Applications of 3D Coastal Circulation Numerical Model in Assessing Potential locations of Installing Underwater Turbines[1]

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Abstract

The three-dimensional, coastal circulation numerical model COCIRM-SED was recently adapted and optimized to simulate and predict the flows in southern Discovery Passage and Canoe Pass, BC, Canada. These model results provided reliable, detailed flow information for use in assessing potential locations of installing and operating underwater tidal current turbines. In the application of modeling flows in southern Discovery Passage, the model involved tidal forcing with 69 constituents at open boundaries as well as the effects of the Campbell River freshwater input and the Coriolis. Detailed hourly model flows for typical neap and spring tides were extracted for use in the site assessment of potential locations for tidal current turbines. In the other application of modeling flows in Canoe Pass, the model was used to predict the water flows and water levels through Canoe Pass if the dam in Canoe Pass, which has been in place since the 1940's, were completely removed and replaced by a passage of 40 m wide between Quadra and Maude Islands.

In both studies, the model went through extensive calibration and verification processes using available measurements of water levels and ocean currents at various sites in the modeling areas. It was demonstrated that the 3D model has very good capabilities for simulating water level and currents in both model areas under different conditions.

Introduction

Electricity generation using underwater turbines in areas of strong tidal currents can provide a very dependable and predictable source of clean and renewable energy, often with minimal and/or mitigatible impact on the natural environment. This paper describes a technique using high resolution 3D numerical models to assess potential sites and address key issues for this emerging energy source. This tool is capable of providing such important information as quantifying the total generation potential, input to detailed engineering design of the underwater turbine system, the effects of the turbine system on ambient flow patterns, and potential environmental impact that may arise.

At sites in the Discovery Passage area off the east coast of Vancouver Island, British Columbia, Canada (Figure 1), numerical modeling studies of ocean currents and water levels were recently carried out using the 3D coastal circulation model

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COCIRM-SED to assess the potential at various sites for operation of underwater turbines to generate electrical power. One particular site, Canoe Pass, located between Quadra Island and Maud Island, features an artificial dam or causeway which blocks the passage of water from Seymour Narrows immediately east of the Pass. As a result, significant water level differences exist between two sides of the dam with the maximum heads up to 1.5 m during spring tides and 0.8 m during neap tides. The difference in water levels on either side of the dam has the potential for significant renewable energy through installation of underwater turbines for generating electrical power. Numerical modeling simulations of the currents and water levels were conducted, including the present conditions for model calibration and verification, possible future conditions in which the dam is completely removed and the Pass is restored to its original configuration, and possible future conditions in which the dam is partially removed to allow the passage of water through an underwater turbine. In the other application of modeling flows in southern Discovery Passage, the model was adapted to provide detailed hourly flows of typical neap and spring tides for use in the site assessment of potential locations for tidal current turbines. This paper reports these model approaches and results in details.

Model Approach

The 3D coastal circulation numerical model COCIRM-SED, adapted in these studies, represents a free surface, computational fluid dynamics approach to the study of river, estuarine and coastal circulation regimes, where the pressure is simply assumed hydrostatic. The model explicitly simulates such natural forces as pressure heads, buoyancy or density differences due to salinity and temperature, river inflow, meteorological forcing, and bottom and shoreline drags (Jiang, et al., 2002; Jiang, et al., 2003 and Fissel and Jiang 2008). The model applies the fully three-dimensional basic equations of motion and conservative mass transport combined with a second order turbulence closure model (Mellor and Yamada, 1982) for vertical diffusivity and Smagorinsky's formula (Smagorinsky, 1963) for horizontal diffusivity, then solves for time-dependent, three-dimensional velocities (u,v,w), salinity (s), temperature (T), turbulence kinetic energy (k) and mixing length (l), horizontal and vertical diffusivities (K_h, K_v), and water surface elevation (ζ). The horizontal grid element sizes are typically in the range of 5 – 100 m. The water column may be resolved using either sigma or z grid, with a flexible distribution of typically 10 – 20 layers.

To validate it as a reliable tool for the objectives in these studies, the model at first went through appropriate calibration and verification processes using available water elevation and ocean current data. After validated, the model was then implemented to simulate water levels and ocean currents for different scenarios. The detailed model flows at various vertical levels were mapped and used to assess site potential of installing and operating underwater tidal current turbines, and potential environmental impact that may arise.

The model was initially tested and operated in calibration runs. Various physical parameters, mainly bottom drag coefficient and horizontal and vertical eddy diffusivity coefficients, were repetitively adjusted to achieve optimal agreement with the observations. The vertical diffusivity for the model, as derived from the second order turbulence closure model (Mellor and Yamada, 1982), was found to be robust.

Most efforts were involved in testing and adjusting of the bottom drag and the horizontal diffusivity.

