3-D Modelling and Assessment of Tidal Current Resources in the Bay of Fundy, Canada

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Abstract

The Bay of Fundy, located between the Canadian Provinces of Nova Scotia and New Brunswick, is home to the world's largest tides and has long been identified as one of the world's premier resources of tidal energy. This paper describes the development of a high-resolution three-dimensional hydrodynamic model of tidal flows in the Bay of Fundy, and its application to help quantify and assess the kinetic energy resource throughout the Bay. Information on the scale and character of the tidal currents and the associated kinetic energy resource is presented herein for three of the most energetic parts of the Bay: near Long Island, Passamaquoddy Bay and Minas Passage (where a $70 million pre-commercial deployment of in-stream turbines is presently underway).

Keywords: Bay of Fundy, Minas Passage, Passamaquoddy Bay, hydrodynamic modelling, resource assessment, tidal current, tidal energy, TELEMAC

1 Introduction

Significant strides are taking place in many countries towards creating machines and systems that are able to efficiently convert the kinetic energy of flowing water into more useful forms of energy, such as electricity, without the need for a dam or barrage. These devices extract energy from free flowing water much like windmills and wind turbines extract energy from air currents. Prototype systems are now being installed in the ocean to extract energy from tidal currents, and also in rivers to extract energy from river flows.

The Bay of Fundy (BoF), located between the Canadian Provinces of Nova Scotia and New Brunswick (see Figure 1), is home to the world's largest tides and has long been identified as one of the world's premier resources of tidal energy. The Fundy tides are semi-diurnal; twice each day roughly 115 billion tonnes of seawater flow in and out of the 255 km long Bay. The tidal amplitude near Burntcoat Head, located in Minas Basin, can exceed 8.4 m. The natural geometry and bathymetry of the BoF are the main factors responsible for producing the extraordinarily large tides. The BoF, together with Gulf of Maine, form a funnel with a natural period of approximately 13 hours, close to the 12.42 hour period of the M2 tidal forcing [[11]]. The large tides are a result of the near-resonant response of the BoF – Gulf of Maine system to the M2 tidal forcing.

Several researchers have studied and modelled tidal flows in the BoF over the years, but previous studies [[5]] have not focused on modelling the tidal currents in detail nor on quantifying the associated renewable kinetic energy resources throughout the region. Several studies [[13], [17]] have considered the changes in tidal hydrodynamics that would result from the construction of tidal barrages at various locations in the Bay. Because of the near-resonant state of the existing system, it has been shown that small changes in the geometry of the Bay, associated with the construction of a tidal barrage, could produce significant increases in tidal amplitudes as far away as Boston.

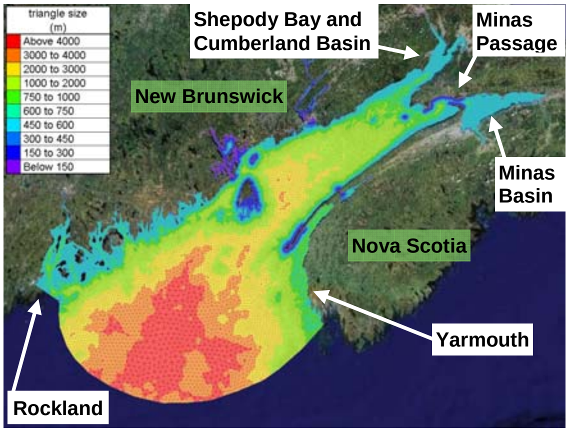

Figure 1: Extent and horizontal resolution of the 3D hydrodynamic model.

Cornett [[3]] analysed existing public data and identified 21 sites around the BoF where the flows might be suitable for energy recovery by in-stream devices. The total mean power was estimated at 2.7 GW. The site with the highest mean power density (17 kW/m^2) was Reversing Falls on the St. John River near St. John, NB. However, Minas Passage, a 5.5 km wide by ~10 km long by up to 160 m deep channel in the upper part of the Bay, was identified as the area with the greatest potential for large scale kinetic energy recovery. The mean power associated with the kinetic energy of the water flowing through the channel four times daily was estimated at 1.9 GW.

