Modeling Sediment Disposal in Inshore Waterways of British Columbia, Canada

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Abstract

In support of the environmental assessment and regulatory approval process and as an interim guidance for field work, a number of numerical modeling studies of the sediment disposals were recently carried out by ASL Environmental Sciences Inc. at the designated/potential disposal sites in inshore waterways of British Columbia, Canada, using the 3D numerical model COCIRM-SED and the short-term fate model of sediment disposal STFATE. In these applications, STFATE was used to provide initial distributions of suspended sediment and bottom accumulation in details, typically within the first hour of the sediment disposal operation, as a useful interim guidance for field work and input to the 3D model COCIRM-SED, which was then adapted to examine the transport and fate of all disposal materials over much larger spatial scales and longer periods of time. This paper reports the model approaches and the detailed model results in the Brown Passage application.

Introduction

Dredged marine sediment and excavated terrestrial overburden from coastal engineering projects are commonly disposed at designated sites in ocean and coastal open waters via release from barges or pipelines. However, the sediment disposal in these areas can have adverse environmental impacts, especially on marine life and fish habitats, in the form of bottom accumulation and increasing total suspended sediment (TSS) levels in the water column (Fissel and Jiang, 2011). Thus, the short-term (with durations of hours to about a day) and long-term (with durations of days to months) transport and fate of the disposal sediment during and after the disposal operations are of particular concern to coastal engineers and environmental scientists in assessing potential environmental effects and obtaining regulatory approval. The progress realized in advanced circulation and sediment transport numerical models provides useful and reliable tools in quantitatively predicting transport and fate of disposal sediment.

Recently in ASL Environmental Sciences Inc., numerical modeling studies of the short-term and long-term transport and fate of the disposal sediment were successfully carried out at a number of designated/potential sediment disposal sites in the inshore waterways of British Columbia, Canada (Figure 1). These studies used the ASL's own 3D COastal CIRculation and SEDiment transport Model (COCIRM-SED) and the Short-term FATE model of sediment disposal (STFATE), developed by the U.S. Army Corps of Engineers. The model results were used to address the potential impacts of the sediment disposal on the natural environment of receiving ambient

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waters, and to support regulatory approval process as well as provide interim guidance for field work.

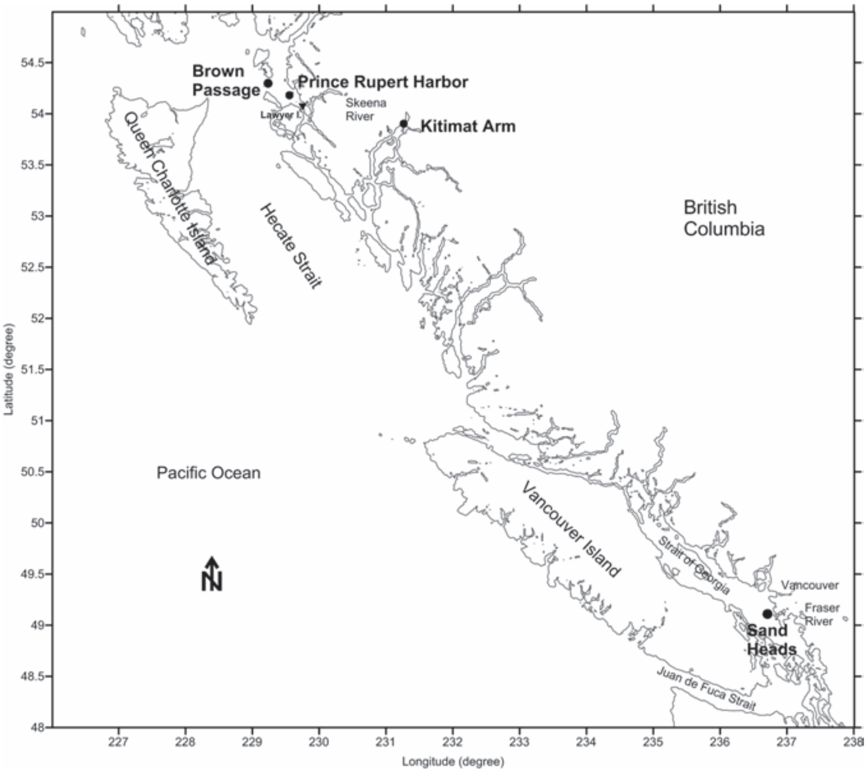

Figure 1. A map showing locations of the sediment disposal sites in the inshore waterways of British Columbia, Canada.

One particular regional ocean disposal site in Brown Passage involves the disposal of dredged marine sediment and possible excavated terrestrial overburden from Prince Rupert Harbor development site via release from barge (Jiang and Fissel, 2010). In this application, STFATE was used to model the initial operation of each disposal trip and to provide detailed input information of initial bottom accumulation and suspended sediment concentration (SSC) in the water column to COCIRM-SED, which then simulated the transport and fate of all disposal sediment as well as potential resuspension over a much larger spatial scale and a longer period of time.

This paper presents the model approaches and the detailed model results in the Brown Passage application, including TSS values above background level, TSS plumes, total bottom accumulation and potential long-term resuspension of the disposal sediment deposited on the seabed.

Model Approach

COCIRM-SED and STFATE Overview

STFATE, developed by the U.S. Army Corps of Engineers, is a short-term fate model of sediment disposal, which is accepted by the U.S. Environmental Protection Agency (EPA and USACE, 1995). The STFATE model was used to simulate the short-term fate and near-field distribution of the disposal material released from the barge immediately following each disposal operation. The STFATE operated on the actual bathymetry using an identical or smaller model mesh to match the 3D model COCIRM-SED grid, and ran over the initial 45 minutes of the disposal operation. During the initial 45 minutes of the disposal operation, the disposal sediment released from the barge underwent the processes of convective descent, horizontal transport under background current, turbulence diffusion, dynamic collapse, and meanwhile, deposition of most coarse sediments with size larger than medium sand. The ocean current input to STFATE included typical tidal stages, such as peak and mean flood and ebb as well as slack water, freshet and dry seasons, and different wind conditions. The STFATE output provided input information to the 3D model COCIRM-SED in detail, including bottom accumulation and suspended sediment concentrations (SSC) and distributions by categories during the initial disposal operation, and COCIRM-SED then simulated the transport and fate of all dredged/excavated materials over much larger spatial scales and longer periods of time.

The 3D coastal circulation numerical model COCIRM-SED, used in these studies, is a highly-integrated, three-dimensional, free-surface, finite-difference numerical model code for use on rivers, lakes, estuaries, bays, coastal areas and seas (Jiang et al., 2003; Jiang and Fissel, 2004; Jiang, et al., 2008; Fissel and Jiang, 2008), and consists of five sub-modules including circulation, multi-category sediment transport, morphodynamics, water quality and particle tracking (Figure 2). All modules operate as subroutines together within the COCIRM-SED model, and the model can be operated on either an integrated or an individual module basis. The model applies the fully three-dimensional primitive equations of motion and conservative mass transport combined with a second order turbulence closure model, then solves for time-dependent, three-dimensional velocities, salinity, temperature, SSC and coarse sediment bed-load transport by size category, turbulence kinetic energy and mixing length, horizontal and vertical diffusivities, water surface elevation, bottom elevation variations, and multiple water contaminant concentrations. It also includes wetting/drying and nested grid schemes, capable of incorporating tidal flats, jet-like outflows, outfall mixing zone and other relatively small interested areas. Horizontal resolution can range from <10 m to a few kilometers, and vertical resolution typically ranges from 10 to 30 layers either as a sigma- or a z-layers coordinate with uneven distribution of layer thickness. In all implementations of simulating sediment disposals, the COCIRM-SED circulation module was validated using historical water level and ocean current data in the model areas.

To activate the sediment transport and morphological modules, one need only input the grain size (d_k) and percentage fraction (f_k) for each sediment category, with typically total category 5 – 20. COCIRM-SED readily simulates settling velocities (w_k), suspended sediment concentration (c_k), bed-load rates ($S_{b,k}$), and bottom elevation changes by size category. For fine-grained sediments with particle size less than 32 – 62 μm (clay – silt range), modeling of cohesive sediment transport will be involved, while for coarse sediments with particle size greater than 32 – 62 μm (sand, granule and fine pebble), modeling of non-cohesive sediment transport will be activated.