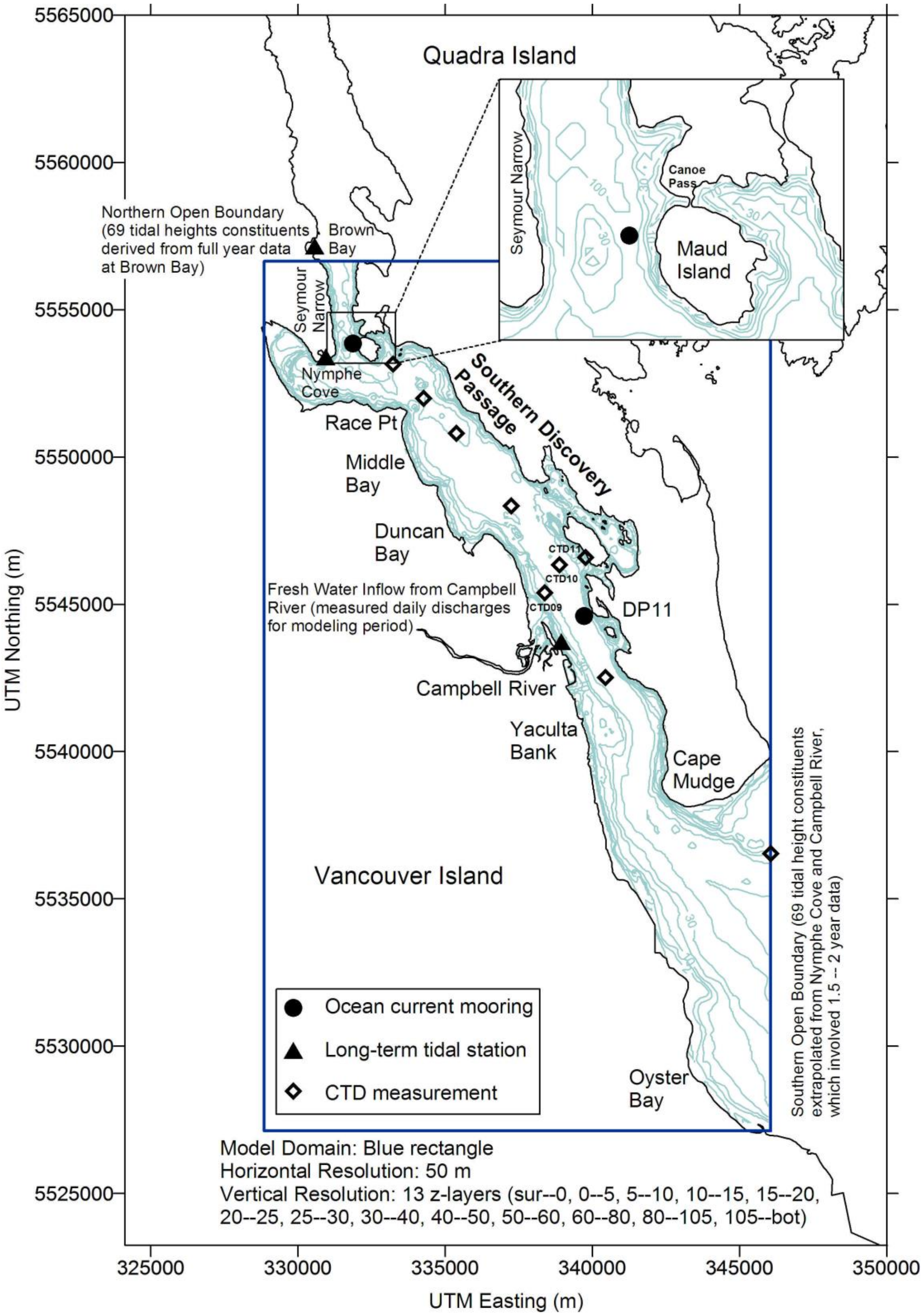


Figure 1. The study area and data sites.

Once reasonable agreement is attained for the calibration cases, the model was next operated in validations runs using the previously optimized physical parameters and compared with different observation data sets. The agreement between the model outputs and the observations is used to assess the capabilities of the model. If the comparisons do not meet the model requirements, or indicate that significant further improvements are needed, the calibration processes can be repeated to improve the model performance.

Modeling Flows in Southern Discovery Passage

The objective in the study of the flows in southern Discovery Passage is to provide some preliminary 3D numerical modeling simulations of the ocean currents, which can be used to investigate the feasible sites for installing and operating underwater tidal current turbines (Jiang and Fissel, 2007). The model domain for this application includes the portion of southern Discovery Passage extending from Oyster Bay in the south to Brown Bay in the north, with an area of about 30 km by 17 km (Figure 1). The whole model domain is resolved by a horizontal grid of size 50 m by 50 m, and 13 vertical z-coordinate layers with higher resolution near the surface in order to appropriately resolve salinity and temperature induced density stratification.

The model involves two open boundaries, respectively the cross-section between Oyster Bay and Cape Mudge to the south and at Brown Bay to the north (Figure 1). The boundary conditions at these two locations were specified by tidal elevations and inflow salinity and temperature. The tidal elevations at these two open boundaries were derived from 69 tidal height constituents using Foreman's tidal prediction program (Dr. M. Foreman, Institute of Ocean Sciences, Dept. of Fisheries and Oceans, Sidney, B.C., Canada, pers. comm.). The 69 tidal constituents at the northern open boundary were derived from a full year tidal elevation data in Brown Bay. The 69 tidal constituents at the southern open boundary were extrapolated from Nymphe Cove and Campbell River, where 1 – 2 year tidal elevation data were used in the tidal analysis. The tidal elevations are assumed to be approximately uniform over the cross-sections of both open boundaries. In COCIRM-SED, geostrophically balanced elevations due to Coriolis force at each open boundary are calculated and superimposed on tidal components at every time step.

The inflow salinity and temperature at the southern open boundary were specified by the monthly salinity and temperature profile data at this boundary (Crean and Ages, 1971). The inflow salinity and temperature at the northern open boundary were extrapolated from the data at the southern open boundary in terms of the salinity and temperature horizontal gradients derived from the CTD-bottle profile data inside Discovery Passage (Figure 1).

At Campbell River, the freshwater discharges were given in the model, which were retrieved from daily discharges in Canadian Hydrological Data Base. The discharge was assigned a zero salinity (i.e. freshwater) and realistic temperature for each model case.

The 3D model was calibrated and validated by comparison of model output to the tidal analysis results from existing data sets as shown in Figures 2 and 3. Good agreement was achieved between model- and data-based currents and water elevations. The root mean square errors of modeled versus predicted current speeds and water levels are respectively 1.21 m/s and 0.32 m for the calibration results as shown in Figure 2, and 0.34 m/s and 0.44 m for the verification results as shown in Figure 3. To demonstrate the ability of the model to sustain a surface brackish layer that is typically found in estuarine environments, the modeled and measured salinities are compared at three CTD stations for the verification case. It is seen that the modeled salinities do include a brackish layer in the vicinity of Campbell River, and given the approximate boundary conditions for salinity, the model salinities are in reasonable agreement with observations (Figure 4).

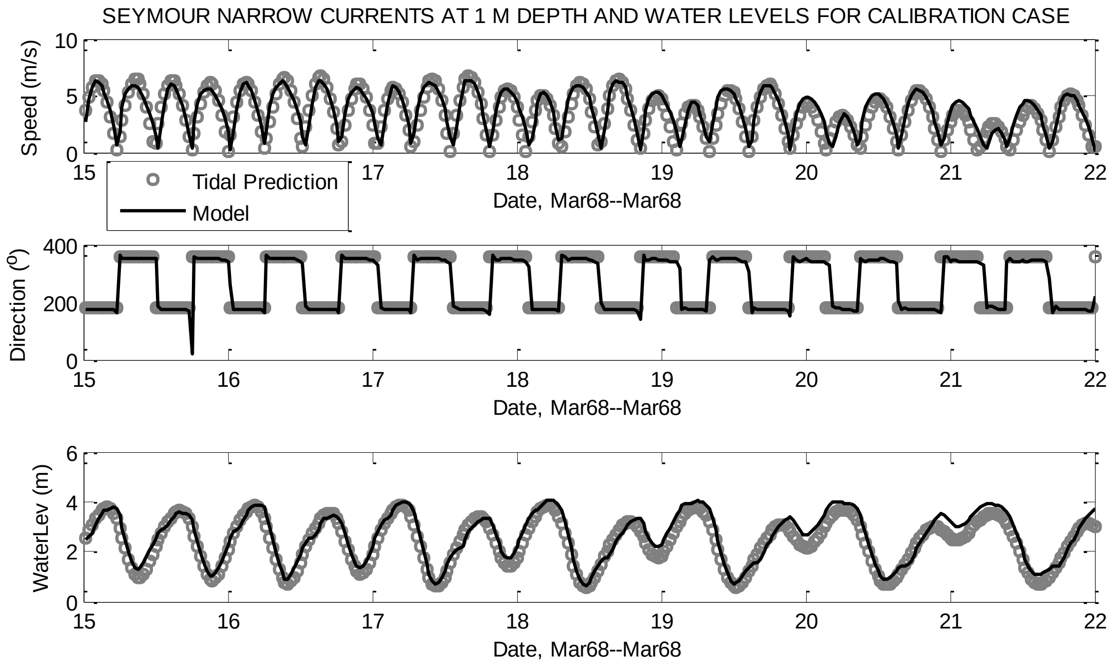


Figure 2. Calibration model results of currents at 1 m depth and water levels at the site Seymour Narrow, with comparisons to the tidal prediction results.