EPRI [[6], [7]] identified 14 promising sites for in-stream tidal power along the BoF shore, and estimated the kinetic power at each site, again leveraging existing public data and simple empirical approaches.

More recently, Karsten et al. [[15]] modelled and investigated the far-field changes in tidal amplitude due to energy recovery by large arrays of in-stream turbines deployed in Minas Channel, in the upper part of the Bay. Their simulations suggest that up to 7 GW of power can be removed from the tidal system, and of this amount, up to 2.5 GW of power can be recovered by in-stream turbines at Minas Passage. As discussed in [[1]], the additional power (beyond the kinetic energy) comes from the potential energy forcing the tidal flows. However, the associated impacts of such large scale power generation on hydrodynamic, sedimentary and biological processes are expected to be substantial and widespread [[12]].

This paper describes the development of a reasonably high-resolution 3-D hydrodynamic model of tidal flows in the BoF, and its application for the assessment of tidal current energy resources. The model was developed using Telemac-3D and BlueKenue software [[14], [16]] specifically to provide improved estimates of the kinetic energy resources throughout the Bay. It features higher resolution in areas where the kinetic power density is high, and lower resolution in areas where the currents are weaker. The new model was calibrated and validated against published water level and velocity data at several locations throughout the Bay; and was also verified against ADCP measurements in Minas Passage. Following successful calibration and verification, the model was employed to simulate three-dimensional tidal flows over a 15-day period containing average spring and neap tides. Results from this 15-day period can be considered to be representative of conditions during a full year. The results were subsequently analysed to provide estimates of the kinetic power density throughout the region, and to quantify various properties of the kinetic tidal energy resource. These simulation results provide a more detailed and more accurate picture of the scale and attributes of the tidal current energy resource throughout the Bay than was previously available.

This paper presents an overview of the methods employed in the study and a summary of the main findings. The scale and character of the hydrokinetic energy resource in several prominent locations is presented and discussed in detail. One of these locations is Minas Passage, where peak depth-averaged velocities routinely exceed 4 m/s. A $70 million pre-commercial deployment of three large in-stream turbines is presently underway in the northern part of Minas Passage [[10]].

2 Numerical Model Development

A three-dimensional model of tidal hydrodynamics in the Bay of Fundy has been developed and applied to simulate tidal flows throughout the Bay and quantify the associated kinetic energy resources. Simulations were conducted using the TELEMAC-3D solver, a part of the TELEMAC modelling system [[14]]. Most phenomena of importance in free-surface flows can be included in this model, such as the friction on the bed and lateral boundaries, wind stress on the free surface, Coriolis force, turbulence, and density effects. The dynamic wetting and drying of the tidal flats influences the tidal hydrodynamics in the upper part of the Bay, and these processes were included in the TELEMAC-3D simulations. TELEMAC-3D can also simulate three dimensional flows affected by stratification (thermal or saline), wind or wave breaking; however these capabilities were not applied in this study.

Using finite-element techniques, TELEMAC-3D solves the Navier-Stokes equations with a free surface boundary condition over an unstructured triangular mesh with multiple layers. The main advantage of this approach is that the density of the grid can be varied to suit the complexity of the shoreline, bathymetry or tidal flows. A fine mesh comprised of small triangles can be used to obtain an accurate representation of the shoreline and provide detailed high-resolution information in areas of special interest, while a coarser mesh comprised of larger triangular elements can be used away from the shore and in areas of lesser interest.

The model domain and the spatial variation of the mesh are shown in Figure 1. The domain extends 334 km from north to south and 454 km from east to west, and covers an area of 46,335 km^2. The domain includes the entire Bay of Fundy from Yarmouth (Canada) and Rockland (U.S.) near the offshore boundary, to Minas Basin, Cumberland Basin, Shepody Bay, Cobequid Bay and Passamaquoddy Bay. The domain was discretized into 209,000 triangular elements in the horizontal dimension, times 5 levels in the vertical. The horizontal element size decreases from over 4 km near the offshore boundary to less than 150 m near the shore and in areas where high-energy flows were expected. The vertical distance between levels varied throughout the domain from less than 0.1m in shallow areas to over 50m in the deepest parts of the Bay.

