Three-Dimensional Numerical Modeling of Sediment Transport For Coastal Engineering Projects in British Columbia, Canada

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***Abstract*— Quantitative understandings of sediment transport for coastal engineering projects, such as removing and installing underwater cables, installing and operating underwater turbines and disposal of dredged marine sediment (or terrestrial overburden) are one of the key requirements in planning these projects, assessing potential environmental impact and obtaining regulatory approvals from government agencies. In support of the environmental assessment and approval, the highly-integrated, three-dimensional finite difference COastal CIRculation Model COCIRM-SED was recently adapted and optimized to predict the sediment transport processes associated with a number of coastal engineering projects in Roberts Bank, Canoe Pass and Brown Passage, British Columbia, Canada. In these applications, the circulation module was validated using historical ocean current data located in the study areas.**

For the Roberts Bank application, the model was used to predict the sediment plumes and deposition resulting from the removal and installation activities of existing and replacement underwater transmission cables across the Strait of Georgia. In the model, a total of six sediment categories from fine silt to medium sand were classified and simulated together in terms of sampled sediment characteristics. The model results were obtained with a trenching rate of 300 m/h and two trench sizes, a wide trench of 1.0 m wide × 1.0 m deep and a narrow trench of 0.2 m wide × 1.0 m deep. The amount of sediment that is suspended above the trench was taken to be 30% of the total volume for the wide trench and 25% for the narrow trench.

In the application of Canoe Pass, the model was adapted to predict the sediment transport resulting from installing and operating the underwater turbines in Canoe Pass, where the causeway dam, being in place since the 1940's, is planned to be completely removed and replaced by two underwater turbine systems for electricity generation in this area of large tidal currents. In the model, a total of 10 sediment categories from medium silt to coarse gravel were classified and simulated together in terms of sampled sediment characteristics. For a worst case scenario regarding sediment transport, the numerical modeling was conducted with the two turbine systems removed, leaving only the duct openings in the barrage. In this case the installation flow resistance is minimal resulting in the highest level of flows between the two basins on either side of the barrage, as in the scenario of having both systems removed for service. The detailed model results of sediment transport were used to examine such regimes and potential issues associated with the underwater turbines as (1) effects on the HMCS Columbia dive site due to silt transport and altered current flows; (2) effects on the Yellow Island Aquaculture Facility due to silt transport and altered current flows and current jets; (3) sediment transport characteristics on either side of Canoe Pass in both Seymour Narrows and the bay to the east of Canoe Pass including the dive site and the Yellow Island Aquaculture Facility.

In the application of Brown Passage, the model was adapted to predict the bottom accumulation and TSS plume resulting from marine dredgate and terrestrial overburden disposal from the Prince Rupert Harbor area, via a barge at a designated disposal site with a water depth of about 200 m in Brown Passage. The distribution of the disposal sediment was initially simulated with the short-term fate model of sediment disposal STFATE, which ran over the initial 45 minutes of sediment disposal under average flood and ebb currents. The STFATE model results of the suspended sediment concentration and initial accumulation on the seabed were then input to the COCIRM-SED model, which simulated the quantity and pattern of the short-term and long-term deposition of disposal sediment and TSS plume during and after the disposal operations.

Keywords: numerical modeling, currents, sediments, deposition, erosion

I. Introduction

Quantitative understandings of sediment transport for coastal engineering projects are one of the key requirements in planning these projects, assessing potential environmental impacts and obtaining regulatory approvals from government agencies. The effects of project-related changes to the natural environment in the form of erosion and deposition of sediments from the seabed and as increased (or decreased) levels of suspended sediments can have adverse environmental effects including: smothering of marine communities or in extreme cases complete burial; decreases in available sunlight; irritation to fish either directly through effects on their gills or indirectly through siltation degrading fish habitats and increased difficulty in locating prey; and effects on recreational use of coastal ocean waters. Increased velocities due to coastal projects can result in increased downstream erosion of the seabed altering the existing benthic communities. The disposal or release of chemically contaminated sediments also presents environmental risks. In support of environmental screening and assessments, numerical models based on reliable and representative field measurements are very useful.

In support of the environmental assessment and approvals the highly-integrated, three-dimensional finite difference COastal CIRculation Model COCIRM-SED was recently adapted and optimized to predict the sediment transport processes associated with a number of coastal engineering projects. In this paper we will illustrate the use of COCIRM-SED in three coastal applications in British Columbia, Canada, including removing and installing underwater cables, installing and operating underwater turbines and disposal of dredged marine sediment (or terrestrial overburden).

II. COCIRM-SED: Model Overview

A. Overview of COCIRM-SED

The high resolution COCIRM-SED (Fig. 1) consists of six integrated modules: circulation, wave, sediment transport, morphodynamics, water quality and particle tracking. The circulation module (COCIRM), developed over the past decade ([1], [2], [3]), represents a computational fluid dynamics approach to the study of river, estuarine and coastal circulation regimes. The sediment transport module involves the dynamics of cohesive and non-cohesive sediment based on multiple size classes. The morphological module solves the bottom elevation variations due to sediment deposition and erosion over different periods. The model explicitly simulates such natural forces as pressure heads, buoyancy or density differences due to salinity, temperature and suspended sediment, river inflow, meteorological forcing, and bottom and shoreline drags. The model applies the fully three-dimensional basic equations of motion and conservative mass transport combined with a second order turbulence closure model [4] for vertical diffusivity and Smagorinsky's formula [5] for horizontal diffusivity, then solves for time-dependent, three-dimensional velocities (u,v,w), salinity (s), temperature (T), suspended sediment concentrations (c_k) and coarse sediment bed-loads (q_k) by size category, turbulence kinetic energy (k) and mixing length (l), horizontal and vertical diffusivities (K_h, K_v), water surface elevation (ζ), 2D wave spectra (S), wave forces (F), and bottom elevation variations (Δh), etc.

