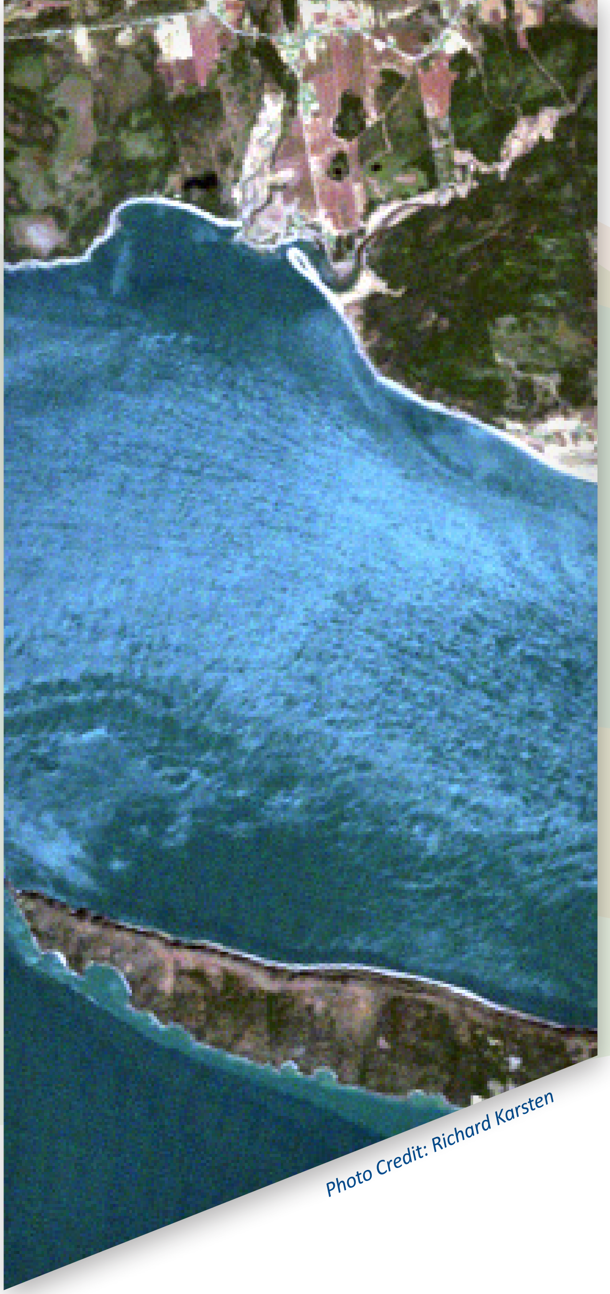

Photo Credit: Richard Karsten

2 MEASURING AND ASSESSING THE TIDAL RESOURCE

A critical aspect of tidal power development is an accurate assessment of the power resource.

**DEFINITION:
TYPES OF RESOURCE**

Theoretical Resource is the power contained in the entire resource.

Technical Resource is the proportion of the theoretical resource that can be captured using existing technology.

Practical Resource is the proportion of the technical resource that is available after consideration of external constraints – for example, environmental impacts.

Economic resource is the proportion of the practical resource that can be economically captured.

(Adapted from a number of sources.)

2 - MEASURING AND ASSESSING THE TIDAL RESOURCE

Author: Dr. Richard Karsten

WHAT DOES THIS MODULE COVER?

The following module describes the tidal resource in Nova Scotia.
It contains:

- Maps of Nova Scotia showing the locations of the largest in-stream tidal resources.
- Calculated extractable power at each location.
- Calculated potential installed capacity of the turbine array that could be deployed at each location.
- A discussion of site assessment.
- A detailed analysis of Minas Channel including bathymetry, tidal flow, and the impact of extracting power.

IS THIS MODULE FOR YOU?

This module is for anyone interested in the size of the potential in-stream tidal resource in Nova Scotia as a whole and at specific locations. It is also for anyone interested in the method of assessing the total resource and the resource at a specific site. It will be of interest to anyone wanting to learn the terminology of tidal resources.

2.0 - INTRODUCTION: NOVA SCOTIA TIDAL RESOURCE

Nova Scotia has significant tidal energy resources. The Bay of Fundy has the world's highest tides, routinely reaching over 16 m in range in the Minas Basin. Several passages along the coast of the Bay of Fundy have strong tidal currents that are suitable for the deployment of tidal energy converters (TEC) that extract energy from the fast moving currents. A critical aspect of tidal power development is an accurate assessment of the power resource. The following two sections summarize the in-stream tidal resource as described in Karsten (2012).

2.0.1 - EXTRACTABLE POWER

The map in Figure 2-1 shows the extractable power for each of the major passages in Nova Scotia. The extractable power is the maximum amount of power that can be taken from the flow through the passage.

