for the Manning coefficient $n$ to determine the Chézy friction coefficient:

$$C = \frac{H^{\frac{1}{5}}}{n}$$  \hspace{1cm} (7)

where $H$ (m) is the water depth, $n$ is the Manning Coefficient $n$ (s m$^{-1/3}$) and $C$ is the Chézy friction coefficient (m$^{1/2}$ s$^{-1}$). To model intertidal velocities, a spatially varying bottom drag coefficient map was developed from the seabed characterization map of the Kingsport Marsh in the Cornwallis Estuary of Minas Basin (Perrott and van Proosdij, 2012). The map provides the location of 180 polygons describing four different bottom roughness types: low marsh vegetation ($Spartina alterniflora$), high marsh vegetation ($Spartina patens$), intertidal mud, and intertidal sand. Values for the bottom drag coefficient, listed in Table 1, for intertidal sand and intertidal mud were taken from previous studies (Pope et al., 2006). Values for bottom drag coefficients for low marsh and high marsh were based on results by Augustin et al. (2009) for the same plant species.

2.3.3 Vegetation Model

The use of high roughness coefficients for vegetated surfaces does not account for the influence of vegetation over the whole water depth, and can result in an overestimation of sediment erosion rates (Temmerman et al., 2005; Temmerman et al., 2007). The vegetation model, which parameterizes the
plants according to the stem diameter, stem height and plant density can better characterize intertidal flows over different marsh grass types. The vegetation model, described by Dijkstra and Uittenbogaard (2010), consists of two parts: an existing one-dimensional vertical (1DV) flow model with k-ε turbulence closure scheme (Uittenbogaard and Klopman, 2001) and a model that simulates the bending of plant stems, based on a force balance that takes account of both vegetation position and buoyancy along the plant segment (s). The force balance for an element with solidity a (m²) is given by:

\[
q_x + \frac{\partial F_x}{\partial s} = \rho_t a \frac{\partial^2 x}{\partial t^2}
\]

\[
q_z + \frac{\partial F_z}{\partial s} = \rho_t a \frac{\partial^2 z}{\partial t^2}
\]

where \(\rho_t\) is the combined total density of the plant stem as well as the surrounding virtual water mass calculated with a Morison-like virtual mass factor (Morrison et al., 1950). \(F_x\) and \(F_z\) are the internal force components. The plant stem position \(x(s)\) and \(z(s)\) relative to its root connection are unknowns, but an additional equation couples the internal moment of a stem cross section to the internal forces:

\[
\frac{\partial M}{\partial s} = \frac{\partial x}{\partial s} F_z - \frac{\partial z}{\partial s} F_x
\]

The internal moment is also unknown, but it is related to the plant stem’s curvature \(\partial \theta/\partial s\) through:

\[
EI \frac{\partial \theta}{\partial s} = M \quad ; \quad \frac{\partial x}{\partial s} = \sin \theta \quad ; \quad \frac{\partial z}{\partial s} \cos \theta
\]

where \(E\) is the elastic modules of the plant stem and \(I\) (m⁴) the moment of inertia, based on width (b) and thickness (d). The problem is closed following a set of boundary conditions (see Dijkstra and Uittenbogaard, 2010) and can be solved and the positions of each plant stem segment can be determined. Shear stresses are also accounted for flow parallel to the leaf:

\[
q_s = \frac{1}{2} \rho_w C_s b |\vec{u}_w - \vec{u}_v| u_s
\]
\[ q_n = \frac{1}{2} \rho_w C_N b |\vec{u}_w| u_N \]

where \( q_s \) and \( q_n \) are the force components (friction and lift) to the plant stem and \( C_s \) and \( C_n \) are the friction and lift drag coefficients for friction and lift respectively. \( U_w \) and \( U_v \) are the velocity vectors of water and vegetation and \( u_s \) and \( u_N \) are the local velocity components that act parallel and normal to the plant stem respectively. The equation used to model flow through porous media (vegetation canopy) and solve the momentum equation for the pore velocity \( u(z) \) (ms\(^{-1}\)) is given by:

\[
\rho_o \frac{\partial u(z)}{\partial t} + \frac{\partial p}{\partial x} = \frac{\rho_w}{1 - A_p(z)} \frac{\partial}{\partial z} \left( \left( 1 - A_p(z) \right) \left( v + v_T(z) \right) \frac{\partial u(z)}{\partial z} \right) - \frac{F(z)}{1 - A_p(z)} \tag{16}
\]

where \( \rho_w \) is the fluid density (kg m\(^{-3}\)), \( \partial p/\partial x \) the horizontal pressure gradient (kg m\(^{-2}\) s\(^{-2}\)), \( v \) the kinematic viscosity (m\(^2\) s\(^{-1}\)), \( v_T(z) \) the eddy viscosity (m\(^2\) s\(^{-1}\) defined by the turbulence model), and \( A_p(z) \) (dimensionless) is the cross-sectional area of the vegetation across a horizontal plane \( b(z) \times d(z) \) (m\(^2\)) of a plant steam multiplied by the number of plant stems (n) per m\(^2\). The thickness (d) takes into account the angle of the plant stem due to the horizontal cross section. \( F(z) \) is the resistance imposed on the flow according to the drag force given by:

\[ F(z) = \frac{1}{2} \rho_w C_D a(z) u(z) |u(z)| \tag{17} \]

where \( C_D \) is the drag coefficient (dimensionless) and \( a(z) = d(z) n(z) \) is the solid area on the vertical plane perpendicular to the flow, per unit depth and width. This model represents a large number of plants by the position of a single plant which makes the model applicable to a spatially uniform region of a vegetated salt marsh.

The vegetation module requires inputs including the average plant stem diameter \( \phi(z) \), the number \( n(z) \) of plant stems per unit area in the horizontal plane, and the height of the plant stems \( z \) above the bottom.
The grid cells where the vegetation module is applied are defined by the seabed characterization map of the Kingsport Marsh (refer to Appendix A). Three model runs were conducted to evaluate the influence of bottom roughness from the four dominant seabed types and vegetation (Figure 6), conceptually shown in Figure 7, and include: 1) constant bottom roughness, 2) variable bottom roughness, and 3) the vegetation module with variable bottom roughness.

![Maps illustrating the numerical scenarios on the fine-resolution grid: a) constant roughness; b) spatially varying roughness; and c) vegetation module with varying roughness. Coefficient values are given in table 1.](image)

**Figure 7:** Maps illustrating the numerical scenarios on the fine-resolution grid: a) constant roughness; b) spatially varying roughness; and c) vegetation module with varying roughness. Coefficient values are given in table 1.

### 2.3.4 Sensitivity Analysis

The three model scenarios were calibrated by adjusting key parameters within the ranges listed in Table 1, to assess sensitivity of the model. Key parameters in the outer grid were adjusted to understand the sensitivity to predicting water levels and currents in the Minas Basin, particularly related to the strong tidal currents in Minas Channel (grid size, bottom friction, horizontal eddy viscosity, tidal boundary conditions). Parameters for the inner and middle grid were adjusted to understand the importance that flow controlling factors had on the hydrodynamics within the Kingsport tidal creek and marsh surface (grid size, bottom friction, and vegetation parameters). The optimal model parameter values, selected after comparison with the observations, are listed in Table 1.
Table 1: Sensitivity analysis for key model parameters varied for the three model scenarios for each grid.

<table>
<thead>
<tr>
<th>Inner and Middle Grid</th>
<th>Model Values Used</th>
<th>Minimum Values Tested</th>
<th>Maximum values Tested</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_d$ (low marsh - Manning’s n)</td>
<td>0.0309</td>
<td>0.007725</td>
<td>1.545</td>
</tr>
<tr>
<td>$C_d$ (high marsh - Manning’s n)</td>
<td>0.0269</td>
<td>0.006725</td>
<td>1.345</td>
</tr>
<tr>
<td>$C_d$ (intertidal mud – Manning’s n)</td>
<td>0.002</td>
<td>0.0005</td>
<td>0.1</td>
</tr>
<tr>
<td>$C_d$ (intertidal sand – Manning’s n)</td>
<td>0.0023</td>
<td>0.000575</td>
<td>0.115</td>
</tr>
<tr>
<td>Vegetation density (low marsh)</td>
<td>4000</td>
<td>1200</td>
<td>4800</td>
</tr>
<tr>
<td>Vegetation density (high marsh)</td>
<td>2500</td>
<td>600</td>
<td>2500</td>
</tr>
<tr>
<td>Inner grid size (m)</td>
<td>8</td>
<td>3</td>
<td>30</td>
</tr>
<tr>
<td>Middle grid size (m)</td>
<td>33</td>
<td>10</td>
<td>50</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outer Grid</th>
<th>Optimal Model Values</th>
<th>Minimum values Tested</th>
<th>Maximum values Tested</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_d$ (Minas Basin – Chezy coefficient C)</td>
<td>65</td>
<td>40</td>
<td>65</td>
</tr>
<tr>
<td>Horizontal eddy viscosity (m$^2$s$^{-1}$)</td>
<td>1</td>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>Tidal boundary time interval (min)</td>
<td>5</td>
<td>5</td>
<td>60</td>
</tr>
<tr>
<td>Grid size (m)</td>
<td>200</td>
<td>50</td>
<td>400</td>
</tr>
</tbody>
</table>