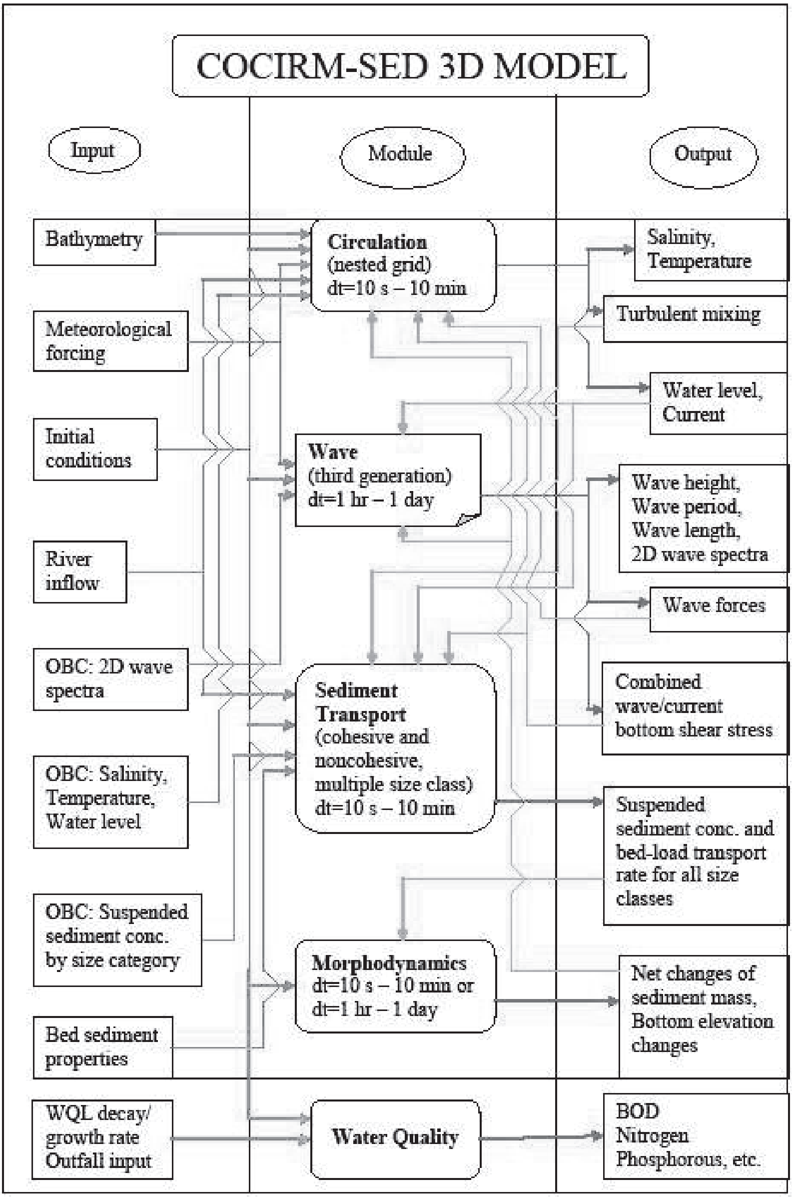

Figure 2. Schematic Diagram of COCIRM-SED system.

For cohesive sediments, bottom deposition, D_k (Krone, 1962), erosion, E_k (Parchure and Mehta, 1985), and settling velocity, w_k (Mehta and Li, 1997) are given by

$$D_k = w_{s,k} c_k S\left[1 - \frac{\tau_{cw}}{\tau_d}\right] \tag{1}$$

$$E_k = f_k M_{\max} \exp(-\chi \tau_e{}^{\lambda}) S[\tau_{cw} - \tau_e] \tag{2}$$

$$w_{s,k} = \left[\frac{a c_k{}^{\alpha}}{(c_k{}^2 + b^2)^{\beta}}\right]\left[\frac{\rho_{s,k} / \rho(\theta, s, c) - 1}{1.65}\right]\left[\frac{10^{-6}}{\upsilon(\theta, c)}\right] F(\theta) \tag{3}$$

where S[-] is a switch function which becomes zero if the quantity inside the square brackets becomes negative, τ_{cw} is the bottom shear stress due to current and wave (Grant and Madsen, 1979), τ_d is the critical shear stress for deposition, τ_e is the critical shear stress for erosion, $M_{\max}$ is the maximum erosion constant at $\tau_{cw} = 2\tau_e$, χ, λ, a, b, α and β are the sediment-dependent empirical coefficients, θ is the temperature, $\rho_{s,k}$ is the sediment granular density of k$^{\text{th}}$ sediment, ρ(θ,s,c) is the temperature, salinity and sediment dependent fluid density, $\upsilon(\theta, c)$ is the temperature and sediment dependent fluid viscosity, and $F(\theta)$ is the temperature effect function on flocculation, $F(\theta)$=1.777-0.0518θ, for θ=0–30 °C (Jiang, 1999). Two types of cohesive sediment beds are classified, namely newly-deposited and fully-consolidated beds. The newly-deposited bed goes through consolidation process (Toorman and Berlamont, 1993), while the dry weight for the fully-consolidated bed is simply computed using empirical profile formula. The shear strength of the bottom cohesive sediments is then calculated in terms of solid weight fraction.

For non-cohesive sediments, the effect of particle interaction on settling velocities is considered as follows

$$w_k = \left(1 - \frac{c}{\rho_{s,k}}\right)^4 w_{k0} \tag{4}$$

where c is the total suspended sediment concentration, and w_{k0} is the free settling velocity. By assuming spherical particles, the Stokes law is a fairly good approximation of free settling velocity with Reynolds number Re < 0.5 ($\mathrm{Re} = w_{k0} d_k / \upsilon$). For higher Reynolds number, the effects of inertia and virtual mass have to be accounted for. Due to the effect of flow separation behind the falling particle, the value of the drag coefficient depends strongly on the level of free stream turbulence, apart from turbulence caused by the particle itself. In this case, the formulas reported in Rijn (1984a) are applied. Two separated parts are involved in coarse sediment transport, namely suspended-load and bed-load. The formulas introduced in Rijn (2001) are used for calculating the bed-load transport rates. For suspended-load transport, the bottom sediment re-suspension and deposition are given by

$$E_k = c_{a,k}\left(\frac{K_v}{\Delta z}\right)$$
$$D_k = c_{1,k}\left(\frac{K_v}{\Delta z} + w_k\right) \tag{5}$$

where K_v is the vertical diffusion coefficient at the bottom of the lowest σ-layer, Δz is the vertical distance from the reference level *a* to the center of the lowest σ-layer, $c_{1,k}$ is the kth sediment concentration at lowest σ-layer, and $c_{a,k}$ is the sediment reference concentration at the reference level *a*, which is determined from (Rijn, 1984b)

$$c_{a,k} = 0.015 f_k \eta_k \rho_{s,k} \frac{d_k^{\,0.7}}{a} \frac{\left[\left(\dfrac{u_*}{u_{*,k}}\right)^2 - 1\right]^{1.5}}{\left[\dfrac{(\rho_{s,k}/\rho - 1)g}{\upsilon^2}\right]^{0.1}} \tag{6}$$

where η_k is the user-specified calibration parameter for kth sediment, u_* is the bed shear stress due to current and wave, *g* is the gravitational acceleration, and $u_{*,k}$ is the critical shear velocity for incipient motion of kth sediment. In determining $u_{*,k}$, the hiding and exposure factor of non-uniform sediment bed is taken into account due to the work by Wu, et al. (2000) as follows

$$u_{*,k} = \left[\left(\frac{\rho_{s,k}}{\rho} - 1\right) g d_k \vartheta_c \left(\frac{p_{h,k}}{p_{e,k}}\right)^m\right]^{0.5} \tag{7}$$

where ϑ_c is the non-dimensional critical shear velocity corresponding uniform sediment or the mean size of bed materials, m is the empirical constant, and $p_{h,k}$ and $p_{e,k}$ are respectively the total hidden and exposed probabilities of kth sediment.