The map shows that Minas Channel is, by far, the largest resource in Nova Scotia with 7200 MW of extractable power. The extractable power in Minas Channel is roughly three times Nova Scotia's maximum electricity usage. It is an incredible resource, resulting from the world's highest tides in Minas Basin and the associated large volume of flow through Minas Channel every tidal cycle.

Although smaller in scale, the passages along Digby Neck (Digby Gut, Petit Passage, and Grand Passage) still have significant extractable power, between 16 and 180 MW. These sites have sufficient power to support the deployment of arrays consisting of 10 to 50 turbines. Although the three passages are similar in size and location, Digby Gut has considerably more extractable power because it is the sole connection between Annapolis Basin and the Bay of Fundy.

The passages in Cape Breton (Great Bras d'Or, Barra Strait) are again smaller in scale. Development here would consist of only a few turbines. Other sites around Nova Scotia may allow for a similar level of development, but these have not been fully assessed at this time. **The extractable power listed on Figure 2-1 is the maximum power that can be removed from the flow through the passage and does not correspond to the electricity that could be generated by a particular tidal energy converter.** The fraction of the extractable power that could (or should) be converted into electricity depends on many factors: the acceptable reduction in flow through the passage, the design of the TEC, the size and arrangement of the array of TECs, the limitations of the supporting infrastructure, etc.

DEFINITION:
EXTRACTABLE POWER

Extractable power is a measure of the theoretical resource. It is the in-stream power that can be extracted from a given tidal resource while accounting for the resulting reduction in the flow speed. The extractable power is the total power removed from the flow, not only the power to generate electricity. Extractable power can be calculated using theory or numerical simulation.

The extractable power in Minas Channel is roughly three times Nova Scotia's maximum electricity usage.

DEFINITION:
MEAN POWER, ANNUAL ENERGY PRODUCTION

Mean Power: The average power produced usually measured in megawatts (MW). For tidal flow, it is roughly 40% of the maximum power that would be produced.

Annual Energy Production (AEP): The total power produced in a year, usually measured in TWh. It can be calculated by multiplying the mean power by the number of hours in a year.

In 2010, Nova Scotia had a total electricity generation of about 11.7 TWh, or a mean generation of 1340 MW. http://www.statcan.gc.ca/pub/57-601-x/2011002/t124-eng.htm

DEFINITION: INSTALLED CAPACITY

Installed capacity is the maximum power generation capacity of a given turbine array. For example, an array of 10 turbines rated to produce 1.2 MW would have an installed capacity of 12 MW.

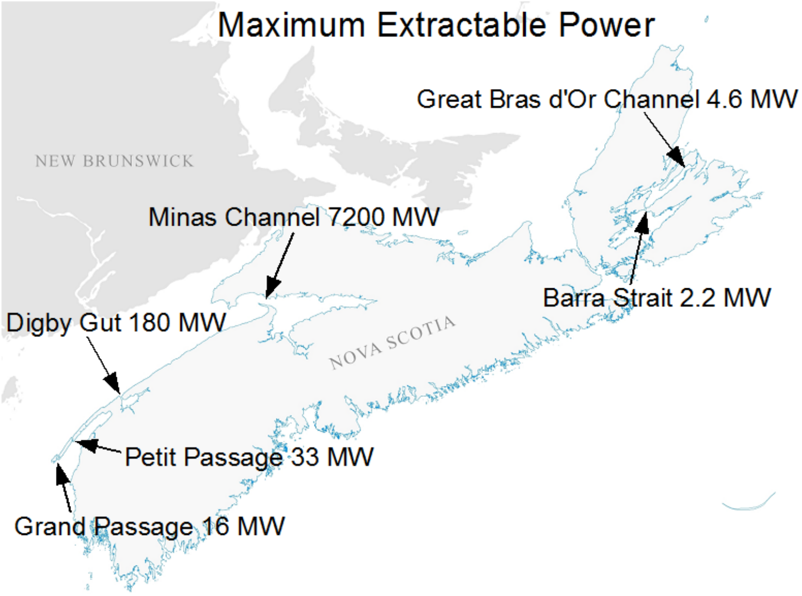

Figure 2-1: Estimated Maximum Extractable Power from Tidal Passages in Nova Scotia

2.0.2 - INSTALLED CAPACITY

The size of turbines and turbine arrays are usually discussed in terms of the installed capacity - the maximum power the turbine array can produce. The map in Figure 2-2: Estimated Maximum Installed Capacity for Tidal Passages in Nova Scotia gives the Karsten (2012) estimate of the maximum installed capacity that each passage could support. The installed capacity at a given site is only a fraction of the extractable power – for the sites examined, the installed capacity ranged from 15% to 40% of the extractable power.