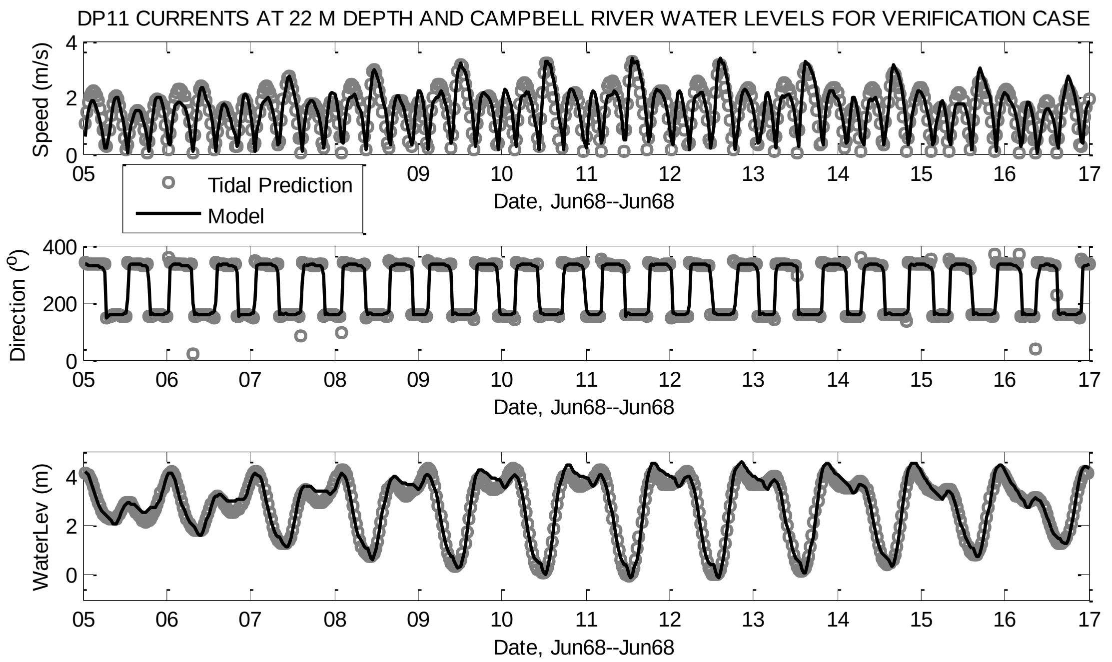


Figure 3. Verification model results of DP11 currents at 22 m depth and Campbell River water levels, with comparisons to the tidal prediction results.

The results of the 3D current model for peak flood and ebb tidal flow conditions at 17.5 m depth are shown in Figure 5. Tidal current results of this type provide the basis for site selection of optimal turbine locations, in combination with considerations of ship traffic routes and site specific environmental considerations.

Modeling Flows in Canoe Pass

The simulations of ocean currents and water levels using the 3D numerical model COCIRM-SED were carried out for Canoe Pass between Quadra Island and Maude Island (Figure 1). Canoe Pass has a man-made causeway (rock dam) across it, which blocks the passage of water from Seymour Narrows immediately east of the Pass (see left panel in Figure 6). The dam has been in place since the 1940's, and originally built as an access way for removing of Ripple Rock in Seymour Narrow (Figure 1), which was a shallow bottom feature with the shallowest portion only several meters below Chart Datum. The Ripple Rock was removed in 1958 using 1,375 tons of explosives from underneath. New Energy Corporation Inc. planned to remove this dam and replace it with at least two underwater turbines supported by bridge structure (see right panel in Figure 6). These turbines will generate a maximum of 500 kW from strong tidal flows expected at this site. The numerical model studies are part of a site investigation to assess the potential for operation of underwater turbines to generate electrical power, including past and present conditions, and potential future conditions related to the installation of an underwater turbine (Jiang and Fissel, 2005).

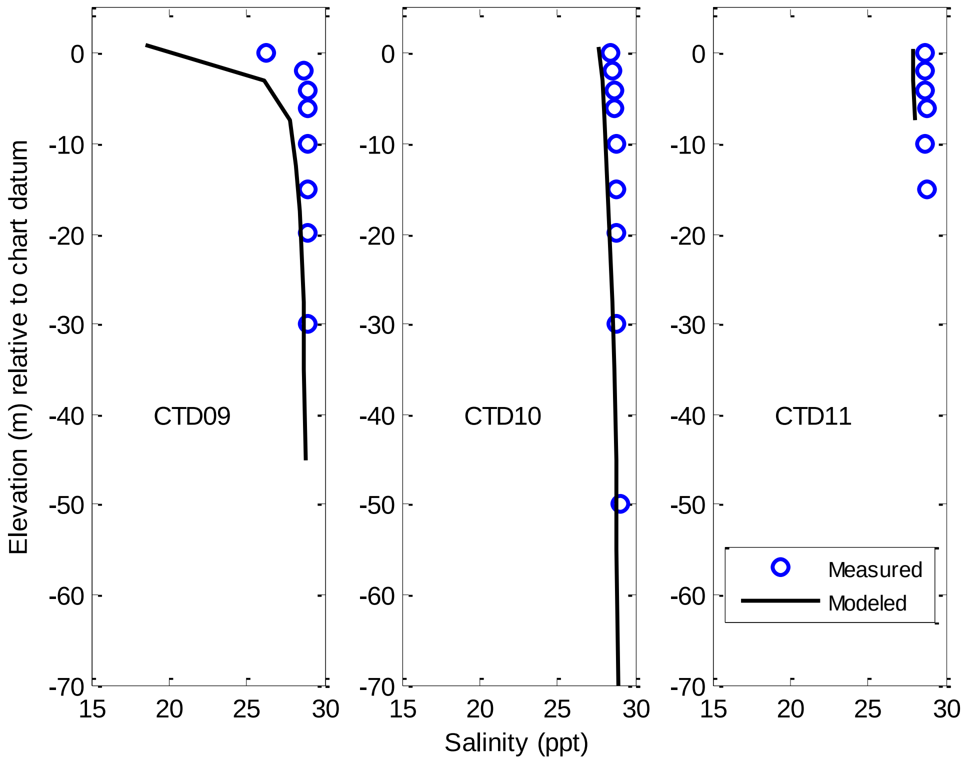


Figure 4. Comparisons between modeled and measured salinity at three CTD stations (Figure 1) outside of Campbell River for the verification case, where the modeled results are those at similar tidal stages with CTD measurements.

For this study, the model was operated over an area of about 8 km by 8 km in total size using a 50 m by 50 m horizontal grid resolution. For an area of 2 km by 3 km centred on Canoe Pass, a higher resolution nested grid was incorporated into the model, with a horizontal grid size of 10 m (Figure 1). Both 50 m and 10 m model grids used 10 equally-spaced vertical sigma-layers with each layer height equal to 0.1*H* (*H* represents the total water depth), and were coupled at interfaces and solved together every time step with a single modeling procedure using the two-way, dynamic nested grid scheme in COCIRM-SED (Jiang, et al., 2003).