In the morphological module, an acceleration factor, f_m (≥1.0), is introduced in dealing with time scale difference between hydrodynamics and morphodynamics. The bottom elevation changes at any model grid cell (i,j) is given by

$$\Delta h_{i,j} = \sum\left[(\Delta S_{bed})_{i,j} + (\Delta S_{sus})_{i,j}\right] f_m dt \tag{8}$$

where $(\Delta S_{bed})_{i,j}$ is the ratio of bed-load rate net change into or out of the model grid cell (i,j) to the dry weight of bottom sediment, $\rho_{d,k}$, and $(\Delta S_{sus})_{i,j}$ is the ratio of net bottom erosion and deposition to the dry weight of bottom sediment, and is determined by

$$(\Delta S_{sus})_{i,j} = \sum_{k=1}^{K} \frac{(D_k - E_k)_{i,j}}{\rho_{d,k}} \tag{9}$$

where K is the total number of sediment fractions.

Model Set-up

In the model implementations, particular attention was paid on selecting an appropriate study area, model open boundaries and horizontal and vertical resolution. This process involves the consideration of such regimes as study area geometry, availability of water level, salinity and temperature data for model open boundary conditions, the strength and nature of the ocean currents in the study area, possible maximum distance of disposal sediment plume out from the disposal site, disposal barge size, and practical computer time (normally several hours to several days) for simulating entire disposal operation, typically lasting from a few weeks to a year.

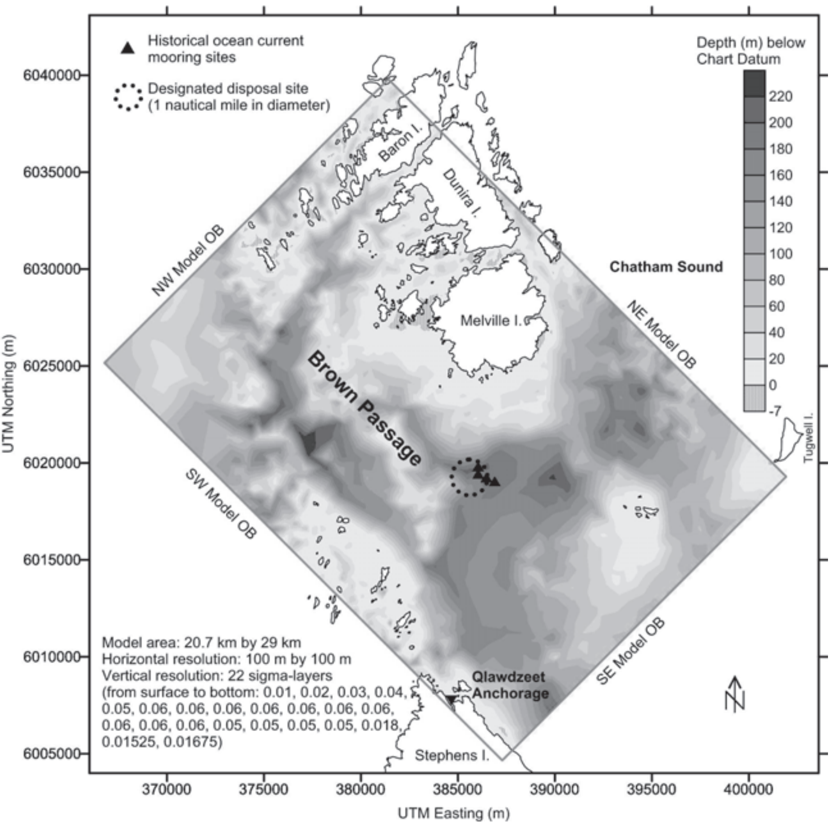

Figure 3. The study area and data sites in Brown Passage.

In the application of Brown Passage (Jiang and Fissel, 2010), the COCIRM-SED model 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 (Figure 3). 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 (see the sigma-layer thickness listed in Figure 3). The digital bathymetric data set, in the format of UTM Easting, UTM Northing and seabed elevation relative to chart datum, was gridded to provide suitable representation of the water depths in the model. The model was forced by tidal height elevations spanning four open boundaries and by surface winds. The four model open boundaries consist of the four adjoining sides of Brown Passage (Figure 3). Tidal elevations at these four open boundaries were derived from 7 major tidal height constituents (O1, P1, K1, N2, M2, S2, K2) using the Department of Fisheries and Oceans (DFO) standard tidal prediction program. The tidal constituents for the reference port of Prince Rupert and the secondary port of Qlawdzeet Anchorage, Lawyer Islands were obtained from Canadian Hydrographic Service of DFO. The wind data are obtained from the nearby Prince Rupert airport weather station, operated by Environment Canada. In the COCIRM-SED model, geostrophically balanced elevations due to Coriolis force at each open boundary are calculated and superimposed on tidal components at every time step.

Sediment Parameter Input

In modeling sediment disposal operations, STFATE and COCIRM-SED models require detailed input information of disposal barge and sediment parameters, including total disposal volume, sediment density on the barge, barge size, capacity and number of daily trips, and sediment categories. Table 1 listed these input parameters for the planned marine dredging and possible terrestrial overburden disposals in the Brown Passage application. The disposal sediment density and categories (content and size) were obtained and identified from detailed sediment sampling data at the project construction site. The bulking factor reflects the disposal sediment volume increasing when placed under water, typically ranging from 1.0 to 1.4. In the Brown Passage application, the lower limit value 1.0 was used. In other words, the disposal material volume when placed under water was assumed to be the same as on the barge. The capacity of disposal barge was taken to be 2,000 m^3, with 7 trips per day. The disposal trips were simply assumed to run 24 hours a day with a constant time interval between each trip. It should be noted that adverse weather conditions may delay trips out to the disposal site during which time the disposal material would be accumulated on barges near the project site, and then the disposal operations would continue when weather permits.

It was also assumed that dredging/excavation and disposal activities would occur during fall and winter to minimize the effects of high turbidity that may be detrimental to marine life. In the Brown Passage application, the marine dredging disposal will have a total of 90 trips for a duration of about 13 days. Accordingly, the model simulated the marine dredging disposal from late November to early December. After completion of all dredging, the model run was continued for another 21 days to let all suspended disposal sediment settle out on the seabed. The terrestrial overburden disposal will have a total of 520 trips for a duration of about 74 days, and the model run started in early December and ended in the following late February. After completion of all overburden, the model run continued for another 17 days to let all suspended disposal sediment settle out on the seabed.

There are no sediment measurement data available in the study area for validating sediment parameters regarding settling velocity and critical shear stresses for suspended sediment deposition and bottom sediment erosion. These parameters were thus computed based on previous publications and studies. The cohesive sediment parameter were based on the works of Krone (1962), Parchure and Mehta (1985), Mehta and Li (1997), and Jiang (1999). The non-cohesive sediment parameters were based on the works of Shields (1936), Bagnold (1966), Rijn (1984a, 1984b, and 2001), and Wu, et al. (2000).

Table 1. Summary of barge and sediment input parameters for the marine dredging and terrestrial overburden disposals in Brown Passage.

Parameter			Marine dredging	Terrestrial overburden
Total disposal volume (m^3)			180,000	1,040,000
Sediment bulk density on barge (kg/m^3)			1,340	2,189
Sediment dry density on barge (kg/m^3)			512.69	1,900
Barge capacity (m^3)			2,000	2,000
Daily trip			7	7
Dumping duration (minutes)			2	2
Bulking factor			1.0	1.0
Modeling period			Nov. 20 – Dec. 24	Dec. 11 – Mar. 12
Barge size		Length (m)	80	80
		Width (m)	11.4	11.4
		Draft (m)	4.5	4.5
Sediment category	Content (%)	Clay	20.85	6.61
		Fine silt		13.01
		Coarse silt	24.15	8.98
		Fine sand		7.09
		Medium sand	55	23.09
		Coarse sand		13.02
		Gravel		28.20
	Size (mm)	Clay	0.004	0.003
		Fine silt		0.011
		Coarse silt	0.03	0.033
		Fine sand		0.102
		Medium sand	0.2	0.426
		Coarse sand		1.667
		Gravel		14.485

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 a 40 year wind data set recorded at Prince Rupert airport weather station and tidal elevations predicted using major tidal constituents, the winds and tidal elevations from a typical fall and winter seasons (late November, 2008 – early March, 2009) were chosen as the input of driving force to the model.

Model Validation

To validate the 3D model COCIRM-SED as a reliable tool for the sediment disposal modeling study, the model at first went through appropriate calibration and verification processes using available water elevation and ocean current data in the study areas. In the Brown Passage application, the model was validated using ocean current data at the DFO current meter mooring site located near the regional ocean disposal site (Figure 3).