The estimates of the installed capacity for the passages give a rough idea of the size of the turbine array that might be deployed at each site. Current TEC technology has focused on turbines with a capacity of roughly 1 MW. As such, Minas Channel could support an array of roughly 1000 turbines, Digby Gut around 50 turbines, Petit and Grand Passages 5 to 10 turbines each, and the Cape Breton passages (Great Bras d'Or, Barra Strait) 1 large or 2-3 small turbines. Although these are rough estimates, they do give a first idea of the size of industry that might develop around each site.

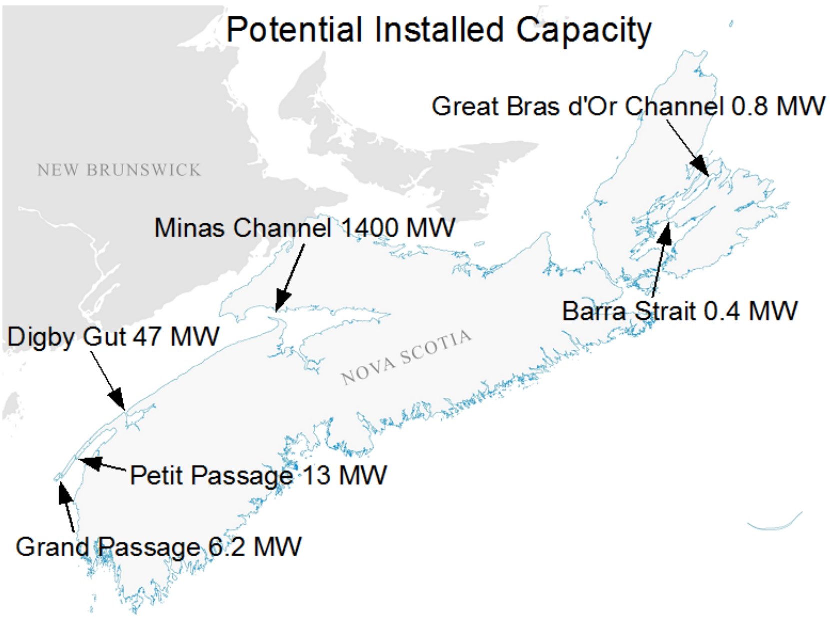

Figure 2-2: Estimated Potential Installed Capacity for Tidal Passages in Nova Scotia

In Table 2-1: A Comparison of Installed Capacity, from Karsten (2012) and EPRI (2006), the power estimates and installed capacity in Figures 2-1 and 2-2 are compared to the estimate of installed capacity in the Electric Power Research Institute (EPRI) report (Hagerman et al. 2006). This comparison is presented to emphasize that such estimates will change depending on how the analysis is completed and the accuracy of the data used. As well, the changes are not uniform for all passages. The Karsten (2012) estimates for tidal-basin systems, like the Minas Channel-Minas Basin and Digby Gut-Annapolis Basin systems, are larger than the EPRI (2006) values. On the other hand, the estimates for the other passages are smaller.

Table 2-1: A Comparison of Installed Capacity from Karsten (2012) and EPRI (2006). Values are in MW.

LOCATION	INSTALLED CAPACITY (KARSTEN 2012)	EPRI INSTALLED CAPACITY
Minas Channel	1400	595
Digby Gut	47	9.8
Petit Passage	13	18
Grand Passage	6.2	13
Great Bras d’Or Channel	0.8	2.8

2.0.3 - POWER DENSITY

The extractable power and installed capacity are not the only measures to consider when assessing potential in-stream tidal power. The velocity of the tidal current plays a critical role in determining if a site can be developed and what technology can be deployed. The power generated by a TEC increases with the cube of the water speed. Therefore, a small increase in tidal currents will result in a significant change in the amount of power that can be generated. The power of a flow is typically given by the power density – the power per unit of cross-sectional area.

In Table 2-2, the mean speed and mean power density for the Nova Scotia passages are listed. It should be noted that a time-averaged or mean speed of 2m/s corresponds to maximum speeds during a spring tide of 4 to 5 m/s. As can be seen in the table, the power density can be converted into the power an idealized 16 m diameter turbine, operating at 40% efficiency, would produce. Such a turbine would be rated to produce 1 MW at a rated speed of 2.9 m/s. The information provided in Table 2-2 illustrates that the high flow speeds in Minas Channel and Petit Passage can produce significantly more power for a given turbine than the other passages. Such numbers make it obvious that the development of each of these passages will require different turbine technologies.