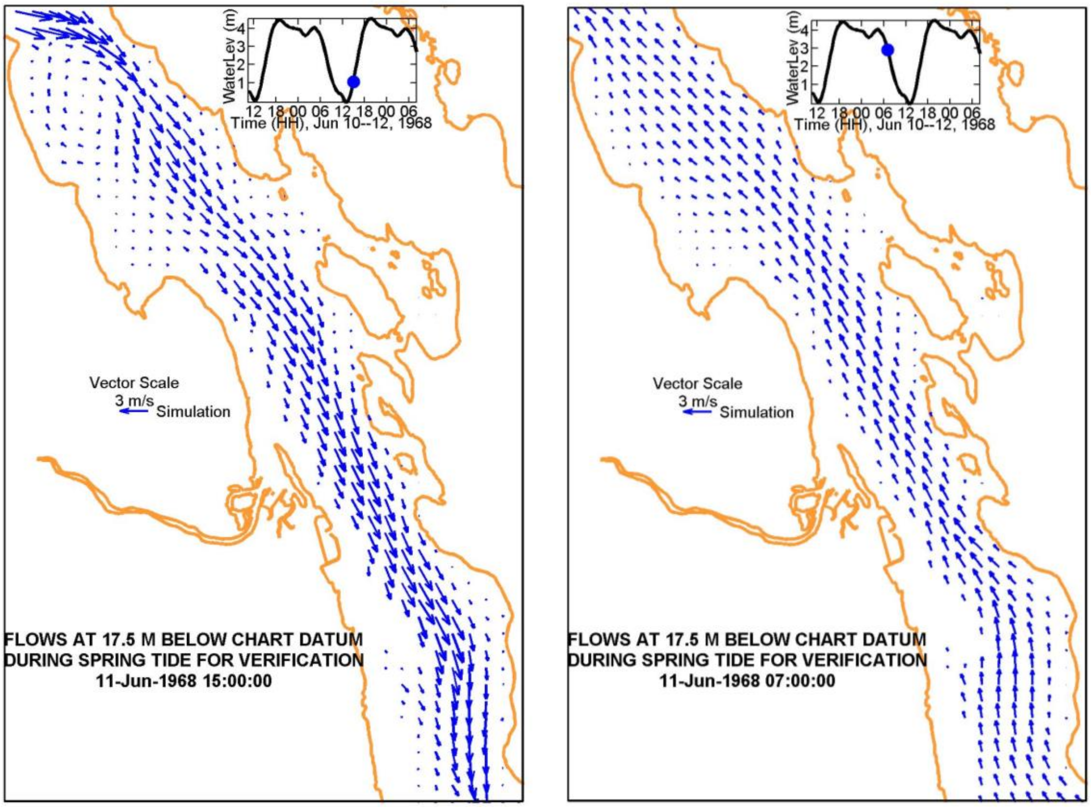


Figure 5. Model peak flood flows (left panel) and peak ebb flows (right panel) at 17.5 m below chart datum during a spring tide.

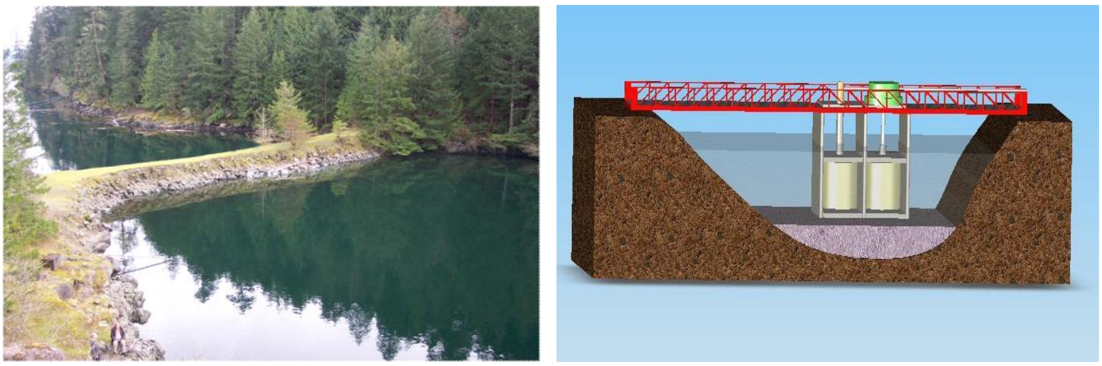


Figure 6. Photo (left) showing existing rock dam and depicted graph (right) showing replacement of the dam with two underwater turbines.

The model involved two open boundaries, respectively in the Duncan Bay in the south and in the Brown Bay in the north (Figure 1). The boundary conditions at these two locations were specified by tidal elevations, which were computed using 9 major tidal constituents: O_1, P_1, K_1, N_2, M_2, S_2, K_2, M_4, MS_4, which were derived by Canadian Hydrographic Service from the field data of 29 days duration in Duncan Bay and of 367 days in Brown Bay. Again, the tidal elevations are assumed to be approximately uniform over the cross-sections of both open boundaries, and the geostrophically balanced elevations due to Coriolis force at each open boundary are calculated and superimposed on tidal components at every time step.

Model Validation

The model was calibrated by comparisons to the observations of water heads across the dam as given in Figure 7 with good agreement being achieved. The model was operated both with and without the Ripple Rock in place, which was removed in 1958. As seen from the model results, the effect of the Ripple Rock on the water heads across the dam is very minor. Further model validations were obtained by comparing model output with direct current meter measurements made in the Seymour Narrows area using historical oceanographic data sets, and the model results are in good agreement with observations (not shown).

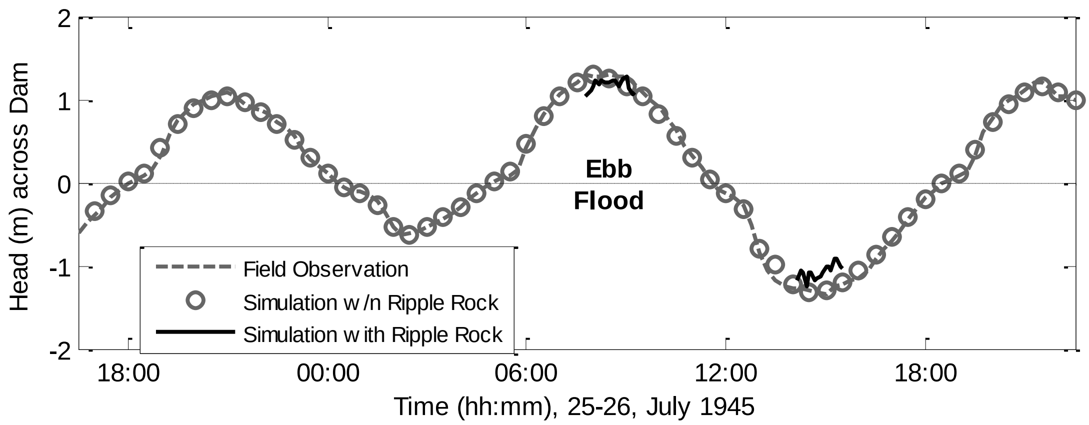


Figure 7. Modeled head across the Dam before Ripple Rock removed, with comparison to the data and simulations with Ripple Rock removed.