Bathymetry

The elevation of the seabed throughout the model domain was developed by merging the best and most recently available information from several sources:

- High-resolution bathymetric data collected over several years prior to 2007 by Natural Resources Canada using a multi-beam sonar and interpolated on a 100 m grid.
- Bathymetric contours and spot heights from nautical charts published by the Canadian Hydrographic Service.
- Various bathymetric data sets from the Massachusetts Geographic Information System.

Figure 2 shows a portion of the multi-beam bathymetry data for Minas Passage, while Figure 3 shows the bathymetry of the 3D hydrodynamic model.

Boundary Conditions

Time varying water levels were applied along the offshore boundary of the 3D hydrodynamic model.

These levels were derived from the 10 tidal constituents included with the WebTide Tidal Prediction System distributed by Fisheries and Oceans Canada. [[8]]

The flows from rivers discharging into the Bay are highly variable and small in comparison with the tidal flows, and were excluded from the simulations.

The bottom roughness was represented in the 3D hydrodynamic model with a Strickler friction coefficient. A coefficient of 40 was generally used throughout the model area, gradually decreasing to 20 to increase the roughness in shallower areas (water depth less than 3 m). These values are typical for natural channel conditions.

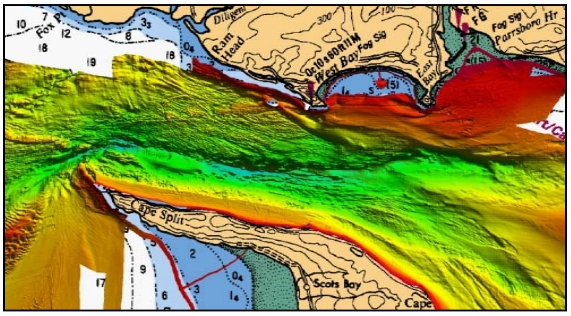

Figure 2: Minas Passage bathymetry (Multi-beam image).

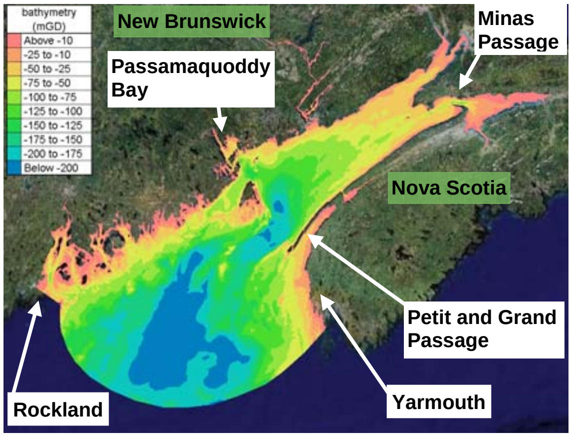

Figure 3: Bathymetry of the 3D hydrodynamic model.

3 Calibration and Validation

The hydrodynamic model was calibrated and validated before being applied to define kinetic energy resources throughout the Bay. Calibration was carried out using water levels over a 7-day period centered on an average spring tide, while validation was carried out using water levels for a different 7-day period centered on an average neap tide. This approach, as opposed to calibration against a single tidal cycle, enhances the accuracy of the calibration/validation exercise. The model predictions were also validated through comparison with velocity measurements at Minas Passage and several other sites.

Official water level predictions were available for seven stations throughout the model domain. The model predictions over the 7-day calibration period were compared with published tide elevations [[9]], and the bed friction throughout the model domain was adjusted to optimize the numerical simulation as much as possible. Following some iteration, the amplitude and phase of the tide wave was eventually well predicted throughout the domain. The small differences that remained were attributed in part to forcing the model with 10 (computed) tidal constituents, rather than the full tide signal.