Table 2-2: Typical Mean Speed, Mean Power Density, and Mean Power for a 16 m Diameter Turbine (kW) by Tidal Passage

LOCATION	TYPICAL MEAN SPEED (M/S)	MEAN POWER DENSITY (KW/M^2)	MEAN POWER FOR A 16 M DIAMETER TURBINE (KW)
Minas Channel	2	6.8	540
Digby Gut	1.2	1.5	120
Petit Passage	2.2	9.0	720
Grand Passage	1.6	3.5	280
Great Bras d'Or Channel	~1.0	0.85	68
Barra Strait	~0.7	0.3	23

2.1 - SUMMARY

In summary, Nova Scotia has significant tidal power resources. Minas Channel is in a category on its own, with an extremely high extractable power resource and a high energy density. Digby Gut has a high extractable resource, but a lower power density. Taking advantage of the large power resource will require a large number of turbines that run efficiently at lower flow speeds. On the other hand, Petit Passage has a much lower total power resource, but a high power density. This means a moderate amount of power could be generated by a few properly designed turbines. Grand Passage has a lower total power and moderate power densities, and may be better suited to testing turbines. The Cape Breton passages are low-level resources, both in terms of extractable power and power density, suitable for only a couple of low-flow turbines.

2.2 - SITE ASSESSMENT

When we shift our focus to specific sites, we must address questions like:

- how should a specific site be chosen,
- what size of turbine array could be deployed,
- what type of turbines should be used,
- how much power can be generated, and
- what impact will installing the turbines have on the environment?

2.2.1 - MEASUREMENTS OF TIDAL FLOW

As mentioned in the section on resource assessment, the speed of a tidal flow is critical in determining the resource and the technology that is best to deploy. The velocity of the tidal flow is most often measured using an Acoustic Doppler Current Profiler (ADCP). ADCPs provide a vertical profile of the flow, from near the bottom to near the surface, every sampling period, which can vary from 1 second to several minutes. Since ADCPs give velocity data at a single location, the deployment of several ADCPs at different locations around a site may be required to properly observe the tidal flow.

Typically, ADCP measurements of the tidal currents must be taken for at least 35 days. This allows a tidal harmonic analysis of the flow to be completed. This analysis can be used to predict the tidal flow for years into the future, as is done to predict tidal heights and times for most harbours. The ADCP data also allow the analysis of other details of the flow: the asymmetry in amplitude and direction of the flow between the flood and ebb tide; the variation in the direction in flow within a given flood or ebb tide; the mean vertical profile of the flow and the variation in this profile; information about the bottom boundary layer; and the amplitude and spectra of the turbulence in the flow.

All these characteristics can be important in the choice of turbine to be deployed. For example, the tidal constituent analysis will be used to calculate a histogram of water speeds over a typical year. Combined with a power curve for a given turbine, the histogram can be used to predict the Annual Electricity Production (AEP) for the turbine. Other characteristics of the flow may favour a specific turbine design. For example, if there is a large asymmetry between the ebb and flood direction, a turbine that yaws (changes direction) or a vertical axis turbine may be more suitable for the location. If there is strong vertical shear or a high level of turbulence, the result could be much larger forces on a turbine - in particular, large twisting forces on the turbine blades. Such a site may require a more robust turbine or may not be suitable for turbine deployment at all.

DEFINITION: TIDAL HARMONIC ANALYSIS

A tidal harmonic analysis can be completed on any data connected to tides – water depth, water velocity, turbine power. The analysis connects the data to the regular, predictable motions of the Earth, Moon, and Sun (see discussion of tidal cycles in Module 1). Each tidal constituent describes one aspect of these motions with a particular period. For example, the M2 tide is the primary tide associated with the Moon and has a period of 12.42 hours, while the S2 tide is primarily associated with the sun and has a period of exactly 12 hours. A tidal harmonic analysis calculates an amplitude (i.e., the height of the tide) and a phase (i.e., the time when high tide occurs) for each tidal constituent. The results can be used to predict the tidal data at any time. This type of analysis is used to generate the tide predictions in typical tide charts.

For more discussion and a list of tidal constituents, see http://en.wikipedia.org/wiki/Theory_of_tides#Harmonic_analysis.

2.2.2 - NUMERICAL MODELING AND FLOW IMPACT

Numerical models of the circulation around a proposed site can also be an important part of the flow analysis. The numerical models complement the ADCP data, confirming many of the results above. As well, the numerical model can give the spatial variation of these characteristics, leading to the choice of a site with the most suitable conditions for turbine deployment. Numerical model results will also highlight surrounding bathymetric features that can produce eddies or waves that may disturb the tidal flow and make a site less desirable. The predictions of a tidal model can also be used to improve deployment and scheduled maintenance.

Finally, validated numerical models should be used to determine the impact that a turbine array will have on both the local and far-field flow. The cumulative impact of an array of turbines may not be a simple multiple of the impact of a single turbine; that is, 100 turbines may not have 100 times the impact of one turbine. This is especially true for large arrays that occupy a large portion of a passage. As well, turbine arrays can have effects far from where they are deployed. For example, turbines placed in Minas Passage will reduce the flow through the passage and therefore reduce the tidal range in Minas Basin, but, they will also have a small impact on the tides throughout the rest of the Bay of Fundy and the Gulf of Maine.

