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Competent *vs.* Observed Grain Size on the Seabed of the Gulf of Maine and Bay of Fundy

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ABSTRACT

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The output of a three-dimensional tidal circulation model and nearly 10,000 sediment samples are used to compare observed and competent grain sizes on the floor of the Gulf of Maine and Bay of Fundy. Competent grain size is the largest grain size a flow is capable of mobilizing. Competent and observed grain sizes have similar broad spatial distributions. Coarser observed grain sizes are found in regions of larger stress, and associated coarser competent grain sizes and finer observed sizes are found in regions with finer competent sizes. Areas in which competent sizes are finer than observed sizes likely have significant sources of seabed stress that are not included in the model, specifically from waves and subtidal flows. Areas in which competent sizes are coarser than observed sizes likely are regions where sediment input into the region overwhelms the ability of near-bed flows to transport sediment away from the region, leaving the seabed with a texture similar to that of the supply. The results indicate that sediment texture is unlikely to change greatly if large-scale tidal power development is pursued in Minas Passage, which connects the Minas Basin to the Outer Bay of Fundy. Forecast changes of sediment texture in the Gulf of Maine are small, and in the Bay of Fundy, sediment texture is unlikely to change because it is dominated by sediment supply, which should not be affected by tidal power development.

ADDITIONAL INDEX WORDS: *Sediment texture, tides, tidal power, cliff erosion*.

INTRODUCTION

The Gulf of Maine and Bay of Fundy on the east coast of North America (Figure 1) together form an embayment with a natural period that is nearly resonant with M2 tides (Garrett, 1972). Resonance, combined with the funnel shape of the Bay, produces large tidal ranges and associated strong tidal currents, making the region an attractive target for the development of tidal power generation. The push to develop tidal power is accompanied by efforts to evaluate the environmental effects of large-scale extraction of energy. This research is motivated by interest in whether tidal power generation will affect grain size on the seabed in the Gulf of Maine and Bay of Fundy.

The Gulf of Maine comprises three deep basins that are separated from the North Atlantic Ocean by Georges and Browns Banks (Figure 1). Wilkinson Basin occupies the southwestern portion of the Gulf, Jordan Basin lies in the northeastern part of the Gulf, and Georges Basin is in the southeastern part of the Gulf, just inside of Georges Bank. Connection to the deep Atlantic is through the Northeast Channel. The Bay of Fundy extends to the northeast of the Gulf of Maine (Figure 1). The head of the Bay, alternatively known as the Inner Bay of Fundy (Parker, Westhead, and Service, 2007), comprises two sub-basins. Chignecto Bay lies to the north and west, and the Minas Basin lies to the south and east.

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The Minas Channel and Minas Passage connect the Minas Basin to the Outer Bay of Fundy. Twice each day, 15 billion m^3 of water surge into and out of the Minas Basin (Parker, Westhead, and Service, 2007). The flow of this large volume of water through the relatively narrow and shallow Minas Passage produces observed maximum surface current speeds of more than 5 m s^{-1}, and maximum bottom currents are as high as 1.5 m s^{-1} (Oceans Ltd., 2009). These strong and regular tidal currents have the potential to deliver up to 2.5 GW of electrical power without significant changes to tidal amplitudes in the region (Karsten *et al*., 2008).

Hasegawa *et al*. (2011) used a model to show that extraction of tidal energy from the Minas Passage would have an effect on tidal circulation in the whole Bay of Fundy and Gulf of Maine system. Because seabed sediment texture has been shown in other tidal environments to correlate with bed shear stress (Signell, List, and Farris, 2000; Uncles, 1983; Ward *et al*., 2015), tidal power generation may have an effect on sediment texture in the system. Changes in sediment texture would be of ecological and economic importance because sediment texture affects the suitability of the seabed for spawning, shelter, and food acquisition for economically important species (*e.g*., Methratta and Link, 2006).

Two basic modeling approaches predict the effect of tidal power on sediment texture. The first one, which has been developed most fully for gravel-bed rivers (Buffington and Montgomery, 1999), makes use of the concept of competent grain size. The competent grain size is the largest particle size that a flow is capable of mobilizing. In the absence of sediment supply to a sediment bed, the surface grain size approaches the competent grain size (Buffington and Montgomery, 1999;

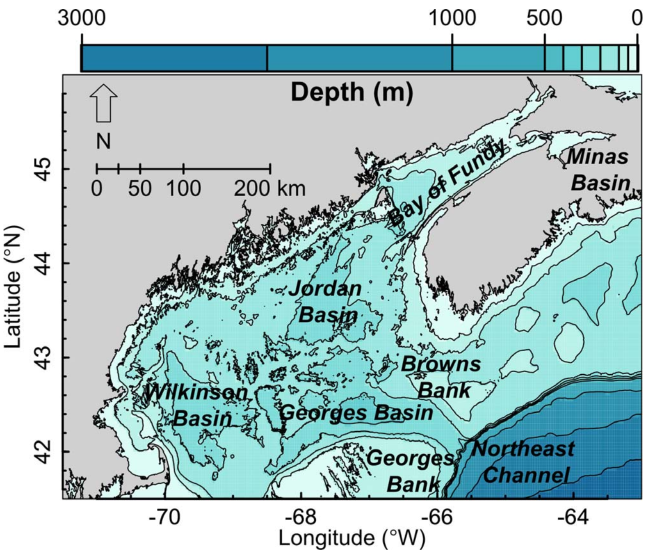

Figure 1. Map of the Gulf of Maine and Bay of Fundy region. Isobaths are drawn at 50, 100, 200, 300, 400, 500, 1000, 2000, and 3000 m. (Color for this figure is available in the online version of this paper.)

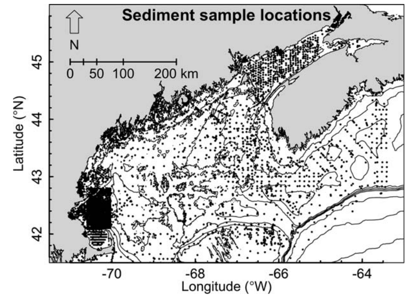

Figure 2. Compiled database sample locations in the Gulf of Maine and Bay of Fundy. (Color for this figure is available in the online version of this paper.)

Parker, Hassan, and Wilcock, 2008). To illustrate, consider emplacement of a mixed grain size bed that is subsequently exposed to flowing water. Initially, the flow will resuspend and transport the sediment sizes that it is competent to mobilize. Without resupply, these grain sizes are eventually depleted, and the resulting sediment bed is composed of grain sizes that the flow is not competent to mobilize. When it reaches this condition, the bed is in hydrodynamic equilibrium with the overlying flow, and the grains that compose the sediment bed form a static armor that shields the substrate below from further removal of finer sediment grains. Faster flows produce beds with surface grain sizes that are larger than beds formed under slower flows (Pitlick *et al*., 2008). According to this simple hydrodynamic equilibrium model, one can use flow competence to predict a change in grain size that would result from a change in flow. This represents a simpler approach than a second approach to modeling sediment texture, which is a coupled hydrodynamic and sediment transport model that tracks the evolution of the seabed (*e.g.,* Blaas *et al*., 2007; Warner, Butman, and Dalyander, 2008).