The model was initially tested and operated in the calibration run. Various physical parameters, mainly bottom drag coefficient and horizontal and vertical eddy diffusivity coefficients, as well as major tidal constituent phases were repetitively adjusted to achieve optimal agreement with the observations and physically reasonable flow patterns in Brown Passage. Some adjustments of the horizontal diffusivity and bottom drag were made through the user-specified calibration parameter in Smagorinsky's formula (Smagorinsky, 1963) and bottom effective roughness height. Because there is not sufficient tidal elevation data to derive the tidal constituents at all four model open boundaries, the major tidal constituent phases were the most important parameter for the purpose of this model calibration.

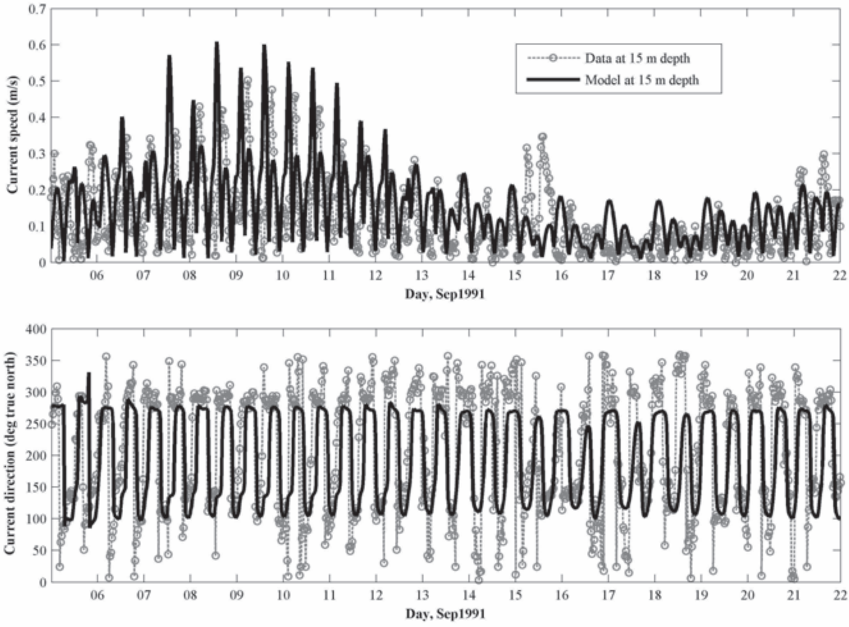

Figure 4. Calibration model results of ocean currents at 15 m depth near the disposal site, with comparison to observations at the same location.

The calibration results of modeled versus measured ocean current speed and direction at the mooring site are shown in Figure 4 for 15 m depth and Figure 5 for 98 m depth. It is seen that the model results are in reasonably good agreement with observations. The model peak ebb and flood flows at 15 m depth for a spring tide are shown in Figure 6. The modeled flow patterns are found to be physically reasonable in the entire model domain including the areas near the model open boundaries. The most noticeable discrepancy is seen at 15 m depth on September 15, 1991 under neap tide conditions (Figure 4), where the model considerably under-predicted the ocean current speed compared with the measurement. This discrepancy is believed to be caused by much weaker wind input to the model on this particular day, which used the nearby land-based weather station data at Prince Rupert Airport. On this particular day, the weather station data show a moderate SE wind with the speeds of 2 – 7 m/s, while the measured data at a more distant offshore buoy in Hecate Strait show much stronger ESE winds with the speeds ranging from 8 m/s to 13 m/s.

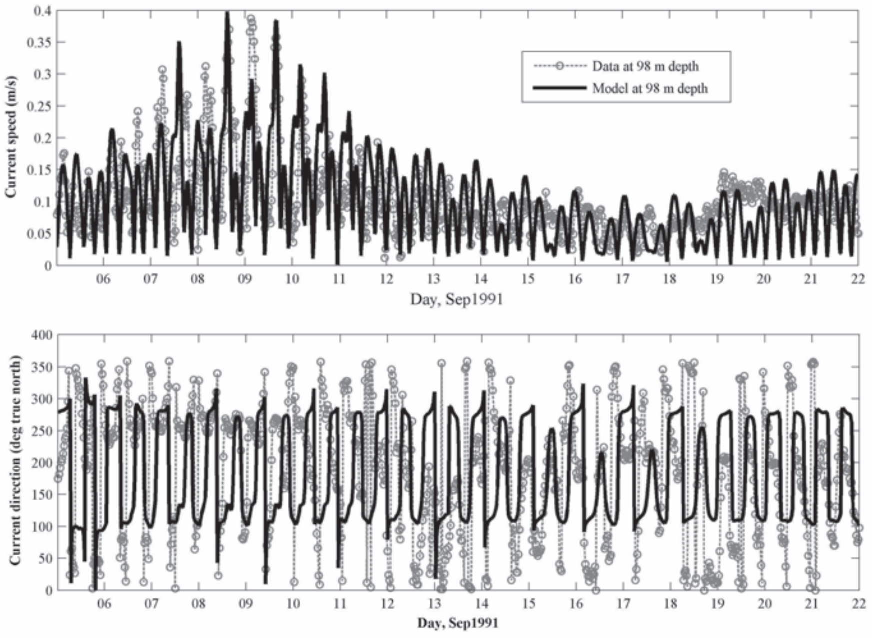

Figure 5. Calibration model results of ocean currents at 98 m depth near the disposal site, with comparison to observations at the same location.

The model was next operated in validations runs using the previously optimized physical parameters and tidal constituents, 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. The verification results (Figures 7 and 8) appear to be in reasonably good agreement with observations as well.

A statistical analysis of the calibration and verification model results shows that the correlation coefficients between modeled and measured current speeds and directions are greater 0.5, with a maximum value up to 0.71. Relatively weak correlation with a coefficient at about 0.4 occurs for the verification case at 98 m depth, where the measured current speeds during spring tides (Figure 8) are abnormally weak. The cause of this weak flow feature is unknown. Based the model calibration and verification results, it is concluded that the circulation module was reasonably well validated and is thus suitable for simulating disposal sediment transport and fate in Brown Passage.

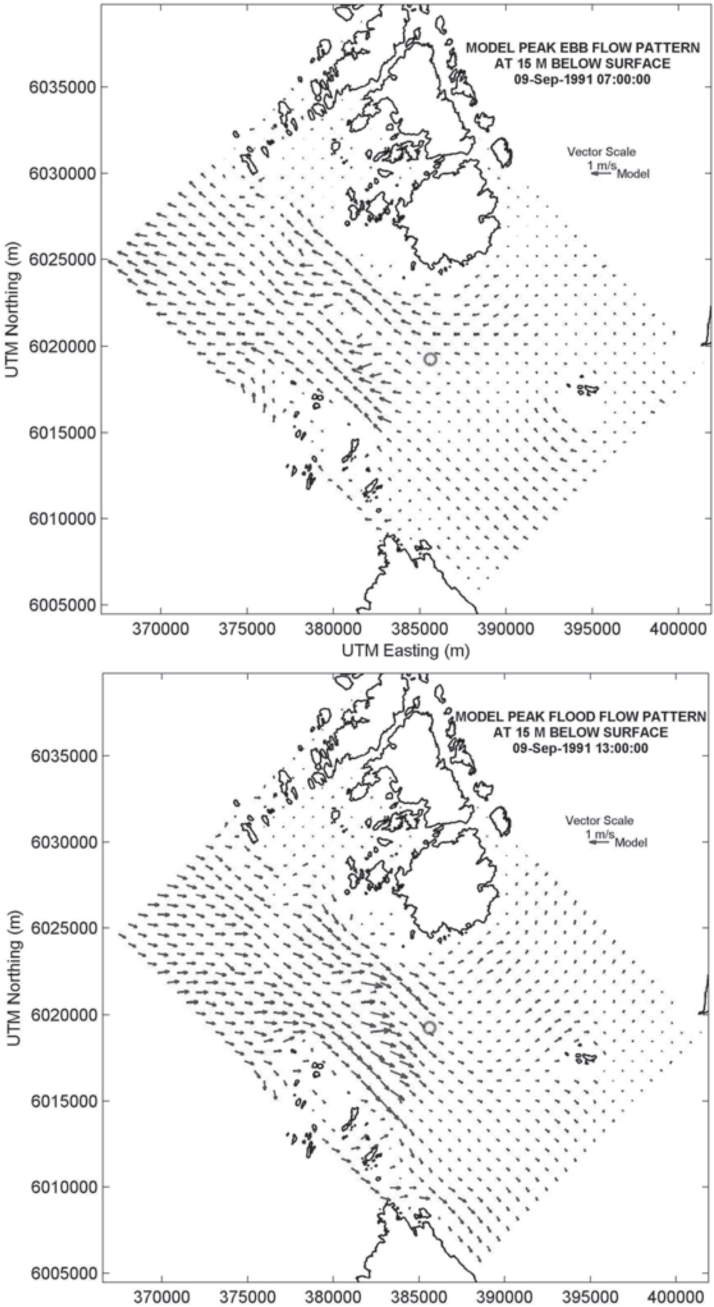

Figure 6. Model results of peak ebb (upper) and flood (lower) flows at 15 m depth.

