
CHARACTERIZING TIDAL FLOWS AND TURBINE POWER PRODUCTION IN PETIT PASSAGE USING OCEANOGRAPHIC AND CFD MODELS VALIDATED BASED ON ADCP DATA

FINAL REPORT

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LIST OF REVISIONS

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0	March 15th, 2016	Initial release	VK, TW, RK, GT

SUMMARY

The main objective of this project was to use a combination of computer models, field measurements and local knowledge to specify potential turbine deployment locations in Petit Passage, NS and subsequently quantify power generation over a single ebb and flood tidal cycle.

To reach the project objective, Mavi and Acadia compared their computer models (CFD and ocean models, respectively) of Petit Passage against ADCP data collected by Dr. Alex Hay's group from Dalhousie University and Greg Trowse of Fundy Tidal. This ADCP data was collected in 2012 as part of the OERA funded Southwest Nova Scotia tidal energy resource assessment.

The level of agreement between the two computer models and ADCP field measurements was generally good during the portion of the tidal cycle that saw the highest speed flows. A number of future investigations and enhancements to the models were proposed to improve the agreement over the entire tidal cycle.

The team subsequently identified three sets of test case deployment locations for two 10m diameter turbines in Petit Passage. Three different turbine configurations were run to evaluate the effects of turbine location and turbine spacing on power production. The first configuration placed the two turbines on a high-energy mid-channel streamline and showed a significant power drop for the downstream turbine due to wake effects. The second and third turbine configurations successfully avoided wake interactions.

This project provides a baseline study with insights useful for array design in Petit Passage and similar sites. This project also highlights areas where more detailed work is required to better inform the project developers and technology providers in order to minimize lifecycle costs and decrease project risk.

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1 INTRODUCTION

The primary objective of this project was to use computer models, validated against ADCP field data, to pinpoint suitable turbine deployment locations in Petit Passage and subsequently predict the power generation.

The following two computer models were used for this project:

- FVCOM – a coastal ocean circulation model used by Acadia University and developed by the University of Massachusetts-Dartmouth, and,
- Star CCM+ - a computational fluid dynamics (CFD) commercial software suite used by Mavi and developed by CD-Adapco.

Ocean models such as FVCOM are routinely used to model flows through tidal passages. CFD models, on the other hand, are typically used to model the actual turbines to predict performance, blade loading and wake.

Over the past few years, Mavi and its project partners have been pushing the boundaries of CFD modeling into simulating tidal channels and stretches of river. The motivation for this is rooted in the fact that the geometry of the channel can have a significant impact on the turbine performance, and CFD models have greater built in capacity to model wakes, which is important for laying out turbine arrays. Concurrently, progress is also being made on improving the accuracy of ocean models and methods are being developed for including simplified turbines and wakes within the ocean models for array layout. Both modeling approaches will therefore continue to be used as researchers push model boundaries and define their limitations.

This project started by first comparing the CFD and Oceanographic computer models to ADCP field data. This allowed the team to determine how effective each model is at locally predicting the transient tidal flow.

The next step in the project was to including turbines in the CFD model (represented as drag elements) in order to quantify power generation and wake interaction between the turbines. This information is important for project lifecycle cost analysis since power production is linked directly to revenue generation.

For reference, this work directly addresses OERA's priority as outlined in the "Marine Renewable Marine Priorities" document by informing future project build-out. It also builds on previous OERA projects and the ecoEII site assessment project by utilizing the results of existing research and building new collaborative relationships.

2 METHODOLOGY AND RESULTS

2.1 FVCOM - OCEAN MODEL

Acadia University completed a month-long simulation of the flow through Petit Passage using the Acadia-Digby Neck numerical model. The simulation covers the September 2012 deployment of ADCPs in Petit Passage that was part of the South West Nova Scotia Tidal Resource Assessment.

To validate the simulations, the model results were compared to the ADCP results. The results of the FVCOM simulations showed a bias, the simulated velocities were consistently faster than the observations.

For the validation, Acadia completed two comparisons. The first comparison used ADCPs BPa and BPd, located at the north and south entrances of the passage, respectively (see Figure 1 and 2). At these locations the simulation bias was 20%. This bias was removed from the forcing data by multiplying the water speeds by a factor of 0.7939.

The validation results presented in this report concentrate focused on the second comparison, namely on ADCP BPb and BPc, the two ADCPs that were located within the passage (see Figure 1). These ADCPs had the cleanest data amongst the ADCP data sets, and ADCP BPc is closest to the envisaged turbine deployment sites, depicted with red markers in Figure 1. At these ADCP locations, the simulation bias was approximately 6%. All results in the remainder of this report have had this interior bias removed; the FVCOM simulated data has been multiplied by a factor of 0.9377.

The discovery of the need for two different bias adjustments is an important result of this project for Acadia. Acadia researchers have implemented a better representation of bottom roughness in their model and are in the process of calibrating and validating these new simulations.