Model Results with the Rock Dam Fully Removed

The model was then run to simulate the tidal currents that would result from removal of the dam blocking Canoe Pass and essentially reverting to the conditions before the dam was installed in the 1940's. Figure 8 shows the bathymetry after and before the construction of the rock dam. The model results show that very strong tidal currents would occur through the narrow Pass, with a maximum flood current of about 4 m/s and a maximum ebb current of about 3.5 m/s (Figures 9 and 10).

In order to extend the nested grid model velocities for spring and neap tides to a whole month, the fitting between nested grid and coarse grid model velocities at the centre of former Dam was processed. It is found that simply multiplying the coarse grid model velocities by a factor of 0.95 results a very good agreement between nested grid and coarse grid model results for spring and neap tides. The correlation coefficient between coarse and nested grid model velocities is up to 0.99.

The converted coarse grid model velocities were then used to derive tidal current constituents with the standard tidal current analysis program, which were used to predict currents over a full year at the former Dam. The predictions for the same month as the coarse model run show that the predictions fit the simulations very well, with a correlation coefficient up to 0.99. The predictions of one year currents, at 15 minute time intervals, at the former Dam were used to compute the probability histogram of the currents through Canoe Pass (Figure 11), with the Dam removed. The results reveals maximum flow speeds of 9.02 knots (4.51 m/s) for flood and 8.95 knots (4.48 m/s) for ebb. Typical flood and ebb velocities are 3.5 knots (1.75 m/s) and -5.0 knots (2.5 m/s).

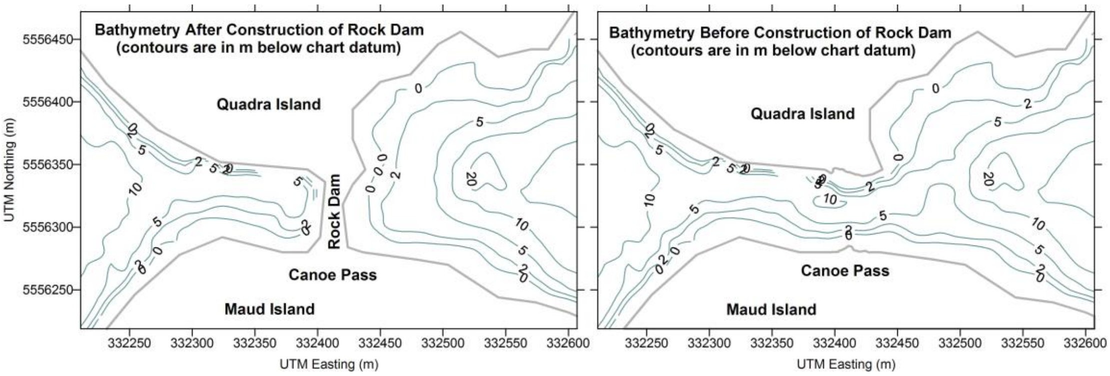
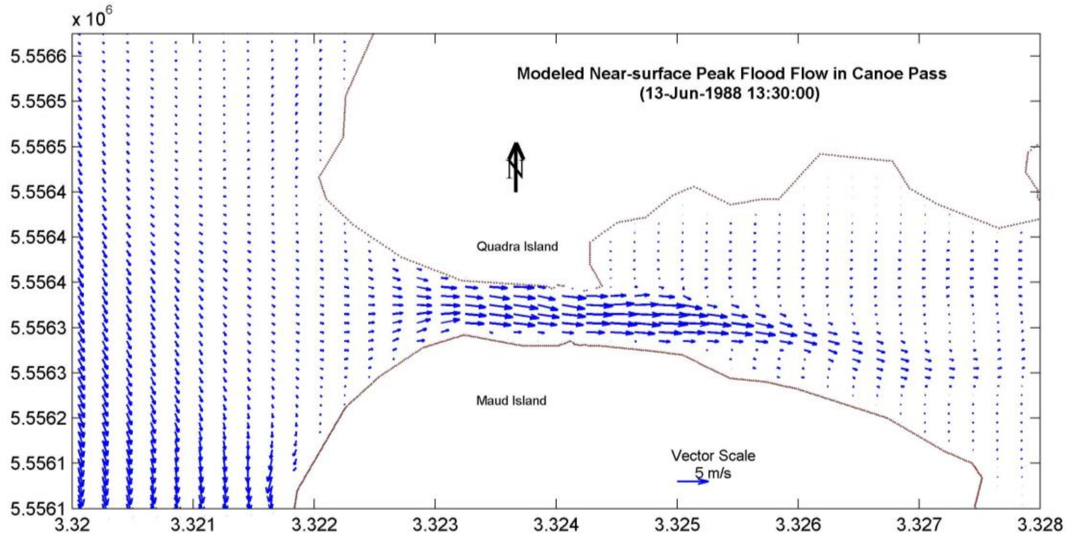


Figure 8. The bathymetry in the Canoe Pass before and after construction of the Rock Dam, as represented by depth contours on 10 m by 10 m nested model grid.



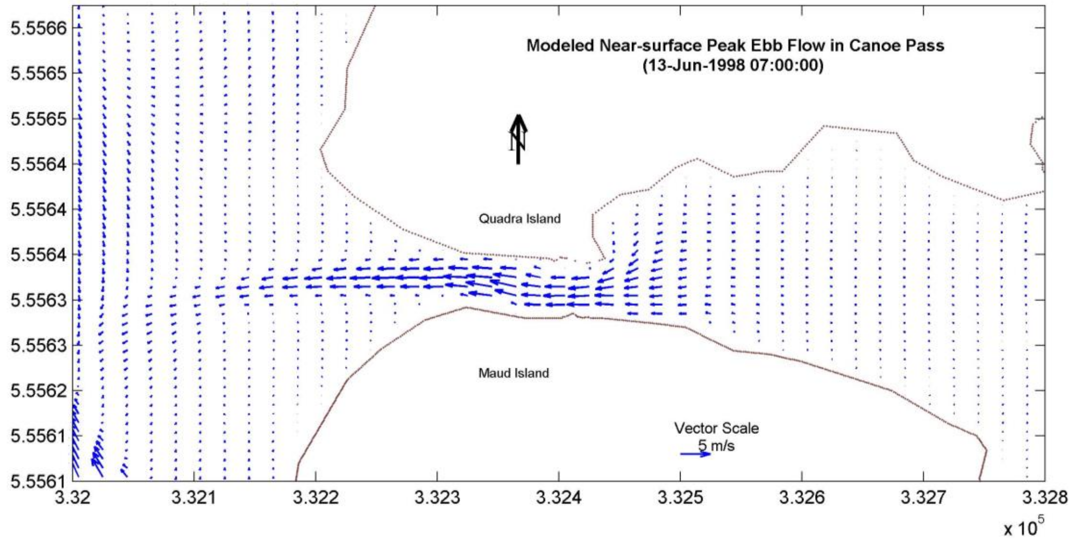


Figure 9. Peak flood (upper) and ebb (lower) in Canoe Pass with the Dam removed.