On wave-dominated continental shelves, the concept that equilibrium exists between near-bed stress and sediment texture has been applied successfully to prediction of the depth of the sand-mud transition (Dunbar and Barrett, 2005; George and Hill, 2008). Observed grain sizes on the seabed also have been shown to vary with modeled seabed stresses in tidally dominated environments (Uncles, 1983; Ward *et al*., 2015) The match between competent and observed grain size that would emerge under equilibrium has been posited for the Bay of Fundy and Gulf of Maine region on qualitative grounds (Amos, 1978; Emery and Uchupi, 1972), but such a relationship has not been evaluated quantitatively. The primary goal of this paper is to examine whether there is evidence of equilibrium between near-bed tidal flow and sediment texture in the Bay of Fundy and Gulf of Maine region. The secondary goal of this paper is to use the match or mismatch between competent and observed grain size to assess the potential effect on sediment texture of large-scale tidal power development in the Bay of Fundy.

METHODS

Maps of observed grain sizes are generated with archived sediment texture data, and the output of a three-dimensional (3D) model of tidal currents is used to map associated competent grain sizes. Use of modeled stress, as opposed to point measurements of near-bed stress, enables the type of spatially extensive comparison of competent and observed grain size that is required to assess the potential large-scale effects of tidal power extraction on sediment texture.

Sediment Data

Sediment textural data were acquired from two databases and one data set that together provide 9357 spatially distributed estimates of sediment size in the Bay of Fundy and Gulf of Maine region (Figure 2). The first database used was the usSEABED database of the U.S. Geological Survey. In this database, 7116 samples reported mean sediment size and standard deviation within the study region. The second database used was the Expedition database of the Geological Survey of Canada with a total of 2118 samples in the study region. Sediment samples compiled in the databases were collected over six decades, from 1950 to 2010, using a variety of techniques, including both grab and core samples. The data set used comes from the Bedford Institute of Oceanography (Tim Milligan, *personal communication*). The 123 samples of this data set were collected throughout the Bay of Fundy in the years 1977 and 1994.

For a given sample in the dataset, generally available variables are gravel, sand, silt, and clay content (%) and the mean, standard deviation, kurtosis, and skewness of the grain size distribution. The parameter chosen for comparison between competent and observed grain sizes is the mean grain size. Mean grain sizes are expressed in ϕ units, which are related to grain diameter D (mm) according to the relationship: $\phi = -\log_2(D/D_0)$, where the reference diameter $D_0 = 1$ mm. The estimated one standard deviation (1σ) uncertainty in the usSEABED database is 0.8ϕ (Reid *et al*., 2005), which is assumed to be representative of the entire collection of data.

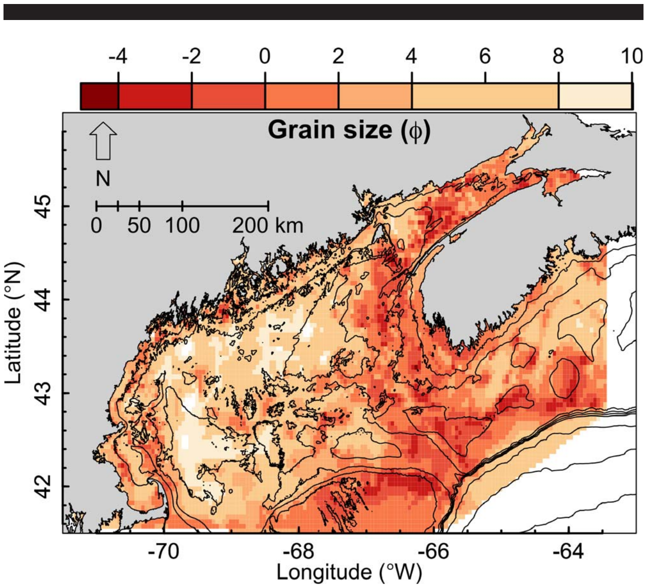

Figure 3. Map of observed mean grain size (ϕ units) in the Gulf of Maine and Bay of Fundy. The observations were interpolated with bilinear interpolation on a grid with 0.05° node spacing. Mean grain sizes tend to be coarser (lower ϕ) on banks and in the Bay of Fundy and finer in the basins of the Gulf of Maine. (Color for this figure is available in the online version of this paper.)

Ocean Circulation Model

An ocean circulation numerical model was developed by Hasegawa *et al.* (2011) to simulate the tidal elevations and circulation of the Bay of Fundy and Gulf of Maine area. The model is based on the Princeton Ocean Model (POM). Its main characteristics are that it is 3D and uses sigma coordinates in the vertical. Sigma coordinates are terrain-following coordinates widely used in coastal models and are defined as $\sigma = (z - \eta)/(H + \eta)$, where z is a specified depth within the water column (negative), η is the sea surface elevation, and H is the water depth (all in meters). In the model, the water column is divided into 31 equal σ levels. An advantage of this coordinate system is the higher vertical resolution in shallower regions of a domain.

The model comprises child and parent submodels that exchange information through a two-way nested-grid technique. The child submodel's domain covers the Bay of Fundy with a horizontal resolution of ~1.5 km, whereas the parent submodel's domain covers the Gulf of Maine with a resolution of ~4.5 km. In the study of Hasegawa *et al.* (2011), these different resolutions were chosen because tidal energy extraction scenarios take place in the Bay of Fundy. Water density and salinity are assumed constant throughout the domain, so the modeled ocean circulation is barotropic. The model is forced at the parent submodel open boundary by sea surface elevations and depth-mean current velocities of five tidal constituents: M_2, N_2, S_2, K_1, and O_1. The model's equations are discretized on an Arakawa C-grid and solved with an external-internal–mode time-splitting technique for separate integrations of the depth-mean equations (external mode) and vertical structure equations (internal mode). See Hasegawa *et al.* (2011) for details.

Hasegawa *et al.* (2011) validated the model with observations made at 10 tide stations within the Bay of Fundy and Gulf of Maine region. A comparison of the M_2 tidal constituent values of amplitude and phase between the 10 tide stations, the WebTide tidal prediction model, and the model of Hasegawa *et al.* (2011) show that average relative errors in the Hasegawa amplitude (ε_A) and phase (ε_φ) are similar to those of WebTide, which is the main tidal prediction model used by Fisheries and Oceans Canada. The model was also validated with acoustic Doppler current profiler measurements at three locations in the Minas Passage. Observed and modeled data are in good agreement (Hasegawa *et al.* 2011).

Bed Shear Stress Parameterization

Bed shear stress in the model developed by Hasegawa *et al.* (2011) is calculated using the quadratic drag law (Mellor, 2004),

$$\tau_0(x, y, t) = \rho C_D U^2 \tag{1}$$

where x, y, and t are horizontal coordinates and time, respectively; ρ is the seawater density; C_D is the drag coefficient; and U is the instantaneous near-bed current speed. In the quadratic drag law, C_D is calculated as follows: $C_D = \max[\kappa^2/\ln^2(z/z_0),\ 2.5 \times 10^{-3}]$, where "max" is the maximum value among enclosed quantities, κ is the Von Karman constant ($\kappa \approx 0.4$), z is the (positive) vertical coordinate (from the seabed) at which the near-bed current velocity is modeled, and z_0 is the roughness parameter. The value of z varies throughout the model domain and is taken at middepth of the σ level closest to the seabed in the vertical. The remainder of the parameters necessary for the calculation of τ_0 are given the following values: $\rho = 1024$ kg m^{-3} and $z_0 = 0.01$ m. This value of z_0 is the default value in the POM.