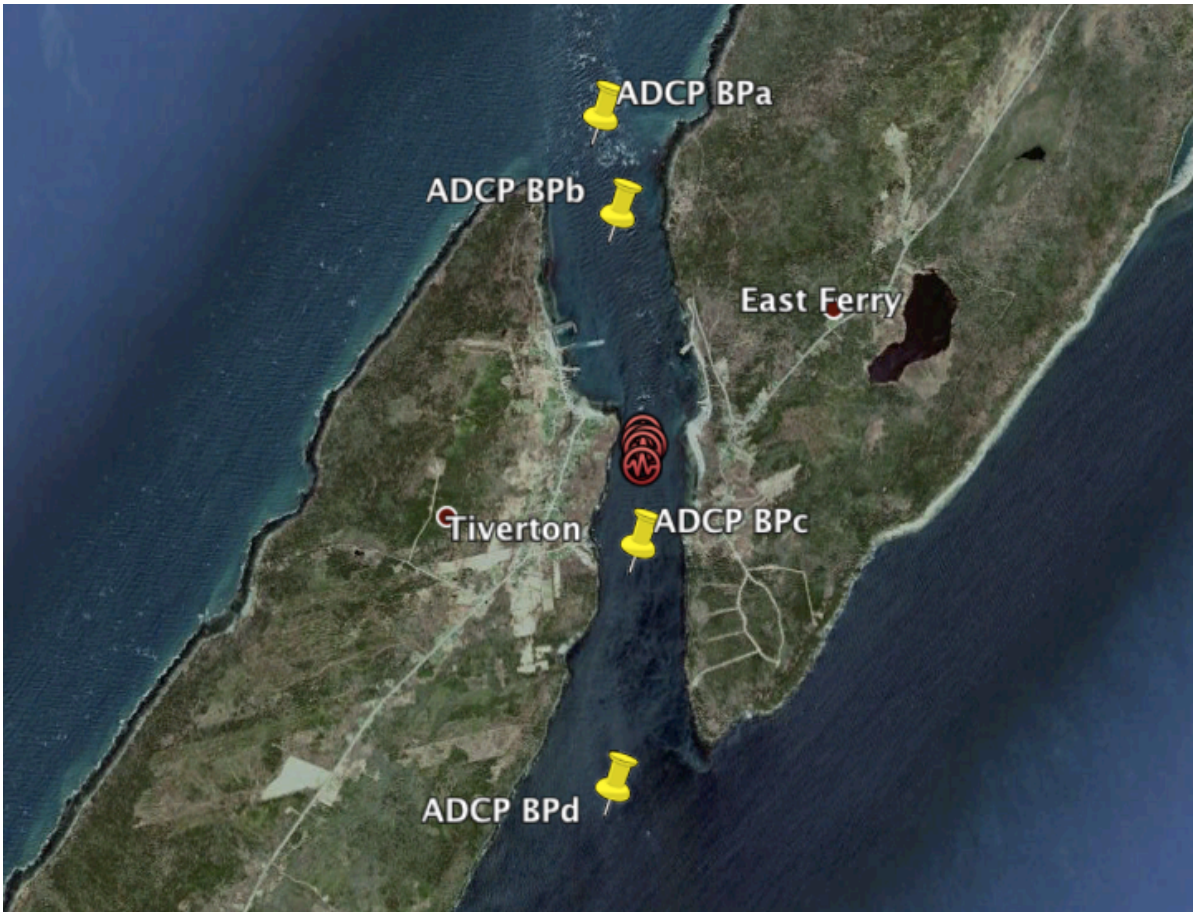


Figure 1: Locations of ADCP deployments in Petit Passage and test case turbine deployment locations in throat of channel (shown with red circular marker)

The data from the simulation was used to calculate the volume flux across the northern and southern openings of the passage, as shown in Figure 2. The time-varying elevation at the northern and southern openings of the passage (see Figure 2) was also provided to Mavi to be used as forcing data for their CFD simulations.

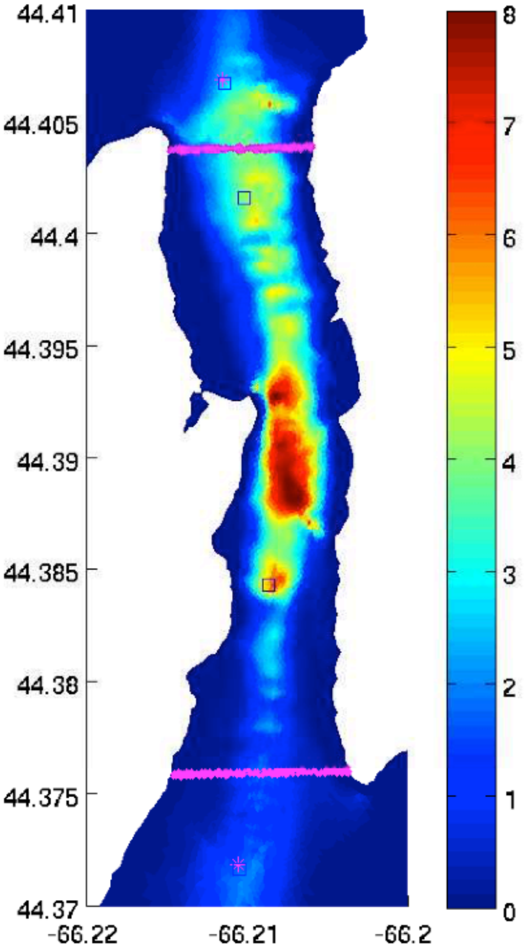


Figure 2: The power density (kW/m^2) as calculated from the Acadia model. The pink lines are the locations where the volume fluxes are calculated. The pink stars are the locations where the water level was calculated and the black boxes are the locations of ADCP measurements.

2.2 CFD MODEL

2.2.1 Geometry

A 3D model of Petit Passage was created using bathymetric data matching the oceanographic model. This bathymetry data consists of a point cloud with a resolution of 2m. The point data is defined in terms of latitude, longitude, and elevation.

A 3D bathymetry surface, shown in Figure 3, was created using this bathymetry data. A 3D CFD domain was then created using this bathymetric surface. In order to reduce the required computational resources, these simulations represent the water surface using a slip wall as opposed to a surface free to rise and lower with the changing tides.

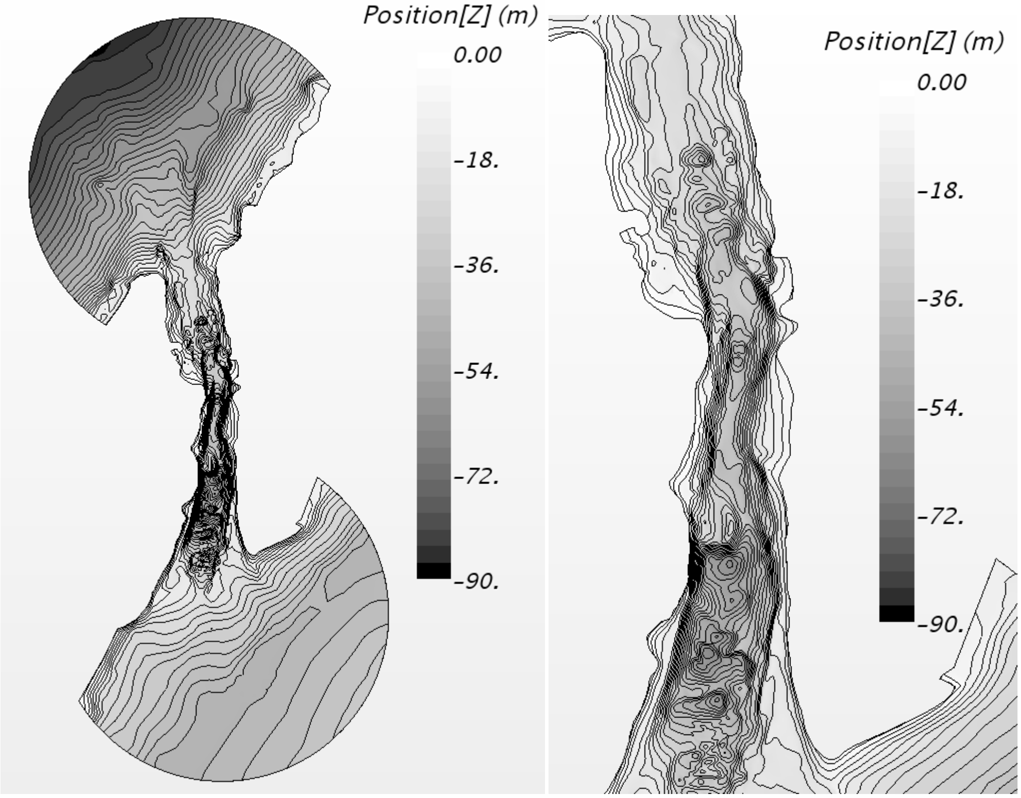


Figure 3: Petit Passage bathymetry contours

2.2.2 Boundary Conditions

Data from 3D oceanographic simulations was used to define the conditions at the north and south boundaries of the CFD model, and to set the water elevation. The inlet boundary condition is a mass flow inlet that varies with time based on oceanographic data. The seabed surface is a no-slip wall with a global roughness height on the order of 25 cm, which is representative of a 'clean and straight' natural channel. A study of the impact of roughness height on the model results could not be attempted as part of this project due to the time/budgetary limitations.

The water surface boundary is a fixed slip wall placed at the average water elevation during the flood or ebb tide. The authors recognize that this imposes an important limitation on the model and will have an effect on the current speeds predicted because the channel cross-sectional area remains fixed and wetting and drying at the shore is not accounted for.