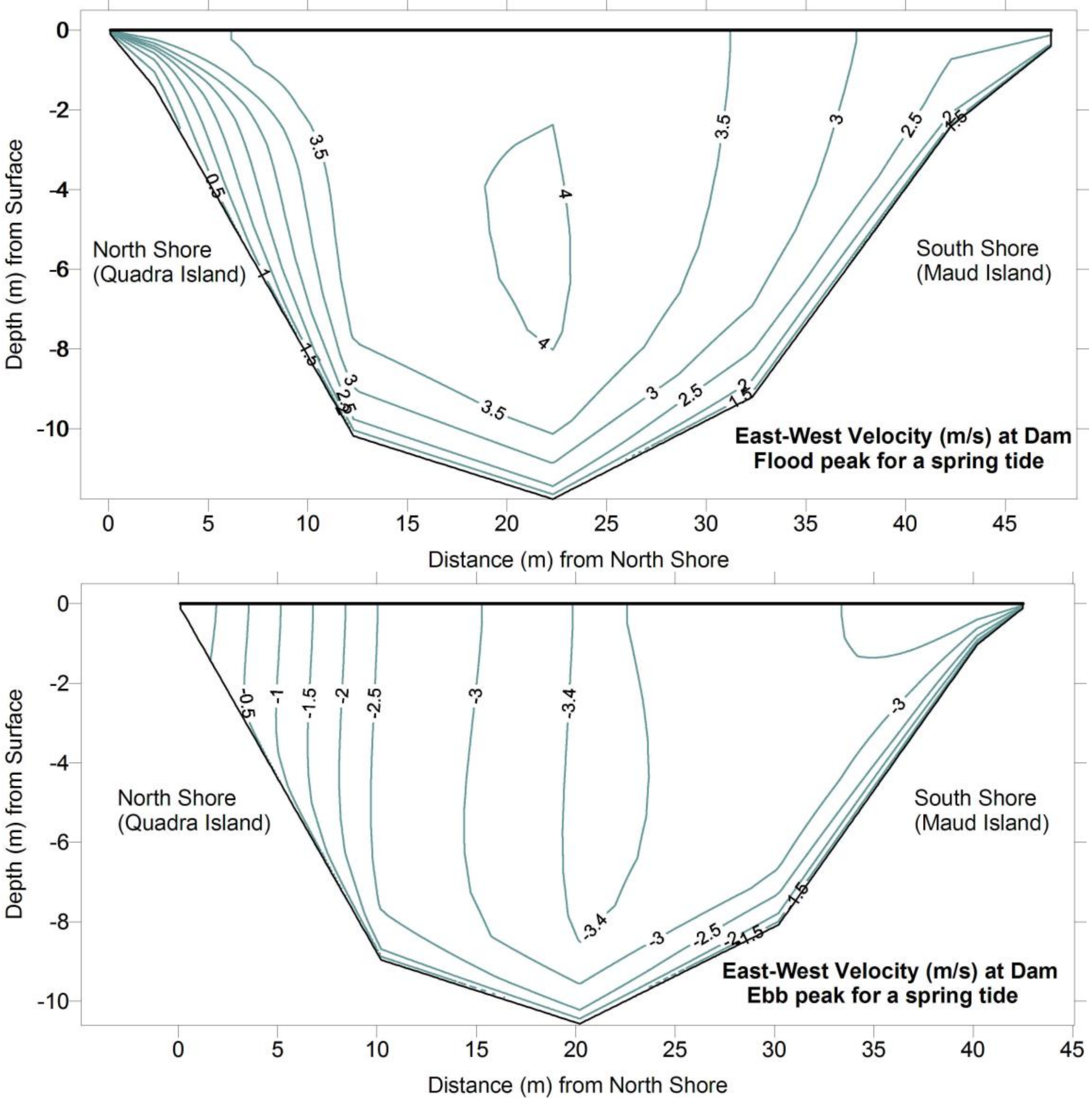


Figure 10. Velocity distribution over the cross-section of the Dam during flood peak (upper) and ebb peak (lower) of a spring tide.

Modeling Underwater Turbine

In order to demonstrate the model capability of simulating underwater turbine, a preliminary modeling experiment of Canoe Pass flow with a turbine in place was carried out in this study. Here, the Canoe Pass Dam is opened to allow a 10 m by 3 m gap at the middle of its cross section (Figure 12). One horizontal nested grid, which has the size of 10 m, and three vertical sigma-layers are used to represent the gap. The bottom elevation was adjusted along with the fluctuation of surface elevation to guarantee the 3 m vertical gap, represented by those three sigma-layers, at all times. Pressure head loss due to the turbine was applied to these open mesh faces only.

To represent the turbine opening appropriately, the model used the unique technique for mesh face barriers developed in COCIRM-SED, which has been fully validated in a number of practical applications as introduced in Jiang, et al. (2002), Jiang, et al. (2003), Jiang and Fissel (2004), Fissel and Jiang (2008), and Fissel and Jiang (2009). This technique allows one to place a barrier at any mesh face as long as the remaining open faces at a mesh side are consecutive (Figure 13). In the bottom and top open faces, appropriate drags are included similar with those for a solid wall. The model then solves the semi-implicit differential momentum equation for the barrier mesh side in the same way as the normal mesh side (Jiang, et al., 2003).

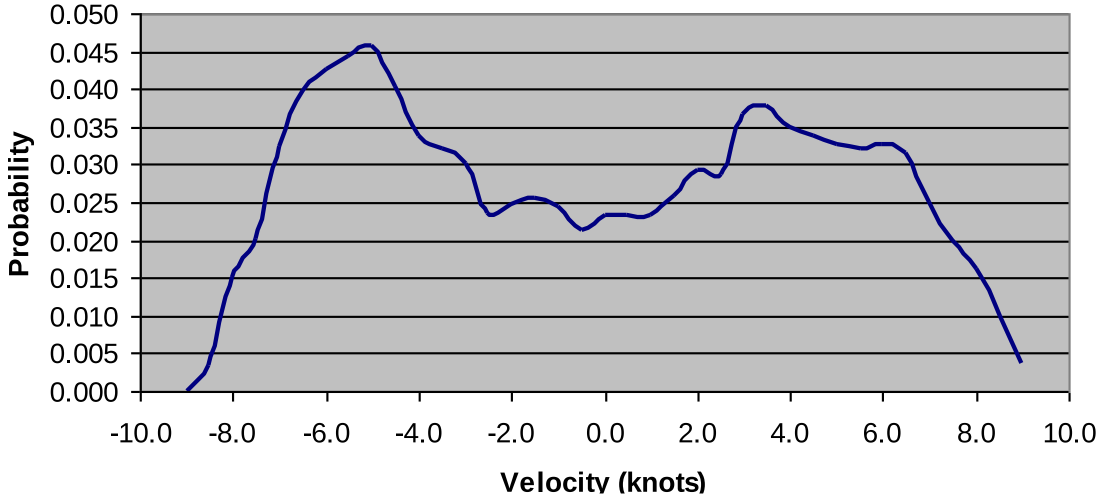


Figure 11. Probability histogram of Canoe Pass flows based on one year predictions.