2.4 Model Results for Tidal Creek Hydrodynamics

To validate the hydrodynamic model results at site C4 in the Kingsport Marsh tidal creek, predictions were compared with acoustic observations from the bottom-mounted upward-facing Aquadopp profiler. The model creek results show an amplitude gain of 2.2 m and a phase lag of 1.12 hours from the boundary at Cape Chignecto ($B_{WL}$) to the intertidal field site in the Kingsport Marsh (C4). The water levels and depth-averaged flow velocity components were compared to the model results, resulting in correlation coefficients of 0.99, 0.90, and 0.65 for $\eta$, $u_{along}$ and $u_{cross}$ respectively (Table 2). The results
indicate that the model flow velocities in the creek at in very good agreement with observations (cross-
channel flows are very weak, < 0.10 ms\textsuperscript{-1}), showing strong shallow along-channel flows up to 0.35 ms\textsuperscript{-1} at
the onset of flooding and at the end of ebb (Figure 8). The model does not predict the same inundation
times as the observations, which may be due to the flooding and drying of the model cells that are
influenced by a threshold depth (0.01 m) above which hydrodynamic calculations are performed in each 8
m wide model grid cell. In reality, the v-shaped channel would be deeper in some parts of the 8 m wide
grid cell area and therefore improvements could be made using a more computationally demanding higher
resolution grid; however tests using 3 m horizontal resolution were determined to be prohibitively slow.
The model produces an average peak along channel flood velocity of 0.32 ms\textsuperscript{-1} while average observed
peak depth averaged along channel velocities are 0.35 ms\textsuperscript{-1}. Similarly, the model produces an average
peak depth averaged along channel ebb velocity of -0.34 ms\textsuperscript{-1} compared to an average observed peak
along channel velocities of -0.35 ms\textsuperscript{-1}. Model results agree with observed values in the 2\textsuperscript{nd} order creek at
site C4 indicating a flood tide dominance which produces landward bound velocities at high tide rapidly
followed by a change to faster flowing ebb tidal currents. Modelled and observed depth-averaged cross-
channel velocities were generally very low (< 0.10 ms\textsuperscript{-1}).
Figure 8: Model-data comparison in the Kingsport Marsh creek at C4, including time-series and scatter plots of water levels, along-channel and cross-channel velocity components. Correlation coefficients are listed in Table 2. Colored lines indicate observations and black lines indicate simulated results.

The vertical structure of horizontal velocity over the water column was compared between observed and modelled results at site C4 for horizontal velocities in each vertical layer as a function of time and water depth (Figure 9). Since the fine grid has a resolution of 8 m and bathymetric values in the model are centered at each grid cell vertex, the model depth at C4 does not represent the full ‘V-notch’ geometry of the salt marsh creek. Therefore the model cells flood slightly later and dry slightly earlier (approximately 20 minutes) than indicated by the observations, and the near-bed region of the channel is not well resolved compared to the observed bathymetry.
Figure 9: Time evolution of vertical current profiles (ms\(^{-1}\)) in the tidal creek over one tidal cycle on May 25, 2013, at C4: a) observed along-channel component; b) observed cross-channel component; c) observed magnitude; d)-f) corresponding model results using 18 vertical layers.
The horizontal velocities in 18 $\sigma$-layers from the model results were compared against the horizontal velocities at C4 in 18 vertical bins above the instrument (Figure 9). Results indicate that both the observed and modelled currents are nearly depth-uniform except close to the bottom. The model does not completely capture the same observed water level at site C4, with a lower water level elevation just prior to high tide. One possibility for the discrepancy could be due to forcing the model with a tidal prediction model with only 5 constituents.

2.5 Discussion of the Influence of Vegetation on Flow

The instruments deployed in the Kingsport Marsh were arranged in a line perpendicular to the creek, providing a spatial data set to compare with results from the different model scenarios (Figure 10). The results were evaluated by comparing the rotated depth-averaged velocity components ($u_{\text{along}}$, $u_{\text{cross}}$) with observations. The model run with vegetation is in the best agreement with observations over the marsh, while the model runs without vegetation produce currents that are much stronger than observations. This is best shown by the results at the two high marsh instruments, M1 and M2, where the dense vegetation on top of the marsh reduces the flow considerably. Without vegetation, the model predicts velocities of up to 0.1 ms$^{-1}$ when the observed velocities are much weaker. At the creek bank (M3) the vegetation model indicates a rapid increase in velocity and slightly overestimates the $u_{\text{along}}$ velocity component.
With the inclusion of the vegetation module, the comparison between modelled and observed velocities on the marsh surface are in better agreement, particularly at the instruments sites (M1-M3) located in the saltmarsh vegetation. Without the vegetation model the velocities are much higher at these sites and do not produce similar trends to the observations. The addition of vegetation in the model does not have a major influence in the channel at C4 and does not help to predict similar velocities at high tide. The correlation coefficient (R) for each model is given in Table 2 and overall, the results indicate that the vegetation model increases the correlation between modelled and observed velocities.
Table 2: Correlation coefficients (R) determined for three model scenarios

<table>
<thead>
<tr>
<th></th>
<th>Constant bottom roughness</th>
<th>Variable bottom roughness</th>
<th>Vegetation module, variable bottom</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>η</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>u_{along}</td>
<td>0.07</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td>u_{across}</td>
<td>0.31</td>
<td>0.33</td>
</tr>
<tr>
<td>M2</td>
<td>η</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>u_{along}</td>
<td>0.19</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>u_{across}</td>
<td>0.63</td>
<td>0.73</td>
</tr>
<tr>
<td>M3</td>
<td>η</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>u_{along}</td>
<td>0.63</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td>u_{across}</td>
<td>0.69</td>
<td>0.71</td>
</tr>
<tr>
<td>C4</td>
<td>η</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>u_{along}</td>
<td>0.88</td>
<td>0.89</td>
</tr>
<tr>
<td></td>
<td>u_{across}</td>
<td>0.64</td>
<td>0.61</td>
</tr>
</tbody>
</table>

Velocity-stage curves (Figure 11) provide further validation for the vegetation module by comparing model and observed depth-averaged along-channel velocities ($u_{along}$) at sites C4 and M3 over an inundation cycle. The initiation of flow in the channel on the flood tide has an initial velocity pulse, and when the water level decreases just below marsh level on the ebb a second velocity pulse that results in the highest velocity over the tidal cycle in agreement with the pattern identified by Bayliss-Smith et al. (1979) for salt marsh creeks in a macrotidal environment. Maximum velocities during this pulse on the ebb are usually greater than that for the previous pulse on the flood. In both scenarios, the model results underestimated the peak ebb velocities, but the model results at site M3, both model scenarios overestimate the peak ebb velocities (Figure 11b). The vegetation model results are in much better agreement with data in the marsh at site M3. Without the simulated vegetation the model predicts currents
of 0.14 ms\(^{-1}\) greater than observations at M3 at high tide, and with the vegetation the difference between predicted and observed values are less than 0.07 ms\(^{-1}\) at M3.

Figure 11: Observed and predicted depth-averaged velocity-stage curves over an inundation cycle on May 25, 2013, from 01:00-07:00. Model results are shown for two cases, constant bottom roughness and vegetation module with variable bottom roughness at: a) C4 and b) M3. Horizontal lines indicate the minimum elevation of low (3.2 m) and high (5.8 m) marsh vegetation canopies. Note axis are different between the subplots.

In the creek (C4) the flow routing history over a tidal cycle is very similar with and without the vegetation, except for elevations above the marsh platform. On the creek bank where low marsh is located (M3), the vegetation model significantly affects flow in vegetated areas (Figure 11) but without incorporating the vegetation module, the simulated horizontal velocities over the water column are significantly over-predicted (Figure 12). The model results indicate that the horizontal velocity profile changes with time, as the water level rises above the vegetation canopy during an inundation cycle. Temmerman (2005) identifies two vertical zones of flow: within the vegetation canopy where flow velocities are reduced due to friction, and above the height of the vegetation canopy where the flow can reach higher velocities (Figure 12). The results of the present study in a macrotidal environment are in
agreement with previous studies that have applied the Delft3D vegetation module in mesotidal environments (Kusters et al., 2003; Temmerman et al., 2005).

Figure 12: Water depth and times of velocity profiles (top), and simulated vertical profiles of horizontal velocity magnitude (bottom) at site M3 for flood and ebb tide in one inundation cycle on May 25, 2013. Solid lines correspond to the constant bottom roughness case and dashed lines indicate the vegetation module with variable bottom roughness. (Bottom). Point velocity observations at M3 are shown by circles for the same times.