Three options exist for future studies aimed at varying the water surface elevation to mimic the tides:

1. Specify a free-surface boundary condition at the air-water interface – this would take a lot of computational resources and studies to ensure a stable solution that are beyond the time/budget for this project
2. Implement a deforming free surface that matches the predictions made by the oceanographic model – this would take development work that is beyond the time/budget allowance for this project.

3. Create a series of models with varying water level elevations (modeled as a slip wall) representing short intervals of time (a few minutes) – the uncertainty with this approach is whether the flow field, especially the large-scale vortices, would develop. The shape, size and strength of the vortices are very transient over the course of a tidal cycle. A simulation of a short duration in time without prior knowledge of the flow field may therefore differ quite substantially from a simulation of a complete tidal cycle. This would need to be verified.

For this study, fixing the water elevation at a mean height but running the simulation for the entire tidal cycle was deemed to be the right approach given the time and budget constraints of this project.

Figure 4 shows the 3D CFD domain used in the CFD simulations, along with boundary labels.

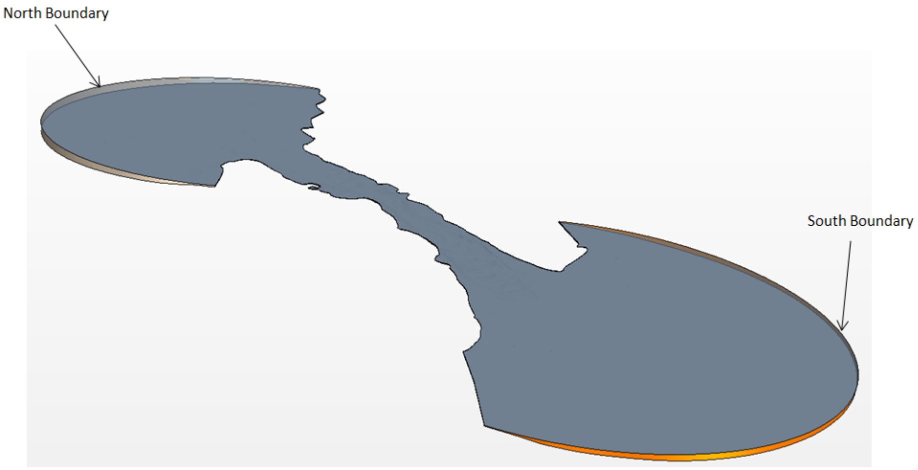


Figure 4: CFD domain

The CFD model was run for the following flood and ebb cases:

- Ebb (north to south flow)
    - Start: September 18th, 2012 – 15:20
    - End: September 18th, 2012 - 21:20
- Flood (south to north flow)
    - Start: September 18th, 2012 – 21:20
    - End: September 19th, 2012 – 3:30

These flood and ebb cases correspond to the largest head difference that occurred over the 2-week period over which the oceanographic model was run. These cases were selected so that the simulations would model the largest range of velocities recorded over the 2 week time period.

The changes in water elevation for the ebb and flood tides are shown in Figure 5 and Figure 6, respectively. The mean water elevations set for the CFD models are:

- Ebb: 1.0 m
- Flood: -1.0 m

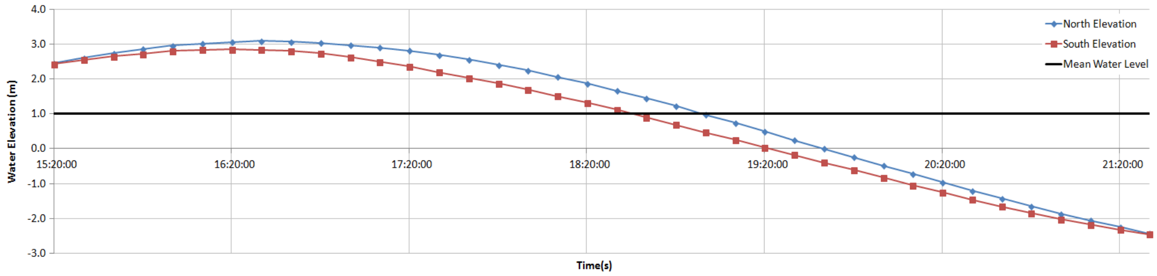


Figure 5: Change in water elevation on Sep 18th, 2012 - Ebb

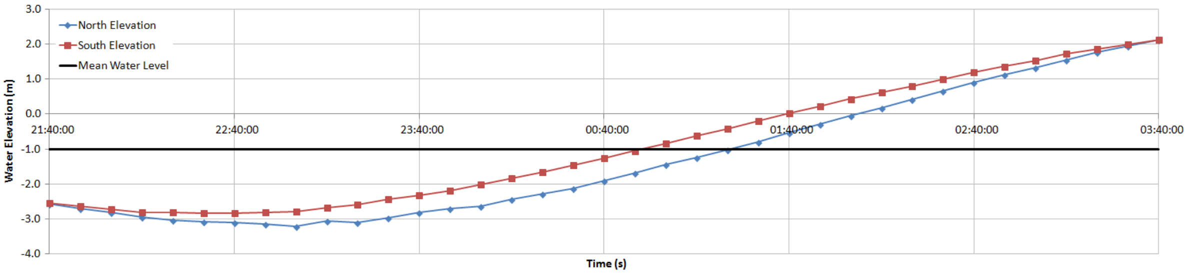


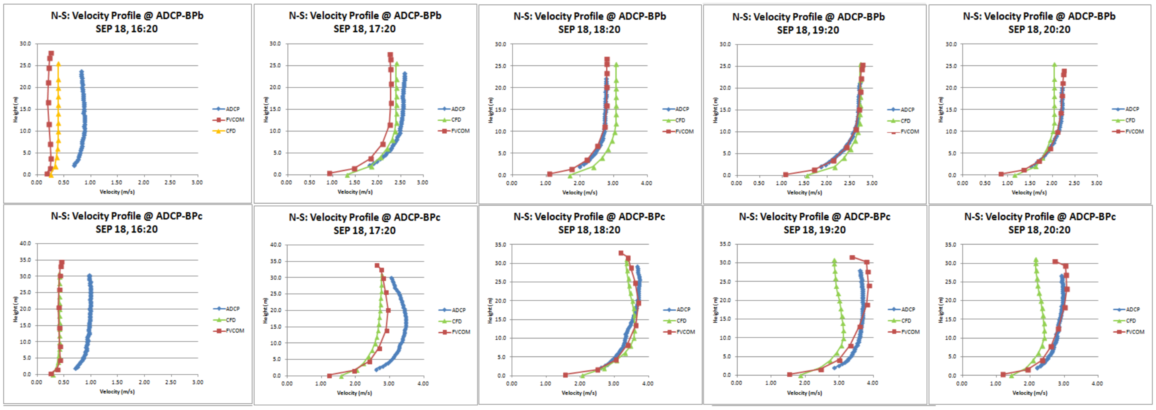
Figure 6: Change in water elevation on Sept 18th & 19th - Flood

2.3 VALIDATION OF OCEANOGRAPHIC AND CFD MODELS

The ocean model and CFD simulations were compared to ADCP measurements at ADCP deployment locations BPb and BPc at every hour over the course of the tidal cycle. Figure 7 and Figure 8 provide a comparison of the flow speed as a function of the ebb and flood tides respectively.

