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Variability in suspended sediment concentration in the Minas Basin, Bay of Fundy, and implications for changes due to tidal power extraction

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ABSTRACT

The Bay of Fundy in eastern Canada has the world's largest tidal range of over 16 m with tidal currents up to 5 ms^{-1} making it an ideal place for tidal power extraction using tidal in-stream energy conversion devices in the Minas Passage. 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 of the Minas Basin with measurements of water levels, current profiles, waves, suspended sediment fluxes and suspended sediment concentration (SSC) profiles. The sediment conditions are initialized using a bi-modal sediment distribution map and the model simulates both cohesive and non-cohesive sediments in the Minas Basin. Model results for fine-grained suspended sediment concentrations are compared horizontally, vertically, and temporally to observations and indicate strong data-model agreement for SSC from 5 to 287 mg L^{-1}. The implications of constructing a large-scale turbine farm within the Minas Passage and the impacts on suspended sediment within the Minas Basin are investigated using the model. The farm is simulated by adding semi-permeable structures that use an energy loss term in the fluid momentum equations to parameterize turbine regions 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 that extracts maximum power could reduce SSC by 37% on average across the basin which would influence physical and biological processes particularly on the fine-grained intertidal areas around the macrotidal basin.

1. Introduction

The power of tidal currents is a reliable source of renewable energy and the Bay of Fundy in Eastern Canada is known to be a major contributor to the world's tidal energy resource (Karsten et al., 2008). The Bay of Fundy is a large macrotidal embayment connected to the Gulf of Maine on the Atlantic Ocean, and it is a near-resonant system with a natural period of approximately 13 h that is very close to the 12.42 hour M_2 lunar tidal period. Minas Basin, the terminal basin in the Bay of Fundy, is connected to the Bay of Fundy via Minas Channel (15 km wide) and Minas Passage, which narrows to a width of approximately 4.5 km. The tidal regime is semi-diurnal and the tidal range is the highest in the world (e.g., 16 m at Burntcoat Head, NS), exchanging about 110 billion tonnes of water twice a day (Greenberg, 1979). The strongest currents in the Bay of Fundy occur in the Minas Passage with flow speeds up to 5 ms^{-1}. This makes it an ideal location for tidal power extraction by harnessing either potential energy using tidal barrages (Cornett et al., 2013; Greenberg, 1979; Sucsy et al., 1993) or kinetic energy using in-stream turbines (Hasegawa et al., 2011; Mulligan et al., 2013). It is estimated that there is 1.15×10^{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% 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 seabed morphology (Tao et al., 2014). In 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 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. Recent studies include an investigation of bedforms and non-cohesive bedload sediment transport in the Minas Channel (Li et al., 2014) and studies of sediment transport in the Minas Basin based on numerical models that are compared with historical observations (Wu et al., 2011) and recent remotely sensed observations that are limited to the surface suspended sediment concentrations (Tao et al., 2014). There has been renewed attention (Garrett and Cummins, 2004; Hasegawa et al., 2011; Karsten

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et al., 2008; Mulligan et al., 2013) to tidal power extraction in the Bay of Fundy using tidal in-stream energy conversion (TISEC) devices, also known as tidal current turbines. TISEC devices are underwater turbines that generate power from tidal currents, and in the future could be deployed in large numbers in a multi-unit array to generate power on the scale of other renewable energy sources. Many different device types and shapes have been proposed and tested, and a useful review of technology is provided by Khan et al. (2009). The leading example is the Marine Current Turbines Ltd. twin 16 m diameter axial flow rotor 1.2 MW 'SeaGen' turbine deployed in Strangford Lough in Northern Ireland, the world's first grid-connected device (Douglas et al., 2008). In the Bay of Fundy, a 10 m diameter open-centre 1.0 MW OpenHydro Ltd. turbine was tested in the Minas Passage in 2009 (OpenHydro Press Release, 2009). The future deployment of arrays of turbines in the Minas Passage heightens the importance of understanding the dynamics of suspended sediment concentrations to evaluate the possible far-field environmental impacts in the Minas Basin.