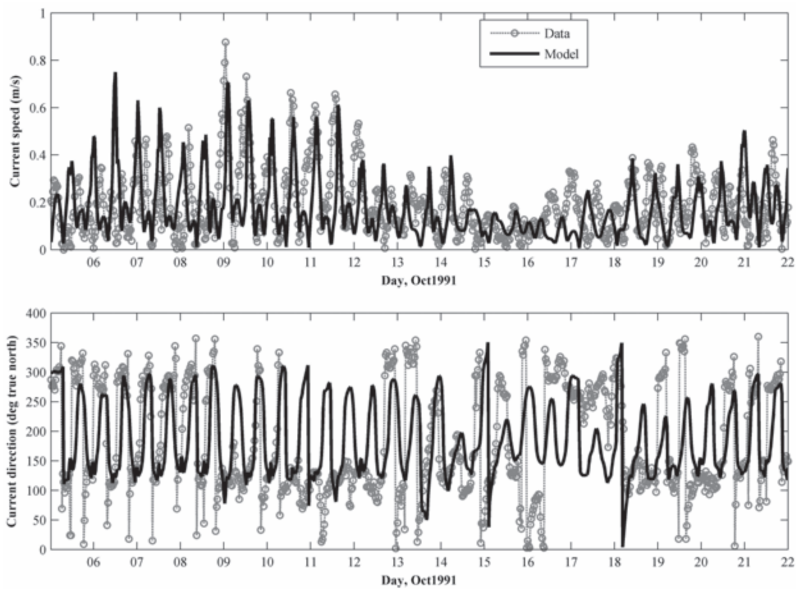

Figure 7: Verification model results of ocean currents at 15 m depth near the disposal site, with comparison to observations at the same location.

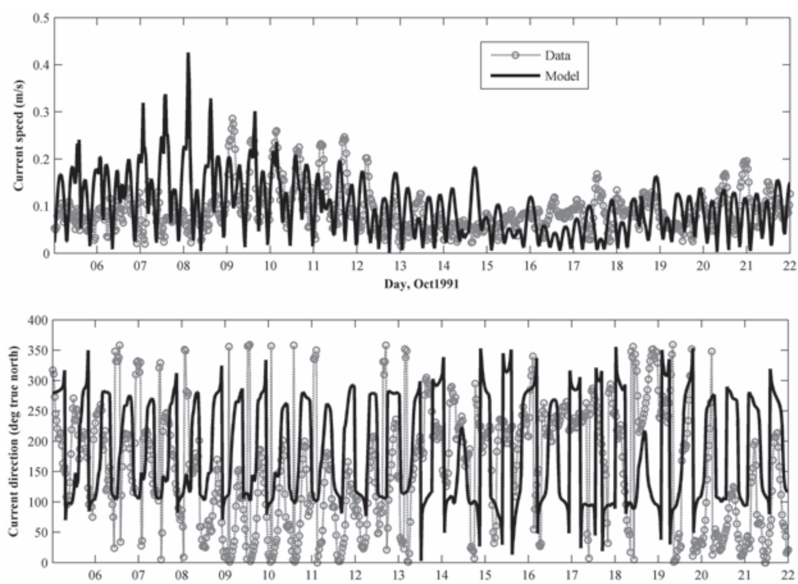

Figure 8. Verification model results of ocean currents at 98 m depth near the disposal site, with comparison to observations at the same location.

Modeling Marine Dredging Disposal

This model case deals with a scenario for the disposal in Brown Passage of the planned deeper marine dredging materials, with a high clay and silt composition and a low dry density of about 513 kg/m^3. The three sediment categories considered in the model are respectively clay (20.85%), silt (24.15%) and medium sand (55%) (Table 1).

The STFATE model results show that during the initial 45 minutes of each marine dredging disposal operation, most of sand settles out on the seabed, while most of the clay and silt remains suspended in the water column, with a total initial bottom accumulation of about 56% and the remainder still in suspension. It is also seen that the suspended sediment is mostly concentrated within 10 m of the bottom, with maximum near-bottom TSS (total suspended sediment concentration) values up to about 540 mg/L above the background level (Figure 9), and with the initial suspended sediments spreading into an area of about 1 km in diameter.

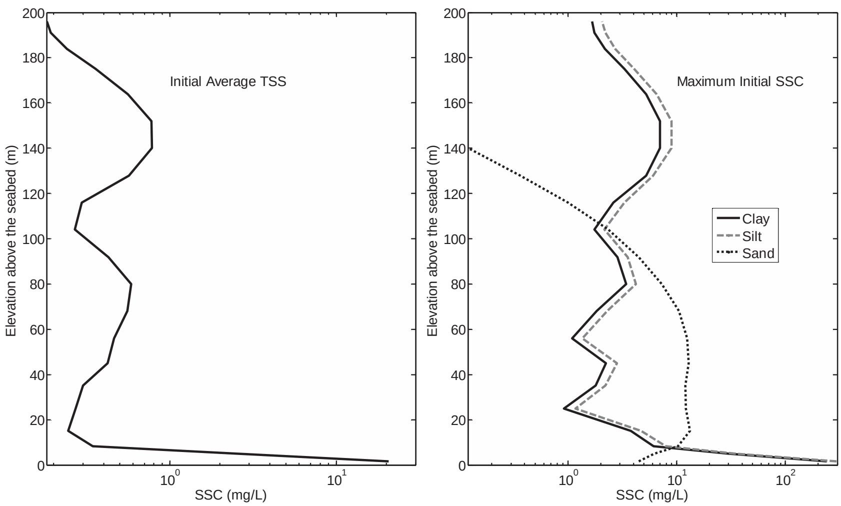

Figure 9. STFATE model results of average TSS (left) and SSC (right) profiles after the initial 45 minutes of disposal operations for marine dredging under average ebb current.

The COCIRM-SED model results of the TSS plumes and time series (Figures 10 and 11) show that maximum near-bottom (bottom 1% of the water column) TSS values right after each disposal trip is up to about 540 mg/L above background. As the model progressed, the TSS level decreased from the initial value (540 mg/L) input based on the STFATE estimates due to sediment settling as well as dilution. As a result, the maximum near-bottom TSS value is less than 50 mg/L within about 2 hours after each disposal event.

In the vertical, TSS values generally decrease towards the surface. Near-surface TSS during disposal is mostly less than 3 mg/L. Higher near-surface TSS values of about 5 mg/L only occur at the center of the dumping site right after each disposal trip. Consequently, the minimum depth with TSS values greater than 25 mg/L, the province of British Columbia (BC) water quality guideline for background levels, is greater than 140 m over the entire disposal period.

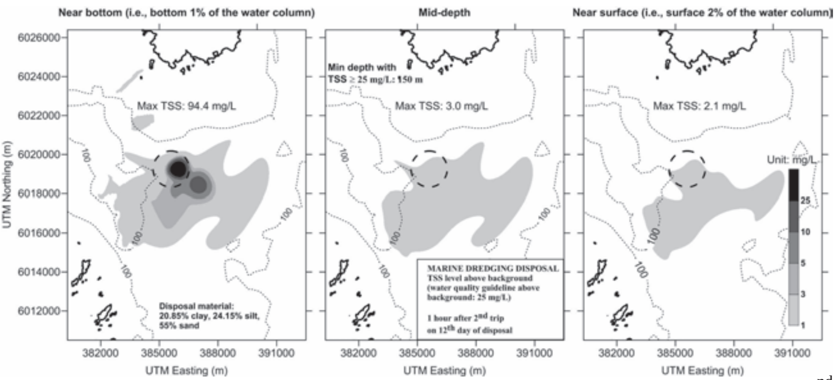

Figure 10. TSS plume at near-bottom, mid-depth and near-surface 1 hour after 2nd trip on the 12th day of the marine dredging disposal.