The following observations are made for the ebb tide:

- Both FVCOM and the CFD simulations under-predict the flow speed early in the tidal cycle. Given the fact that the CFD simulations are driven by the mass flow rate predicted by FVCOM, the consistency between CFD and FVCOM is to be expected.
- Good agreement is shown between the CFD, FVCOM and ADCP BPb measurements later in the tidal cycle during periods of high flow
- The CFD results deviate from FVCOM and ADCP measurements at ADCP BPc during the latter part of the tidal cycle. This is likely due to the fact that the CFD model predicts larger eddy formations – more turbulence is predicted at ADCP BPc location. Introducing higher bottom roughness into the CFD model would likely help dampen the turbulence and improve the results.



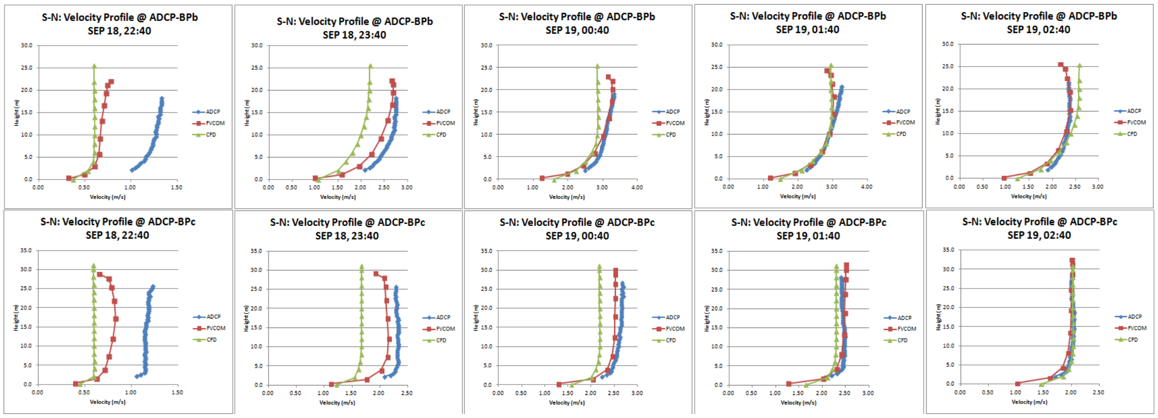
N-S: Velocity Profile @ ADCP-BPb SEP 18, 16:20
N-S: Velocity Profile @ ADCP-BPb SEP 18, 17:20
N-S: Velocity Profile @ ADCP-BPb SEP 18, 18:20
N-S: Velocity Profile @ ADCP-BPb SEP 18, 19:20
N-S: Velocity Profile @ ADCP-BPb SEP 18, 20:20
N-S: Velocity Profile @ ADCP-BPc SEP 18, 16:20
N-S: Velocity Profile @ ADCP-BPc SEP 18, 17:20
N-S: Velocity Profile @ ADCP-BPc SEP 18, 18:20
N-S: Velocity Profile @ ADCP-BPc SEP 18, 19:20
N-S: Velocity Profile @ ADCP-BPc SEP 18, 20:20

Figure 7: Ebb Tide - comparison of CFD, FVCOM and ADCP measurements

The following observations are made for the flood tide:

- Both FVCOM and the CFD simulations under-predict the flow speed early in the tidal cycle as was the case during the ebb tide.
- Good agreement is shown between the CFD, FVCOM and ADCP measurements later in the tidal cycle during periods of high flow

It should be noted that the CFD simulations did not employ a bias correction as was used for FVCOM (see Section 2.1). Therefore, the CFD simulations are representing the spatial variation of the flow in the passage more accurately that the FVCOM simulations. This suggests that higher resolution of the bottom variations and turbulent flow improves the model simulations.



S-N: Velocity Profile @ ADCP-BPb SEP 18, 22:40
S-N: Velocity Profile @ ADCP-BPb SEP 18, 23:40
S-N: Velocity Profile @ ADCP-BPb SEP 19, 00:40
S-N: Velocity Profile @ ADCP-BPb SEP 19, 01:40
S-N: Velocity Profile @ ADCP-BPb SEP 19, 02:40
S-N: Velocity Profile @ ADCP-BPc SEP 18, 22:40
S-N: Velocity Profile @ ADCP-BPc SEP 18, 23:40
S-N: Velocity Profile @ ADCP-BPc SEP 19, 00:40
S-N: Velocity Profile @ ADCP-BPc SEP 19, 01:40
S-N: Velocity Profile @ ADCP-BPc SEP 19, 02:40

Figure 8: Ebb Tide - comparison of CFD, FVCOM and ADCP measurements

Figure 9 shows the flow speed at the CFD model surface over the ebb and flood tidal cycles simulated. As is to be expected, the flow speeds are greatest through the narrowest point in the channel. This area was therefore selected for turbine placement. It is important to note that the flow speeds outside the channel, namely out in the Bay of Fundy and St. Mary's Bay are not considered to be accurate. The large open regions outside of the channel were created to allow the flow to enter and exit the channel more naturally but any currents that may exist out in the bays was not considered.