On the Kingsport high marsh platform, water levels rarely exceed elevations above the high marsh vegetation canopy height such that vegetation almost always has a strong impact on flows before and after a high spring tide. As a result, high drag in the vegetated areas causes water to flow preferentially over the
lower friction un-vegetated surfaces (Figure 13). In the case of the model run without vegetation, the results indicate that tidal flows propagate just as easy over the marsh platform as they do through creeks, and the platform is not flooded from the creeks but by sheet flow from the marsh edge. This trend can be visualized by comparing flow velocities in the constant bottom scenario which show a more uniform depth profile from the surface to bottom layer (Figure 13). The model run with constant bottom roughness allows water to flow at higher velocities over the marsh surfaces, and the model run with vegetation reduces flows over the marsh and increases flows in the channels. The vegetation model results indicate that at the edge between the low marsh and the tidal creek, large differences in flow direction and magnitude occur (Figure 13).
Figure 13: Contour maps of model results in Kingsport Marsh at 06:00 on May 27th 2013 for: a) water depth (m) and b-d) surface and bottom layer horizontal velocities (ms⁻¹) for the constant bottom roughness case and vegetation module case. The black lines indicate elevation contours at an interval of 4 m and black vectors indicate flow direction.

Once the water levels exceed the level of the creek banks, the marsh platform is flooded from the creeks. During this time, the flow velocities are reduced in the emerging vegetation from the open creek and the flow direction is perpendicular to the creeks (Figure 13c, d). This vegetation effect explains the changing flow directions during inundation of a marsh platform as reported from other field studies (Temmerman et
The data and model results indicate that the local flow on the marsh surface is perpendicular to the creek axis before high tide. (Figure 14b,c). In addition, the model results in vegetated areas show reductions in flow velocity (Figure 14). The model results predict a notable flow routing trend that is also observed at C4 where positive along-channel velocities occur after high tide and the start of ebb tide (Figure 10). This trend can be visualized during an early stage in the ebb tide shown in Figure 14b. The velocity pulse occurs due to a formation of another seaward connection to Minas Basin at the end of the creek that only exists at high inundation levels, generating two exits to the creek. This connection becomes part of the drainage network for the immediate marsh tributary area during the start of ebb tide, resulting in the positive along-channel velocity at site C4 that continue from flood tide, through high tide and into ebb tide.
Figure 14: Maps of simulated velocity vectors (black) with model bathymetry relative to the CGDV28 vertical datum (coloured) in each grid cell in a tidal channel (location is shown in Figure 3). The magenta squares indicate instrument locations, the red arrows show observed velocities and the green lines indicate vegetation polygon borders between high marsh vegetation, low marsh vegetation, and unvegetated mud at hourly intervals before and after high tide on May 25, 2013: a) 3:40pm; b) 4:40pm; c) 5:40pm; and d) 6:40pm.

2.6 Conclusions and Recommendations

A high-resolution three-dimensional hydrodynamic model is used to examine the tidal flooding and draining of muddy channels and vegetated salt marsh flats in Minas Basin. The model results are compared to field observations collected in May 2013 over 6 tidal cycles using acoustic Doppler current profilers, acoustic velocimeters, pressure sensors, and LIDAR topographic surveys. Sensors were positioned to obtain flow characteristics in different roughness regimes corresponding to high marsh vegetation, low marsh vegetation and a muddy channel. The model uses 18 topography-following vertical
layers and the horizontal domain is composed of three grids connected using domain decomposition to achieve high spatial resolution in the salt marsh. A spatially varying bottom roughness map was constructed based on satellite imagery and LIDAR measurements for the different salt marsh flow regimes. Model-data comparisons were in good agreement, resulting in an amplitude gain of 2.2 m and a phase lag of 1.12 hours from the boundary at Cape Chignecto to the intertidal field site in the Kingsport saltmarsh.

The model incorporates a 1DV hydrodynamic vegetation module that simulates the bending of plant stems based on a force balance that takes account of both vegetation position and buoyancy and the force applied by the flow. The vegetation model, parameterized by stem diameter, stem height, stem strength and plant density, can characterize intertidal flows over different marsh grass types. To assess the influence of vegetation on current flow in the salt marsh, three model scenarios were evaluated including a constant bottom roughness scenario, a spatially varying bottom roughness scenario, and a spatially varying vegetation module with spatially varying roughness. Varying a wide range of parameters indicated different degrees of variability in the model yielding more accurate values for these parameters, as indicated by higher correlation values.

The vegetation model scenario with variable bottom roughness was able to replicate very similar flows observed over the marsh while the model scenarios without vegetation produced currents that were much stronger than observations, particularly at the two high marsh instruments, M1 and M2. Current velocity profiles in the channel at C4 indicate fairly good agreement between model and observations, and minor influence of vegetation on flows in the 2nd order creek except when water levels exceed the vegetation height. The initiation of flow in the channel on the flood generates an initial velocity pulse, and when the water level decreases just below marsh elevation on the ebb a second velocity pulse occurs which results
in the highest velocity over the tidal cycle in agreement with other studies on flow patterns in salt marsh creeks. The model results predict the observed trend of local current flow at the instrument site which indicates local flood tide dominance and fast flowing ebb tides in the 2nd order creek due to the formation of another seaward connecting flow pathway opening at high inundation levels. Flow velocities near the bottom (below the top of the vegetation canopy) are reduced in vegetated areas and enhanced in unvegetated area and as a consequence, the majority of flow over the marsh is contained in the channels. Without the vegetation cover, near-uniform sheet flow occurs in the model.

This work indicates the importance of vegetation in controlling the small-scale hydrodynamics in salt marshes via tidal channel networks and on top of marsh platforms in a macrotidal environment. The results from this work are in agreement with other studies that investigate effects of vegetation on tidal flow in a salt marsh. By investigating the effects of vegetation on the flow, this work provides a foundation for developing a more extensive model to investigate the anthropogenic change due to tidal energy extraction in a macrotidal environment.

Future work should be focused on developing a coupled wave, current and sediment transport model to examine the small scale-scale effects of vegetation on suspended sediment concentrations over salt marsh platforms and in drainage channels in a macrotidal estuary. Once validated using field observations the model can investigate the impacts of tidal energy extraction in a salt marsh. Prior to investigating sediment transport in the salt marsh, the large-scale sediment transport dynamics in Minas Basin must be understood. This is described in Chapter 3, and in comparison with detailed field observations of vertical profiles of currents and suspended sediment concentrations, this model will help to develop an understanding of the large-scale sediment processes in Minas Basin and to investigate potential future environmental changes due to tidal energy extraction.
Chapter 3: Variability in Suspended Sediment Concentrations in the Minas Basin, Bay of Fundy, and Implications for Change due to Tidal Power Extraction

Abstract

The Bay of Fundy in eastern Canada exhibits the world’s largest tidal range and exchanges approximately 110 billion tonnes of water twice a day with tidal currents up to 5 ms\(^{-1}\) making it an ideal place for tidal power extraction using Tidal In-Stream Energy Conversion (TISEC) devices in the Minas Channel. Field observations collected from ship-based and bottom-moored sensors over an 8-day period in 2013 are used to validate a 3D hydrodynamic and sediment transport model with measurements of water levels, current profiles, waves and suspended sediment concentration profiles. The sediment conditions are initialized using a bimodal sediment distribution map and the model simulates both cohesive and non-cohesive sediments in the Minas Basin. Modelled suspended sediment concentrations are compared horizontally, vertically, and temporally to observations and the results indicate strong data-model agreement for suspended sediment concentrations (SSC) over a range of 5 to 287 mgL\(^{-1}\). The implications of constructing a large-scale turbine farm within the Minas Channel and the impacts on suspended sediment within the Minas Basin are investigated. The turbine farm is simulated by adding semi-permeable structures in the model that use an energy loss term in the fluid momentum equations in the hydrodynamic model. The results emphasize the sensitivity of the system to changes in flow and suggest that a large scale tidal energy farm could reduce SSC by 37% on average across the basin which would disrupt physical and biological processes particularly on the fine-grained intertidal areas around the macrotidal basin.
3.1 Introduction
The Bay of Fundy is a large macrotidal embayment connected to the Gulf of Maine in Eastern Canada, and it is a near-resonant system with a natural period of approximately 13 hr that is very close to the 12.42 hr $M_2$ lunar tidal period. The tidal regime is semi-diurnal and the tidal range is the highest in the world (e.g., 16 m at Burncoat Head, NS), exchanging about 110 billion tonnes of water twice a day (Greenberg, 1974). The strongest currents in the Bay of Fundy occur in Minas Channel as water is advected at speeds up to 5 ms$^{-1}$. This makes it an ideal location for tidal power extraction by harnessing either potential energy using tidal barrages (Greenberg, 1979; Sucsy 1993; Cornett, 2013) or kinetic energy using in-stream turbines (Karsten et al., 2008; Mulligan et al., 2013; Hasewaga et al., 2011). It has been estimated that there is $1.15 \times 10^{14}$ J of mean potential energy in the Minas Basin in the upper Bay of Fundy (Greenberg, 1979) and this is equal to over 10 GW of power, about 15 percent of Canada’s annual electrical power consumption (Karsten et al., 2008).