The calibrated model was then used to predict the tides during the 7-day validation period. Based on the close agreement between the model predictions and the published data over this period, it was concluded that the model provides a good prediction of water level fluctuations throughout the Bay for both spring tides, neap tides and intermediary tides.

The predicted tidal currents were compared with several sets of velocity data, including data from a 28-day ADCP deployment in the northern part of Minas Passage. This comparison (shown in Figure 4) confirmed that the numerical model provides a good prediction of tidal currents (speed and direction) at this location in Minas Passage. Even the vertical velocity profile was modelled with good fidelity. Positive results such as this are important to enhance ones confidence in the numerical model predictions.

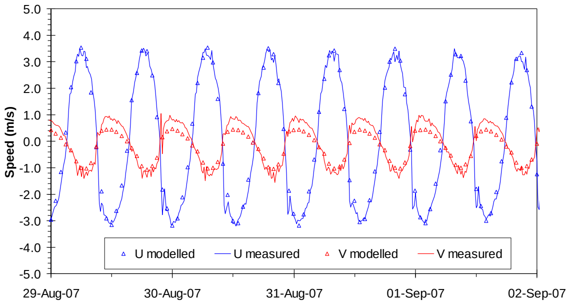

Figure 4: Predicted and measured velocities in the northern part of Minas Passage.

4 Assessment of Tidal Current Resources

Tidal currents vary rapidly with space and time. At most sites, the flow velocity approaches zero from two to four times per day, and reaches its peak annual value for only a few hours per year. The velocity fluctuation during each half cycle is roughly sinusoidal, but the peak speed varies from cycle to cycle as a consequence of the lunar and solar gravitational forcing. At most sites, the direction of flow also reverses between two and four times per day.

The kinetic power in a stream of water is proportional to the cube of the flow velocity. The instantaneous kinetic power density can be written as

$$p = 0.5\rho U^3$$

where ρ is the fluid density and U(t) is the instantaneous flow speed. Tidal current resources are best characterized by parameters such as the annual mean power density, $\overline{p}$, which represents an averaging of the temporal fluctuations over time [[4]]. The annual mean power density for a site is the average value of p(t) over the year. This mean power density characterizes the average intensity of the flow at the site; however, it is important to bear in mind that for a tidal flow, the speed and available energy will vary dramatically over time, and that energy extraction will not be feasible if/when the flows are too weak for efficient operation of an energy conversion device. Conversely, safe installation, operation and maintenance could also be difficult if/when the flows are excessively strong. The power recovered by an isolated in-stream turbine will typically be less than 50% of the kinetic power of the undisturbed flow.

The temporal variability of the flow speed and kinetic power density at a site are important attributes that must be considered during site selection. The temporal variation of the energy resource can be well represented as a probability distribution or frequency histogram. Another important resource attribute worth considering is the vertical distribution of the flow speed over the water depth. At many sites, the flow speed (and energy density) varies significantly with depth. Other important flow properties influencing the suitability of a particular site include turbulence intensity, vorticity, directionality and the presence of orbital velocities due to waves.

Following successful calibration and validation, the hydrodynamic model was applied to simulate tidal flows for a single 15-day period including both an average spring and an average neap tide. The 15-day period was carefully selected so that mean conditions over this period would be very similar to mean conditions over much longer durations. The model predictions (water levels and velocities) were then analysed to compute 15-day time histories of kinetic power density throughout the 3D domain, and the power density based on the depth-averaged flow. Frequency histograms, probability distributions, velocity roses and tidal ellipses were prepared to characterize the temporal variability of the flow throughout the domain. Representative statistical quantities, such as the mean value and standard deviation of the tide range, flow speed and kinetic power density, were also computed for all nodes in the domain.