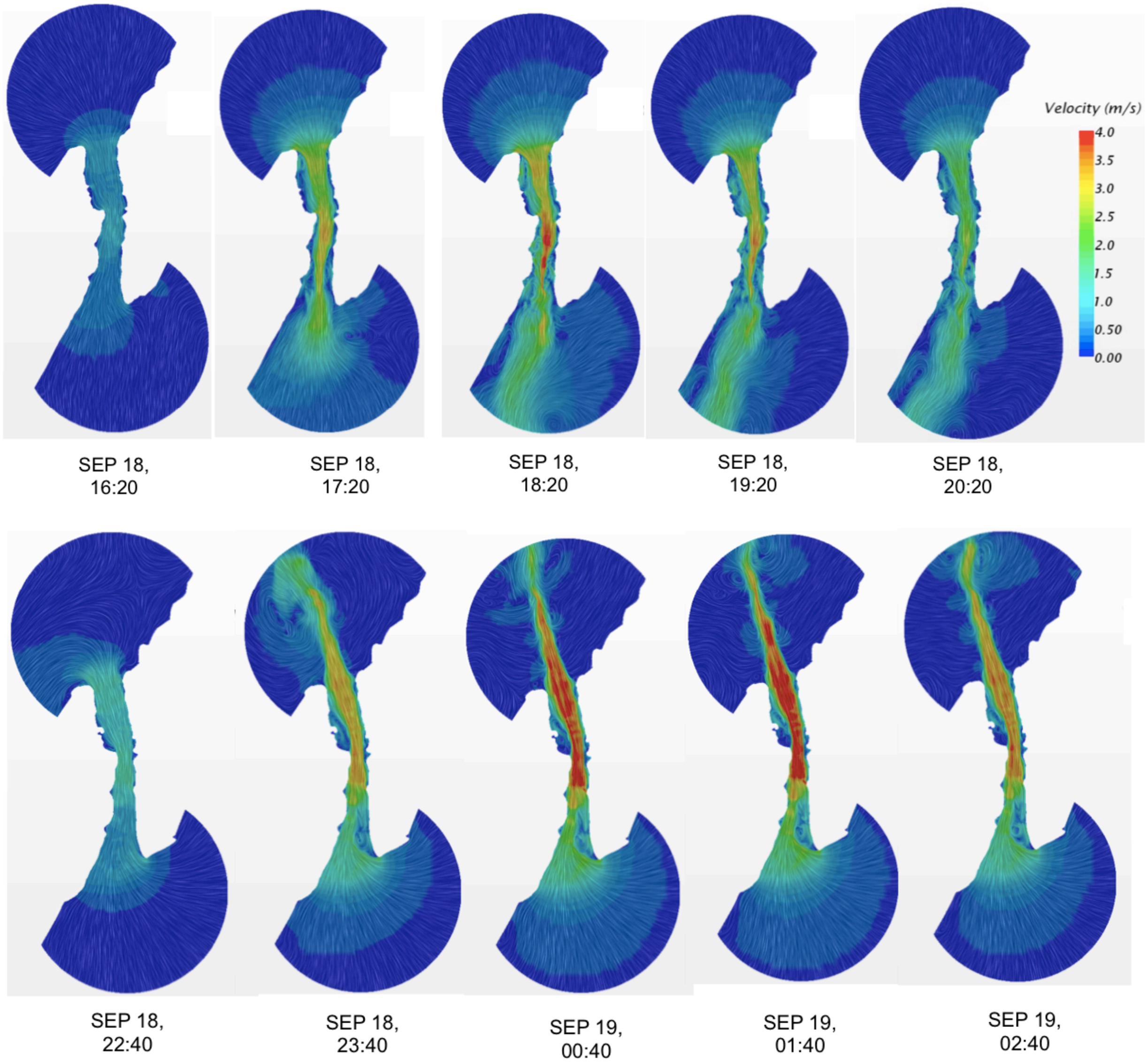


Figure 9: Flow speeds along water surface as predicted by CFD model

2.4 TURBINE SPECIFICATION

Two axial flow tidal turbines with a 10 meter diameter with a 15m hub height were specified for this study. The turbines are rated at 500 kW in 3m/s flow. The cut in speed was specified as 1m/s. Cutout speeds of 3.5m/s and 4m/s were considered for the study. A cubic power curve was assumed for flow speeds between 1 and 3 m/s with constant power regulation between 3 m/s and cutout speed conditions.

2.5 METHODOLOGY FOR MODELING THE TURBINES IN CFD

A simplified model of the turbine is used in the CFD model to calculate power generation over a tidal cycle and assess wake interactions. The turbine is represented by an actuator disk that characterizes the momentum drop the turbine would create in the flow. The simplified model can be further tuned to emulate the power and drag behavior of a specific turbine and, to a limited extent, the wake.

Typically, the turbine power is calculated based on a power coefficient referenced to an upstream velocity using the following formula:

$$P = \frac{1}{2}\rho A v^3 C_p$$

where:

ρ = density
A = turbine frontal area
v = incoming water speed
C_p = power coefficient

This formula, however, is difficult to apply in practice because in complex channels, the velocity upstream of the turbine is not necessarily uniform. Furthermore, the turbine performance coefficient varies with parameters such as water depth and channel width (channel blockage) as well as flow turbulence that may be the result of a natural bathymetric feature or an upstream turbine.

For the above reasons, the power coefficient is re-defined based on aperture velocity, namely the volume averaged velocity passing through the turbine. This approach to defining turbine performance has been shown to be valid by Mavi and the University of Laval as part an ongoing project due to be completed end of March 31, 2016 entitled: *Quantifying extractable power in a stretch of river using MHK turbines*. The results form the project will be posted on the IEC-TC114 website: http://tc114.oreg.ca

2.6 TURBINE DEPLOYMENT LOCATIONS

Simulations were run for three different test cases of turbine deployment locations. Table 1 provides the coordinates for the turbine deployment locations considered as part of this project. Figure 10 shows their location in the channel.

Table 1: Coordinates for turbine deployment locations

Configuration	Turbine location	Latitude	Longitude
1	B	44.38965	-66.20767
	C	44.38898	-66.20782
2	B2	44.39000	-66.20783
	B3	44.38993	-66.20733
3	A2	44.39050	-66.20767
	C2	44.38883	-66.20775

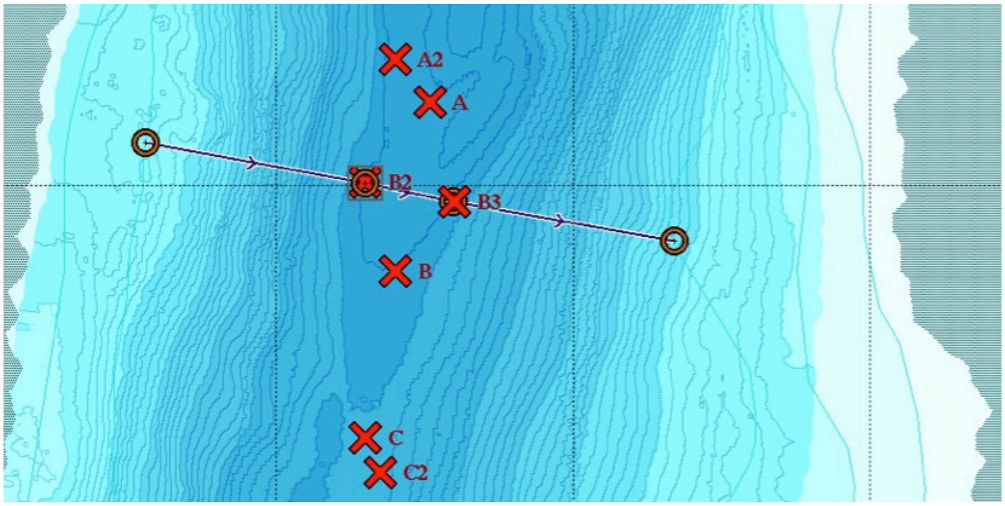


Figure 10: Turbine deployment locations considered as part of this study. See Table 1 for coordinates

2.7 RESULTS

2.7.1 Configuration 1: Turbines at locations B&C

The first set of simulations was run for two turbines placed at locations labeled as B and C. These locations are along a mid-channel streamline approximately 7 turbine diameters apart. Strong interactions were observed between the two turbines as shown in Figure 11. The wake shed by the upstream turbine therefore significantly reduced the power produced by the downstream turbine. The impact on power production is clearly shown by plotting the turbine instantaneous power production over the course the tidal cycle (see Figure 12).

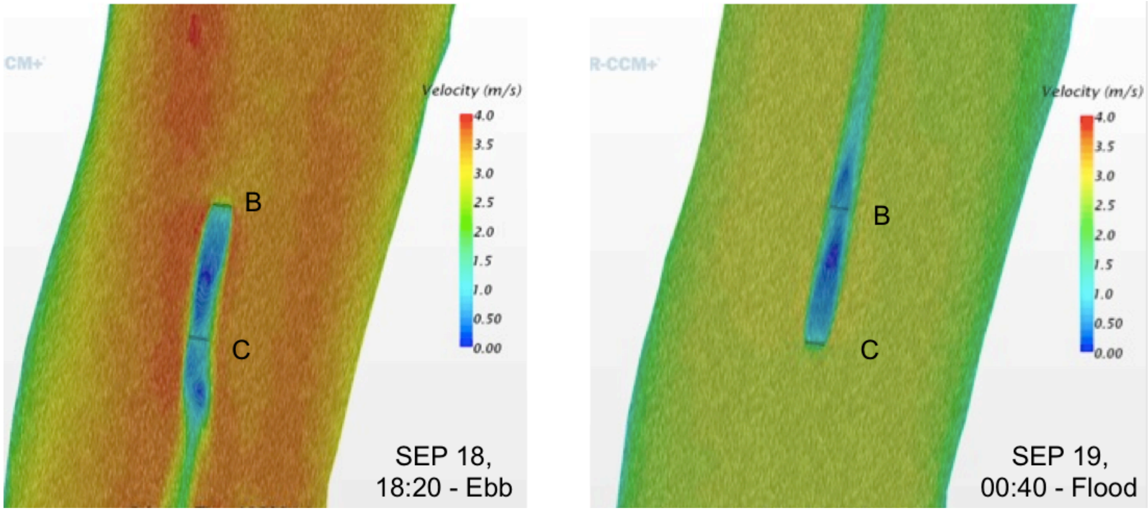


Figure 11: Velocity magnitude plot for a snapshot in time for turbines placed at location B and C showing turbine wake interaction