Critical Erosion Shear Stress Model

The model of Wiberg and Smith (1987) was used to calculate critical erosion shear stress (τ_c) as a function of grain size. In the calculations, the bed was assumed to be flat. Grain angle of repose was set at 60°, as proposed by Wiberg and Smith (1987) for the type of rough beds typically found in the energetic Gulf of Maine and Bay of Fundy. Sediment density was assumed to 2650 kg m^{-3}, representative of quartz, and sediment grains were assumed to be spheres.

Interpolation

Bilinear interpolation was chosen for interpolation of data in this paper. Bilinear interpolation's main assumption is that a variable's rate of change is linear between data locations. Bilinear interpolation is often used for estimation with gridded data (Glover, Jenkins, and Doney, 2011).

RESULTS

Areas of coarser and finer mean grain sizes (Figure 3) generally correspond to areas of larger and smaller maximum tidal bed shear stresses (Figure 4), respectively. Coarser mean grain sizes ($< 2\phi$) are found on the banks that define the eastern margin of the gulf and along a broad swath of the seabed extending from the banks into the Bay of Fundy (Figures 1 and 3). These regions experience relatively large maximum tidal shear stresses (>1 Pa, Figure 4). Coarser mean

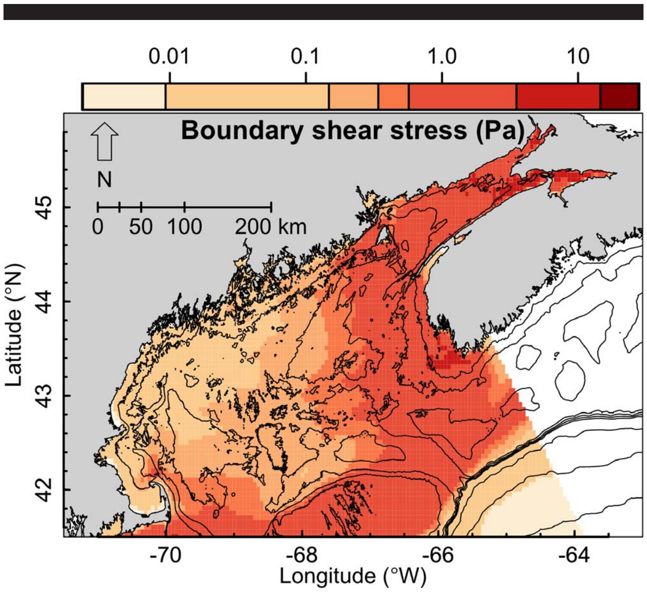

Figure 4. Map of maximum modeled tidal bed shear stress (Pa) for the Gulf of Maine and Bay of Fundy for the simulation ~30-d period. The color bar is arranged to display the critical erosion shear stress boundaries calculated for the grain size boundaries used in Figure 3, so it essentially is a map of competent grain sizes. Stresses generally are higher on banks and in the Bay of Fundy, and they are lower in basins. (Color for this figure is available in the online version of this paper.)

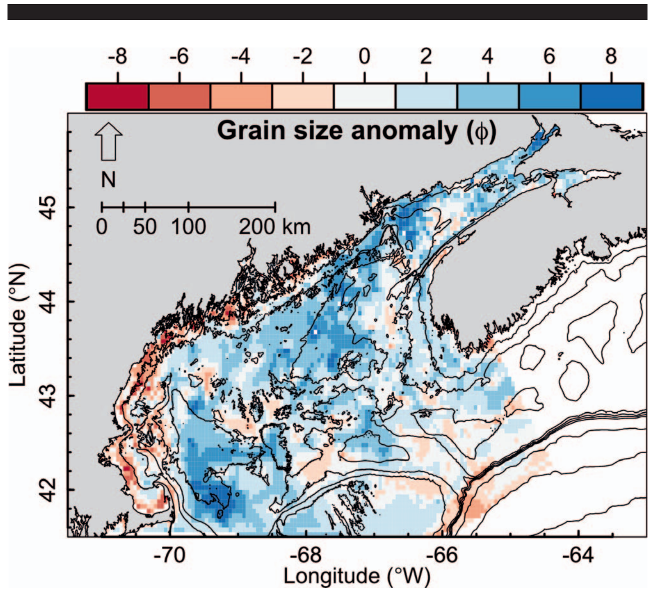

Figure 5. Map of grain size anomaly for the Gulf of Maine and Bay of Fundy. Positive anomalies indicates that observed grain sizes are finer than competent grain sizes, and negative grain size anomalies indicate that observed grain sizes are coarser than competent grain sizes. Regions of largest positive anomalies are the basins of the Gulf of Maine, an area on the northwestern margin of the Bay of Fundy where it meets the Gulf of Maine, and in the Inner Bay of Fundy. Regions of largest negative anomalies are the shallow areas on the southwestern margin of the Gulf of Maine and the Northeast Channel.

grain sizes also are found in shallower areas on the western margin of the gulf, particularly on Stellwagen Bank, which lies to the west of Wilkinson Basin (Figure 1). The basins of the Gulf of Maine are characterized by finer mean grain sizes and lower maximum tidal shear stresses (Figures 1, 3, and 4).

A map of the mean grain size anomaly, defined as the observed minus competent grain size, reveals that the smallest anomalies generally are found on the banks and extend into the middle part of the Bay of Fundy (Figure 5). The largest positive anomalies, which indicate that observed mean grain sizes are finer than competent grain sizes, appear in three regions (Figures 1 and 5): the deep basins of the Gulf of Maine, a triangular area of seafloor on the northwestern margin of the Bay of Fundy where it meets the Gulf of Maine, and the Inner Bay of Fundy. Observed grain sizes are coarser than the predicted competent grain sizes in the shallow areas on the western boundary of the Gulf of Maine and along the southern boundary and mouth of the Northeast Channel (Figures 1 and 5).

Under the assumption that grain sizes observed on the seabed are in hydrodynamic equilibrium with tidal stresses, the predicted effect of tidal power development can be explored by examining changes in competent diameters. Effect is defined as the difference between competent mean sizes in the absence and presence of simulated tidal power extraction. The tidal power scenarios of Hasegawa *et al*. (2011) extract tidal flow (kinetic) energy from the Minas Passage. The scenario adopted here extracts 2.0 GW of power from flow within 20 m of the seabed. Production of 2.0 GW of power with 1 MW per turbine, which is typical of turbines with 20-m diameters, would represent a large-scale installation of 2000 turbines in the Bay of Fundy. Predicted effects on sediment texture of this simulated extraction scenario occur in the Bay of Fundy, where competent diameters decrease because of reduced maximum tidal stresses, and between 42° and 43° N latitude and 67° and 71° W longitude, where competent diameters increase because of increased maximum tidal stresses (Figure 6). Maximum predicted changes in size are up to 2ϕ units, but throughout both of these regions, predicted decreases or increases in competent diameters generally fall within –0.5ϕ to 0.5ϕ.