Marine Kinetic Energy Explorer (MarKE)

A software application, named MarKE (short for Marine Kinetic Energy Explorer) was developed to facilitate easy access to the results of the model simulation and to the numerous quantities computed to define and characterize the scale and attributes of the kinetic energy resource throughout the Bay. MarKE features an easy to use graphical interface, interactive browsing and mapping, and several analysis tools, including the ability to forecast the power generation by a hypothetical energy converter (turbine) located anywhere within the model domain. The device size and the performance curve defining its efficiency can be customized by the user. With this capability, MarKE can be used to quickly estimate and compare the power generation by hypothetical devices in numerous locations throughout the Bay of Fundy. The MarKE application can also be adapted and applied, with modest effort, to view and analyse the results from numerical simulations of other regions. It should be noted that MarKE does not yet take into account the influence that the energy converter may have on the flow, nor the interaction between devices in arrays, and therefore is less suitable for predicting the performance of large scale projects.

Minas Passage

Figure 5 shows the predicted depth-averaged flood and ebb flows through Minas Passage (Nova Scotia) during a typical spring tide. On the flood, a large eddy forms immediately north of Cape Split which forces the main flow towards the central and northern parts of the Passage, and the flow reverses along the southern shore. On the ebb, the main flow is distributed more evenly across the Passage. As a result, in many parts of the passage, the peak velocities during flood tend to be slightly stronger than the peak velocities during ebb. There are also several large eddies that form in bays along the shore which then detach when the tide turns and are subsequently swept through the Passage.

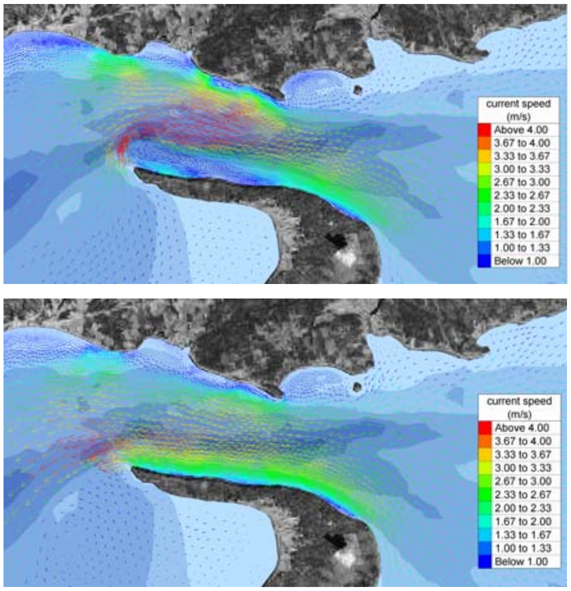

Figure 5: Depth-averaged currents in Minas Passage: a) spring flood; b) spring ebb.

For an average spring tide, the model predicts depth-averaged tidal currents in excess of 5 m/s in the waters NW from the tip of Cape Sharp. Moreover, the peak depth-averaged velocity exceeds 3.5 m/s over a ~2.5 km wide by ~12 km long area in the central part of Minas Passage. The mean depth-averaged power density (see Figure 6) is predicted to reach ~11 kW/m^2 near the centre of the Passage, at a location where the mean depth is 70 m, and reaches ~24 kW/m^2 over a small area NW of the tip of Cape Split. The maximum depth-averaged power density for an average spring tide is predicted to exceed 50 kW/m^2 near the centre of the Passage, and exceed 80 kW/m^2 near the tip of Cape Split.

Figure 7 shows the vertical distribution of the mean and maximum current speed, the mean kinetic power density, and the mean power that might be generated by a hypothetical turbine with unit area, all derived from analysis of ADCP data, for a site roughly 1 km from the north shore of Minas Passage where the local depth is 52 m. The current speed and power density vary substantially with depth, and are much weaker near the seabed than at higher elevations. The vertical shear in the velocity profile is also greatest near the seabed. As discussed in [[2], [4]], good information on the variability of tidal flows with elevation is clearly an important aspect of comprehensive resource assessments.