B. Model Testing and Validation

To validate the model as a reliable tool, appropriate calibration and verification processes are applied to the model 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 model is 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 [4], was found to be robust. Most efforts were involved in testing and adjusting of the bottom drag and the horizontal diffusivity.

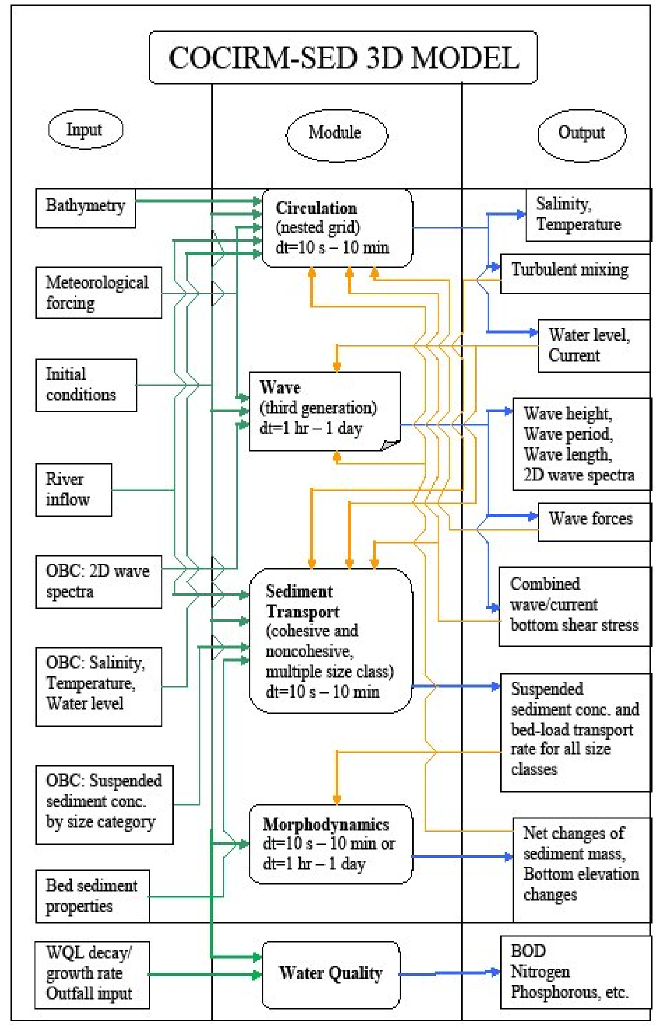

Figure 1: Schematic diagram of the COCIRM-SED numerical model.

III. Application to Removal and Installation of Large Electrical Cables at Roberts Bank, BC

For the Roberts Bank application, the COCIRM-SED model was used to predict the sediment plumes and deposition resulting from the removal and installation activities of existing and replacement underwater transmission cables across the Strait of Georgia (Fig. 2).

In the model, a total of six sediment categories from fine silt to medium sand were classified and simulated together in terms of sampled sediment characteristics. The model results were obtained with a trenching rate of 300 m/h and two trench sizes, a wide trench of 1.0 m wide × 1.0 m deep and a narrow trench of 0.2 m wide × 1.0 m deep. The amount of sediment that is suspended above the trench was taken to be 30% of the total volume for the wide trench and 25% for the narrow trench. The fate of the suspended sediments is determined by the type of surficial sediments present at each of the four landing sites and ambient flow conditions. Sediment types were identified based on sediment sampling data.