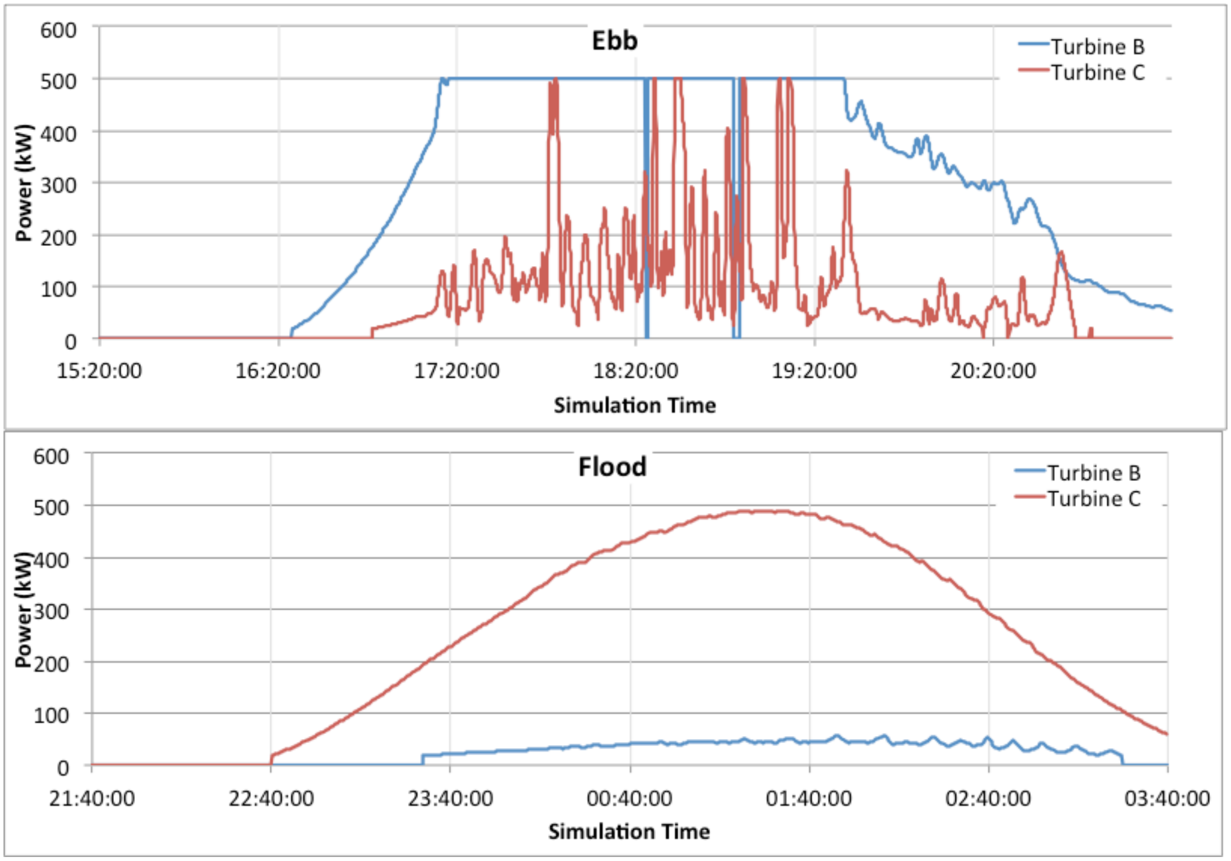


Figure 12: Instantaneous Turbine power production for ebb and flood tides - turbine cutout set at 4m/s

2.7.2 Configuration 2: Turbines at locations B2 & B3

The second set of simulations were run for two turbines placed side by side to ensure that there is no wake interaction leading to reduced performance. The wakes generated behind the turbines are shown in Figure 13 at instants in time corresponding the fastest ebb and flood flows through the channel. Figure 14 shows the instantaneous power produced by each turbine over a tidal cycle.

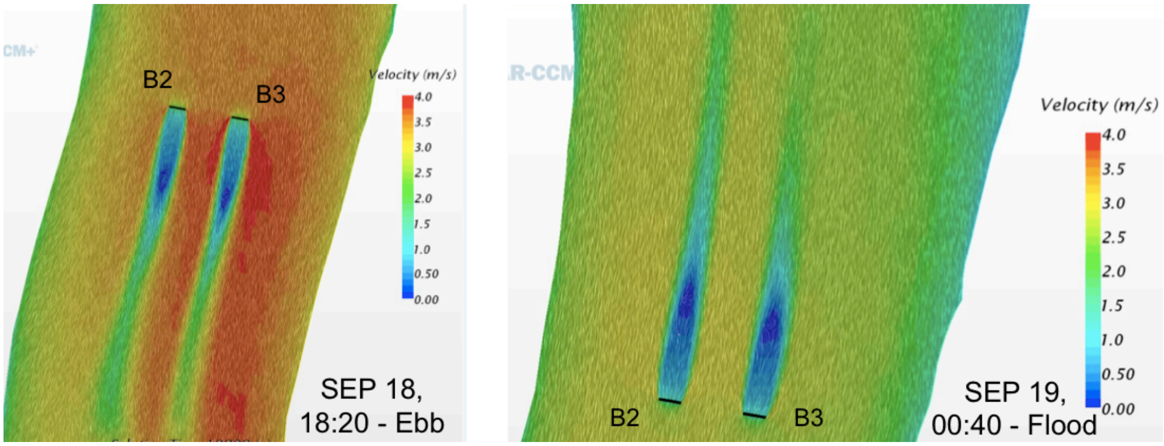


Figure 13: Velocity magnitude plot for a snapshot in time for turbines placed at location B2 and B3