DISCUSSION

In general, spatial distribution of grain sizes in the Gulf of Maine and Bay of Fundy is similar to the distribution of stresses, but large areas of disagreement exist. Observed grain sizes are finer than competent grain sizes in the deep basins of the Gulf of Maine, on the northwestern margin of the Bay of Fundy where it joins the Gulf of Maine, and in the Inner Bay of Fundy. Observed grains sizes are coarser than competent grain sizes in the shallow areas on the western margin of the Gulf of Maine and in the vicinity of the Northeast Channel. Mismatch arises from a variety of possible sources. Either measured grain sizes, modeled stresses, or the assumptions of the equilibrium model are in error.

Errors in Sediment Grain Size

Reid *et al*. (2005) cautioned that sediment textural data compiled from a variety of sources using different methodolo-

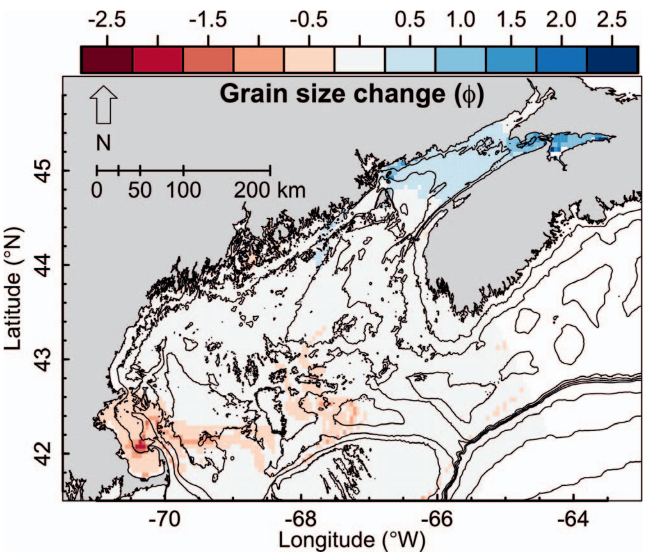

Figure 6. Map of effect (Δϕ) on competent mean grain size for 2.0-GW tidal power development scenarios in the Gulf of Maine and Bay of Fundy. Effect is defined as the difference between present-day and affected competent grain sizes. Positive values mean a fining of sediments, whereas negative values indicate a coarsening of sediments. Sediment fining is localized in the Bay of Fundy, and coarsening is predicted to occur in an area between 42° and 43° N latitude and 67° to 71° W longitude. Generally, predicted effects are less than 0.5ϕ, and maximum effects are less than 2ϕ.

gies over a long period of time, as in this study, have inherent uncertainties that are difficult to quantify. For example, some size analyses would have excluded coarse fractions such as shell fragments and gravel. Other textural descriptions of sediment would have emphasized certain size fractions of particular interest while de-emphasizing or disregarding other components. Some sediment samples would have come from the sediment surface, and others would have been unquantified admixtures of surficial and deeper sediments. These sorts of unquantifiable uncertainties are assumed to introduce random variability into the sediment textural data, rather than producing any systematic and spurious spatial trends in the data. As long as the uncertainties are smaller than the magnitude of spatial variations that are being analyzed, the uncertainties should not lead to spurious interpretations. Reid *et al*. (2005) indicate that the 1σ uncertainty in estimates of mean grain size is 0.8ϕ in the usSEABED database. This level of uncertainty is significantly smaller that the >12ϕ range of variation in observed grain sizes. Therefore, the unquantified uncertainty in grain size is not a likely source of mismatch between observed and competent grain sizes.

Errors in Modeled Stress

Inaccurate modeled stresses can produce a mismatch between observed and competent grain sizes. Actual stresses may be larger than modeled stresses because the model run is only 30 days, and the model does not consider the effects of waves, baroclinic flows, or subtidal currents on seabed stresses.

A model run of 30 days was chosen to be long enough to capture a full spring-neap cycle. The maximum tidal stresses, therefore, are representative of typical spring tides. Ward *et al*. (2015) observed that maximum stress, defined is this way, is a useful predictor of seabed sediment texture. Monthly maximum stresses are not representative of maximum stresses associated with the largest tides that recur at much longer periods. The implicit assumption of the approach here is that seabed sediment grain size is determined by typical monthly maximums in stress. If maximum stresses that occur less frequently determine competent grain sizes, then observed grains sizes would be larger than competent grain sizes calculated from monthly maximum stresses. If, on the other hand, mean rather than maximum shear stresses determine competent grain sizes, then the stresses used to determine competent grain sizes are overestimates. Of these two possibilities, the latter is more likely, given that more of the seabed is characterized by observed grain diameters that are finer than the competent grain diameters (Figure 5).

Wave-generated bed shear stresses can resuspend sediments and facilitate subsequent transport by near-bed tidal currents. These can also enhance bed shear stress when occurring at the same time as current-induced bed shear stress (Grant and Madsen, 1979). In the Gulf of Maine, Butman *et al*. (2014) proposed that tidal flows dominate but that wave resuspension occurs at depths shallower than 100 m. Similarly, Li *et al*. (2015) noted that in the Bay of Fundy, wave-generated bed shear stresses play a minor role in the distribution of sediments, except in shallow coastal areas. Shallow regions in the western Gulf of Maine are areas that would be exposed to wave-induced seabed stresses, providing a good explanation for why observed grain sizes are coarser than the modeled competent grain sizes in these areas.

Baroclinic flows represent another source of bed shear stress that could cause estimated stresses and associated competent diameters to be in error. In a baroclinic fluid, lines of constant pressure cross lines of constant density. Baroclinically generated bed shear stresses have not been investigated in this paper. Signell, List, and Farris (2000) found that in Long Island Sound (northeastern United States), simulated baroclinically driven speeds 1 m above the seabed could reach 6–8 cm s^{-1} but that they played a minor role in the distribution of sediments. In the Gulf of Maine, Xue, Chai, and Pettigrew (2000) forced an ocean circulation model with monthly climatological wind and heat flux to find that monthly averaged velocities at a depth of 100 m were generally < 20 cm s^{-1}. The highest values were found offshore the coast of Maine. This is a region where modeled maximum tidal speeds 1 m above the seabed in the present study are lowest and grain size anomalies are negative. These results suggest that baroclinic flows may play a role in creating stress on the seabed in the western Gulf of Maine that makes observed grain sizes coarser than the modeled competent grain sizes.

In the Bay of Fundy, Aretxabaleta *et al*. (2008) modeled depth-averaged baroclinic current speeds of ~5 cm s^{-1} near its connection with the Gulf of Maine for the months of May and June. Generally, modeled maximum tidal speeds 1 m above the seabed in the present study are <10 cm s^{-1} for that region (Gelati, 2012), and overall observed grain sizes are finer than predicted in that region. Well-mixed waters also characterize most of the Bay of Fundy for times of the year (July and August) when thermal stratification would be expected to occur (Garrett, Keeley, and Greenberg, 1978). Well-mixed waters, the small magnitude of baroclinic flows, and the positive grain size anomaly indicate that lack of inclusion of baroclinic flow in the Bay of Fundy is unlikely to produce a mismatch between observed and modeled competent grain sizes.