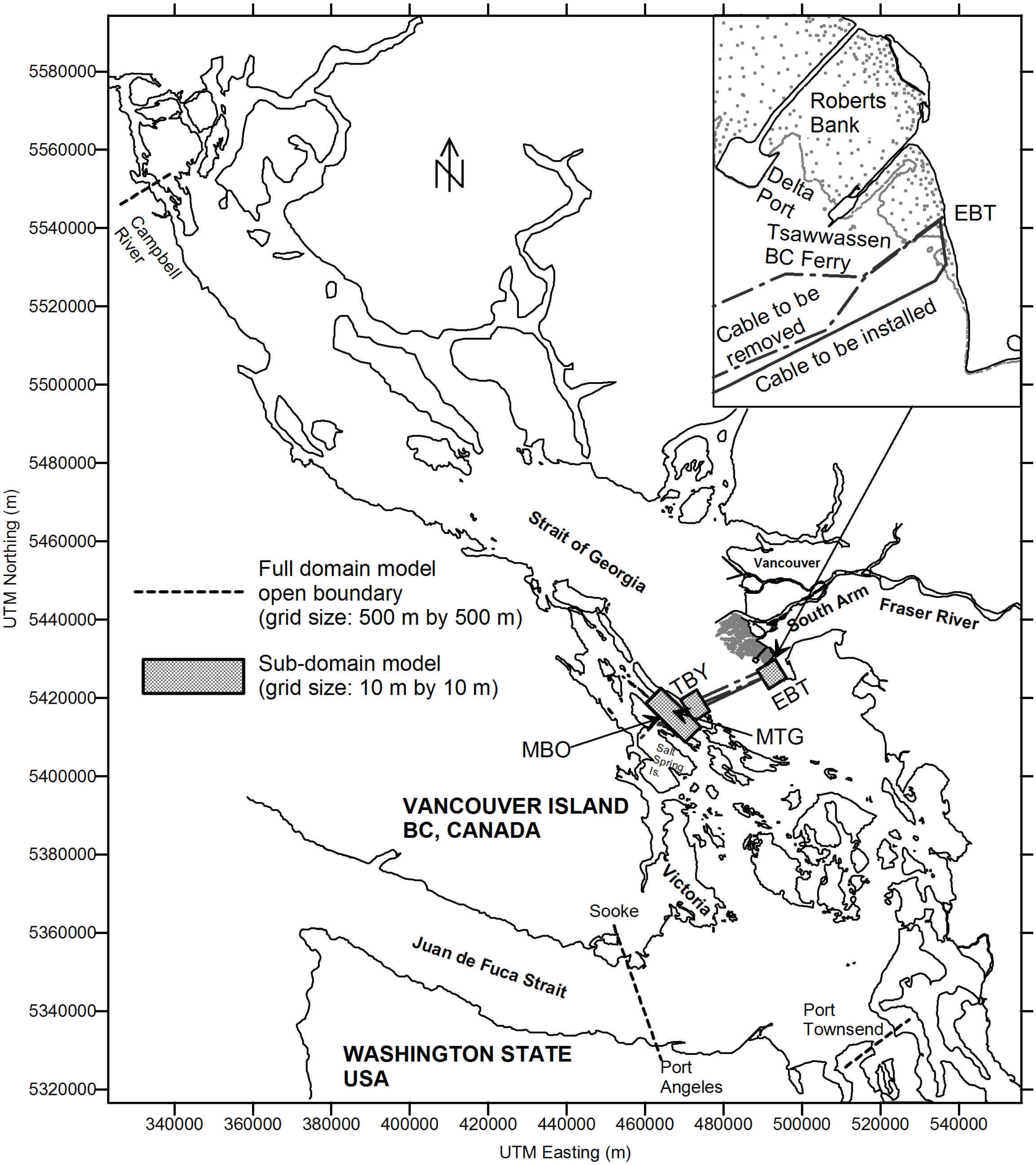

Figure 2: A map of the study area showing the existing underwater transmission cables and the COCIRM-SED basin scale model domain and the high resolution sub-domains at EBT, TBY and MBO landing sites.

In general, sediment types are dominated by sands with very small amounts of silt and clay, but there is a considerable amount of variability among the landing sites. At the EBT landing site, a total of six sediment categories, with grain sizes ranging from fine silt to medium sand were identified and simulated together in the model. Details of simulating sediment settling, erosion, deposition and particle interaction, etc., are described in [6].

An example of the model predictions of sediment plumes and depositions associated with the removal of one existing cable at EBT on Roberts Bank are presented in Fig. 3 and Table 1. Complete details and additional model results can be found in [6]. The modeling of the removal of the existing cable involved a total route length of about 400 m, corresponding to a removal time of 80 minutes at the removal rate of 300 m/h. The installation of the new cables follows a shallow water route parallel to the shoreline over a distance of more than 1 km before turning offshore, with a total route length of about 1.8 km. Installation is carried out for about 3 hours during each of the two tidal cycles.

TSS concentrations are shown at the surface and bottom levels (Fig. 3). In the tabulated results, maximum TSS and areas having TSS values exceeding 25 and 75 mg/L are provided. Background levels of 25 to 50 mg/L, and more during freshet (snow melting from May to August), are expected to occur in the Fraser River plume and the shallow portions of the Fraser River delta (Jiang and Fissel, 2006). The 75 mg/L TSS value is used as criteria when considering possible effects of turbidity in freshwater environments [7].

From the model results for the removal of one existing cable and the installation of one new cable at EBT, it is shown that during cable removal and installation activities, very high TSS values greater than 10,000 mg/L near the bottom and greater than 1,000 mg/L near the surface are predicted to occur only in the immediate vicinity of the trenching activities within 10 m or so. During the removal and installation operations, the areas having TSS levels above 25 mg/L are usually less than 0.26 km^2, and the areas with TSS > 75 mg/L are usually less than 0.12 km^2. Following completion of the removal and installation activities, the maximum TSS concentrations decrease very rapidly with time, as the dominant sand categories quickly settle out to the bottom. In general, the areas having TSS levels above 25 mg/L and 75 mg/L decrease to zero after 3 – 6 hours and longer. The sediment deposition thickness resulting from the removal and installation of one cable is less than 5.5 cm, and the areas with deposition thickness greater than 1 cm occur in a very narrow corridor along the cable route within 10 – 20 m or so.

Because the 10 m model grid size is much larger than the actual trench width of 1.0 m, the suspended sediment concentrations will be larger within a few meters of the trench than the values predicted by the model. To overcome the model resolution limitation, the COCIRM-SED model system has recently been enhanced by incorporating a Lagrangian-based, three-dimensional particle tracking module (PTM), which is capable of simulating dissolved or suspended substances released from coastal development activities in a more realistic manner.

Table 1: Summary of TSS and plume areas for cable removal at the cable EBT landing site.