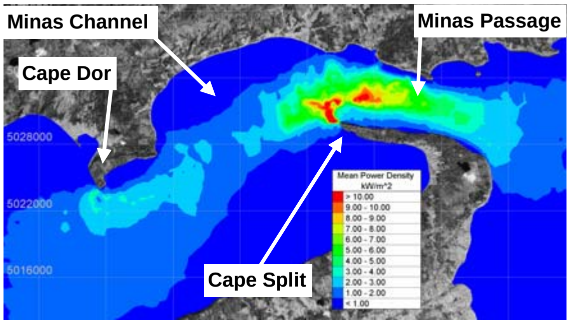

Figure 6: Mean depth-averaged kinetic power density.

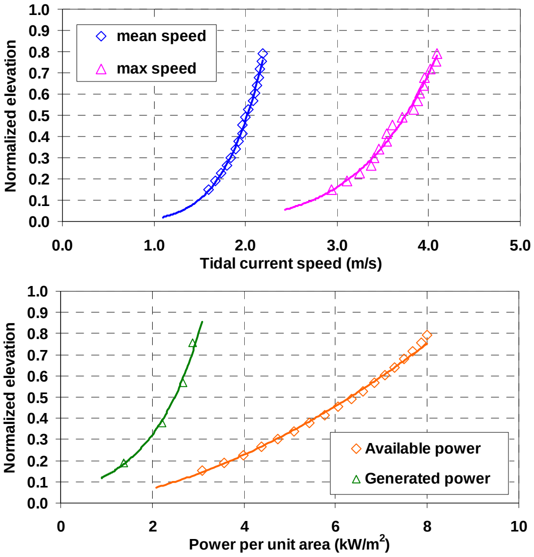

Figure 7: Vertical distribution of current speed and kinetic power density in the northern part of Minas Passage.

Passamaquoddy Bay

Figure 8 shows the predicted depth-averaged flood and ebb flows through the archipelago at the entrance to Passamaquoddy Bay during a typical spring tide. The most energetic flows are found in Letete Passage (New Brunswick), and in the narrows within Cobscook Bay (Maine). *Old Sow*, the largest tidal whirlpool in the western hemisphere, occurs in Western Passage. Figure 9 shows the predicted variation of flow speed with depth and distance across Letete Passage during a typical spring flood. The mean depth-averaged power density (see Figure 10) reaches 3.2 kW/m^2 in Letete Passage, at a site where the mean depth is 12 m, and 4.2 kW/m^2 in Cobscook Bay, where the mean depth is only 6 m.

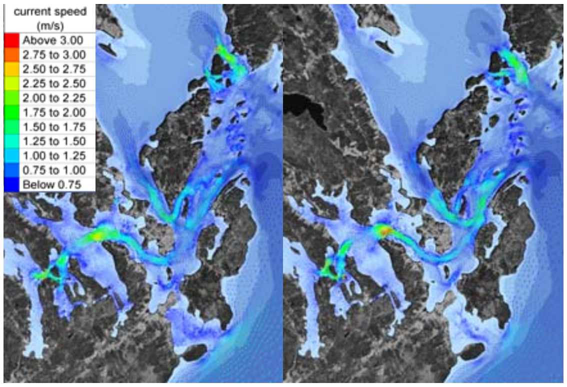

Figure 8: Depth-averaged currents in Passamaquoddy Bay: a) spring flood; b) spring ebb.

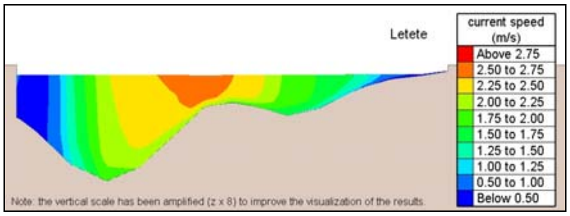

Figure 9: Predicted variation of flow speed within Letete Passage during a typical spring flood.

