APPENDIX A

Plume and Deposition Modeling

Sydney Harbour Dredge Plume Modelling

A three-dimensional, 4-layer hydrodynamic model of Sydney Harbour was developed and calibrated to current measurements using the Danish Hydraulic Institute's MIKE3 finite-element system (CBCL Limited 2008). Dredge plume dispersion modelling was conducted using the mud transport module of the calibrated hydrodynamic model. The sediments resuspended into the water column during dredging are dispersed based on hydrodynamic model results and settling parameters. Modelling was conducted for dredging the channel in the Seaward Arm, and dredging off the proposed container terminal in the South Arm. The modelled dredge plume concentrations were compared to background values, during both calm conditions and hypothetical modelled storm conditions.

1. Inputs and Assumptions for Dredge Plume Modelling

1.1. Simulation Period

Model runs were conducted for a 24-hour dredging scenario, and the simulation period was extended until the suspended sediment concentrations dropped back to near-background levels (less than 10 mg/l).

1.2. Hydrodynamic Conditions

Conditions influencing the dispersion of the turbidity plume are quite different between the Seaward and South Arms. In the Seaward Arm, the sediments are coarser, the residence time is short, the water column is generally well mixed and the plume size will mostly depend on instantaneous current speed (tide and/or seiche influence) and direction (ebb or flow). The South Arm has more fine sediment, the residence time is longer and the tidal currents are weak so the dispersion of the plume will depend on the mean circulation. When dredging in the South Arm, in a typical situation, the estuarine circulation will tend to carry and disperse the bottom (more concentrated) plume up the Arm. Under infrequent anti-estuarine conditions, the bottom currents can reverse. A modelling period was chosen that includes both conditions.

1.3. Sediment Characteristics

- The resuspended sediment was modelled using a moving source 1m above the seabed;
- Constant settling velocities for each sediment type were used, and are listed in Table 1. To be conservative, flocculation (which tends to increase settling velocities for high concentrations) was not included in the calculations;
- The possible current or storm-induced resuspension of material settled from the dredge plume was not modelled.

1.4. Mass Loadings

The major factors influencing the sediment source strength at a dredge are the type of dredge and manner of operation, the sediment type and ambient currents. While dredged sand quickly settles out, fines can remain in suspension for longer and be dispersed by currents and turbulent diffusion. Methods for estimating source strength are presented by Jonhson et al (2000). However the nature of dredging operations in highly variable, so neither of the methods yields highly accurate predictions. Preliminary estimates of resuspended sediment mass loads were obtained from dredging contractor Jan de Nul Group for a typical Trailing Suction Hopper Dredge that would be appropriate for the proposed Project. For the dredging of fines (in the southern section of the channel and at the container terminal), no overflowing was assumed for this type of dredge, and all sediment is released through resuspension at the seabed. For the dredging of sand in the Seaward Arm, overflowing of fines was assumed through a downward pipe releasing the overflow near the bottom.

Sediment inputs and associated mass loadings are presented in Table 1. The fine fractions are highest in the Southern section of the proposed channel and at the container terminal site, while sand prevails in the Seaward Arm. It is noted that the data will become more accurate as more geotechnical data is collected, and the final mass loadings may differ from those modelled depending on sediment characteristics and on the dredge vessel being used.

Table 1 Dredge Plume Modelling Sediment Inputs

Modelled sediment fraction			Silt	Sandy silt	Silty sand		Source of data
Assumed fine fraction			94%	50%	36%		Contractor
Median particle size of fine fraction		d50, mm	0.01	0.023	0.031		Contractor
Settling velocity of fines		mm/s	0.1	0.5	1		Stoke's law
Critical shear stress for deposition of fines		N/m2	0.04	0.07	0.1		Shields law
Channel *- Assumed dredge speed 1.5 knots*							
Seaward Arm, North	*Assumed cycle length: loading 3 hrs, sailing, pumping ashore & sailing back 4hrs.*					Total	Contractor
	Occurrence in borehole data		0%	0%	100%	100%	Boreholes
	Fine fraction of total		0%	0%	3%	3%	
	Mass loading	kg/s	0	0	189	189	Contractor
Seaward Arm, South	*Assumed cycle length: loading 45min, sailing, pumping ashore & sailing back 3 hrs.*						Contractor
	Occurrence in borehole data		5.6%	27.8%	66.7%	100%	Boreholes
	Fine fraction of total		5.3%	13.9%	24.0%	43%	
	Mass loading	kg/s	74	197	341	612	Contractor
Container Terminal *- Continuous dredging assumed*							
Top 1m	Occurrence in borehole data		36%	48%	15%	99%	Boreholes
	Fine fraction of total		34%	24%	5%	63%	
	Mass loading	kg/s	327	232	52	612	
Deeper than 1m	Occurrence in borehole data		15%	15%	38%	68%	Boreholes
	Fine fraction of total		14%	8%	14%	35%	
	Mass loading	kg/s	168	89	163	420	

2. Modelled Dredge Plume Concentrations

Background suspended sediment levels are typically low (less than 10 mg/l), and results are presented in terms of plume concentration above background.