Elapsed time (hours)	Maximum TSS (mg/L)		Area of TSS >25 mg/L (km^2)		Area of TSS >75 mg/L (km^2)	
	bottom	surface	bottom	surface	bottom	surface
0.5	31,188.8	1,515.0	0.016	0.013	0.013	0.010
1	27,947.6	1,242.2	0.091	0.071	0.065	0.036
2	51.3	36.7	0.108	0.078	0.000	0.000
3	23.2	20.5	0.000	0.000	0.000	0.000
6	5.9	4.5	0.000	0.000	0.000	0.000
12	1.3	1.2	0.000	0.000	0.000	0.000

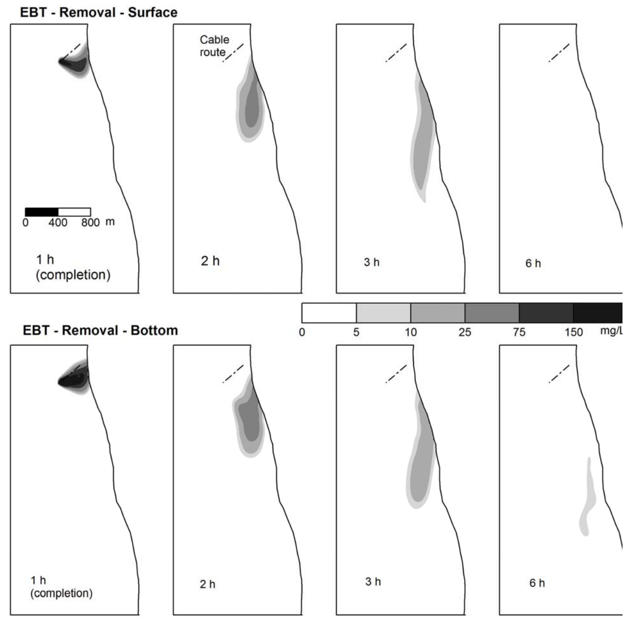

Figure 3: Sediment plumes associated with cable removal at EBT.

IV. APPLICATION TO INSTALLATION OF UNDERWATER TURBINES AT CANONE PASS, BC

In the Canoe Pass application, the COCIRM-SED model was adapted to predict the sediment transport resulting from installing and operating two underwater turbines in Canoe Pass. A previous modeling study ([8], [9]) provides information on the regional and local currents in the Canoe Pass area. The COCIRM circulation model was implemented on two model scales: the full model scale and nest grid scale. The larger, full scale model includes the Discovery Passage from Brown Bay to Duncan Bay (Fig. 4) and works on a coarser horizontal grid size of 46.34 m. The nested grid includes the surrounding region of Canoe Pass with an area of about 1170 m by 420 m, and a much higher horizontal resolution of grid size 6.62 m, which is the same as the duct aperture width for a single turbine. Both the full scale and nested grid models use 12 vertical sigma-layers with a higher resolution near the surface and bottom (Table 1). The nested grids are embedded within the full scale domain and are solved together with the full scale model grids at every time step. The model is forced at its two open boundaries using tidal elevations derived from 9 tidal constituents. Surface wind forcing was also applied using wind measurements at the Campbell River Airport.

The existing causeway dam which blocks Canoe Pass (Fig. 5), was built in the 1940's, and is planned to be completely removed and replaced by two underwater turbine systems for electricity generation in this area of large tidal currents. In the COCIRM-SED model, a total of 10 sediment categories from medium silt to coarse gravel were classified and simulated together in terms of sampled sediment characteristics.