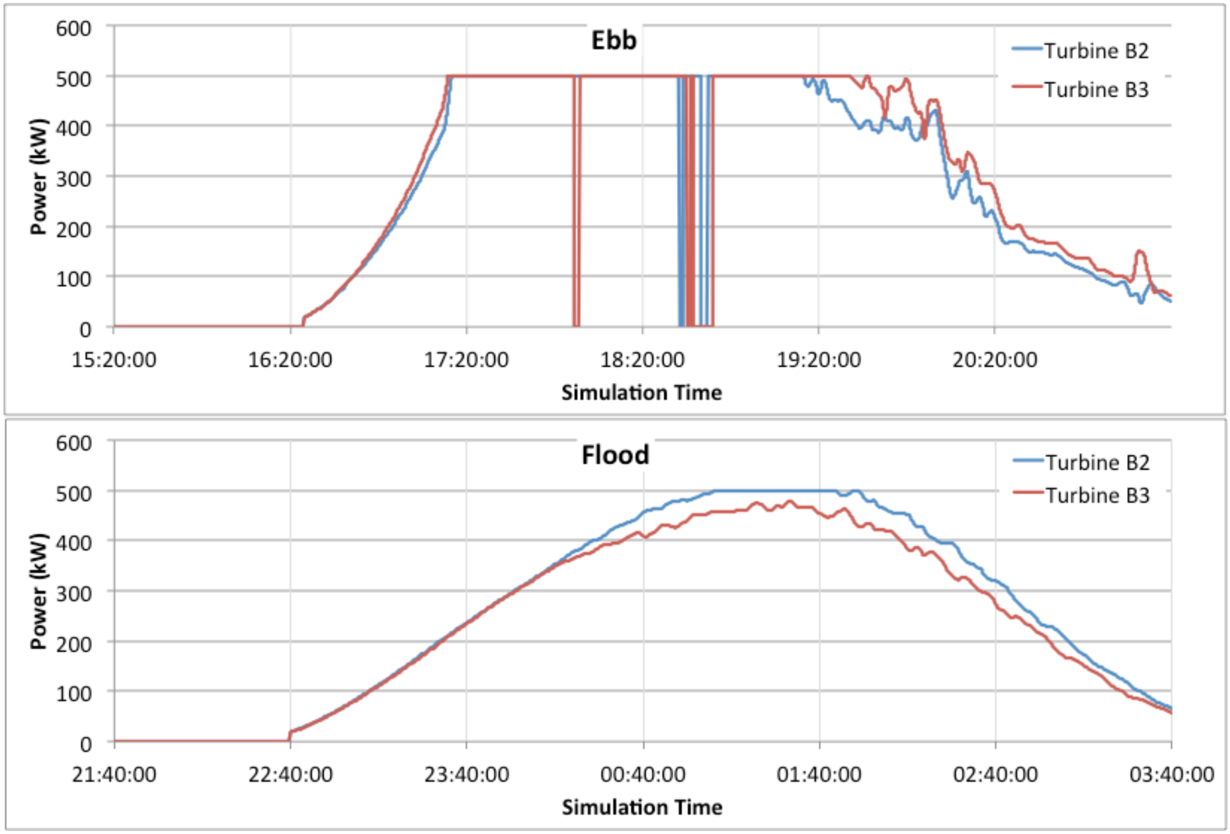


Figure 14: Instantaneous Turbine power production for ebb and flood tides - turbine cutout set at 4m/s

2.7.3 Configuration 3: Turbines at locations A2 & C2

The third set of simulations assessed a two turbine deployment along the length of the channel, as was the case for configuration 1, but the turbines are spaced much further apart and partially offset to avoid wake interactions. As shown in Figure 15, this spacing ensured that the wakes indeed did not interact. The power produced by the two turbines is therefore very similar to configuration 2 (see Figure 16).

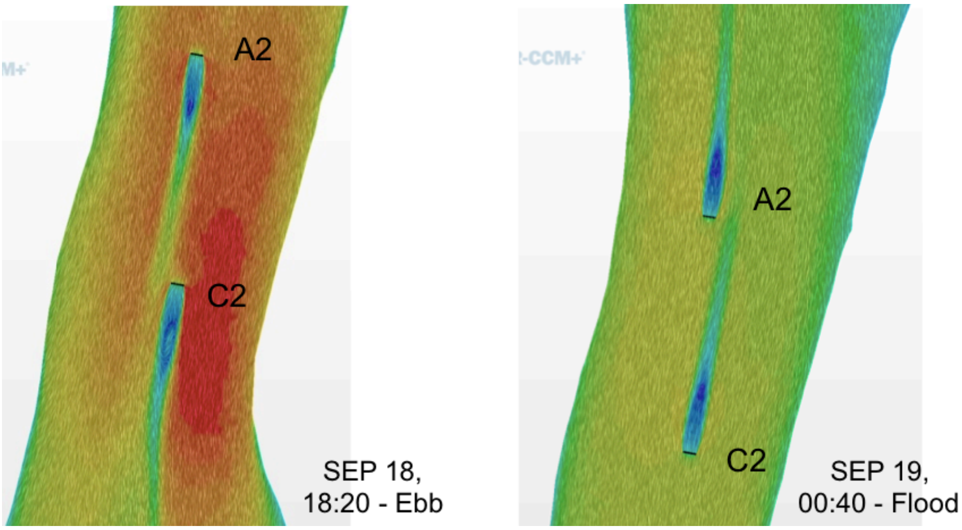


Figure 15: Velocity magnitude plot for a snapshot in time for turbines placed at location A2 and C2

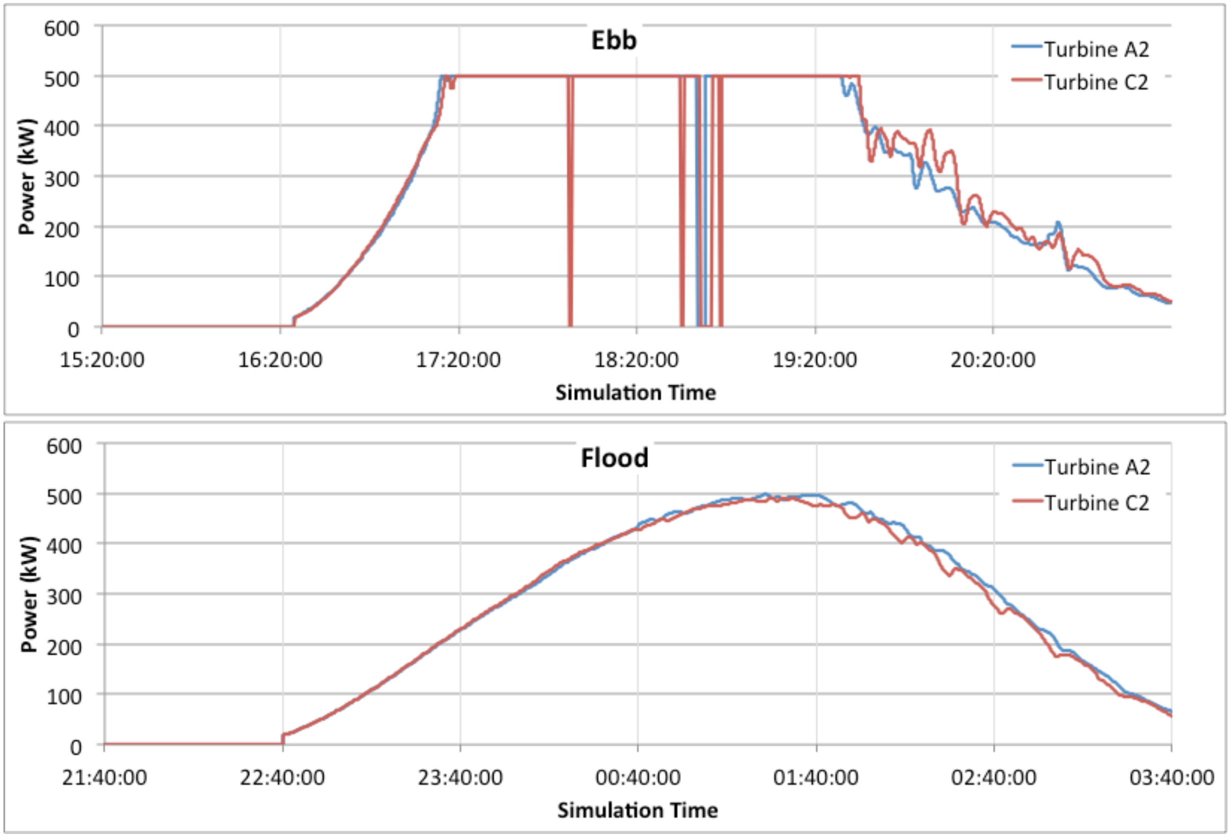


Figure 16: Instantaneous Turbine power production for ebb and flood tides - turbine cutout set at 4m/s

2.8 DISCUSSION

Table 2 summarizes the results of the three turbine configurations studied by comparing the amount of energy produced by the turbines over an ebb and flood tidal cycle.