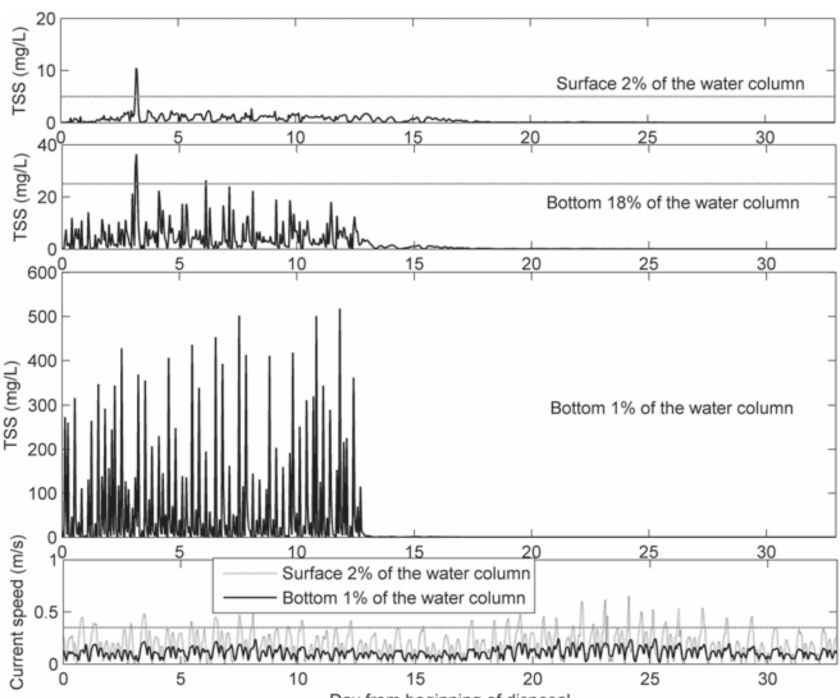

Figure 11. Time series of TSS values and current speeds at the center of the disposal site during and after the marine dredging disposal operations.

After the completion of all disposals, TSS values gradually decrease as the suspended sediment settles out on the seabed and is further diluted (Figure 11). The model results show that maximum TSS levels in Brown Passage are reduced to less than 1 mg/L within 4 days after completion of all disposals.

It is also found that the areas of TSS plumes with values greater than 1 mg/L always surround the disposal site, with the maximum distances out from the center of the disposal site about 4 – 6 km for all vertical levels (Figures 10). Because of the prevailing flood current effect (Jiang and Fissel, 2010), the TSS plumes at all vertical levels are mostly located in an area E to SW to the disposal site.

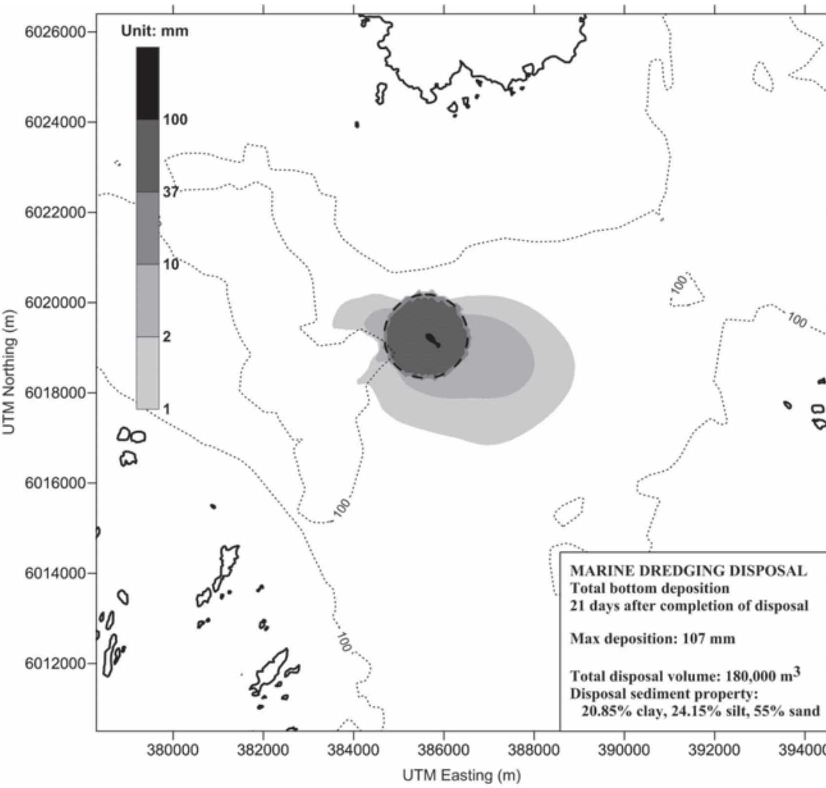

Figure 12. Total bottom accumulation 21 days after completion of all marine dredging disposals.

The total bottom accumulation after 21 days following the completion of all dredging disposals is presented in Figure 12. By this time, all suspended disposal sediments have settled out and are located on the seabed. It is seen that most dredging materials deposit in the deeper water to the SE 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 74% of total marine dredging material, with a deposition thickness ranging from 38 mm to 107 mm. The region with total bottom accumulation greater than 1 mm occurs in water depths greater than 100 m. The total deposition within this region occupies 85% of the total marine dredging material discharged into the ocean. It is also found that the maximum distance of the bottom deposition (exceeding 1 mm thickness) out from the center of the designated disposal site is about 3.4 km to SE of the disposal site.

Modeling Terrestrial Overburden Disposal

This model case deals with a scenario for the disposal in Brown Passage of possible excavated terrestrial overburden, with fully consolidated material and a high dry density of 1,900 kg/m^3. A total of 7 sediment categories were identified and included in the model, respectively clay (6.61%), fine silt (13.01%), coarse silt (8.98%), fine sand (7.09%), medium sand (23.09%), coarse sand (13.02%) and gravel (20.20%) (Table 1).

The STFATE model results show that during the initial 45 minutes of each terrestrial overburden disposal operation, all gravel and coarse sand, and most of the medium and fine sands settle out on the seabed, while most of the clay and silt remains suspended in the water column, with a total deposition of about 71% and the remainder in suspension. It is also found that the suspended sediment is mostly concentrated within 10 m of the bottom, with maximum near-bottom TSS values of up to about 1400 mg/L (not shown) above the background level, and the initial suspended sediments spreading into an area of about 1 km in diameter.

The COCIRM-SED model results of the TSS plumes and time series (Figures 13 and 14) show that maximum near-bottom (bottom 1% of the water column) TSS values right after each disposal trip is up to about 1400 mg/L above background. As the model progressed, the TSS level decreased from the initial value (1400 mg/L) input based on the STFATE estimates due to sediment settling as well as dilution. As a result, the maximum near-bottom TSS value is less than 70 mg/L within about 2 hours after each disposal event.

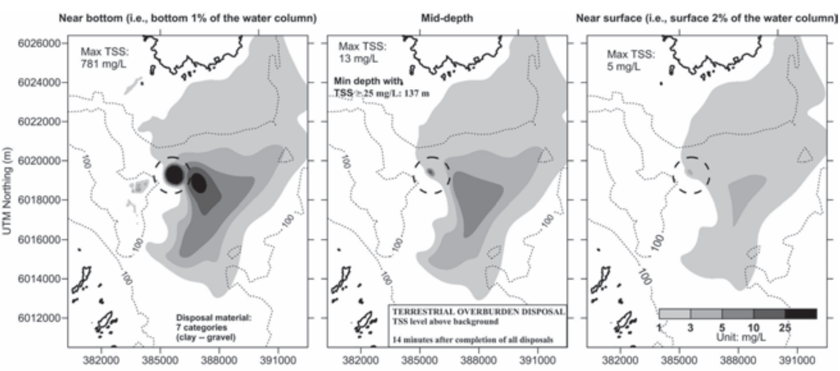

Figure 13. TSS plume at near-bottom, mid-depth and near-surface 14 minutes after completion of all terrestrial overburden disposals.

In the vertical, TSS values generally 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 (the BC water quality guideline for background levels) is greater than 125 m over the entire disposal period.