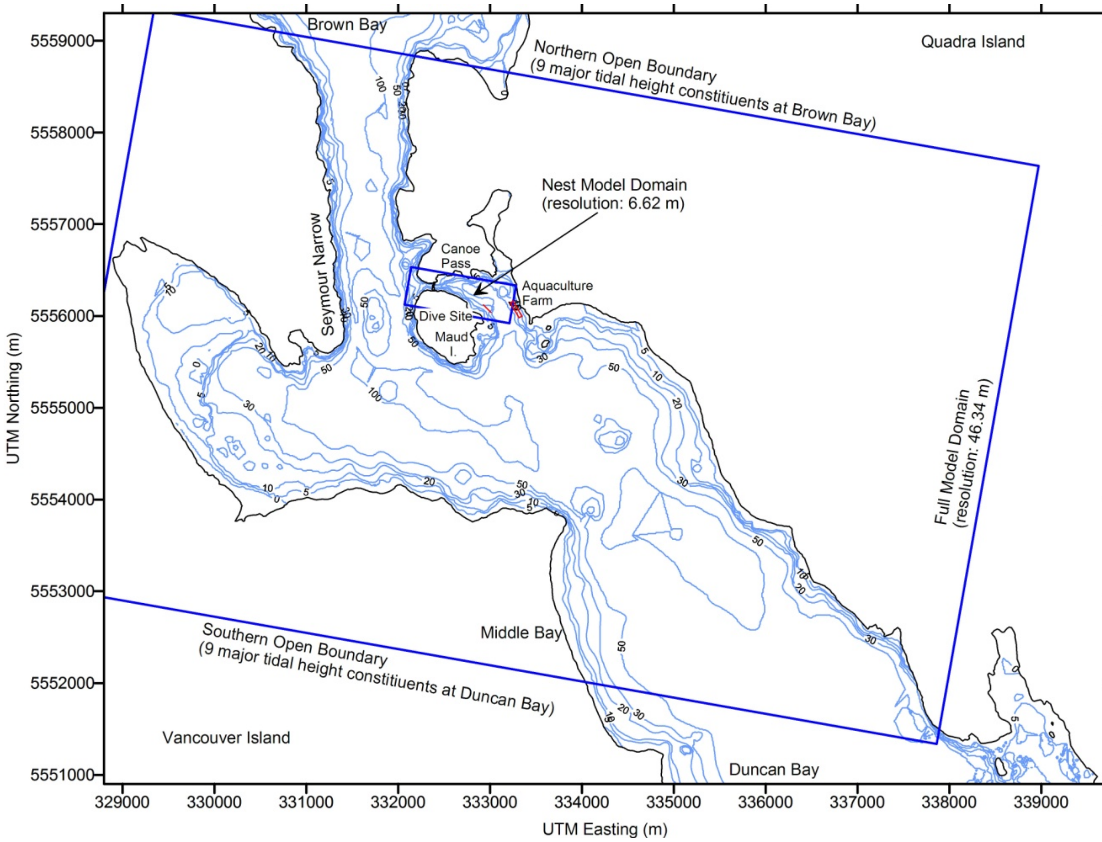

Figure 4: The model domain used for the Canoe Pass sediment simulations. Canoe Pass separates Maud Island from Quadra Island in the Discovery Passage area east of Vancouver Island B.C.

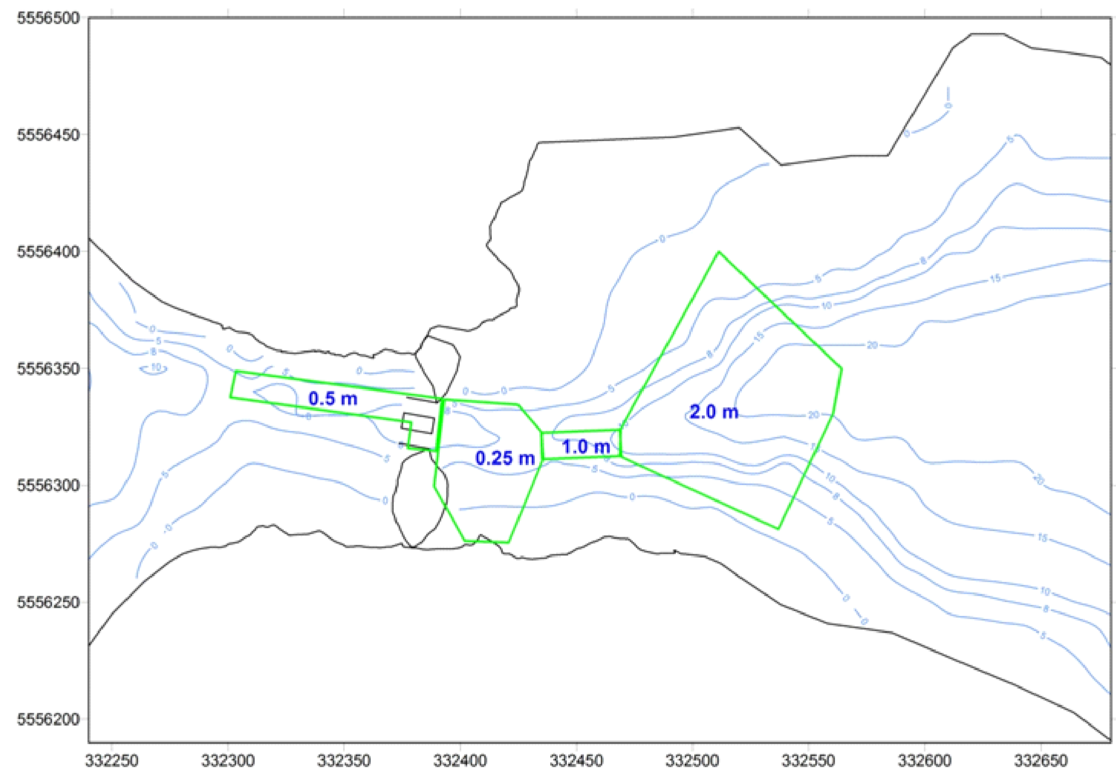

Figure 5: A map showing sandy substrate areas and bottom sediment thickness.

As a worst case scenario regarding sediment transport, the numerical modeling was conducted with the two turbine systems removed, leaving only the duct openings in the barrage. In this case the installation flow resistance is minimal resulting in the highest level of flows between the two basins on either side of the barrage, as in the scenario of having both systems removed for service.

The Canoe Pass substrates are primary bedrock and erodible sandy substrates are only located in deeper canyon and causeway areas. Fig. 5 shows the areas, defined by the green polygons (a total of four areas); with sandy substrates and the sediment thickness in each area (the blue numbers within the polygons, which ranges from 0.25 m to 2.0 m). The sediment categories for these substrates were identified using detailed sampling data (Fig. 5). A total of 10 size categories were classified, ranging from medium silt to coarse gravel. The silt and clay particles, which occupy 15% of total sediment, are treated as a single size class because of the difficulty of further separation using a hydrometer due to very high organic content in the sediment samples.

The detailed model results of sediment transport were used to examine such regimes and potential issues associated with the underwater turbines as (1) effects on the HMCS Columbia dive site due to silt transport and altered current flows; (2) effects on the Yellow Island Aquaculture Facility due to silt transport and altered current flows and current jets; (3) sediment transport characteristics on either side of Canoe Pass in both Seymour Narrows (a major shipping channel within Discovery Passage) and the bay to the east of Canoe Pass including the dive site and the Yellow Island Aquaculture Facility (see Fig. 6 for the locations of the areas identified above).