Numerical models are useful tools to investigate the range of responses to changes in marine systems imposed by structures such as TISEC devices, and provide a way to simulate various fundamental physical conditions of the coastal environment including water level elevations, currents, waves and sediments. The Delft3D (Lesser et al., 2004) and SWAN (Booij et al., 1999) models have been implemented successfully to understand the environmental impacts of renewable energy extraction structures in the marine environment. As examples, Abanades 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 lake water 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 (Shaw et al., 2010; Sucsy et al., 1993) and the associated environmental impacts (Cornett et al., 2013; DFO, 2009; Garrett, 1974; Gordon, 1994; OEER, 2008). 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. TISEC devices have been recently considered as important alternatives to barrages and lagoons due to improvements in power efficiency and potentially lower negative environmental impacts (Blanchfield et al., 2008; Garrett and Cummins, 2004; 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. To the authors' knowledge there have not been any studies targeted to comprehensively investigate the impact of TISEC arrays 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 the Minas Basin, validate the model using oceanographic observations, and use the model to investigate the implications of tidal power extraction from a turbine array on sediment transport. This chapter is organized as follows: a description of the site and field observations are provided in Section 2, the model and forcing conditions are described in Section 3, and the model results and comparisons with observations are discussed in Section 4. Implications of a turbine array on suspended sediment dynamics are discussion in Section 5, and conclusions and recommendations are presented in Section 6.

2. Study area and observations

Minas Basin is a 124 km long and 30 km wide tidal bay, shown in Fig. 1. The basin has a mean depth of 19 m at mid-tide with deep areas in the Minas Passage over 170 m, and 360 km^2 of intertidal flats around the basin especially in the eastern (Cobequid Bay) and southwestern (Southern Bight) regions. The sources of suspended sediment in the Minas Basin, derived from glacial outwash deposits (Shaw et al., 2010), are the result of sandstone cliff erosion and resuspension of seabed material (Amos and Long, 1980). 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) are over 50 mg L^{-1} in Cobequid Bay (Tao et al., 2014) and the mean resident suspended sediment volume in the Minas Basin is approximately 3×10^7 m^3 (Greenberg and Amos, 1983).

Previous sediment studies in the Bay of Fundy have used observations from field studies conducted in the 1970s (Amos and Joice, 1977; Long, 1979). In this study, a rich data set of new observations was collected during an oceanographic research cruise in the upper Bay of Fundy on the Canadian Coast Guard Ship (CCGS) Hudson during the period of June 6–13, 2013. The CCGS Hudson is a 90.4 m long scientific research vessel that 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, suspended 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 the Minas Basin. The current profilers were located in the Southern Bight of Minas Basin (S3-A) and near the center of the Minas Basin (S5-A) as shown in Fig. 1b and were deployed for the duration of the research cruise. The ADCPs measured currents for 5 minute bursts over 30 minute 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., Fig. 2c).

Observations of water properties were collected at 6 different stations listed in Table 1. Water samples were collected using a rosette with 5 L Niskin bottles (attached to a conductivity, temperature and depth (CTD) sensor) and analyzed for SSC as well as other properties including salinity, and concentration of dissolved oxygen and carbon dioxide and chlorophyll. The bottles collected samples at depths of 1 m, 5 m, and 15 m below the water surface and near-bottom (within 1–2 m) hourly over a 12 hour period at each station. The samples were filtered onto Millipore 8.0 μm filters, selected for their small nominal pore sizes and excellent trapping efficiency (Sheldon et al., 1972). A benthic organic bottom (BOB) sampler was deployed at similar times and made measurements at 0.15 m and 0.35 m above the bottom. In total, 60 SSC observations were collected over 9 consecutive tidal cycles at times shown in Fig. 2e. Water column measurements of SSC have similar values to previous field studies in the Bay of Fundy (Amos and Alfoldi, 1979), with values ranging from 0.2 to 30.4 mg L^{-1} (average of 6.6 mg L^{-1}) outside Minas Basin, and from 4.0 to 287.0 mg L^{-1} inside Minas Basin (average of 21.2 mg L^{-1}). 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 voltages observed with the OBS and a co-located McLane water transfer system capable of collecting sediments using in-situ filters. The initial weight of the filter was subtracted from the final weight of the dried (60 °C) and filtered materials to yield the mass and concentration of sediment in the sample. The sediment mass divided by the total volume of water filtered allowed for calculation of SSC (Fig. 2f) at site S3-A, ranging from 3 to 6 mg L^{-1}.

Particle sizes were measured from 32 samples collected over a 2-day period (June 8–9) at S3-A, according to the methods of analysis described by Kranck and Milligan (1991). The disaggregated inorganic grain size (DIGS) of the sediment suspended was determined using a Coulter Counter Multisizer 3. For DIGS analysis samples were placed in a low temperature (60 °C) oxygen/plasma asher to remove the filter and organic matter and to prevent the fusing together of mineral grains.