The Minas Basin has high suspended sediment concentrations that control light attenuation, biological community structure and morphology (Tao, 2014). In other coastal and estuarine environments suspended sediments play a significant role in physical, biological, and chemical processes (Miller et al., 2011, van Proosdij et al., 2009). Sediment transport in the Bay of Fundy is less well understood and is strongly affected by tidal currents, waves and wind-driven re-suspension of bottom sediments (Dalrymple et al., 1990) that are highly variable across the system. Li (2010) investigates bedforms and non-cohesive bed load sediment transport within the Minas Channel but does not include the Minas Basin. Wu (2011) investigates sediment transport in the Minas Basin, but the observations are based on remotely sensed imagery and limited to the surface concentrations of suspended sediment. Recently there has been renewed attention (Garrett and Cummins, 2005; Karsten et al., 2008; Hasegawa et al., 2011, Mulligan et al., 2013) to tidal power extraction in the Bay of Fundy. Recent interest on deployment of Tidal In-Stream Energy Conversion (TISEC) devices in the Minas Channel heightens the importance of understanding the
dynamics of suspended sediment concentration to evaluate possible far-field environmental impacts in the Minas Basin.

Numerical models are useful tools to investigate the range of responses to changes in coastal systems imposed by structures such as TISEC devices, and provide a way to simulate various fundamental physical conditions of the coastal environment such as water level elevations, currents, waves and sediment processes. The Delft3D (Lesser, 2014) and SWAN (Booij, 1999) models have recently been implemented successfully to understand the environmental impacts of renewable energy related structures in the marine environment. As examples, Abandes et al. (2014) altered the wave transmission coefficients in SWAN to simulate wave farms near Plymouth, UK, and examined the impacts of a wave farm on beach profiles. McCombs et al. (2014) simulated turbine monopiles for a wind farm located in Lake Ontario and examined the impacts on waves and circulation. Past numerical studies on tidal power extraction in the Bay of Fundy have assessed the hydrodynamic effects such as changes to water levels (Garrett, 1974; Greenberg and Amos, 1983) and currents (Suesy et al., 1993; Shaw et al., 2010) and the associated environmental impacts (Garrett and Greenberg, 1979; Gordon, 1994; OEER, 2008; DFO, 2009; and Cornett et al., 2013). These studies are based on the implications of tidal barrages (Greenberg and Amos, 1983) and lagoons (Cornett et al., 2013) for tidal power extraction in the Minas Basin. Tidal In-Stream Energy Conversion devices have been recently considered as important alternatives to barrages and lagoons due to improvements in power efficiency and potentially lower negative environmental impacts (Garrett and Cummins, 2004; Blanchfield, 2008a; Karsten et al., 2008; Hasegawa et al., 2011). The regional hydrodynamic numerical model of Karsten et al. (2008) demonstrates that a significant decrease in tidal energy will lead to reduced tidal amplitude in the Minas Basin, which has the potential to disrupt physical and biological processes. No studies have comprehensively investigated the impact of TISEC devices on suspended sediment transport in the Minas Basin.
The goal of this study is to develop a three-dimensional (3D) hydrodynamic and sediment model of Minas Basin, validate it using oceanographic observations, and use it to investigate the implications of tidal power extraction from a turbine array on sediment transport. This chapter is organized as follows: Section 3.2 provides an overview of the site and field observations, Section 3.3 describes the model and forcing conditions, and Section 3.4 provides the model results and comparisons with observations. Section 3.5 discusses the implication of a turbine array on suspended sediment dynamics, and conclusions and recommendations are presented in Section 3.6.

3.2 Study Area and Observations

Minas Basin is a 124 km long and 30 km wide tidal bay (Figure 15). The basin has a mean depth of 19 m at mid tide, with reported deep areas in Minas Channel over 170 m, and 360 km² of intertidal flats around the basin, especially in the eastern (Cobequid Bay) and southwestern (Southern Bight) regions. The high concentrations of suspended sediment are mostly related to the re-suspension of mud from intertidal mudflats through wave and current activity (Dalrymple et al., 1990). Suspended sediment concentrations (SSC) in Cobequid Bay are much higher than in tributary rivers where the tidal influence is weak (Wu et al., 2011) and the mean resident suspended sediment volume in Minas Basin is approximately $3 \times 10^7$ m³ (Greenberg and Amos, 1983). The abundance of sediment in Minas Basin is the result of erosion from Triassic sandstone cliffs that surround the shoreline, supplemented by the input of glacial outwash sand (Tao, 2013).
Figure 15. Map of Minas Basin in the upper Bay of Fundy indicating bathymetry (m), model boundaries (red lines) and observation stations (black dots): a) coarse grid with outer boundary at water level gauges B_n, B_s and station S1; b) fine grid with internal model boundary, stations S2-S6 where A indicates an upward-looking ADCP on the bed, and W is the wind observation site.
Previous studies investigating sediment transport in the Bay of Fundy have used observational data from field studies conducted in the 1970’s (Amos and Joice, 1977; Long et al., 1979; Amos and Long, 1980; Li et al., 2010). In this study, a rich data set of new observations was collected during a oceanographic cruise in the upper Bay of Fundy on the Canadian Coast Guard Ship (CCGS) Hudson during the period of June 6-14th, 2013 is examined. The CCGS Hudson is a 90.4 m long scientific research vessel and it was used as a platform to collect water column and seabed data in the Upper Bay of Fundy including measurements of water levels and current velocities, and collection of samples to determine suspended sediment concentrations, particle sizes, settling velocities, and bed sediment sizes. Hydrodynamic observations were made in the water column with bottom-moored upward looking RDI Acoustic Doppler Current Profilers (ADCPs) at two locations in Minas Basin. The current profilers were located in the Southern Bight of Minas Basin (S3-A) and near the center of Minas Basin (S5-A) as shown in Figure 15b and were deployed for the duration of the research cruise. The ADCPs measured for 5 minute bursts over 30 minutes intervals at a sampling rate of 8 Hz. The sensors at S3-A and S5-A measured velocities over the water column using a bin size of 0.75 m, with the lowest bin located 1.87 m above the bed in mean water depths of 24.5 m and 20.1 m, respectively (e.g., Figure 16c). Two tidal gauges located near the entrance to the Bay of Fundy at St. Martins, NB, and Margaretsville, NS (Bn and Bs, Figure 15b), recorded water levels at 5 minute intervals (Figure 16a).
Figure 16. Example of observations collected during the study period from YD 157-165 (June 6th-14th, 2013): a) winds at W (Parrsboro Airport); b) water levels at the model boundary (B_N, B_N); c) u-velocity current profile over water depth (z) at S3-A (m s^{-1}); d) significant wave height at S3-A; e) water levels at S3-A with circles indicating times when water samples were collected at various stations; and f) near bottom suspended sediment concentration at S3-A.
Observations of water properties were collected at 6 different stations listed in Table 3. Water samples were collected using Niskin bottles attached to a CTD rosette and analyzed for nutrients, chlorophyll-a, dissolved oxygen, salinity, carbon dioxide and suspended sediment concentrations (SSC). The CTD rosette collected samples at depths of 1m, 5m, and 15m below the water surface and near-bottom (within 1-2 m) hourly over a 12 hour period. A Benthic Organic Bottom sampler (BOB) was deployed at similar times and made measurements taken at 15 cm and 35 cm above the bottom. In total, 60 samples of SSC field observations were collected over 9 consecutive tidal cycles (Figure 16e). An optical backscatter sensor (OBS) was co-located with the ADCP mooring at site S3-A. Suspended sediment concentrations were calculated using a linear relationship between the voltage observed by the OBS and the SSC measured using the near-bottom water sample which was filtered using 0.8 um Millipore filters. The initial weight of the filter was subtracted from the final weight of the dried (<60 C) and filtered material to yield the mass of sediment in the sample. The sediment mass divided by the total volume of water filtered allowed for calculation of SSC (Figure 16f). Field measurements of SSC are similar to previous field studies in the Bay of Fundy by Amos et al. (1979), with values ranging from 0.2 to 30.4 mgL$^{-1}$ (average of 6.6 mgL$^{-1}$) outside Minas Basin, and from approximately 4.0 to 287.0 mgL$^{-1}$ inside Minas Basin (average of 21.2 mgL$^{-1}$).
Wind speed and direction were recorded with an anemometer at hourly intervals at the Parrsboro Airport (Site W, Figure 15b). The winds predominately blow from the east to west (-u) direction with average speeds of 2-3 ms\(^{-1}\) (Figure 17a). Two strong wind events occurred during the 8 day data collection period and blow from west to east (+u) direction and have a maximum wind speed of 9 ms\(^{-1}\) (Figure 17a). The ADCP in the center of the Minas Basin at station S5-A was also configured to monitor surface waves and the directional spectrum in 64 frequency bands from 0 to 1.0 Hz and in 36 directional bands with 10° width (Figure 16d). The resulting waves from the strong wind events were observed by the ADCP at S5-A, and a maximum significant wave height of 0.85 m was observed (Figure 17b).
Table 3: Observation stations in Minas Basin from June 6th-14th, 2013.