During flood tide, the Canoe Pass flow has negligible effect on the flow in Seymour Narrow. During ebb tide, there is an effect at the east side of Seymour narrow along a 100 – 200 m wide band, where the near-surface velocities increase by about 0.3 – 1.2 m/s or about 10 – 20 % compared with the original velocities, and the near-bottom velocities decease by about 0.1 – 1.0 m/s or 10 – 20 %, and at the middle depth, the impact of the Canoe Pass flow is marginal.

At the aquaculture farm, the effect of the Canoe Pass flow is negligible during ebb tide. During flood tide, the Canoe Pass jet-like flood flow has largely spread and dissipated and its velocity has dramatically decreased before it reaches the aquaculture farm. As a result, the maximum flood currents are less than 25 cm/s in the upper water column and less than 15 cm/s in the lower water column. Because the magnitude of the altered current is small, the Canoe Pass outflow will have a marginal influence on the flushing at the aquaculture site. The Canoe Pass flow has even smaller values at the dive site where the flood velocities at the northern end of the dive site increase by 15 – 23 cm/s at the middle depth and near-surface levels, and increase by about 5 cm/s near the bottom. Again, the Canoe Pass outflow has a very minor impact on the diving activity because of the small magnitude of the altered currents at this site.

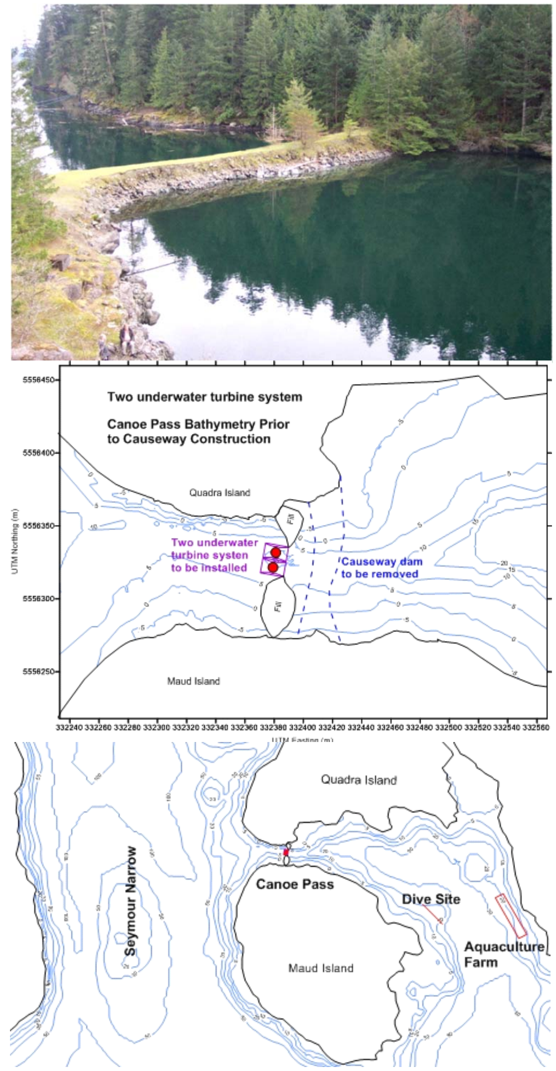

Figure 6: The existing Canoe Pass causeway (upper); the locations of the two underwater turbines in place of the causeway (middle) and the locations of the Dive site, Aquaculture farm and the Seymour Narrows navigation channel

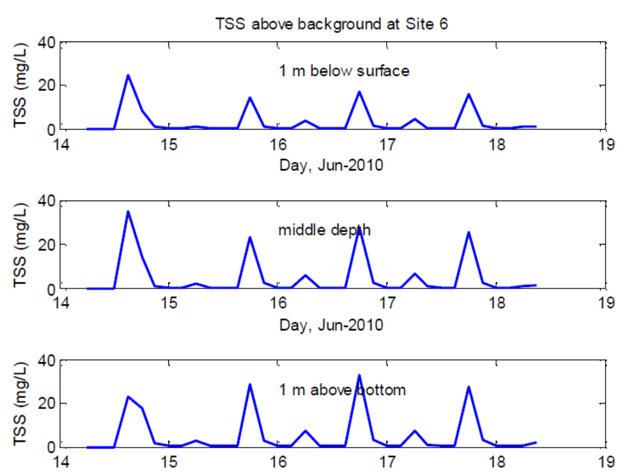

Figure 7: Time series of TSS above background at the

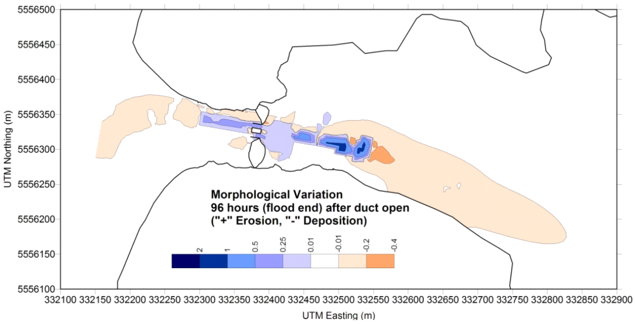

Figure 8: Morphological variation at 96 hours after the empty turbine duct was opened at the beginning of a spring ebb tide.