Flows with subtidal frequencies are not represented in the hydrodynamic model. As with waves and baroclinic flows, subtidal flows are generally of lesser importance than tidally driven flows in the Gulf of Maine and Bay of Fundy, but locally they can be important. The Northeast Channel is a region where subtidal flows have been shown to be relatively strong (Ramp, Schlitz, and Wright, 1985). This area also is characterized by observed grain sizes that are larger than competent grain sizes (Figures 5), indicating a likely influence of subtidal flows on grain size in the Northeast Channel.

Lack of a variable model of roughness is another source of error in modeled stresses and associated competent diameters. The circulation model used in this study has a constant value of roughness length, $z_0 = 0.01$ m, which is more suited to flow over coarse-grained seabeds. Over fine-grained beds, the roughness parameter may be smaller than 0.01 m, which would cause modeled stresses and associated competent diameters to be overestimated (Wu *et al*., 2011). This explanation for mismatch between observed and competent diameters may help to explain why observed grain sizes are finer than modeled competent grain sizes in the basins of the Gulf of Maine and along the northwestern margin of the Bay of Fundy, where it joins the Gulf of Maine. Silts and clays ($\phi > 4$) cover the seabed in these regions, making it likely that the roughness length and stress in the model are overestimates. This explanation does not apply to the Inner Bay of Fundy, where grain sizes on the seabed are coarser.

Fader, King, and MacLean (1977) noted that fine sediments are overconsolidated in the seabed on the northwestern margin of the Bay of Fundy where it meets the Gulf of Maine. Overconsolidated fine sediments also may occur in the Gulf of Maine basins where silts and clays are found. The τ_c model of Wiberg and Smith (1987) does not account for this consolidation of sediments and would underestimate the value of τ_c. Underestimates of the critical shear stress would cause overestimates of competent diameters in these regions, which helps to explain the positive grain size anomalies in the basins and at the mouth of the Bay. This explanation does not help to explain the observed grain sizes that are finer than competent grain sizes in the Inner Bay of Fundy.

Use of maximal tidal stress rather than some other measure of stress may cause mismatch between observed and competent grain sizes. For example, if maximal stress during the 30-day model run is realized only for a brief period, then it might not be the determinant of sediment texture. Li *et al*. (2015) used the Sediment Mobility Index (SMI) to address this potential issue. The SMI equals the fraction of time that the critical erosion shear stress for a given grain size is exceeded multiplied by the average ratio of the boundary shear stress to the critical erosion shear stress for that grain size during those times that the critical erosion shear stress is exceeded. The SMI is a nondimensional index that incorporates both the magnitude and frequency of the sediment mobilization.

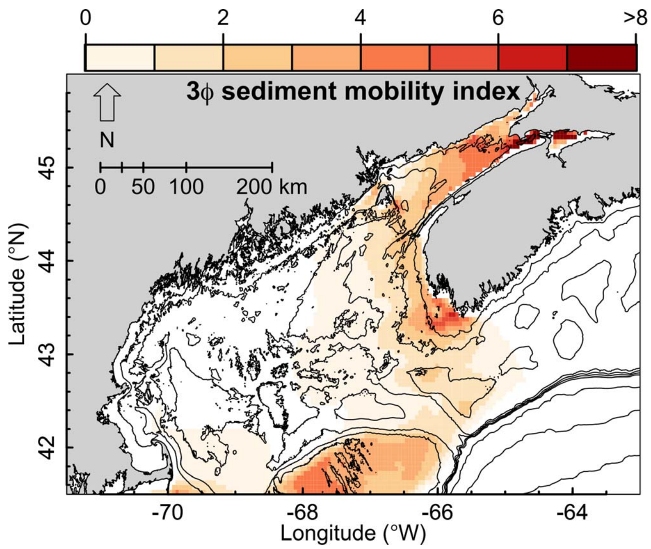

Figure 7. Map the sediment mobility index (SMI) for 3ϕ (125-μm) sand. The SMI is the average ratio of seabed stress to critical erosion shear stress during times when the critical erosion shear stress is exceeded, multiplied by the fraction of time that the critical erosion shear stress is exceeded. It is a measure of both the frequency and magnitude of sediment transport The 3ϕ SMI is generally large in regions of large shear stresses. An exception occurs on the northwestern margin of the Bay of Fundy where it joins the Gulf of Maine. In this region, maximum stresses are high, but SMIs are low. This discrepancy indicates that the modeled peak maximum shear stresses during spring tides were much greater than the typical semidiurnal maximum shear stresses during the 30-d model run. The SMI is very low or zero in the basins of the Gulf of Maine, indicating that the 3ϕ critical erosion shear stress is seldom or never exceeded in these regions during the 30-d model run. (Color for this figure is available in the online version of this paper.)

The SMI for 3ϕ sediment overall has a spatial distribution similar to the shear stress. It is high on the banks and in the Bay of Fundy and low in the basins (Figure 7). Interestingly, however, the region of finer-than-predicted grain sizes where the Bay of Fundy meets the Gulf of Maine (Figure 5) is a region of relatively high maximum stress, but the 3ϕ SMI is low (Figure 7). The low SMI indicates that maximum stress in this region may be too large for calculation of a competent diameter.

Effects of Sediment Supply on Grain Size

Violation of the assumptions underlying the competent grain size model can account for differences between observed and competent grain sizes. The simplest form of hydrodynamic equilibrium between bed shear stresses and surficial grain sizes assumes that a wide range of sizes are available in the original sediment bed, that sediment supply to the seabed is small, and that, for oscillating tidal flows, a residual near-bed current is present to carry away resuspended particles. If there is no residual tidal near-bed flow, resuspended sediments will deposit near their original location of resuspension.

One might expect *a priori* that in the Gulf of Maine and Bay of Fundy, conditions are right for good agreement between observed and competent grain sizes. First, a variety of grain sizes are present. Second, residual currents are relatively large, especially in the Bay of Fundy (*e.g.*, Li *et al*., 2015). Third,

Table 1. *Annual rates of volumetric supply and removal of sediment from the Minas Basin, Bay of Fundy.*

	Annual Volume ($\times 10^6$ m^3 y^{-1})
Supply	
Coastal Erosion[a]	1.2
Excavation of Minas Channel and Minas Passage[b]	1.4
Removal	
Subtidal Sediment[c]	0.5
Intertidal Sediment[b]	1.5

[a] *Source: Wilson* et al. *(2016).*
[b] *Source: Shaw* et al. *(2012).*
[c] *Source: Amos and Joice (1977).*

fluvial sediment supply is limited (Amos and Long, 1980). Locally, rivers that supply fine and coarse material to the coasts of the Gulf of Maine and Bay of Fundy may influence sediment texture. Emery and Uchupi (1972) noted that along the western margin of the Gulf of Maine, the source of nearshore sands is mainly fluvial. Fader, King, and MacLean (1977) demonstrated that the Saint John River contributes a substantial amount of fines to the seabed along the northwestern margin of the Bay of Fundy where it meets the Gulf of Maine (Figure 3). Overall, however, fluvial sediment supply is small.