<table>
<thead>
<tr>
<th>Name</th>
<th>Latitude °N</th>
<th>Longitude °W</th>
<th>Mean Water Depth (m)</th>
<th>Observations:</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>45.1891</td>
<td>-65.0721</td>
<td>70.0</td>
<td>SSC, Water Levels</td>
</tr>
<tr>
<td>S2</td>
<td>45.2445</td>
<td>-64.7994</td>
<td>45.0</td>
<td>SSC, Water Levels</td>
</tr>
<tr>
<td>S3-A</td>
<td>45.2556</td>
<td>-64.2650</td>
<td>24.5</td>
<td>SSC, Water Levels, Currents</td>
</tr>
<tr>
<td>S4</td>
<td>45.3284</td>
<td>-64.2134</td>
<td>25.0</td>
<td>SSC, Water Levels</td>
</tr>
<tr>
<td>S5-A</td>
<td>45.3179</td>
<td>-64.0130</td>
<td>20.1</td>
<td>SSC, Water Levels, Currents, Waves</td>
</tr>
<tr>
<td>S6</td>
<td>45.3403</td>
<td>-63.7950</td>
<td>17.0</td>
<td>SSC, Water Levels</td>
</tr>
<tr>
<td>W</td>
<td>45.4133</td>
<td>64.3491</td>
<td>N/A</td>
<td>Wind speed, Wind Direction</td>
</tr>
</tbody>
</table>

3.3 Model

3.3.1 Hydrodynamics and Waves

The model used herein is the Delft3D hydrodynamic model (Lesser, 2004), a three-dimensional, structured grid ocean model. Delft3D uses a finite difference scheme to solve the horizontal momentum equations, numerically simulating water-levels and currents driven by atmospheric (e.g., wind and pressure) and boundary forcing (e.g., currents, tides, river flows). It uses topographically following σ-coordinates in the vertical dimension and calculates non-steady flow and transport phenomena, using a second order k-epsilon turbulence closure scheme (Uittenbogaard et al., 1992; Bijvelds., 2001) and can incorporate the effects of wind- and wave- driven mixing. The sediment component includes parameterizations of hydrodynamic roughness in the bottom boundary layer, bed-load and suspended-load transport, cohesive and non-cohesive sediment types, deposition, erosion, and evolution of bed morphology. The wave model SWAN (Booij et al., 1999) can be coupled with the hydrodynamic model and enhanced bed shear stress from wave induced currents in the bottom boundary layer are calculated.
The model domain in the present study extends from near Saint John, NB, to the eastern end of Cobequid Bay in Minas Basin, covering 170 km in the east-west direction and 80 km in the north-south direction (Figure 15a). A 2-way nesting technique called domain decomposition is used to enhance resolution in the Minas Basin, using two separate but connected hydrodynamic grids. The coarse grid had a horizontal resolution of 800 m, and extends eastward from Saint John to Cape Chignecto and includes the Cumberland Basin. The fine grid has a resolution of 200 m and the domain extends east of Cape Chignecto and encompasses all of Minas Basin. The bathymetric grid for Minas Basin was constructed by combining existing hydrographic survey data with high-resolution multi-beam bathymetry (Parrott et al., 2008). The model used four vertical topographically-following $\sigma$-layers each representing 5, 15, 30 and 50% of the water depth. Four layers are used for computational efficiency, with little difference from results with a greater number of layers (e.g., 6, 12 and 18 layers were tested). The model time step was 30 seconds to maintain a stable Courant condition for the highest resolution grid. The model was forced by tides near the entrance to the Bay of Fundy at B_n and B_s (Figure 15b) and the boundary conditions were developed from water level observations from International Hydraulic Organization (IHO) tidal gauges, spatially interpolated along the boundary between the two stations. Wind observations at hourly intervals at Site W were used to force both wind driven hydrodynamics and wind-generated surface waves. A Chezy bottom drag coefficient of 50 m$^2$s$^{-1}$, a minimum background horizontal eddy viscosity of $1 \times 10^6$ m$^2$s$^{-1}$ and minimum background vertical eddy viscosity of $1 \times 10^{-6}$ m$^2$s$^{-1}$ were used over the entire domain. The simulation was run over a period of 30 days allowing 22 days of model spin up prior to 8 days of comparison with data.

The SWAN (Booij et al., 1999) wave model computed directional wave spectra on the same computational domain as the hydrodynamic model, using two nested grids that have the same resolution as the grids used in the hydrodynamic model. The wave model used 36 direction bins with 10$^\circ$ resolution,
and the JONSWAP bottom friction formulation was used with a default coefficient of 0.067 m²s⁻³. The model was coupled to the hydrodynamic model, which communicated every 30 minutes.

### 3.3.2 Sediment Transport

The sediment transport and morphology module supports both bedload and suspended load transport of non-cohesive sediments and suspended load of cohesive sediments. Three-dimensional transport of suspended sediment is calculated by solving the three-dimensional advection-diffusion (mass-balance) equation for the suspended sediment:

\[
\frac{\partial c_l}{\partial t} + \frac{\partial u c_l}{\partial x} + \frac{\partial v c_l}{\partial y} + \frac{\partial (w - w_l s) c_l}{\partial z} + \underbrace{\frac{\partial}{\partial x}(\varepsilon_{s,x} \frac{\partial c_l}{\partial z}) - \frac{\partial}{\partial y}(\varepsilon_{s,y} \frac{\partial c_l}{\partial z}) - \frac{\partial}{\partial z}(\varepsilon_{s,z} \frac{\partial c_l}{\partial z})}_{\text{diffusion}} = 0 \tag{18}
\]

where \(l\) designates the sediment fraction (cohesive or non-cohesive), \(c_l\) is the mass concentration of the sediment fraction \(l\) [kgm⁻³], \(u\), \(v\) and \(w\) are the flow velocity components [ms⁻¹], \(\varepsilon_{s,x}\), \(\varepsilon_{s,y}\) and \(\varepsilon_{s,z}\) eddy diffusivities of sediment fraction \(l\) [m²s⁻¹], \(w_l s\) is the sediment settling velocity of sediment fraction \(l\) [ms⁻¹]. The eddy diffusivities depend on the flow characteristics and account for the effects of high sediment concentrations on damping turbulent exchange processes, and the influence of waves due to wave-induced currents and enhanced bottom shear stresses. The output of the k-ε turbulence closure scheme is the eddy viscosity at each layer interface and from this the vertical sediment mixing coefficient is calculated according to \(\varepsilon_s \beta = B \varepsilon_f\), where \(\varepsilon_s\) is the vertical sediment mixing coefficient for the sediment fraction \(l\), \(\beta\) is the van Rijn factor and for cohesive sediment fractions and for fine sand (< 150μm) is equal to 1.0, and \(\varepsilon_f\) is the vertical fluid mixing coefficient. The exchange of material in suspension and the bed is modelled by calculating the sediment fluxes between computational layers. The boundary condition at the bed is given by:
\[-w_s^l c^l - \varepsilon_s^l \frac{\partial c^l}{\partial z} = D^l - E^l, \quad \text{at } z = z_b \tag{19}\]

where $D^l$ is the sediment deposition rate and $E^l$ is the sediment erosion rate of sediment fraction $l$. For cohesive sediment fractions the fluxes between the water phase and the bed are calculated with the Partheniades et al. (1965) formulations while the non-cohesive sediment fractions fluxes are calculated by the formulations by van Rijn (1993, 2000). The settling velocity $w_s^l$ for sand and mud are formulated very differently. The settling velocity of sand is calculated following van Rijn (1993) based on the nominal sediment diameter and the relative density of the sediment particles. The settling velocity of mud is affected by the formation of “flocs” which cause the particles to group together and settle faster. In high concentration mixtures, the settling velocity of a single particle is increased due to the presence of other particles, following Richardson and Zaki (1954).

The hydrodynamic model is initialized with a bi-modal sediment distribution map to define the location of cohesive and non-cohesive sediments bed thicknesses, developed from sediment texture maps published by Amos et al., (1980). The initial conditions result in sediments in suspension that are sourced by eroding fine muddy (cohesive sediments) from the intertidal mudflats (depths up to 10 m) and coarse sand (non-cohesive sediments) from depths of 10 m to 24 m, where depths prescribed are relative to the mean sea water level datum CGDV28. No sediment is initially prescribed (bedrock) for depths greater than 24m. Sediment and morphological inputs were selected based on previous Delft3D model results in the Minas Basin developed by Tao et al. (2014) who analyzed a matrix of initial conditions that control morphological processes (setting velocity, critical shear stresses, sedimentation and erosional rates). The initial condition for suspended sediment concentration within the model was initialized at 2.0 mgL$^{-1}$ for cohesive sediment and zero concentration for non-cohesive sediment. The non-cohesive sediment within the model is defined as having a $d_{50}$ grain diameter of 2 mm. The settling velocity was defined to be 0.4
mms$^{-1}$ for cohesive and non-cohesive sediment, the critical shear stress threshold for erosion and deposition was defined as 1.0 kg m$^{-2}$ s$^{-1}$ and 0.2 N m$^{-2}$ and an erosion parameter of $5 \times 10^{-6}$ all following the optimal sediment parameters found by Tao et al. (2014).