The sediment transport modeling results (Fig. 8) over a 4 day spring tide period show that bottom sediment erosion and deposition occur along the course of the turbine outflow and a quasi-steady state of sediment erosion and deposition is reached within a one-half to two day period except some areas with the substrate thickness of 2.0 m at the east side. It is also found that the quasi-steady erosion levels are about 30 – 40 % of the substrate thickness. In other words, the sediment particles coarser than coarse sand have either very slow or no erosion. It is expected that the erosion decreases after the modeling period under neap tide conditions and the flow slows down until the next spring tide, and a more steady state sediment transport regime will be established during and after the second spring tide.

Time series of TSS values above background reveal that high TSS values greater than 25 mg/L (the B.C. water quality guideline above background) only occur at the lower water column in the erodible substrate areas before a quasi-steady state is reached. In the upper water column, the TSS values are always less than 25 mg/L. At the northern edge of the dive site, the TSS values range from 0 to 30 mg/L (Fig. 7). At the northern edge of the aquaculture farm, TSS values ranging from 20 – 25 mg/L only occur on the first day, followed by TSS values that are always less than 10 – 20 mg/L.

V. Application to Disposal of Sediments at Brown Passage, BC

In the application of Brown Passage on the northern BC coast, located well to the west of Prince Rupert [11], the COCIRM-SED model was adapted to predict the bottom accumulation and TSS plume resulting from marine dredgate from the Prince Rupert Harbor area, via a barge at a designated disposal site with a water depth of about 200 m in Brown Passage (a designated ocean disposal site administered by Environment Canada; all disposal operations must be reviewed and received prior approval). The total volume of disposal materials is 0.295 million m^3. The distribution of the disposal sediment was initially simulated with the short-term fate model of sediment disposal STFATE [10], which ran over the initial 45 minutes of sediment disposal under average flood and ebb currents. The STFATE model results of the suspended sediment concentration and initial accumulation on the seabed were input to the COCIRM-SED model, which then simulated the quantity and pattern of the short-term and long-term deposition of disposal sediment and TSS plume during and after the disposal operations.

The COCIRM-SED model for the Brown Passage sediment modeling was operated over a realistic numerical model domain for the full area of Brown Passage, with a total area of 20.7 km by 29 km (Fig. 9). A horizontal grid size resolution of 100 m by 100 m was used for the model area. In the vertical, the model used 22 sigma layers with higher resolutions realized near the surface and bottom. The model was forced at tidal height elevations spanning four open boundaries and by surface winds. The four model open boundaries include the four adjoining sides of Brown Passage (Figure 9). Tidal elevations at these four open boundaries were derived from 7 major tidal height constituents (O1, P1, K1, N2, M2, S2, K2). The tidal constituents for the model boundaries were obtained from Canadian Hydrographic Service of DFO. The wind data are obtained from the Prince Rupert airport weather station, operated by Environment Canada.

The COCIRM model was first validated through model calibration and verification runs using ocean current data at the DFO current meter mooring site located to the southeast of Kinahan Island. The calibration case dealt with the 17 day long summer period of September 5th – 22nd, 1991, when the wind effect was relatively weak. The verification case dealt with a 17 day fall period of October 5th – 22nd, 1991, when the wind effect was relatively strong. The calibration run only involved the tidal forcing at the open boundaries, while the verification run involved both tidal forcing at the open boundaries and surface wind forcing using measured hourly winds at the Prince Rupert airport weather station for the same period.

Following model calibration and verification, the model was then used to simulate the transport and fate of the sediments released during and after the disposal operations at the designated disposal site in Brown Passage (Fig. 9) using

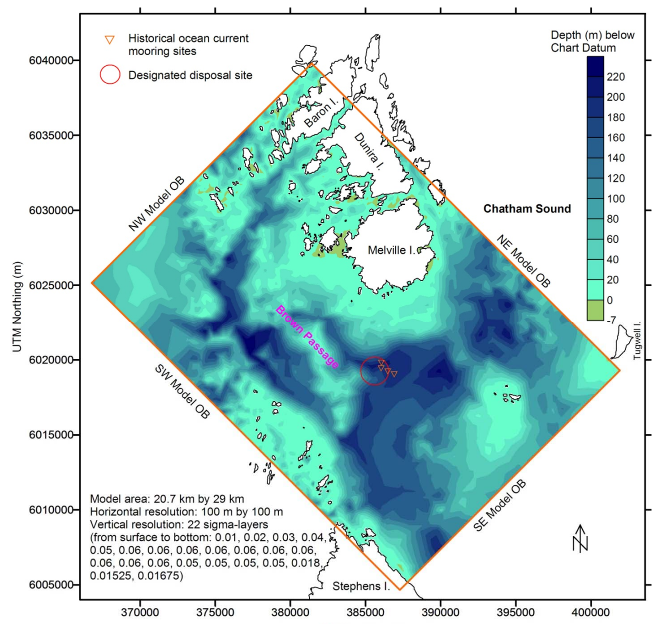

Figure 9: A map showing the Brown Passage study area including the model domain, bathymetry, designated disposal site and historical ocean currents mooring sites.

realistic particle size distributions for the marine sediments (Table 2).

It was assumed that dredging and disposal activities would occur during fall and winter, to minimize levels of high turbidity that may be detrimental to marine life. Therefore, the disposal operation simulated in the modeling began in late November. The marine dredging disposal will have a total of 147.5 trips for a duration of about 21 days from late November to early December. After completion of all dredging, the model run continued for another 21 days to let all suspended disposal sediment settle out on the seabed.