2.2.3 - OTHER SITE ASSESSMENT FACTORS

Many other factors may affect the assessment of a site for turbine deployment. Here, we list some that should be considered for all sites:

WAVES: The wave conditions at a site are important. Large waves can affect the loading on a turbine and turbine performance even when the turbine is well below the surface. Large waves can also cause difficulty during deployment and maintenance. In general, the smaller the waves and swell are, the better.

WEATHER: The weather conditions can also change the flow. Large pressure systems can enhance or reduce the tidal flow and storm surges can cause strong flow that can damage turbines. Weather can also affect deployment and maintenance by limiting access to the site.

SEA BOTTOM: The sea bottom may determine if specific turbines can be deployed, or how the turbine will be moored in place. Careful geotechnical analysis of the seabed is required to determine if it can support large gravity bases or will allow for piles to be drilled into the seabed. The bottom roughness and sediments may also affect deployment or lead to a turbulent near-bottom flow.

PROXIMITY TO SHORE, GRID CONNECTION, PORTS, ETC.: The geographic location of a site will often determine its suitability. How close the site is to shore and a suitable grid connection or how near it is to ports with suitable infrastructure for deployment and maintenance can have an important effect on the cost of turbine deployment, power production, and maintenance.

2.2.4 - TIDAL ARRAYS AND BLOCKAGE RATIO

When a large array of turbines is to be deployed, all the above issues must be considered, not only for the individual turbines but for the array as a whole. It is critical that there is sufficient space to deploy the array so that the wakes of the turbines do not interfere with the performance of turbines downstream, since the turbine wake is an "energy shadow." Recent studies suggest a downstream spacing of 10-20 times the diameter of one turbine may be required. On the other hand, keeping the turbines as close together as possible may reduce costs. The optimal design of turbine arrays --a design that reduces costs while optimizing power -- is an active area of research. Multiple turbine farms can be deployed in a single passage. The total power they extract from the resource will result in a reduction in flow through the passage that will affect all the turbine farms.

A specific issue that needs to be considered when designing a turbine array is the **blockage** ratio – the portion of the cross-sectional area of a channel that is occupied by turbines. It is known that increasing the blockage ratio can increase the efficiency of turbines substantially. But, taking advantage of an increased blockage ratio would require that the turbine be specifically designed for the site. There are many other concerns that limit the blockage ratio. First, creating a very high blockage ratio requires a very high turbine density. For example, consider the case where 20m diameter turbines are deployed across an entire passage that is 30 m deep, with a spacing of 20 m between the turbines. The blockage ratio in this case is only 26%. Second, the spacing of turbines may be determined by their deployment or the need to access them for maintenance. Third, other marine activities (fishing, recreation, marine traffic) may require that a portion of the passage be free of turbines. And, finally, if fish and marine mammals travel through the passage, the blockage ratio may be required to be kept small, leaving routes through the passage that are free of turbines. It is important to ensure that any tests that examine turbine performance, whether in laboratory tank, numerical simulation, or in an actual tidal flow are conducted with a blockage ratio that is similar to the one where the turbine will actually be deployed.

Over the next few years, considerable knowledge about turbine arrays will be gained as small arrays are deployed around the globe. This research will lead to a reevaluation of which site characteristics are most important for a successful deployment.

2.2.5 - EFFECTIVE ASSESSMENT METHODOLOGY

The determination of all the factors that make a site suitable for the deployment of turbines is a considerable task. Site assessment for turbine arrays remains an active area of research. Over the next few years, considerable knowledge about turbine arrays will be gained as small arrays are deployed around the globe. This research will lead to a reevaluation of which site characteristics are most important for a successful deployment. In this section, we have focused on the assessment of the physical characteristics of the site. Social and economic assessment, however, can be equally important aspects of choosing a site.

2.3 - DETAILED ANALYSIS OF MINAS CHANNEL

In this section, we give a more detailed analysis completed for Minas Channel by Karsten (2012). The Minas Channel connects Minas Basin to the Bay of Fundy. It is some 50 km in length, with a width of 20 km in the outer channel that reduces to only 5 km in Minas Passage. The water depths are 50-100 m in the outer channel, increasing to over 150 m in Minas Passage (see Figure 2-3). It has some of the strongest tidal currents in the Bay of Fundy, particularly in Minas Passage where water speeds can reach over 5 m/s. The volume flux through the passage can reach 1,000,000 m^3/s during the largest spring tides, more than the flow of all the rivers in the world combined.