Values are provided for two cases:

1. Turbine cut in speed = 1m/s, cut out speed = 3.5m/s
2. Turbine cut in speed = 1m/s, cut out speed = 4.0m/s

Table 2: MWh of energy production

		Ebb Tide		**Flood Tide**	
	Cut out:	***3.5 m/s***	***4.0 m/s***	***3.5 m/s***	***4.0 m/s***
Config. 1	Turbine B	1.03	1.70	0.15	0.15
	Turbine C	0.44	0.45	1.50	1.50
Config. 2	Turbine B2	1.15	1.65	1.57	1.57
	Turbine B3	0.97	1.69	1.45	1.45
Config. 3	Turbine A2	1.18	1.65	1.52	1.52
	Turbine C2	1.08	1.64	1.49	1.49

The results from this specific set of simulations are summarized as follows:

- The amount of energy generated is shown to be of very similar magnitude for all locations considered to date, provided that the turbine is not placed in the wake of an upstream turbine as was the case for configuration 1;
- Increasing the cutout speed of the turbine from 3.5m/s to 4.0 m/s increases power production by about 50% during the more energetic ebb tide. The increased cut out speed does not have an impact on power generation during the flood tide because current speeds don't exceed 3.5 m/s for the simulated day.
- It's interesting to note that the simulations show that less power will be produced during the stronger ebb tide when the turbine cutout speed is limited to 3.5m/s compared to the less energetic flood tide. This occurs because the turbine would be forced to cutout for the strongest portion of the ebb tide.

It is important to bear in mind that the results provided here are for a single ebb and flood cycle for a specific day. The impact of factors such as cut out speed on project revenues and lifecycle costs need to be considered over many tidal cycles.

Moreover, the accuracy of the energy production predictions is limited by the accuracy of the CFD model and the method used to represent the turbine. More sophisticated turbine models for use in these types of CFD simulations are presently under development. These models will be able to replicate the turbine performance and thrust as well as tune the wake.

This work therefore provides a stepping-stone for further studies that will be required to finalize the turbine deployment locations and specify the equipment requirements.

3 CONCLUSIONS

The objective of this project was to compare Acadia's ocean model and Mavi's CFD model of Petit Passage to ADCP measurements followed by selecting turbine deployment locations, and subsequently predict power generation of an ebb and flood tidal cycle.

The comparison of the computer simulations to the ADCP data revealed that:

- The flow through Petit Passage accelerates at a faster rate than predicted by the computer models. The models therefore predict slower current speeds in the first couple of hours of the tidal cycle (see Figure 7, Figure 8). This discrepancy needs to be addressed by understanding the root cause of the slower ramp up speed prediction by FVCOM.
- The agreement between the computer models and ADCP measurements is good later in the tidal cycle when the flow speeds are high. Some discrepancies are observed in the CFD model predictions that are likely attributed to the over prediction of large scale eddies. Adjustments to the bottom roughness specification are expected to improve results by damping the turbulence.

Three configurations of two 10m diameter turbines (rated at 500kW in 3m/s flows) were modeled in Petit Passage (see Table 1) using the CFD model. The results of the first turbine configuration showed a significant reduction in power because the turbines were placed along the same streamline without sufficient spacing to allow for wake dissipation. The second and third turbine configurations successfully utilized information from the first configuration and industry knowledge to avoid wake interactions.

The energy production over the ebb and flood cycles was calculated for each turbine. Specific outcomes from the three sets of simulations are summarized in Section 2.8. In general, as long as there were no interactions between the turbine wakes, the power generated at the 6 deployment locations considered did not vary substantially over the time period simulated. However, financial models for tidal energy projects are highly sensitive to revenues from energy production and the effects of natural and wake induced spatial variation ("micro-siting") on long-term energy production should be investigated further. Other factors also need to be considered in more detail to finalize the deployment location of the two turbines such as ease of sub-sea cable deployment, marine operations tolerances, distance to shore station, impact of local bathymetry on foundation or anchor deployment, and navigational constraints.

4 FUTURE WORK

This project was a first step in validating the FVCOM and CFD models of Petit Passage, selecting turbine deployment locations and quantifying power produced.

More R&D work is required to improve the tools and methods used for tidal flow and turbine modeling. More work is also required to provide the project developers and technology providers with accurate tidal flow information and predictions of the power the turbines will generate over the duration of the project to inform engineering design and financial models.

The following is a list of focus areas for future work:

- Perform additional Ocean model and CFD model validation using existing and new drifter data;
- Investigate the cause of the slower tidal current ramp up speed prediction by FVCOM compared to ADCP measurements;
- Improve the representation of the turbines in the CFD model – tune the power, drag and wake of the turbine to a specific technology;
- Develop a methodology for varying the water level elevation in the CFD model;
- Run simulations for a series of tidal cycles to quantify the importance of turbine cutout speed on project lifecycle costs.

5 DISSEMINATION AND TECHNOLOGY TRANSFER

The outcomes of this project will be communicated to all stakeholders by distributing this report and presenting at the annual OERA conference. All three project partners are very active in the ocean energy industry. They will therefore apply the lessons learned to future projects, whether it be the build out of the Petit Passage site or continued R&D on tidal channel and turbine modeling.

6 PUBLICATIONS

This work will be published on the OERA website in the form of a report.

7 EXPENDITURES OF OERA FUNDS

A summary of project expenditures is provided in Table 3. Mavi spent a significant amount of extra time on the project to complete the validation and turbine simulation work. This is reflected in the additional in-kind person and computer hours.

Table 3: Summary of expenditures
(Unavailable in web copy of report)

8 EMPLOYMENT SUMMARY

A list of individuals working on this project is provided below.

Name	Position	Student	PhD., MSc., Undergrad	Full or Part-Time	Scientific contributions made to the research	Work-months
Acadia University						
Richard Karsten	Professor	No	PhD	Part-time	Developing validated FVCom computer models of Petit Passage	5
Fundy Tidal Inc.						
Greg Trowse	Principal	No	MASc	Part-time	Providing ADCP validation data, identifying turbine deployment locations, review and discussion of CFD modeling results	5
Mavi Innovations Inc.						
Timothy Waung	Project Engineer	No	MASc	Part-time	Developing validated CFD computer models of Petit Passage	5
Voytek Klaptocz	Technical Director	No	MASc	Part-time	Developing validated CFD computer models of Petit Passage	5