Typical wind and tidal forcing in Brown Passage during the fall and winter seasons were used to drive the ocean currents in the model. Through an analysis of 40 year wind data recorded at Prince Rupert airport weather station and tidal elevations predicted using major tidal constituents, the winds and tidal elevations over the period of late November, 2008 to early 2009 were used as the input of driving force to the model.

The COCIRM-SED model results of near-bottom and near-surface TSS plumes are presented immediately after the marine dredging disposal (Fig. 10). From the model results, it is found that maximum near-bottom TSS values after each disposal trip is up to about 1200 mg/L, which reflects the initial near-bottom TSS derived from the STFATE model inputs. The high near-bottom TSS clears up quickly due to sediment settling and strong dilution, with a maximum near-bottom TSS value of less than 70 mg/L within about 2 hours after each disposal event.

In the vertical, TSS values decrease towards the surface. Near-surface TSS during disposal is mostly less than 5 mg/L. Higher near-surface TSS values of 5 – 10 mg/L occur only at the center of the dumping site right after each disposal trip. Consequently, the minimum depth with TSS values greater than 25 mg/L (which reflect BC water quality guideline above background level) is greater than 110 m over the entire disposal period.

The COCIRM-SED model was also used to compute the total bottom deposition after 21 days following the completion of all marine dredging disposals (Fig. 10) when all suspended disposal sediments have settled out and are located on the seabed. It is seen that most dredging materials are deposited in the deeper water to the southeast of the designated disposal site where water depths are greater than 150 m and where the near-bottom ocean currents are relatively weak, usually less than 0.2 – 0.3 m/s. Total deposition within the designated disposal area (1 nautical mile in diameter) occupies 83.90% of total marine dredging material, with a deposition thickness ranging from 78 mm to 173 mm. The area with total deposition greater than 1 mm is located in deeper water where water depths are greater than 100 m. The total deposition within this area occupies 90.45% of total marine dredging material.

Table 2: Summary of sediment categories, average sizes and fractions for marine dredging.

	Category	Clay	Silt	Sand
Marine dredging	Size (mm)	0.004	0.03	0.2
	Fraction (%)	12.60	14.60	72.80

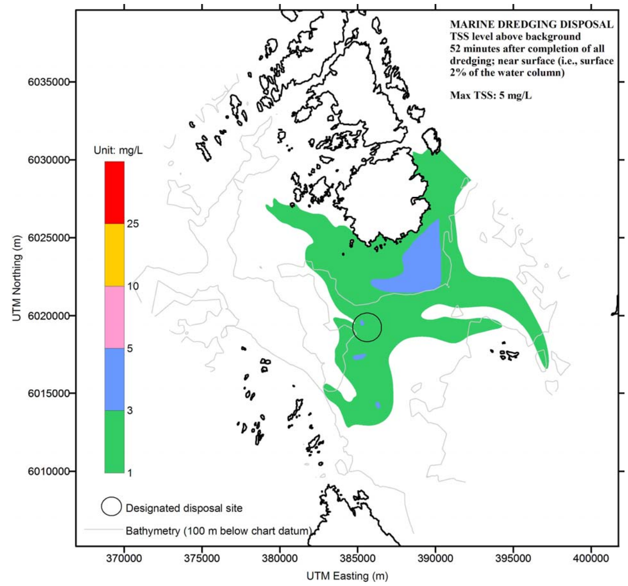

Figure 11: Marine dredging disposal near-surface TSS levels above background 52 minutes after completion of all disposals.

VI. Summary and Conclusions

Coastal engineering projects, having activities that involve changes to marine sediments, can benefit from the use of high resolution, integrated numerical models. The advanced numerical models, such as COCIRM-SED, after suitable calibration and validation of their 3-D circulation modules and with detailed inputs on the particle size distributions of the sediments, can provide quantitative estimations of the time dependent total suspended sediment concentrations within the water column associated with the project activities. The models also provide detailed maps of the gain or loss of bottom sediments resulting from the project.

Advanced 3-D numerical model results are presented for three different coastal engineering project applications in

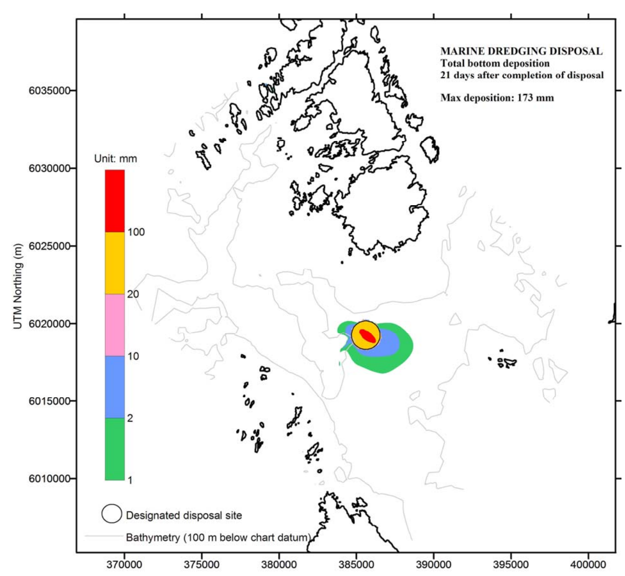

Figure 10: Total bottom deposition of marine dredging material 21 days after completion of all disposals.

British Columbia using COCIRM-SED which illustrate the capabilities and the degree of detail provided in the simulation results. The model outputs from COCIRM-SED have proven to be effective in the process of environmental assessments leading to obtaining regulatory approvals for the coastal engineering projects.

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