3.4 Results

3.4.1 Hydrodynamics

The observed depth-averaged currents in the southern (S3-A) and eastern (S5-A) regions in Minas Basin are shown in Figure 18, where the mean water depths are 24.5 m (S3-A) and 20.1 m (S5-A) and the mean tidal amplitude is 6 m at both sites. At S3-A the tidal current direction is dominant in the north-south direction with magnitudes up to 1.0 ms$^{-1}$. At S5-A the tidal current direction is dominant in the east-west direction with magnitudes up to 1.7 ms$^{-1}$. The model predicts slightly stronger tidal currents during flood tide and weaker currents during ebb tide than shown by observations (Figure 18). This could be attributed to instrumentation error in the current profiler recording velocities at the limit of its observable range. However, overall the modelled water level and depth averaged velocities are well correlated with observations. At station S3-A the correlation coefficients (R) were determined to be 0.99, and 0.96 for $\eta$ and $v$ respectively, but due to instrumentation error with the ADCP at S3-A the u-velocity component did not correctly record for the entire tidal cycle. Station S5-A correlated very highly with data and exhibited a correlation coefficient of 0.99, 0.98 and 0.97 for $\eta$, and $u$ and $v$ velocity components respectively.
Figure 18. Scatter plots over the 8-day study period and time-series comparisons of observed and modelled water levels and depth-averaged current velocity components over a selected 4 day period for model validation: a)-c) at S5-A; d)-f) at S3-A.

The vertical variability of the horizontal flow in the southern and eastern regions in Minas Basin are shown in Figure 19, at the time of the suspended sediment concentration measurements at each location. The colours in Figure 19 correspond to different periods of the tidal cycle with dark blue indicating low tide and dark red indicating high tide. At S5-A observed near surface currents at maximum reach 2.0 ms\(^{-1}\) while near bottom currents at the same time were 1.1 ms\(^{-1}\), indicating strong vertical shear between high and low tide. Overall the model is in very good agreement with observations and is able to reproduce the vertical variability in horizontal velocity in the water column over the tidal cycle.
Two strong wind events occurred on June 8 and 12, YD 159 and 163 (Figure 16a, 20b) resulting in the largest waves that occurred during the study period. Winds reached 9 ms\(^{-1}\) blowing from east to west (-x direction) for both wind events. The waves were observed by the RDI ADCP at S5-A in a depth of 20.1 m, and wave statistics are computed from hourly spectral observations. The first wind event occurred on June 8, 2013 and reached significant wave heights (H\(_s\)) of up to 0.84 m and peak wave periods (T\(_p\)) of 5 s (Figure 20c). The second wind event occurred on June 12, 2013, and reached significant wave heights (H\(_s\))
of up to 0.85 m and peak wave periods ($T_p$) of 5.0 s. The model simulated the wave events with significant wave heights of 0.95 m and 1.1 m and a peak wave period of 4.6 s and 4.7 s respectively. During high energy periods when $H_s > 0.5$, the predicted significant wave heights were in best agreement with observations. Model results indicate these wave events increased the critical stress on the mudflats.
which increased sediment erosion and suspended sediment in water column. Without instruments on the mudflats, no validation or comparison could be conducted.

3.4.2 Sediment Transport
Simulated suspended sediment concentrations were compared temporally, vertically and horizontally with the field observations. In Figure 21, observed suspended sediment concentrations at three stations (S5-A, S3-A, S6) along the axis of Minas Basin are compared with the model results. The observations typically indicate higher suspended sediment near the bottom and lower surface concentrations during low tide periods in Cobequid Bay than the model predictions. At S6 observation indicate higher vertical variability in suspended sediment concentration than is predicted by the model, particularly at low tide (~100.0 mgL$^{-1}$ difference). This could be attributed to too few computational layers in the model to accurately predict the observed bedload. At S3-A the model predicts the same range of suspended sediment over one tidal cycle (3.0 – 8.0 mgL$^{-1}$) as observations, where sediments have advected from shallow intertidal areas to the central part of the basin. The results indicate important sediment transport phenomena are correctly simulated, including higher suspended concentrations in source areas (intertidal flats and river mouths), lower concentrations in the central part of Minas Basin and in Minas Passage, and the change in SSC throughout a tidal cycle at each station.
Figure 21. Vertical profiles of suspended sediment concentrations over one tidal cycle at three stations (S3-A on June 7; S5-A on June 10; S6 on June 11): a)-c) water levels and coloured circles that indicate the time of observed SSC profiles; and b) vertical SSC profiles for observed (solid lines) and predicted (dashed lines) over one tidal cycle. Vertical lines in c) indicate the times shown in Figure 23.

The initial bi-modal sediment distribution map defines where cohesive and non-cohesive sediments can be eroded from the bed (Figure 22a), where different colours indicate areas of no sediment, sand and mud. Figure 22b illustrates the final erosion and deposition patterns that occur within the bay after a 30 day simulation. These results cannot be compared to any observations but indicate that in adjusting from simplified initial seabed conditions the model can reproduce large-scale natural depositional features that occur near the Minas Channel such as the Cape Split banner bank associated with the Scots Bay sand wave field (Li et al., 2011; Miller and Fader, 1990), and lack of deposition that defines high-energy erosional features such as the Minas Channel scour trough (Shaw et al., 2012). Defining two different factions of sediment with sharp boundaries in the model, numerical errors at the boundaries of each
sediment fraction occur (Figure 22b). However general trends indicate that sediment in Minas Passage moves eastward into Minas Basin and deposits in Cobequid Bay and lesser amounts southward into the Avon River.

Figure 22. Simulated bed sediment thickness maps for three time periods: a) initial sediment distribution map (sand in light green, mud in dark green and no sediment in blue); b) difference in sediment thickness over the 30-day simulation (May 14- June 14); and c) difference in sediment thickness over the 8-day data study period (June 6-14). Sites S2-S6 are indicated by the black circles.
Tao et al. (2014) used remote sensing to show that suspended sediment concentrations at the sea surface have a strong seasonal variation, and an order of magnitude difference in concentration from winter to summer. In the present study for summer conditions, sediment in the Southern Bight of Minas Basin barely erodes. Suspended sediment concentrations vary spatially in Bay of Fundy from less than 2 mgL\(^{-1}\) at anchor station S1 outside Minas Basin, up to 200 mgL\(^{-1}\) at station S6 in Cobequid Bay. Field measurements from previous field studies of suspended sediment concentrations in the Bay of Fundy report similar results, from 0.2 to 30.4 mgL\(^{-1}\) with an average of 6.6 mgL\(^{-1}\) outside of Minas Basin, and concentrations from approximately 4.0 mgL\(^{-1}\) to 287.0 mgL\(^{-1}\) in Minas Basin (Amos, 1979). The present model results indicate that the majority of sediment exchanged within the Minas Basin originates from the intertidal flats, in agreement with Greenberg (1979), and Cobequid Bay is one of the largest areas of sediment exchange in the Minas Basin. The distribution of average SSC in Minas Basin from sites S6, S5-A and S3-A is 74 mgL\(^{-1}\), 20 mgL\(^{-1}\) and 5 mgL\(^{-1}\) respectively. Figure 23 illustrates the predicted depth averaged suspended sediment concentrations at low and high tide on June 12\(^{th}\) 2013. Higher suspended concentrations occur in source areas (intertidal flats and river mouths), and lower concentrations in the central part of Minas Basin and in Minas Passage. The model results exhibits a discrepancy in computing suspended sediment concentrations in the far eastern region of Cobequid Bay, where past studies observed very high suspended sediment. This topic requires a separate and detailed study to be done in the future.
3.5 Discussion of Turbine Impacts

To simulate the effects of turbines in models where individual turbine structures cannot be resolved, several parametric approaches have been used in other studies. Karsten et al. (2008) locally modified bottom friction in Minas Passage, Hasegawa et al. (2011) introduced a quadratic friction term in the water column, and Mulligan et al. (2013) used a semi-permeable barrier over the lower half the water column. Following a similar method to Mulligan et al. (2013) but improving the spatial distribution of TISEC
devices to develop a more realistic scenario, a farm of in-stream turbines regions (Figure 24) are defined. The turbines are parameterized as hydraulic structures (semi-porous plates) in Minas Channel for two different model scenarios representing low (16 turbine regions) and high (41 turbine regions) tidal power extraction cases. The turbine arrays are idealized, but allow the model to be used to assess the implications of a turbine farm in Minas Channel and far field effects in Minas Basin. In the model, a hydraulic structure causes a local loss of energy in addition to the loss by bottom friction. At the TISEC locations, an additional force term is added to the horizontal momentum equation to parameterize the extra loss of energy. By defining specific grid cells as semi-porous hydraulic structures, simplistic TISEC devices are defined using the Q-H relation which relates the flow rate to the difference between the upstream and downstream water levels:

$$Q = \mu A \sqrt{2g |\zeta_u - \zeta_d|}$$ (20)

where $\mu$ is a contraction coefficient, $A$ is the flow-through area, and $\zeta_u$ and $\zeta_d$ are upstream and downstream water levels respectively. The contraction coefficient is dependent on the type of hydraulic structure and is used to determine the additional quadratic friction term in the momentum equation. The Q-H relation is used to determine the quadratic $C_{loss}$ coefficient in momentum equation according to:

$$M_x = g \frac{\zeta_u - \zeta_d}{\Delta x} = \frac{c_{loss} - u}{\Delta x} u \sqrt{u^2 + v^2}$$

$$M_y = g \frac{\zeta_u - \zeta_d}{\Delta y} = \frac{c_{loss} - v}{\Delta y} v \sqrt{u^2 + v^2}$$ (21)

where $\Delta x$ and $\Delta y$ are the grid cell side lengths, and $u$ and $v$ are the velocity components, and $c_{loss}$ is a dimensionless loss coefficient. In the high tidal power extraction case, $c_{loss}$ was specified as a value 100 which when used to simulate a tidal barrage across the Minas Channel, corresponds to a 23% reduction in tidal amplitude at S3-A (Mulligan et al., 2013). For the low tidal power extraction case $c_{loss}$ was specified as a value of 1. The turbine farms for both scenarios are defined by hydraulic structures in Minas Channel that are spaced in rows uniformly 850 m apart and extend vertically from the bottom to 20% of
the water column. Employing the same initial boundary forcing and conditions as the model runs described in section 3.3, the turbine farm scenarios were simulated and compared to the previous results. Previous work by Karsten et al. (2008) derived the potential tidal power expected in the Minas Channel and the responding tidal amplitude decrease in Minas Basin. To equate the present turbine scenarios to power extraction, water levels in the Minas Channel resulted in a 1% and 15% decrease in tidal amplitude after implementing the turbine array. According to Karsten et al. (2008) a corresponding tidal amplitude decrease in the Minas Channel results in a 0.77 and 5.6 GW of tidal power respectively for the low and high tidal power extraction case. The model results and relative changes from the low and high tidal power extraction scenarios are reported in Table B1.