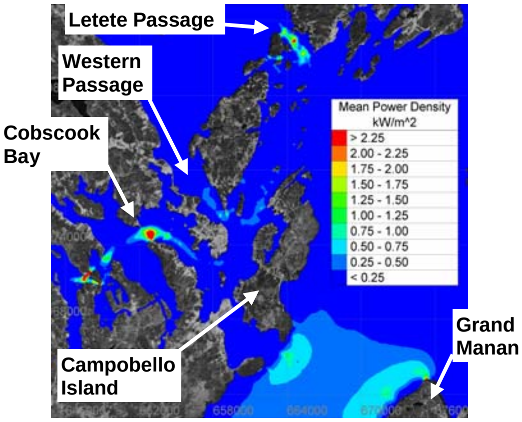

Figure 10: Mean depth-averaged kinetic power density.

Long Island, Nova Scotia

Figure 11 shows the predicted depth-averaged flood and ebb flows around Long Island (Nova Scotia) during a typical spring tide. The narrow channels north and south of Long Island are known respectively as Petit Passage and Grand Passage. Petit Passage features depths up to 50 m and peak depth averaged currents around 3.0 m/s and 3.2 m/s during typical spring ebbs and floods. The mean depth-averaged power density around Long Island (see Figure 12) peaks at 5.5 kW/m^2 in Petit Passage, at a site where the mean depth is 28 m. The maximum depth-averaged power density at this location is 17 kW/m^2. The flows through Grand Passage and to the south and west of Briar Island are slightly less energetic.

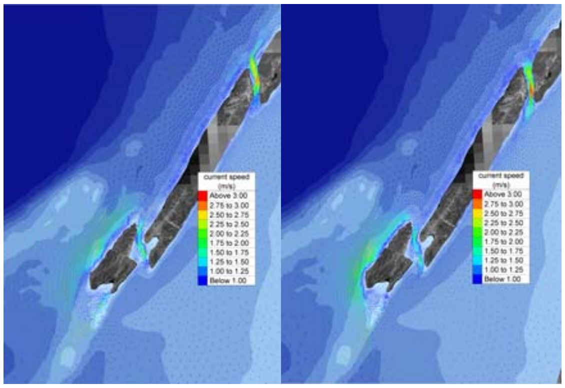

Figure 11: Depth-averaged currents near Long Island: a) spring flood; b) spring ebb.

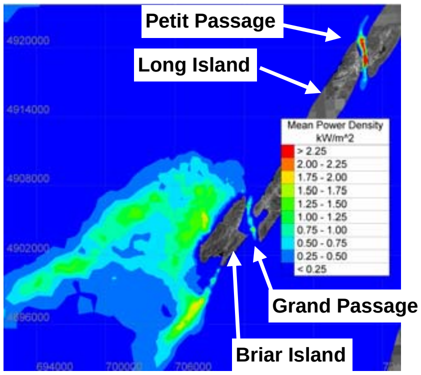

Figure 12: Mean depth-averaged kinetic power density.

5 Conclusions

Through a specific application in the Bay of Fundy, we have shown that with proper care and attention to detail, fairly realistic high-resolution three-dimensional simulations of tidal hydrodynamics can be developed using available modelling software in general and TELEMAC-3D in particular. The importance of accurate detailed bathymetry information, and of calibrating and validating the model against measurements to ensure that the simulations are realistic, cannot be over-stressed.

Moreover, the results from these simulations (currents and water levels) can be readily analysed to provide valuable detailed information on the scale, temporal fluctuations and spatial variability of the kinetic tidal energy resource throughout a large region, such as the Bay of Fundy. A user friendly software application known as MarKE has been developed to make it easier for stakeholders to access and benefit from the simulation results and the detailed information on the kinetic energy resource derived from them.

There are numerous sites with high-energy currents around the Bay of Fundy where energy recovery by in-stream turbines might be feasible, including (but not limited to) the waters around Long Island, and certain channels in the archipelago guarding the entrance to Passamaquoddy Bay. However, Minas Passage, a 5.5 km wide channel at the entrance to Minas Basin, appears to be among the best potential sites available worldwide for large scale energy recovery by in-stream tidal turbines. A $70 million pre-commercial deployment of in-stream turbines presently underway in the northern part of Minas Passage represents a first step towards developing this world-class tidal resource.

Acknowledgements

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