Despite small fluvial inputs of sediment, sediment supply may, in fact, be a source of disagreement between observed and competent grain sizes, particularly in the Inner Bay of Fundy, where other mechanisms fail to explain why observed grain sizes are finer than the competent grain sizes. Two nonfluvial but relatively large sources of sediment in the Bay of Fundy are coastal erosion and excavation of the seabed by strong tidal currents. Easily eroded sandstone cliffs fringe much of the Bay, and they act as a significant sediment source. Wilson *et al.* (2016) analyzed archived aerial photographs to estimate an annual rate of supply just to the Minas Basin of 1.2×10^6 m^3 y^{-1} (Table 1). The sediment delivered to the Basin by cliff erosion is predominantly sand, which is finer than the competent sizes (Wilson *et al.*, 2016). Another source of sediment in energetic tidal environments is excavation of the seabed (*e.g.*, Harris *et al.*, 1995). In regions of maximum stress, often at bathymetric constrictions, tidal currents scour the seabed, and the resulting sediment is delivered to the surrounding seabed by a combination of advective and diffusive processes. Declining stress with distance from the site of maximum stress produces characteristic progression of sediment cover on the seabed, from scoured bedrock, to actively transported bedload sands, to hydrodynamically sorted sands, to muddy sands in regions of low stress (*e.g.*, Harris *et al.*, 1995; Knebel *et al.*, 1999). Based on observations of seabed character and on a model, Li *et al.* (2015) and Shaw *et al.* (2012) argued that active scour in the Minas Channel and Minas Passage supplies large amounts of sediment to the Bay of Fundy, and this source of sediment forms relatively fine sands in energetic parts of the Bay. Shaw *et al.* (2012) estimated that 5×10^9 m^3 of sediment have been excavated from the Minas Channel and Minas Passage over the past 3500 years. Assuming a steady excavation rate, the annual production rate of sediment is 1.4×10^6 m^3 y^{-1} (Table 1). Shaw *et al.* (2012) proposed that much of this sediment is stored in intertidal marsh deposits in the Minas Basin.

When there is a supply of sediment to a flow and the supply is smaller than the competent grain size, sediment size at the bed surface is finer than the competent sediment size (Buffington and Montgomery, 1999; Dorrell, Hogg, and Pritchard, 2013; Parker, Hassan, and Wilcock, 2008). When there is a supply of sediment to a flow, surficial sediment grain size becomes finer than the competent size because flow capacity, in addition to flow competence, affects the texture at the surface of the sediment bed (Dorrell, Hogg, and Pritchard, 2013). Flow capacity is defined generally as the mass of particulate material that a flow can support.

In systems where the supply of sediment is greater than the flow capacity, net deposition occurs. In these systems, coarser grain sizes are removed preferentially because of their larger settling velocities and smaller erosion rates (Dorrell, Hogg, and Pritchard, 2013). Finer sizes are transported away preferentially. The extent of size fractionation depends on the amount by which the sediment supply exceeds the flow capacity. If sediment supply only slightly exceeds capacity, then only the coarsest sizes are transferred to the bed, and surficial sediment grain size is similar to the competent size. At the other extreme, if sediment supply is much larger than flow capacity, then virtually all of the supplied sediment is transferred to the seabed, and grain size distribution resembles the grain size of the sediment source. At intermediate sediment supply rates, the grain size of the surficial sediment lies between the competent grain size and the source grain size (Buffington and Montgomery, 1999; Dorrell, Hogg, and Pritchard, 2013; Parker, Hassan, and Wilcock, 2008).

Given this simple conceptual model, it is possible to assess whether sediment supply and flow capacity, rather than flow competence, determine sediment grain size in the Inner Bay of Fundy. Focusing on the Minas Basin, where sediment budgets have been constructed previously, it is apparent that sediment is supplied faster than it is removed. Amos and Joice (1977) estimated that a minimum of 3.0×10^9 m^3 of sediment has accumulated in the subtidal portions of the Minas Basin over the past 6300 years. Assuming that accumulation rate has been constant over that period, annual volumetric accumulation is 0.5×10^6 m^3 y^{-1} (Table 1). Another repository for sediment in the Minas Basin is intertidal marsh deposits. Shaw *et al.* (2012) proposed that intertidal areas have accumulated sediment at a rate adequate to keep up with sea level since their formation 3500 years ago. Sea-level rise over this period is 9 m, and marsh area is 5.9×10^8 m^2. Assuming that accumulation rate has been constant over that period, annual volumetric accumulation rate in intertidal deposits is 1.5×10^6 m^3 y^{-1} (Table 1).

This sediment budget for the Minas Basin has net sediment sources totaling 2.6×10^6 m^3 and net sediment sinks of 2.0×10^6 m^3 (Table 1). Given the approximations and assumptions involved in deriving these numbers, they are similar and suggest that the Minas Basin is an effective sediment trap. The large supply of sediment that is not removed rapidly enough results in a net depositional system in which the grain size on the seabed is influenced by the grain size of the sediment source. Wilson *et al.* (2016) supported this interpretation by showing that cliff erosion introduced fine sands into the Minas Basin and that the floor of the Basin is covered, on average, with medium sands, which suggests winnowing and removal only of the finest fractions. Although the dynamics of the tidal circulation and sediment transport in the Bay of Fundy are clearly much more complex than the idealized model for grain size in a sediment bed presented by Dorrell, Hogg, and Pritchard (2013), the underlying concepts still apply. In short, as sediment supply increases relative to capacity in net depositional flows, grain size in the seabed evolves from the competent diameter at low supply to the grain size of the source material at high supply. This analysis provides a working hypothesis for why observed seabed grain sizes are finer than competent grain sizes in the Inner Bay of Fundy.

Sediment supply also offers an explanation for observed grain sizes that are smaller than competent grain sizes in the basins of the Gulf of Maine (Figure 5). Butman *et al.* (2014) used a model and sediment erodibility measurements to propose that there is no sediment resuspension in the basins. This hypothesis is supported by observations of cores from the Jordan Basin that show very high resolution, continuous records of sedimentation (Keigwin and Pilskaln, 2015). With no sediment remobilization, the size distribution on the seabed is the same as the source, which for these basins is silt and clay winnowed from sediments deposited in more energetic parts of the region.

The foregoing indicates that in the Gulf of Maine and Bay of the Fundy, sediment texture on the seabed is not determined solely by hydrodynamic stresses. It also depends on sediment supply. This means that future efforts to model sediment texture in the Bay of Fundy in particular will need to include supply from adjacent cliffs and from excavation of the seabed. Nonetheless, knowledge gained in this study can help to assess the predicted effects of potential tidal power development in the Bay of Fundy on sediment texture.

Effects of Tidal Power Extraction on Grain Size

For the Bay of Fundy, without further modeling that would include supply, it can be posited that the effect of tidal power development on seabed sediment texture will be small. Modeled decreases in current speed are relatively small in the Inner Bay of Fundy, producing modeled changes in competent diameter that are generally less than 0.5ϕ (Figure 6). Changes of this magnitude are much smaller the 2ϕ–4ϕ positive grain size anomalies observed in the Inner Bay of Fundy (Figure 5), indicating that the effect of sediment supply would continue to overwhelm the effect of hydrodynamic stress on seabed surficial grain size. The other location that shows the effect of tidal power extraction on competent grain size is on the southwestern margin of the Gulf of Maine, where tidal stresses are predicted to increase (Figure 6). Predicted increases in competent grain size, however, are relatively small, and they occur in a region where observed grain sizes exceed competent grain sizes by amounts that are much greater than the predicted change from tidal power extraction. Neglect of wave stresses in the model likely is responsible for the apparent underestimation of competent diameters in this region.