![Figure 24: Model predictions of surface (top row of plots) and near-bed (bottom row of plots) tidal current magnitude velocities (|u|, ms$^{-1}$) in Minas Channel during a selected flood tide (05:30, June 7, 2013) with and without a farm of 41 turbines: a)-b) no turbines; c)-d) low tidal power extraction case; and e)-f) high tidal power extraction case.](image)

Compared to no turbines, the current speeds are significantly altered in Minas Channel due to implementation of the high tidal power extraction case as shown in Figure 24, with surface and bottom velocities are strongly reduced leading to localized differences of up to 1.5 ms$^{-1}$. These effects propagate
into the Minas Basin, where the depth averaged velocity components from the turbine models are compared against observations and the model results without turbines at stations S3-A and S5-A in Figure 25. In the the high tidal power extraction case, the velocity decreases by 0.2 and 0.6 ms\(^{-1}\) at site S3-A and S5-A during flood and ebb. The low tidal power extraction case does not significantly affect the currents in the Minas Basin, with differences in current as low as 0.02 m/s corresponding to a relative change of 1.2%.

![Figure 25: Depth-averaged tidal current velocity components (u,v, ms\(^{-1}\)) over a selected 3-day period for observed (red), simulated with turbines (grey) and simulated without turbines(black): a), c) at S3-A; , and b), d) at S5-A.](image)

The changes in suspended sediment concentrations from the addition of a high tidal power extraction turbine array could lead to a major potential environmental impact in the Minas Basin. The lower velocities as a result of tidal power extraction reduces sediment mobilization and increases deposition on
the tidal flats in Cobequid Bay. The changes in SSC are quantified by comparing the correlated modelled and observed SSC in the Minas Basin to the two turbine models to understand a best and worst case scenario from tidal power extraction. The change in suspended sediment transport in Minas Basin from the high power turbine array is significant, most notably in Cobequid Bay (station S6) where the largest change occurs. There is a uniform reduction in SSC by up to 70 mgL⁻¹ in each layer at low tide (Figure 26 c,f) but very little change at high tide due to the influx of low SSC water from the Bay of Fundy outside Minas Channel. As opposed to the change from the high tidal power scenario, the low power turbine array shows a very small difference in suspended sediments in Cobequid Bay (up to 13 mgL⁻¹). The change in SSC from tidal power extraction is reduced at stations in the central part of Minas Basin. From the high tidal power scenario, moderate reductions in SSC up to 15 mgL⁻¹ occurs during the ebb stage of the tidal cycle at station S5-A. At station S3-A, located close to the middle of Minas Basin, there is very little change in suspended sediment transport (~4 mgL⁻¹) and therefore the highest impacts occur further from the turbines in places with lower tidal current speeds like tidal flats where the fractional change in velocity is highest.
Figure 26: Time series of observed and predicted of SSC and predicted water levels at three sites over a tidal cycle: a)-c) without turbines implemented in the model; and d)-f) with turbines included. Depth-averaged SSC observations are indicated by red boxes that span the time and concentration range for each vertical profile. Modelled SSC of both fractions (mud and sand) is shown by the black lines for each vertical layer.

The depth and time averaged suspended sediment concentrations were calculated at the five stations for the observed, modelled and both modelled turbine scenario results in Figure 27, indicating that the suspended sediment transport in Cobequid Bay has the highest SSC and is the most impacted area after implementing a turbine farm. The SSC in other areas of the Minas Basin have small decreases except outside the basin at station S2, which has an increase in SSC but the concentrations are very small (e.g., <2 mgL⁻¹) compared to inside the basin. The horizontal-, vertical-, and time-averaged SSC over the study period results in values of 21.2 mgL⁻¹, 20.6 mgL⁻¹, 19.5 mgL⁻¹ and 13.0 mgL⁻¹ for the observed, modelled
without turbines, modelled with low tidal power extraction, and the model results with high tidal power extraction. This implies a SSC reduction of 5.6% and 37% due to the addition of a low and high tidal power extraction scenario in the Minas Channel.

Figure 27: Map of predicted time- and depth-averaged suspended sediment concentrations (mgL\(^{-1}\)) with bar plots indicating the observed (red) and predicted (black = no turbines; dark grey = 16 turbines; light grey = 41 turbines) time- and depth-averaged SSC at 5 sites (S2-S6) over the period of June 6-14, 2013. The lower right plot indicates the basin-wide (time, space, and depth) averaged SSC.
3.6 Conclusions
Hydrodynamics and sediment transport in the upper Bay of Fundy, where significant changes in tidal processes could occur in the future due to tidal power extraction, have been investigated using a coupled three-dimensional hydrodynamic, wave and sediment model. Observations from an 8-day period in June 2013 that include water levels, currents profiles, surface waves and suspended sediment concentration profiles were used to validate the hydrodynamic and sediment model, obtained from bottom-moored Acoustic Doppler Current Profilers and sensors deployed from the CCGS Hudson research vessel. The water level elevations, wave heights and vertical distributions of the horizontal velocity components are generally well reproduced by the model, indicated by high correlation coefficients.

A sediment distribution map using bi-modal sediment types (cohesive and non-cohesive) was used to initialize the model and the sediment transport formulations include both bed load and suspended load. The transport of the sediment is compared to vertical, horizontal, temporal and spatial observations and model-data comparison indicated that the observed trends in major depositional features are generally reproduced by the model such as the banner bank near Cape Split (Li et al., 2010; Miller and Fader 1990).

To develop an understanding of changes in suspended sediment transport in the Minas Basin due to tidal power extraction, two idealized model scenarios were used to simulate different sizes of in-stream turbine device (TISEC) farms. Arrays of 16 and 41 turbine regions were modelled as semi-porous plates acting over the bottom 20% of the water column, to simulate low and high tidal power extraction cases. In the high tidal power extraction scenario, far-field intertidal areas in Cobequid Bay are the most affected, with a decrease of 70 mgL\(^{-1}\) in mean SSC, while very small changes occur at other stations. Overall, the change in suspended sediment concentration averaged over time and throughout the water column at 5 stations indicates that the implementation of low and high tidal power extraction turbine arrays causes 5.6 and 37% decreases in suspended sediment concentrations in the Minas Basin which could affect small-
scale physical and biological processes particularly on the fine-grained intertidal areas around the macrotidal basin.

The idealized tidal power extraction scenarios that are numerically implemented in this study are used to quantify the impacts of turbine farms on currents and suspended sediment concentrations in the Minas Basin. The model was validated using water levels, currents, and suspended sediment concentrations but was not validated for changes in flows or SSC at small scales around individual in-stream turbines, which would require additional observations in regions of high velocities and turbulence. Modelling the turbines as semi-porous hydraulic structures provides a basic understanding for quantifying the far field implications of tidal power extraction but future work should focus on investigating the near-field impacts of TISEC on velocities and suspended sediment concentrations in Minas Channel. This would provide a foundation for research into the potential change in the suspended sediment concentrations in the Minas Basin and the greater Bay of Fundy and could lead to a more efficient turbine design and lower impacts on the marine environment.
Chapter 4: Conclusions and Recommendations

4.1 Conclusions

According to the objectives defined in Chapter 1 of this thesis, the following major points summarize the work completed that is described in detail in Chapters 2 and 3.

i. A high-resolution three-dimensional hydrodynamic model was used to examine the tidal flooding and draining of muddy channels and vegetated salt marsh flats in a macrotidal environment. The model uses 18 vertical layers and the horizontal domain is composed of three grids connected using domain decomposition with 8 m resolution in the finest grid, constructed from LIDAR and multibeam bathymetry sets to achieve high resolution in the salt marsh. Pressure sensors from field observations collected in May 2013 over 6 tidal cycles were compared to model water levels. Model-data comparisons were in good agreement, resulting in an amplitude gain of 2.2 m and a phase lag of 1.12 hours from the boundary forcing the model at Cape Chignecto to the intertidal field site in the Kingsport saltmarsh.