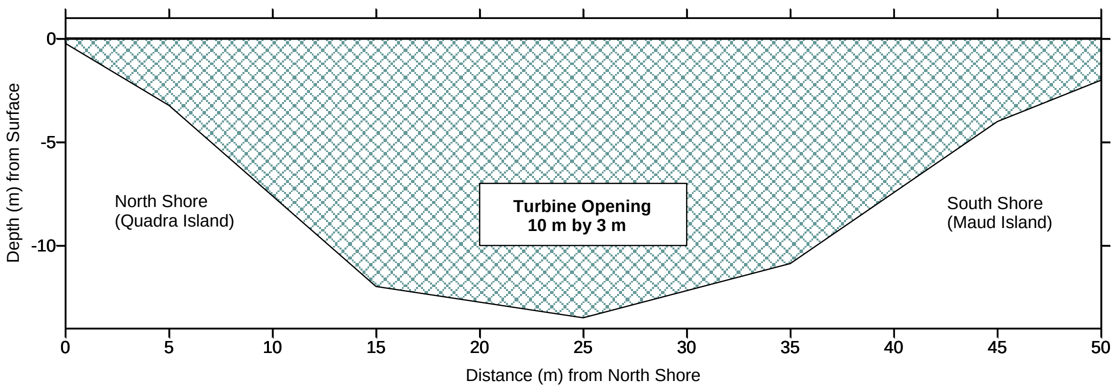


Figure 12. Map showing the 10 m by 3 m opening for turbine.

Figure 13 shows an example of model mesh with barriers. The left panel shows the staggered horizontal C-grid, and the right panel shows the vertical meshes with barriers (shaded faces), where *u*, *v*, *w* (z-coordinate), and ω (sigma-coordinate) are the 3D velocity components, *H* and *h* are the total and undisturbed water depths, c represents a scalar property such as temperature, salinity, suspended sediment or water quality constituent concentrations, etc., ζ is the water elevation, ρ is the water density, and *N* is the number of vertical layers. In solving the semi-implicit differential momentum equation using the standard computational approach described in Casulli and Cheng (1992), the model at first locates the bottom and top layers (Table 1), and then solves the momentum equation for these open layers after involving appropriate boundary conditions. The resulted linear equations for each layer have the generalized form as follows

$$(u,v)_k^{n+1} = b_k^n - c_k^n \Delta\zeta^{n+1} \tag{1}$$

Where the subscript *k* denotes the vertical kth layer, the superscript *n* represents the time step, the *b* and *c* are the coefficients dependent on hydrodynamic properties at time step *n*, and the $\Delta\zeta$ is the water elevation difference between two consecutive grid cells. For those closed mesh faces, such as barrier faces, and near-surface empty or near-bottom solid faces in z-coordinate, the values of *b* and *c* are equal to zero. Therefore, velocities across those closed mesh faces automatically equal to zero, and furthermore, no advection and diffusivity occur across the closed mesh faces. Substituting Eq. (1) into differential continuity equation leads to a linear system for water surface elevations, which is then solved effectively by the pre-conditioned conjugate gradient method (Casulli and Cheng, 1992).

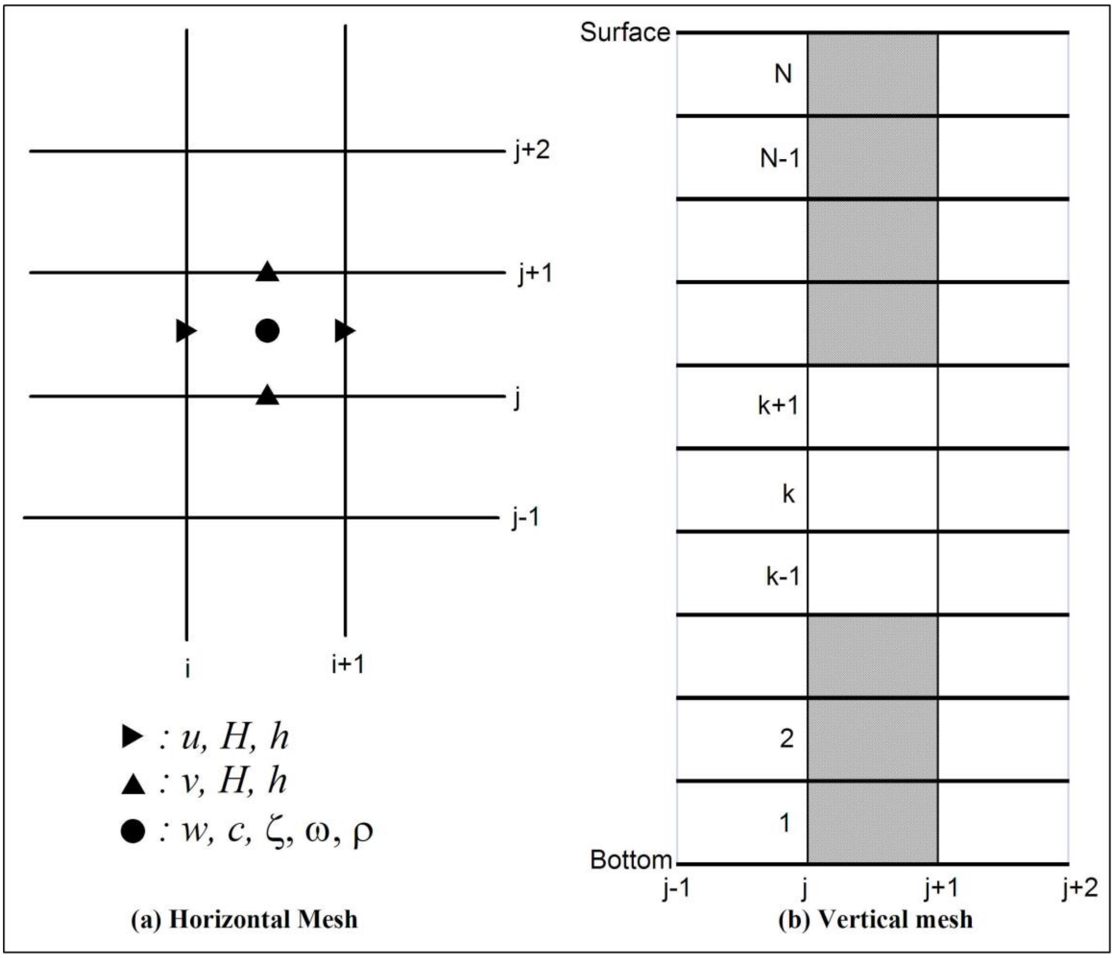


Figure 13. Schematic Diagram of computational mesh, notation and barriers for specific model sides.