After the completion of all disposals, TSS values gradually decrease as the suspended sediment settles out on the seabed and is further diluted (Figure 14). The model results show that maximum TSS levels in Brown Passage are reduced to less than 1 mg/L within 7 days after completion of all disposals. It is also found that the maximum distances of TSS plumes with values greater than 1 mg/L are 7 – 10 km out from the center of the disposal site. Because of the prevailing flood current effect (Jiang and Fissel, 2010), the TSS plumes at all vertical levels are mostly located in the eastern half plan.

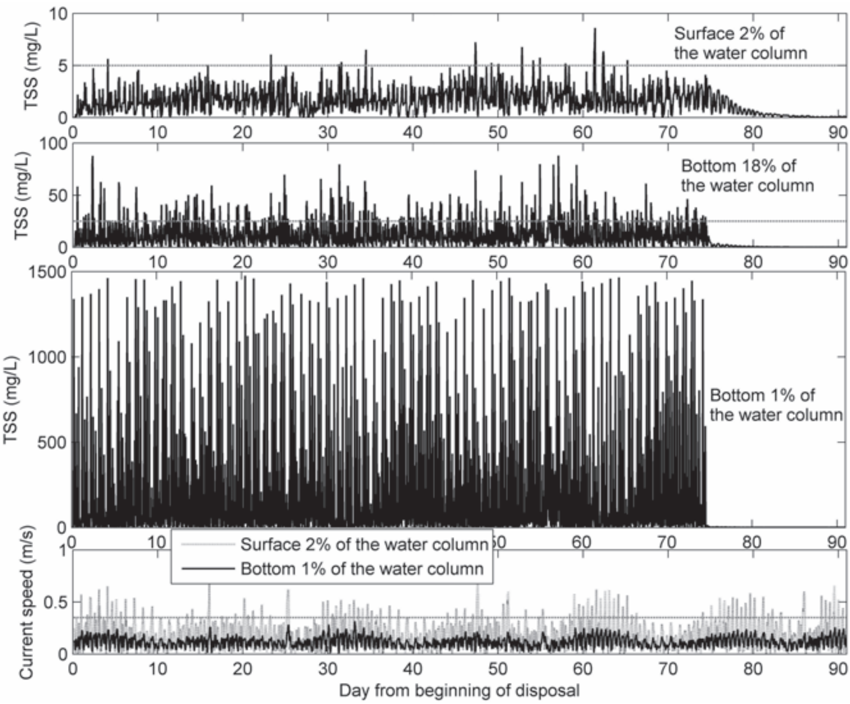

Figure 14. Time series of TSS values and current speeds at the center of the disposal site during and after the terrestrial overburden disposal operations.

The total bottom accumulation after 17 days following the completion of all dredging disposals is presented in Figure 15. By this time, all suspended disposal sediments have settled out and are located on the seabed. It is seen that most dredging materials deposit in the deeper water to the SE 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% of total marine dredging material, with a deposition thickness ranging from 276 mm to 616 mm. The region with total bottom accumulation greater than 1 mm occurs in water depths greater than 100 m. The total deposition within this region occupies 96% of the total marine dredging material discharged into the ocean. It is also found that the maximum distance of the bottom deposition (exceeding 1 mm thickness) out from the center of the designated disposal site is about 6 km to SE of the disposal site.

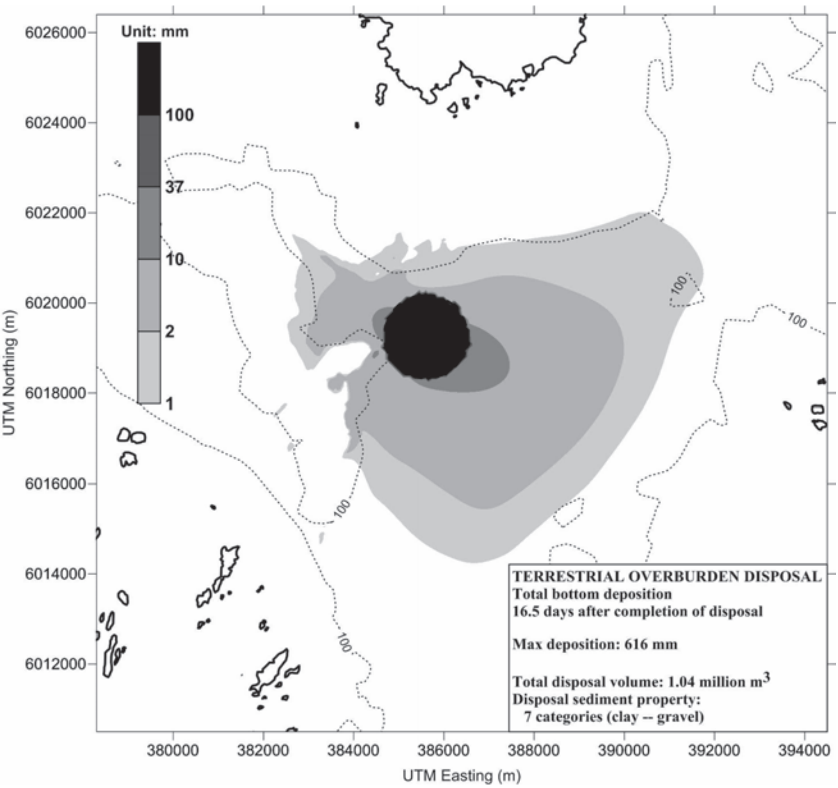

Figure 15. Total bottom accumulation 17 days after completion of all terrestrial overburden disposals.

Potential Long-Term Resuspension

In order to investigate potential long-term resuspension of the disposal sediment deposited on the seabed in Brown Passage, modeling worst case scenario was carried out, which involved an extreme wind event and tidal forcing over a 40 year period. The model simulation was conducted over an 11 day period with the first day for model spin-up, and the following 10 days for simulating the resuspension of bottom sediments that were originally deposited through the sediment disposal from this project. The initial erodible bottom sediment is the total combined deposition of marine dredging and terrestrial overburden (left panel in Figure 16).

This worst case scenario assumed that the extremely energetic winds coincided with extremely energetic tides. The extreme events for both wind and tide were taken as the maximums over a 40 year record. However, it is extremely unlikely that two independent 40 year maximum current situations, arising from the largest tidal currents and the largest wind driven currents, would happen to occur simultaneously. This scenario is considered to be extremely conservative with the results representing an upper bound of the potential resuspension of the disposal sediment on the seabed.

The model results for this worst case scenario (Figures 16 and 17) show that the maximum velocity within the major deposition area (with total deposition greater than 1 mm) is up to 0.64 m/s, which is well above the critical resuspension velocity (about 0.35 m/s) for newly-deposited fine-grained sediments (clay, silt and fine sand) (Mehta and Li, 1997). However, the strong near-bottom velocities only appears in the relatively shallower area where water depths are less than about 100 m (not shown) and where the total bottom deposition of the disposal sediment is mostly less than 3 mm. As a result, noticeable resuspensions of bottom sediments for this extreme scenario only occurs in those shallower areas (Figure 16), with a maximum resuspension value of about 2.9 mm and an average resuspension of about 0.3 mm over the 10 day modeling period. The total amount of the resuspension is about 1,900 m^3 (Figure 17). It is also found that the maximum near-bottom TSS values over the 10 day period are less than 15 mg/L above background, which is well below 25 mg/L, the BC water quality guideline above the background level. Near the surface, the maximum TSS value is only 0.2 mg/L (Figure 14).

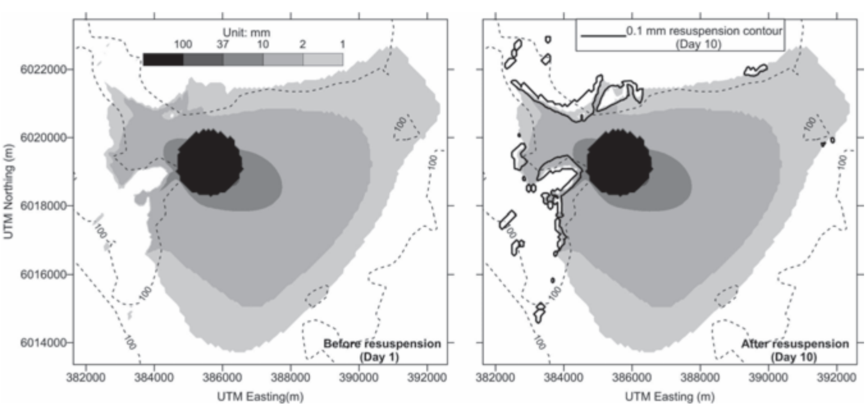

Figure 16. Disposal sediment on the seabed before (left) and after (right) resuspension under an extreme wind event and tidal forcing over a 40 year period.