ii. A flexible plant-flow vegetation module was implemented, parameterized by stem diameter, stem height and plant density, to characterize intertidal flows over different marsh grass types. Observations from an acoustic Doppler current profiler and three acoustic velocimeters were compared to model results and indicate good agreement. The initiation of flow in the channel on the flood tide has an initial velocity pulse, and when the water level elevation decreases just below the marsh level on the ebb tide a second velocity pulse occurs which has the highest speed in the tidal cycle. The model results capture the observed trend of local current flow at the instrument sites which indicate local flood tide dominance and relatively fast ebb tidal currents.
in the 2nd order creek due to the formation of another seaward connecting creek opening at high inundation levels. Flow velocities near the bottom (below the top of the vegetation canopy) are reduced in vegetated areas and enhanced in un-vegetated areas and, as a consequence, the majority of flow over the marsh is contained in the channels. Without the vegetation cover, uniform sheet flow occurs in the model. This work indicates the importance of vegetation in controlling the small scale hydrodynamics in salt marshes via tidal channel networks and on top of marsh platforms.

iii. Field observations collected from ship-based and bottom-moored sensors over an 8-day period in 2013 are used to validate a 3D hydrodynamic and sediment model with measurements of water levels, current profiles, waves and suspended sediment concentration profiles. The sediment transport is initialized using a bi-modal sediment distribution map and the model simulates both cohesive and non-cohesive sediments in the Minas Basin and the sediment transport formulations include both bed load and suspended load. Modelled suspended sediment concentrations are compared to observations and the results indicate strong data-model agreement. The model predicted trends such as: higher SSC in the bottom layer than the top layer, higher SSC in the eastern end of Minas Basin, spikes in SSC just after slack water when sediment is mobilized, major depositional features are generally reproduced such as the Cape Split banner bank associated with the Scots Bay sand wave field, and sediment-free bed in the location of the Minas Passage scour trough. Modelled winds and wave activity, however little, amplified erosion exhibited on the intertidal flats but the results were not major.

iv. The implications of constructing large-scale turbine farms within the Minas Channel and the impacts on suspended sediment within the Minas Basin are investigated using a coupled three-dimensional hydrodynamic and sediment model. Arrays of 16 and 41 in-stream turbines devices (TISEC) were modelled as semi-porous plates acting over the bottom 20% of the water column, for two idealized low and high tidal power extraction scenarios corresponding to 0.77 and 5.6 GW of power extraction that provided critical results for understanding alterations in suspended
sediment transport in the Minas Basin. Cobequid Bay at the eastern end of Minas Basin is affected the most, with a 37% decrease for combined bedload and suspended sediment transport, while very small changes occur at other locations. Overall, the change in suspended sediment concentration averaged over time and throughout the water column at 5 stations indicates that the implementation of a low and high tidal power extraction large-scale turbine array causes a 5.6% and 37% decrease in suspended sediment concentrations in the Minas Basin which could affect small-scale physical and biological processes particularly on the fine-grained intertidal areas around the macrotidal basin.

4.2 Future Work and Recommendations

The results of this study could lead to other studies related to hydrodynamics, intertidal salt marsh vegetation, sediment transport and tidal power extraction in the Minas Basin. Some prominent ideas for further research include:

a. Sediment dynamics in the salt marsh channels: This work indicates the importance of vegetation in controlling the hydrodynamics in a macrotidal salt marsh. Future work should be focused on developing a coupled wave, current and sediment transport model to examine the small-scale effects of vegetation on suspended sediment concentrations over salt marsh platforms and in drainage channels in a macrotidal estuary. In particular the sediment exchanges between salt marshes and tidal flats via tidal channel networks could be examined.

b. Longer simulations, higher resolution and more computational power: The work completed in this thesis was simulated on a single desktop computer. By using a cluster of computers or cores, longer simulation times could be performed to simulate seasonal or annual cycles. Higher resolution could also
be implemented, both horizontally and vertically, that would necessitate a smaller time step and also demand higher computational power. A greater number of vertical layers could improve model results related to wetting and drying in the intertidal areas and the fluctuations in bed thickness on the basin scale. Especially with regard to the V-notched salt marsh creeks, a horizontal resolution of 8 m averages out some channel features. Grid spacing for future model runs could be higher and an unstructured grid approach (e.g., flexible mesh) could be implemented. This could improve the bathymetry in the intertidal zone and reduce the computational power needed.

c. Initial bottom sediment conditions: The sediment distribution map used in Chapter 3 was based on bottom sediments mapped in 1980. Field work has recently been done (2013) to map the bed conditions, and results indicate large differences since the work in 1980. A new modelling study should be conducted to incorporate and implement these new bed conditions. This study can investigate the differences in sediment transport phenomenon that results between these two different initial bottom sediment maps, and further high resolution bathymetry surveying should be conducted to improve our understanding of this environment.

d. Implementation of turbines: Modelling the turbines as semi-porous hydraulic structures provides a basic understanding for quantifying the far-field implications of tidal power extraction, but future work should focus on investigating the near-field impacts of TISEC devices on velocities and suspended sediment concentrations in Minas Channel. This would involve higher resolution around individual turbines and would also require coupling with a different type (e.g. turbulence resolving) numerical model. The results would provide a foundation for research into the potential change in the suspended sediment concentrations in the Minas Basin and the greater Bay of Fundy and could lead to a more efficient turbine design and lower impacts on the marine environment.
References


Appendix A:

Table A1: Vegetation densities determined from individual stem counts within a 0.2 m diameter circle.

<table>
<thead>
<tr>
<th>Vegetation Density (plant/m²)</th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Alive</td>
<td>Dead</td>
<td>Alive</td>
</tr>
<tr>
<td>May 4 2012</td>
<td>828</td>
<td>1846</td>
<td>2515</td>
</tr>
<tr>
<td>May 9 2012</td>
<td>1814</td>
<td>1273</td>
<td>1337</td>
</tr>
<tr>
<td>June 2012</td>
<td>3119</td>
<td>2069</td>
<td>4584</td>
</tr>
<tr>
<td>July 2012</td>
<td>5539</td>
<td>3342</td>
<td>2960</td>
</tr>
<tr>
<td>August 2012</td>
<td>1560</td>
<td>2005</td>
<td>2069</td>
</tr>
<tr>
<td>Sept 2012</td>
<td>3788</td>
<td>3661</td>
<td>955</td>
</tr>
<tr>
<td>Nov 2012</td>
<td>286</td>
<td>2928</td>
<td>0</td>
</tr>
<tr>
<td>Jan 2013</td>
<td>0</td>
<td>1974</td>
<td>0</td>
</tr>
<tr>
<td>March 2013</td>
<td>N/A</td>
<td>N/A</td>
<td>0</td>
</tr>
<tr>
<td>May 2013</td>
<td>668</td>
<td>2674</td>
<td>N/A</td>
</tr>
<tr>
<td>June 2013</td>
<td>1305</td>
<td>4265</td>
<td>2992</td>
</tr>
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</table>
Table A2: Vegetation heights measured at each instrument on the low and high marsh

<table>
<thead>
<tr>
<th>Max Vegetation Height (cm)</th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 4 2012</td>
<td>32.5</td>
<td>30</td>
<td>42.5</td>
</tr>
<tr>
<td>May 9 2012</td>
<td>35</td>
<td>42.5</td>
<td>35</td>
</tr>
<tr>
<td>June 2012</td>
<td>47.5</td>
<td>25</td>
<td>70</td>
</tr>
<tr>
<td>July 2012</td>
<td>35</td>
<td>35</td>
<td>65</td>
</tr>
<tr>
<td>August 2012</td>
<td>40</td>
<td>40</td>
<td>70</td>
</tr>
<tr>
<td>Sept 2012</td>
<td>45</td>
<td>42.5</td>
<td>82.5</td>
</tr>
<tr>
<td>Nov 2012</td>
<td>45</td>
<td>32.5</td>
<td>47.5</td>
</tr>
<tr>
<td>Jan 2013</td>
<td>37.5</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>March 2013</td>
<td>40</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>May 2013</td>
<td>47.5</td>
<td>40</td>
<td>17.5</td>
</tr>
<tr>
<td>June 2013</td>
<td>40</td>
<td>20</td>
<td>27.5</td>
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<tr>
<td>Average</td>
<td>40</td>
<td>34</td>
<td>48</td>
</tr>
</tbody>
</table>
Figure 28: Characterization map used to parameterize different roughness regimes and locations for vegetated areas (after Parrott and van Proosdij, 2012).
### Appendix B:

Table B1: Summary of results for the low and high power extraction.

<table>
<thead>
<tr>
<th></th>
<th>Low Power Extraction</th>
<th>High Power Extraction</th>
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<tbody>
<tr>
<td>Power Extraction (GW)</td>
<td>0.77</td>
<td>5.6</td>
</tr>
<tr>
<td># of Turbine Regions</td>
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<td>41</td>
</tr>
<tr>
<td>Maximum Relative Tidal Amplitude Change</td>
<td>1%</td>
<td>15%</td>
</tr>
<tr>
<td>Maximum Relative Velocity Change</td>
<td>1%</td>
<td>10%</td>
</tr>
<tr>
<td>Overall Relative SSC Change</td>
<td>5.6%</td>
<td>37%</td>
</tr>
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</table>