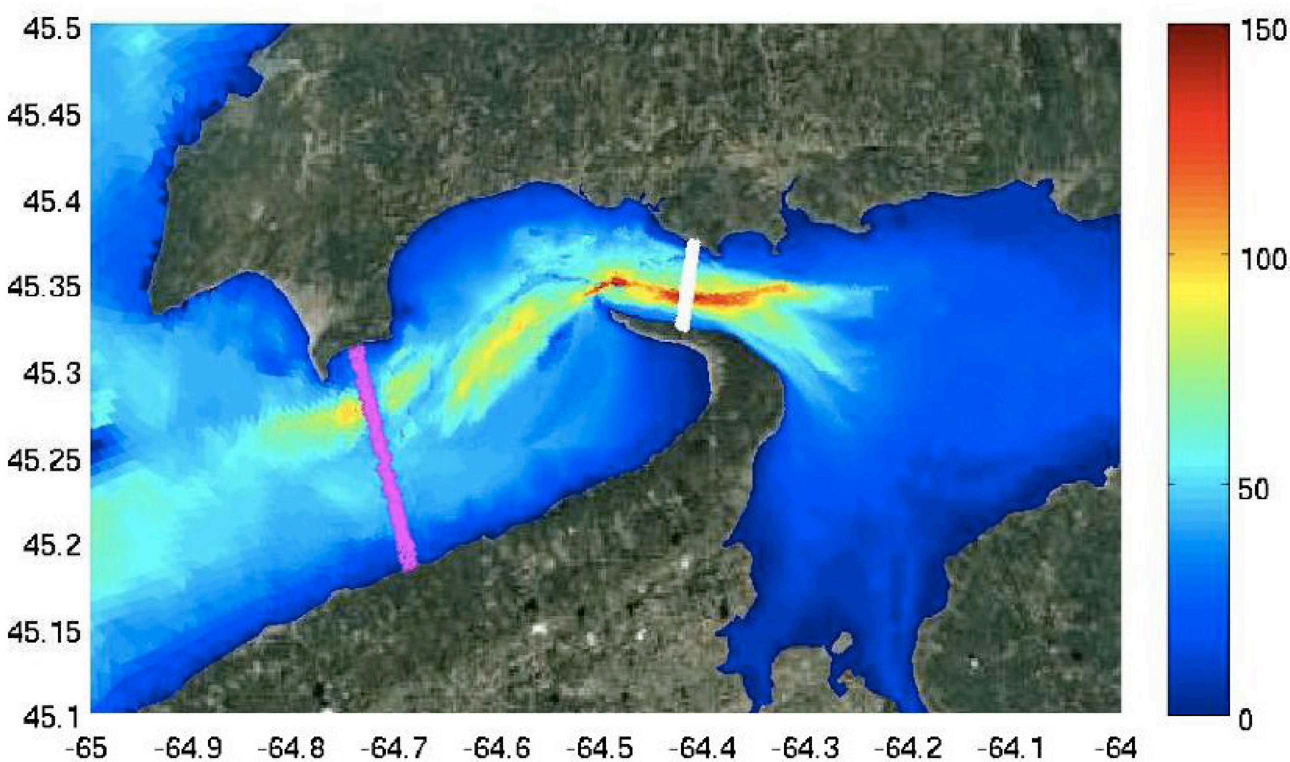

Figure 2-3: The Bathymetry of Minas Channel Used in the Numerical Simulations.

(The colours are the mean water depth in metres. The pink line is the location of the Minas Channel turbine fence; the white line is the location of the Minas Passage turbine fence. These fences are hypothetical and are used for modeling purposes only.)

In Figure 2-4 and Figure 2-5., the mean speed and mean power density for Minas Channel are plotted. Throughout much of Minas Passage, the mean depth-averaged speed exceeds 2 m/s, with maximum depth-averaged speeds between 3 and 4 m/s. The power density in Minas Passage often exceeds 8 kW/m^2. The outer Minas Channel has considerably slower flow, with mean speeds around 1 m/s and only a small region where the mean speed exceeds 1.5 m/s. As such, the power densities in the outer channel are much less than the inner channel, with most of the area below 4 kW/m^2. Therefore, extracting significant power from the outer channel would require a low-flow TEC.