Turbine Head Loss

The head loss (Δh_{loss}) due to the turbine is assumed proportional to the square of the velocity in turbine (V_A), i.e.

$$\Delta h_{loss} = \frac{f V_A{}^2}{2g} \tag{2}$$

where f is the drag coefficient, and g is the gravitational acceleration. The client, New Energy Corp., indicated that the discharge coefficient, representation of turbine losses, can be computed as

$$d_c = \frac{V_A}{(2g\Delta h_{loss})^{1/2}} = 0.58 \tag{3}$$

Substituting Eq. (3) into Eq. (2) yields f=2.9727.

To include the turbine head loss in the model in addition to the bottom drag, the barotropic term in the finite differential momentum equation at the mesh faces representing the turbine is modified as

$$-\frac{g}{dx}\left((\zeta_i-\zeta_{i-1})+\frac{f|u_i|u_i}{2g}\right) \tag{4}$$

where $\zeta_i-\zeta_{i-1}$ is the water elevation difference across the turbine, and u_i is the velocity at the model grid for the turbine. The second term in above formula represents the head loss due to the turbine, which is only applied to the open mesh faces representing for the underwater turbine, instead of the actual bottom at the mesh side (Sutherland, et al., 2007).

Table 1. Vertical layers, boundary conditions and specific requirement for all possible situations.

Mesh side	Vertical coordinate	Bottom layer		Top layer		Specific requirement
		Location	Boundary condition	Location	Boundary condition	
Normal	Sigma	1^{th}	Seabed drag	N^{th}	Surface wind stress	Open faces at each mesh side must be consecutive
	Z	$\geq 1^{th}$ (actual bottom)	Seabed drag	$\leq N^{th}$ (actual surface)	Surface wind stress	
Barrier	All	$\geq 1^{th}$ (specified by user)	Solid wall drag	$\leq N^{th}$ (specified by user)	Solid wall drag	

Preliminary Model Results

The drag coefficient f = 2.9727 derived from above equations for the underwater turbine is about three-order higher than a typical bottom drag. With such a high drag, it is expected that the velocities across the underwater turbine will decrease dramatically because of large head loss. For example, the head loss in the turbine is equal to 3.12 ft (0.95 m) at a velocity of 5.0 knots (2.5 m/s). The model results for spring tides show that the flow through the turbine has a velocity less than 5 knots all times, compared with a maximum velocity of 8 knots without a turbine and with the Dam fully removed (Figure 14). Consequently, the flow rate through former Dam decreases, with maximum values less than 3,000 cfs (85 m^3/s), and head difference across the Dam increases (Figure 14), which is almost back to the situation with the Dam fully closed since there is insufficient flow to balance water levels at the two sides of the Dam.

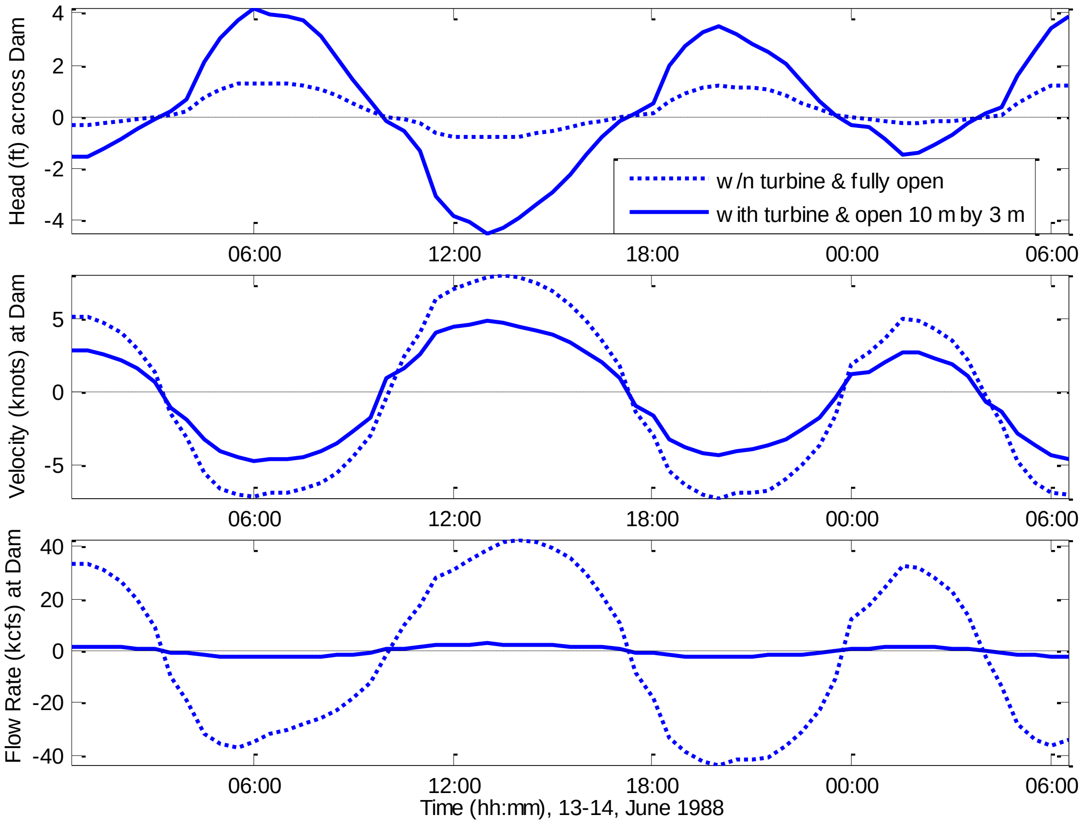


Figure 14. Model results with a turbine and an opening of 10 m by 3 m at the Dam for a spring tide, with comparisons to model results without turbine and with the Dam fully removed, upper panel for head across Dam, middle panel for velocity at center of the Dam, and lower panel for total flow rate across the Dam.

Conclusion and Discussion

The COCIRM-SED numerical model used in this study is a full three dimensional circulation model, based on the Reynolds-averaged Navier-Stokes fluid dynamics equations, with finite difference volume elements. The model uses a rectilinear grid in the horizontal and, in the vertical, either sigma or z coordinate grid with a flexible distribution of typically greater than 10 layers. The two modeling studies that were recently carried out in the Discovery Passage area provide examples of the capabilities of very high resolution circulation models for assessing site potential for tidal current generation for both free standing bottom turbines (such as Middle Bay) and for a turbine mounted with a dam in a very narrow tidal passage (such as Canoe Pass). The numerical models provide very high resolution of the three dimensional tidal currents at 50 m horizontal grid size over model domains of tens of kilometers in size. Much high horizontal resolution, of 10 m, is achieved within a nested grid area around potential turbine sites.

The numerical modeling capabilities described in this paper provide tidal current development companies with essential information to find the optimal sites for their turbine units, to simulate the operation of the turbine and its effects on the local oceanographic conditions and also to provide a quantitative basis for addressing environmental approval issues.

Acknowledgments

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We especially wish to thank our clients, including the consortium of companies involved in the Canoe Pass and Discovery Pass Tidal projects (Clayton Bear and Bob Moll of New Energy Corp; Thor Peterson and Chris Knight of Discovery Pass Tidal Power; Bill Johnston of Focus Environmental) and to the Middle Bay Project (R. Buchanan) and Norman Allyn of Westmar Engineers.

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