Tidal power extraction is unlikely to diminish the importance of sediment supply and waves for determination of grain size in regions where forecasted effects are largest. Forecasted decreases of tidal level of 0.5%–1.5% and localized decreases in tidal current speeds in the Bay of Fundy (Wu *et al.*, 2016) may diminish the intensity of erosive forces at the bases of cliffs, but cliff erosion is a complex process that depends on marine and terrestrial processes, many of which would not be affected by tidal power extraction. Tidal power extraction also could alter the rates and positions of excavation of the seabed, which also would alter supply to the Bay. Estimating changing supply from the highly nonlinear process of seabed excavation poses a significant challenge for existing models. Tidal power extraction also will not affect wave energy in the Gulf of Maine and Bay of Fundy. Therefore, in regions where the predicted effects of tidal power extraction are largest, key processes that affect grain size on the seabed are unlikely to be affected by power extraction. This observation leads to the hypothesis that tidal power extraction will not have a large effect on grain size in the Gulf of Maine and Bay of Fundy. It will be difficult to test this hypothesis before large-scale development of tidal power. Coupled hydrodynamic and sediment models with spatially resolved sediment sources could be used. Otherwise time series analysis of grain size from cores gathered in areas of predicted effect before and after tidal power development offers the only other approach to resolving the effect of tidal power development on grain size in the Gulf of Maine and Bay of Fundy.

CONCLUSIONS

The spatial distribution of competent grain sizes calculated from a hydrodynamic model of the tides in the Gulf of Maine and Bay of Fundy broadly matches the spatial distribution of observed seabed sediment grain sizes assembled from archived data. Coarser grain sizes are observed in regions of higher stress, and associated coarser competent diameters, on Georges Bank, on Browns Bank, and along a swath of seafloor extending into the Bay of Fundy. Finer grain sizes are found in regions of lower stress and finer competent grain sizes in the basins of the Gulf of Maine. These findings support the hypothesis that competent grain sizes based on modeled stresses are a useful tool for explaining or predicting grain size on the seabed (Ward *et al.*, 2015).

Despite broad similarities in spatial patterns of observed and competent grain sizes, large areas of mismatch exist, emphasizing the need for caution in applying the concept of an equilibrium competent grain size. In the shallow regions of the southwestern Gulf of Maine and in the vicinity of the Northeast Channel, observed grain sizes are larger than predicted based on tidal stresses. The likely cause of underprediction of competent grain size is failure to account for all of the sources of stress on the seabed. In shallow parts of the Gulf, wave stresses, which were not included in the model, increase stress on the seabed, and in the Northeast Channel, sub-tidal flows, also not included in the model, increase stress. In the basins of the Gulf of Maine and in the Inner Bay of Fundy, observed grain sizes are finer than predicted based on tidal stresses. The likely cause of overprediction of competent diameters is sediment supply that overwhelms the capacity of currents to transport it. As rate of supply increases, grain size in the sediment evolves from the competent grain diameter to the grain diameter of the source (Buffington and Montgomery, 1999; Dorrell, Hogg, and Pritchard, 2013; Parker, Hassan, and Wilcock, 2008).

Development of tidal power could affect sediment texture in the Bay of Fundy and Gulf of Maine, specifically, by causing decreases in grain size in the Inner Bay of Fundy and by causing increases in grain size along the southwestern margin of the Gulf of Maine. Results here indicate that the effect would be small. In the Inner Bay of Fundy, sediment supply likely determines sediment texture, and the processes that determine sediment supply likely would not be affected greatly by tidal power development. Predicted increases in sediment size in the southwestern Gulf of Maine are relatively small, and they occur in regions where grain size is underpredicted already because of neglect of wave stresses.

Future efforts to model sediment texture need to include the influence of sediment supply from adjacent cliffs and seabed scour zones in the Bay of Fundy. The accuracy of estimates of competent diameter could be improved by including other sources of bed shear stress in the calculation of maximum hydrodynamic conditions. Waves and baroclinic and subtidal flows have not been examined in this paper. It is generally accepted that waves have an influence on sediment texture in marginal, coastal areas in the Bay of Fundy and Gulf of Maine (Amos and Judge, 1991; Li *et al*., 2015). Inclusion of baroclinic flows also may improve predictions of stress (Li *et al*., 2015), more so in the Gulf of Maine than in the well-mixed Bay of Fundy. Subtidal flows are important in specific geographic regions, like the Northeast Channel. Inclusion of these other sources of bed stress likely will not affect predictions of sediment texture greatly, however, because of the overriding influence of sediment supply in the Bay of Fundy and the relatively small changes in shear stress caused by simulated tidal power development in the Gulf of Maine.

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LITERATURE CITED

Amos, C.L., 1978. The post glacial evolution of the Minas Basin, N.S.; a sedimentological interpretation. *Journal of Sedimentary Petrology,* 48(3), 965–982.

Amos, C.L. and Joice, G.H.E., 1977. The Sediment Budget of the Minas Basin, Bay of Fundy. *Geological Survey of Canada N.S. Data Series/B1-D-77-3*, 411p.

Amos, C.L. and Judge, J.T., 1991. Sediment transport on the eastern Canadian continental shelf. *Continental Shelf Research*, 11(8–10), 1037–1068.

Amos, C.L. and Long, B.F.N., 1980. The sedimentary character of the Minas Basin, Bay of Fundy. *In:* McCann, S.B. (ed.), *The Coastline of Canada*. Ottawa, Canada: Geological Survey of Canada, pp. 123–152.

Aretxabaleta, A.L.; McGillicudy, D.J., Jr.; Smith, K.W., and Lynch, D.R., 2008. Model simulations of the Bay of Fundy Gyre: 1. Climatological results. *Journal of Geophysical Research*, 113, C10027, doi: 10.1029/2007JC004480

Blaas, M.; Dong, C.; Marchesiello, P.; McWilliams, J.C., and Stolzenbach, K.C., 2007. Sediment transport modeling on Southern Californian shelves: A ROMS case study. *Continental Shelf Research*, 27(6), 832–853.

Buffington, J.M. and Montgomery, D.R., 1999. Effects of sediment supply on surface textures of gravel-bed rivers. *Water Resources Research*, 35(11), 3523–3530.

Butman, B.; Aretxabaleta, A.L.; Dickhudt, P.J.; Dalyander, P.S.; Sherwood, C.R.; Anderson, D.M.; Keafer, B.A., and Signell, R.P., 2014. Investigating the importance of sediment resuspension in *Alexandrium fundyense* cyst population dynamics in the Gulf of Maine. *Deep-Sea Research II*, 103, 79–95.

Dorrell, R.M.; Hogg, A.J., and Pritchard, D., 2013. Polydisperse suspensions: Erosion, deposition, and flow capacity. *Journal of Geophysical Research: Earth Surface,* 118(3), 1939–1955.

Dunbar, G.B. and Barrett, P.J., 2005. Estimating palaeobathymetry of wave-graded continental shelves from sediment texture. *Sedimentology,* 52(2), 253–269.

Emery, K.O. and Uchupi, E., 1972. Western North Atlantic Ocean: Topography, Rocks, Structure, Water, Life, and Sediments. *The American Association of Petroleum Geologists Memoir 17*, 532p.