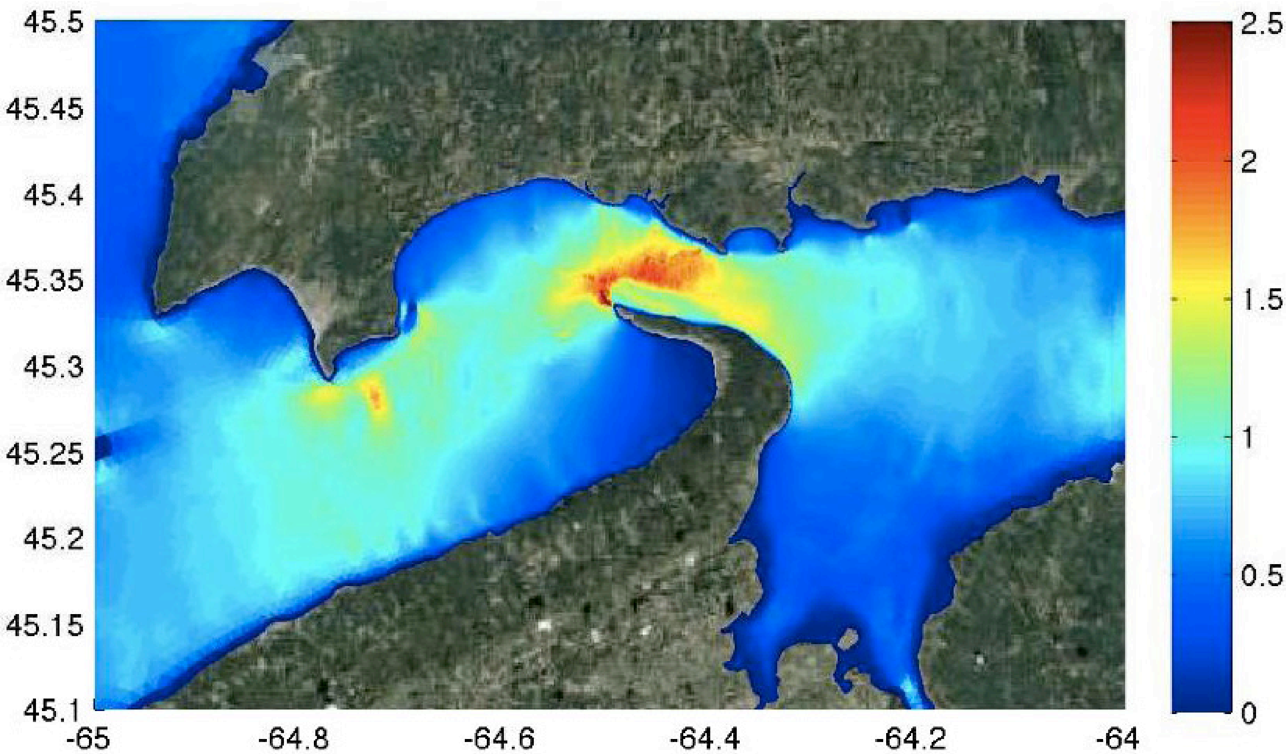

Figure 2-4: The Mean Depth-Averaged Speed in m/s

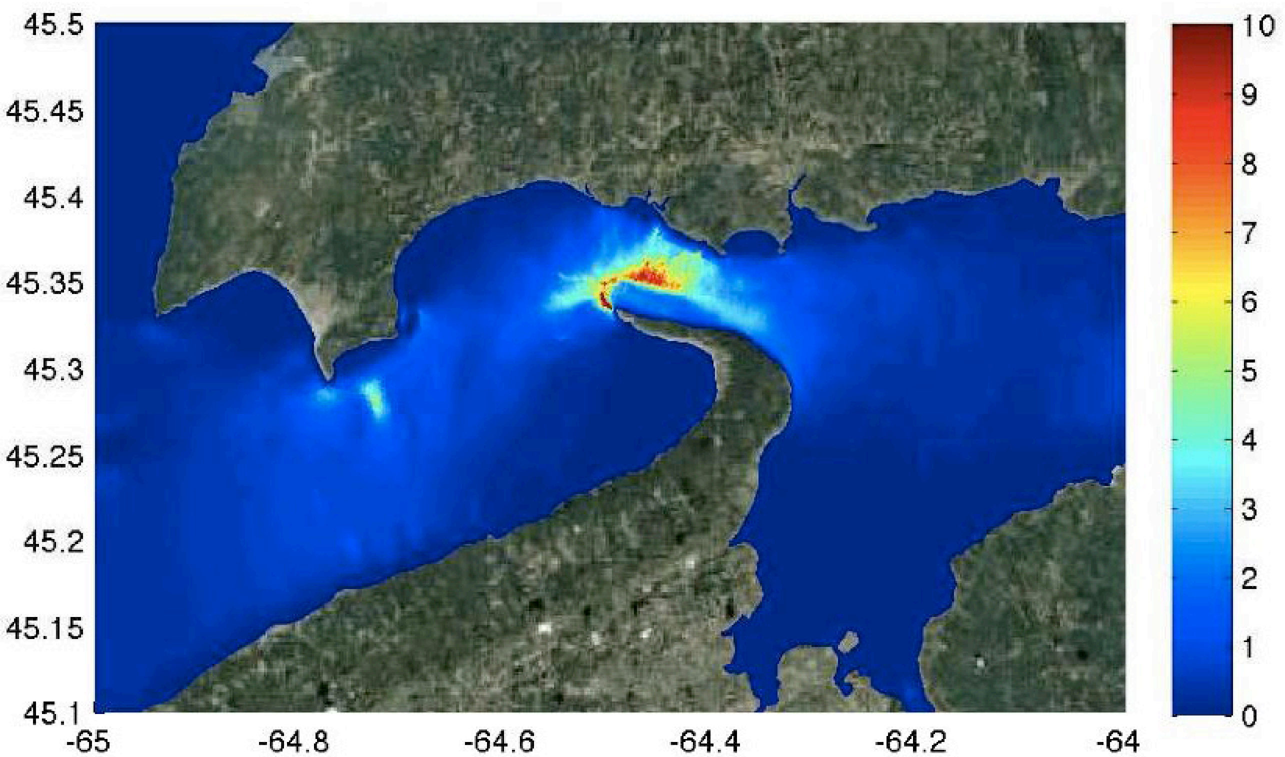

Figure 2-5: Mean Power Density in kW/m^2 for Minas Channel

Possibly, the single most important fact about Minas Channel to keep in mind is that it is a single system. The power that drives the flow through Minas Channel is the tidal head across the channel - the difference in tidal elevation between the opening of Minas Channel and Minas Basin. Any turbines placed at any location in Minas Channel will be extracting power from this same source.

In order to calculate the power potential of the channel, numerical simulations were run with a fence of turbines at two different locations as shown in Figure 2-3. The turbine fences extend across the entire channel at each location. For each simulation, the drag coefficient of the fence is altered and the mean power extracted by the fence and the mean volume flux through the fence are calculated. The extracted power versus reduction in volume flux can be plotted, as in Figure 2-6. This curve is for the outer Minas Channel fence shown in pink in Figure 2-3. The figure shows how the extracted power increases rapidly for a relatively small reduction in the flow through the passages. As the power extraction increases, the reduction in flow becomes greater until a maximum power extraction is reached.

It should be noted that the power curve changes very little if the power is extracted from fences at different locations along the channel. For example, if power is extracted from a fence in Minas Passage, the shape of the curve is the same as that shown in Figure 2-6, but the maximum power is only about 6000 