Conclusion and Discussion

The STFATE and COCIRM-SED models were successfully implemented to simulate the short-term and long-term transport and fate of marine dredging/excavated terrestrial overburden disposals at a number of designated/potential sediment disposal sites in the inshore waterways of British Columbia, Canada. In these applications, the short-term fate model of sediment disposal STFATE was used to provide initial distributions of suspended sediment and bottom accumulation in details, typically within initial one hour of the sediment disposal operation, as a useful interim guide for field work and input to the 3D coastal circulation and sediment transport model

COCIRM-SED, which was then adapted to examine the transport and fate of all disposal materials over much larger spatial scales and longer periods of time. The model results provided the detailed quantitative information of TSS values above background level, the TSS plume area, and total bottom accumulation as well as potential long-term resuspension of the disposal sediment deposited on the seabed.

The Brown Passage application of modeling sediment disposal presented in this paper demonstrates the model capabilities as a useful and reliable tool in simulating the short-term and long-term transport and fate of sediment disposal in offshore waterways. The model results provide essential information for coastal and environmental engineering companies in addressing the potential impacts of the sediment disposal on the natural environment of the receiving ambient water, obtaining the regulatory approval from government agencies and as the interim guide for field work.

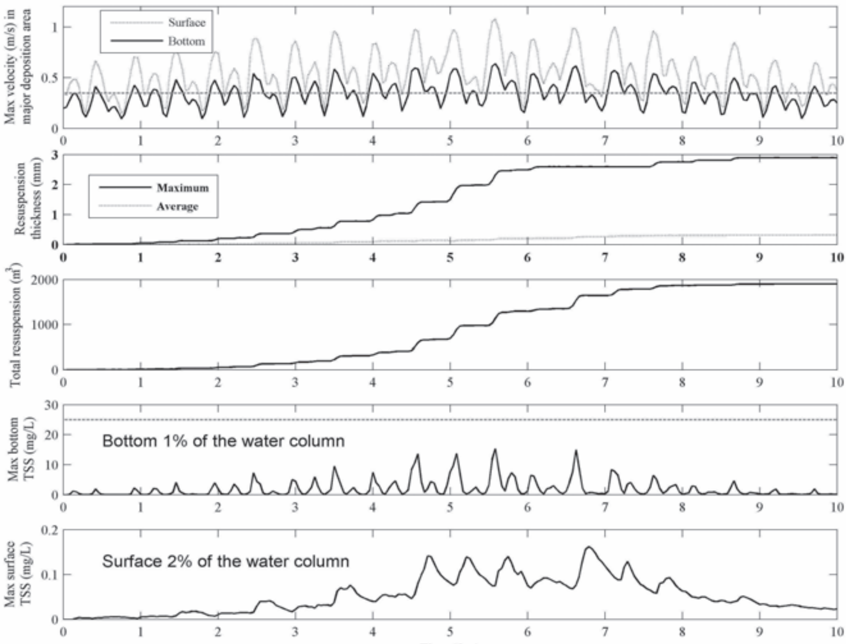

Figure 17. Time series of maximum velocity and resuspension of the disposal sediment on the seabed under extreme wind event and tidal forcing over a 40 year period.

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References

Bagnold, R.A., 1966. "An approach to the sediment transport problem for general physics." *Geological Survey Prof.*, Paper 422-I, USGS, Washington, D.C.

EPA and USACE, 1995. *"Evaluation of Dredged Material Proposed for Discharge in Waters of the U.S. – Testing Manual (Final, Workgroup Draft) (Inland Testing Manual)."* Environmental Protection Agency and United States Army Corps of Engineers, Washington D.C., 86p.

Fissel, D.B. and J. Jiang, 2011. "Three-Dimensional Numerical Modeling of Sediment Transport for Coastal Engineering Projects in British Columbia, Canada." Presented in *Oceans 2011*, Kona, Hawaii, USA.

Fissel, D.B. and J. Jiang, 2008. "3D numerical modeling of flows at the confluence of the Columbia and Pend d'Oreille rivers." In: *Estuarine and Coastal Modeling: proceedings of the Tenth International Conference*, ed. M.L. Spaulding. American Society of Civil Engineers, 928-941.

Grant, W.D. and Madsen, O.S. 1979. "Combined wave and current interaction with a rough bottom." *Journal of Geophysical Research*, 84(C4), 1797-1808.

Jiang, J. 1999. "*An Examination of Estuarine Lutocline Dynamics*." Ph. D. dissertation, Coastal & Oceanographic Engineering Department, University of Florida, 226p.

Jiang, J. and D.B. Fissel, 2010. *"3D Numerical Modeling Study of Transport and Fate of the Sediments Released during and after Disposal Operations in Brown Passage."* Unpublished Report for Stantec Ltd., Burnaby B.C., by ASL Environmental Sciences Inc., Sidney, B.C., Canada, 48p.

Jiang, J. and D.B. Fissel, 2005. *"Numerical modeling of flows in Canoe Pass: Phase 1 Report."* Unpublished Report for Focus Environmental on behalf of Canoe Pass Tidal Energy Corp and New Energy Corporation Inc. by ASL Environmental Sciences Inc., Sidney BC, Canada, 28p.

Jiang, J. and D.B. Fissel, 2004. "3D Numerical modeling study of cooling water recirculation." In: *Estuarine and Coastal Modeling: proceedings of the eighth international conference*, ed. M.L. Spaulding. American Society of Civil Engineers, 512-527.

Jiang, J., D.B. Fissel and K. Borg, 2008. "Sediment Plume and Dispersion Modeling of Removal and Installation of Underwater Electrical Cables on Roberts Bank, Strait of Georgia, British Columbia, Canada." In: *Estuarine and Coastal Modeling: Proceedings of the Tenth International Conference*, ed. M.L. Spaulding. American Society of Civil Engineers, p. 1019-1034.

Jiang, J., D.B. Fissel, and D. Topham, 2003. "3D numerical modeling of circulations associated with a submerged buoyant jet in a shallow coastal environment." *Estuarine, Coastal and Shelf Science*, 58, 475-486.

Krone, R.B. 1962. "*Flume Studies of the Transport of Sediment in Estuarial Shoaling Processes*." Hydraulic Engineering Laboratory and Sanitary Engineering Research Laboratory, University of California, Berkeley, 110p.

Mehta, A.J. and Y. Li 1997. "*A PC-based Short Course on Fine-grained Sediment Transport Engineering*." Coastal & Oceanographic Engineering Department, University of Florida, 91p.

Parchure, T.M. and A.J. Mehta, 1985. "Erosion of soft cohesive sediment deposits." *Journal of Hydraulic Engineering*, 110, 1308-1326.

Rijn, L.C.van, 1984a. "Sediment transport, part II: suspended load transport." *Journal of Hydraulic Engineering*, 110, 1613-1641.

Rijn, L.C.van, 1984b. "Sediment transport, part I: bed load transport." *Journal of Hydraulic Engineering*, 110, 1431-1456.

Rijn, L.C.van, 2001. "*Approximation formulae for sand transport by currents and waves and implementation in Delft-MOR*." WL | delft hydraulics report Z3054.20.

Shields, A. 1936. "Anwendung der aenlichkeitsmechanik und der turbulenzforschung auf die geschiebebewegung." *Mitteilungen der Preussischen Versuchsanstalt fur Wasserbau und Schiffbau, Berlin*, Germany, translated to English by W. P. Ott and J. C. van Uchelen, CalTech, Pasadena, CA.

Smagorinsky, J. 1963. "General circulation experiments with the primitive equations: I. the basic experiment." *Monthly Weather Review*, 91, 99-164.

Toorman, E.A. and Berlamont, J.E. 1993. "Mathematical modeling of cohesive sediment settling and consolidation." In: *Nearshore Estuarine Cohesive Sediment Transport*, A.J. Mehta ed., AGU, Washington D.C., 148-184.

Wu, W., Wang S. and Jia, Y. 2000. "Nonuniform sediment transport in alluvial rivers." *Journal of Hydraulic Research*, 38, 427-434.