Fader, G.B.; King, L.H., and MacLean, B., 1977. Surficial Geology of the Eastern Gulf of Maine and Bay of Fundy. *Geological Survey of Canada Paper 76-17*, 28p.

Garrett, C., 1972. Tidal resonance in the Bay of Fundy and Gulf of Maine. *Nature,* 238, 441–443.

Garrett, C.J.R.; Keeley, J.R., and Greenberg, D.A., 1978. Tidal mixing versus thermal stratification in the Bay of Fundy and Gulf of Maine. *Atmosphere-Ocean*, 16(4), 403–423.

Gelati, S., 2012. Modelling the Impact on Sediment Texture of Large-Scale Tidal Power in the Bay of Fundy. Halifax, Nova Scotia, Canada: Dalhousie University, Master's thesis, 72p.

George, D.A. and Hill, P.S., 2008. Wave climate, sediment supply and the depth of the sand-mud transition: A global survey. *Marine Geology,* 254(3–4), 121–128.

Glover, D.M.; Jenkins, W.J., and Doney, S.C., 2011. *Modeling Methods for Marine Science*. New York, Cambridge University Press, 588p.

Grant, W.D. and Madsen, O.S., 1979. Combined wave and current interaction with a rough bottom. *Journal of Geophysical Research*, 84(C4), 1797–1808.

Harris, P. T.; Pattiaratchi, C.B.; Collins, M.B., and Dalrymple, R.W., 1995. What is a bedload parting? *In:* Fleming, B.W. and Bartholomä, A. (eds.), *Tidal Signatures in Modern and Ancient Sediments*. Oxford, UK: Blackwell Science, pp. 3–18.

Hasegawa, D.; Sheng, J.; Greenberg, D.A., and Thompson, K.R., 2011. Far-field effects of tidal energy extraction in the Minas Passage on tidal circulation in the Bay of Fundy and Gulf of Maine using a nested-grid coastal circulation model. *Ocean Dynamics*, 61(11), 1845–1868.

Karsten, R.H.; MacMillan, J.M.; Lickley, M.J., and Haynes, R.D., 2008. Assessment of tidal current energy in the Minas Passage, Bay of Fundy. *Proceedings of the Institution of Mechanical Engineers Volume 222, Part A: Journal of Power and Energy* (London, United Kingdom) pp. 493–507.

Keigwin, L.D. and Pilskaln, C.H., 2015. Sediment flux and recent paleoclimate in Jordan Basin, Gulf of Maine. *Continental Shelf Research,* 96(2015), 45–55.

Knebel, H.J.; Signell, R.P.; Rendigs, R.R.; Poppe, L.J., and List, J.H., 1999. Seafloor environments in the Long Island Sound estuarine system. *Marine Geology,* 155(3–4), 277–318.

Li, M.Z.; Hannah, C.G.; Perrie, W.A.; Tang, C.C.L.; Prescott, R.H., and Greenberg, D.A., 2015. Modelling seabed shear stress, sediment mobility, and sediment transport in the Bay of Fundy. *Canadian Journal of Earth Sciences,* 52(9), 757–775.

Mellor, G.L., 2004. *Users Guide for a Three-Dimensional, Primitive Equation, Numerical Ocean Model*. Princeton, New Jersey: Princeton University, 56p.

Methratta, E.T. and Link, J.S., 2006. Associations between surficial sediments and groundfish distributions in the Gulf of Maine-Georges Bank region. *North American Journal of Fisheries Management*, 26(2), 473–489.

Oceans Ltd., 2009. Currents in Minas Basin. Halifax, NS, Canada: Oceans Ltd., *Fundy Tidal Energy Demonstration Project*, Volume 2, Appendix 5, 27p.

Parker, G.; Hassan, M.A., and Wilcock, P., 2008. Adjustment of the bed surface size distribution of gravel-bed rivers in response to cycled hydrographs. *In:* Habersack, H.; Piégay, H., and Rinaldi, M. (eds.), *Gravel-Bed Rivers VI: From Process Understanding to River Restoration*. Amsterdam, The Netherlands: Elsevier, pp. 241–289.

Parker, M.; Westhead, M., and Service, A., 2007. Ecosystem Overview Report for the Minas Basin Nova Scotia. *Fisheries and Oceans Canada, Oceans and Habitat Report 2007-05,* 179p.

Pitlick, J.; Meuller, E.R.; Segura, C.; Cress, R., and Torizzo, M., 2008. Relation between flow, surface-layer armoring and sediment transport in gravel-bed rivers. *Earth Surface Processes and Landforms,* 33(8), 1192–1209.

Ramp, S.R.; Schlitz, R.J., and Wright, W.R., 1985. The deep flow through the Northeast Channel, Gulf of Maine. *Journal of Physical Oceanography,* 15, 1790–1808.

Reid, J.M.; Reid, J.A.; Jenkins, C.J.; Hastings, M.E.; Williams, S.J., and Poppe, L.J., 2005. *usSEABED: Atlantic Coast Offshore Surficial Sediment Data Release*. Reston, Virginia: United States Geological Survey, *Data Series 118, 2005 Version 1.0*, 50p.

Shaw, J.; Todd, B.P.; Li, M.Z., and Wu, Y., 2012. Anatomy of the tidal scour system at Minas Passage, Bay of Fundy, Canada. *Marine Geology*, 323–325(1 September 2012), 123–134.

Signell, R.P.; List, J.H., and Farris, A.S., 2000. Bottom currents and sediment transport in Long Island Sound: A modelling study. *Journal of Coastal Research*, 16(3), 551–566.

Uncles, R.J., 1983. Modeling tidal stress circulation and mixing in the Bristol Channel as a prerequisite for ecosystem studies. *Canadian Journal of Fisheries and Aquatic Sciences,* 40(1), S8–S19.

Ward, S.L.; Neill, S.P.; Van Landeghem, K.J.J., and Scourse, J.D., 2015. Classifying seabed sediment type using simulated tidal-induced bed shear stress. *Marine Geology,* 367(1 September 2015), 94–104.

Warner, J.C.; Butman, B., and Dalyander, P.S., 2008. Storm-driven sediment transport in Massachusetts Bay. *Continental Shelf Research*, 28(2), 257–282.

Wiberg, P.L. and Smith, J.D., 1987. Calculations of the critical shear stress for motion of uniform and heterogeneous sediments. *Water Resources Research*, 23(8), 1471–1480.

Wilson, E.K.; Hill, P.S.; van Proosdij, D., and Ruhl, M., 2016. Coastal retreat rates and sediment input to the Minas Basin, Nova Scotia. *Canadian Journal of Earth Sciences*. doi: 10.1139/cjes-2016-0177

Wu, Y.; Chaffey, J.; Greenberg, D.A.; Colbo, K., and Smith, P.C., 2011. Tidally-induced sediment transport patterns in the upper Bay of Fundy: A numerical study. *Continental Shelf Research*, 31(19–20), 2041–2053.

Wu, Y.; Chaffey, J.; Greenberg, D.A., and Smith, P.C., 2016. Environmental impacts caused by tidal power extraction in the upper Bay of Fundy. *Atmosphere-Ocean,* 54(3), 326–336.

Xue, H.; Chai, F., and Pettigrew, N.R., 2000. Model study of the seasonal circulation in the Gulf of Maine. *Journal of Physical Oceanography*, 30(5), 1111–1135.