MW or roughly 80% of the total available at the outer channel location, since the turbine fence in Minas Passage cannot extract power from the tides in the outer Minas Channel. If power is extracted from both a fence in the outer channel and a fence in Minas Passage, the power curve still remains the same shape, with a maximum power that lies between that of Minas Channel and Minas Passage fences alone. While more power can be extracted from the outer Minas Channel than Minas Passage, the power densities in the outer Minas Channel are significantly less than the values in Minas Passage (see Figure 2-1). Extracting power from the outer Minas Channel will likely require a different technology than extracting power from Minas Passage.

Finally, it should be emphasized that any reduction in flow through Minas Channel will proportionately reduce the tidal range in Minas Basin. As a result, a 5% reduction in flow through the channel could have significant impacts on the intertidal zones of Minas Basin. A 5% change in the tidal range in Minas Basin could result in significant areas along the coast of Minas Basin that no longer flood regularly during high tide or no longer go dry at low tide. Calculating these changes requires numerical simulations with improved coastal bathymetry and much higher resolution in the intertidal zones.

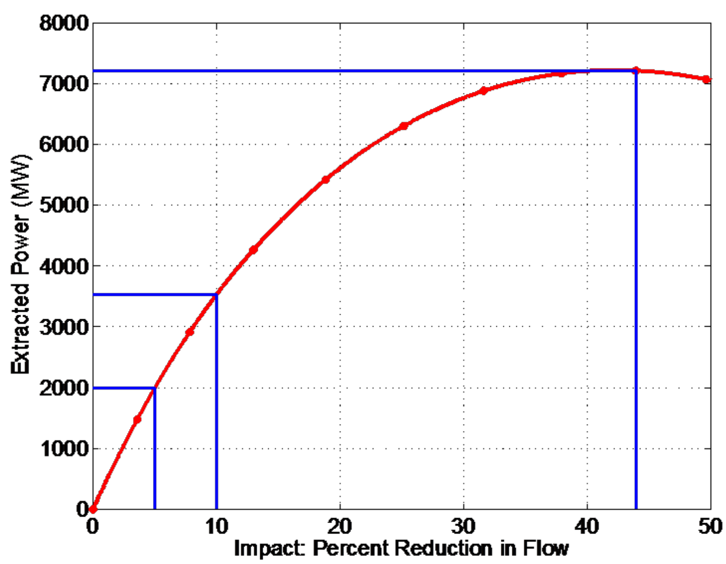

Figure 2-6: Extracted Power versus the Reduction in Flow Through the Channel for Minas Channel. (The blue lines highlight the maximum extractable power, the extractable power with a 10% reduction in flow, and the extractable power with a 5% reduction in flow.)

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