2.1. Channel

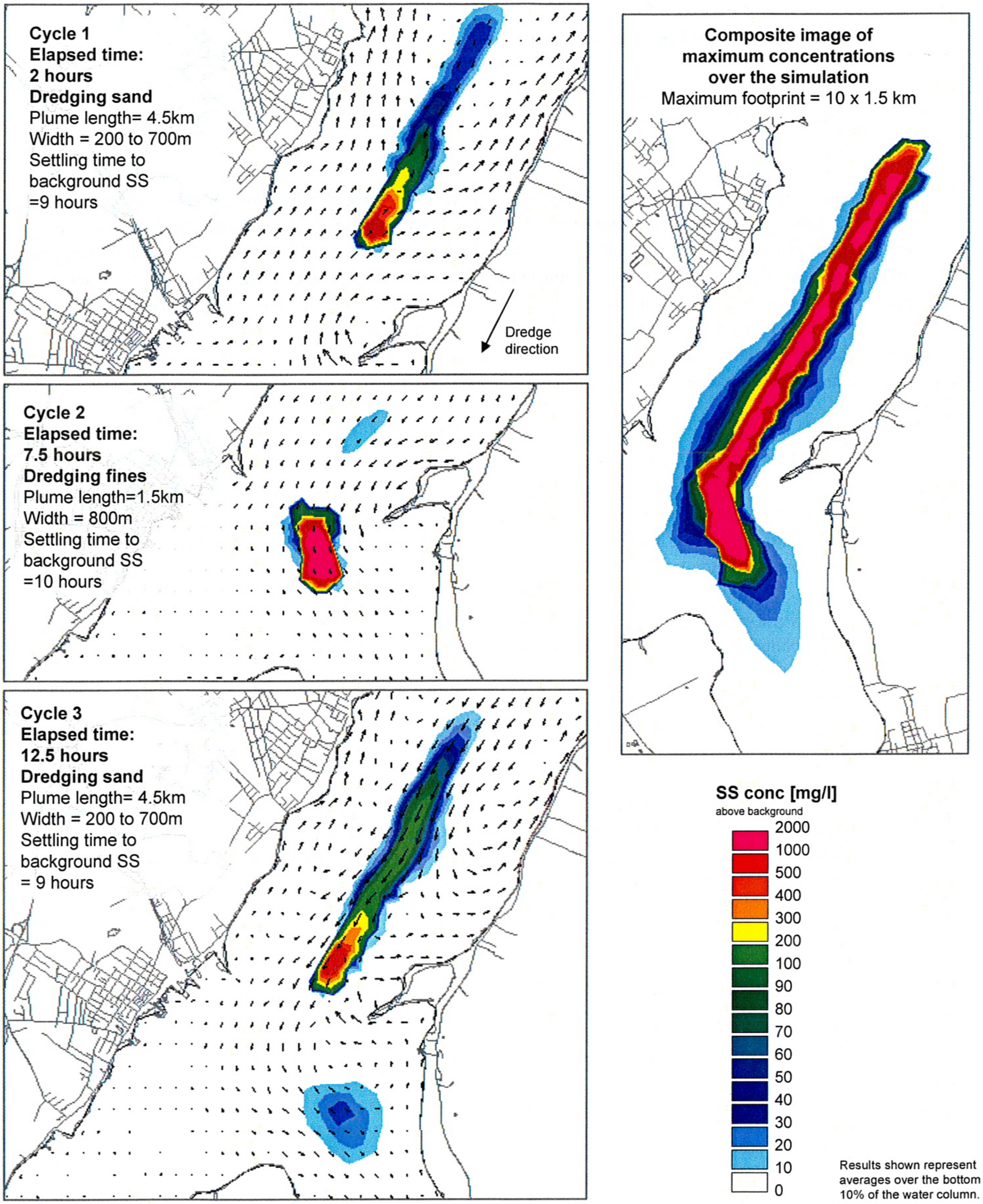
The turbidity plume patterns are shown on Figure 1. A 24-hour sequence of 5 dredging cycles was modelled, alternating between dredging sand in the Seaward Arm and fines in the South section of the channel. A complete dredging cycle (loading, sailing, dumping) was assumed to be 7 hours for sand and 4 hours for fines. Settling time for a plume generated during one cycle is estimated from 8 to 10 hours, so the cumulative impacts of several cycles would be fairly limited. In the Seaward Arm the currents are aligned with the channel, which minimizes the plume width. In the southern section, the speed of currents decreases and more fines are resuspended, which tends to increase both the width of the plume and its settling time. The model indicates that the plume would stay in the centre of the Arm within a 1.5 km-wide track and not reach the shoreline.

2.2. Container terminal

The turbidity plume patterns from 24-hour continuous dredging are shown on Figure 2. The model indicates that the plume and its subsequent re-deposition would be confined to the South Arm, mainly due to the mean up-harbour bottom currents. The infrequent flow reversals are not sustained enough to cause turbidity outside the Arm. Once it exits into the Northwest and Seaward Arms, the concentrations are diluted to background levels. Above-background turbidity levels from a 24-hour continuous dredging period would last about 4 to 5 days.

2.3. Re-deposition from Turbidity Plume

The modelled plume re-deposition from the 24-hour dredging scenarios were extrapolated to represent the projected full-scale footprint based on the following assumptions. In the channel, it is assumed that 3.5 million m^3 will be dredged. Fines will be overflowed when dredging sand, filling the 46,000 m^3 hopper dredge to 80% capacity. No overflow will occur when dredging fines, filling the hopper to an assumed 25% of capacity. The volume of the channel to be dredged is estimated at 25% fines (mostly in the southern section) and 75% sand. , representing 76 cycles for fines and 71 cycles for sand. Operations will be conducted over a period of about a month. At the container terminal, it is assumed 500,000 m^3 need to be dredged, at an assumed rate of 260 m^3/minute. The total dredging time will be about 32 hours. Re-deposition patterns are shown in Fig. 3. The model indicates that plume deposits over 1mm in thickness will be roughly within the footprint where SS will exceed 10mg/l. Deposits are expected to be up to 10 cm over areas with high fine contents.



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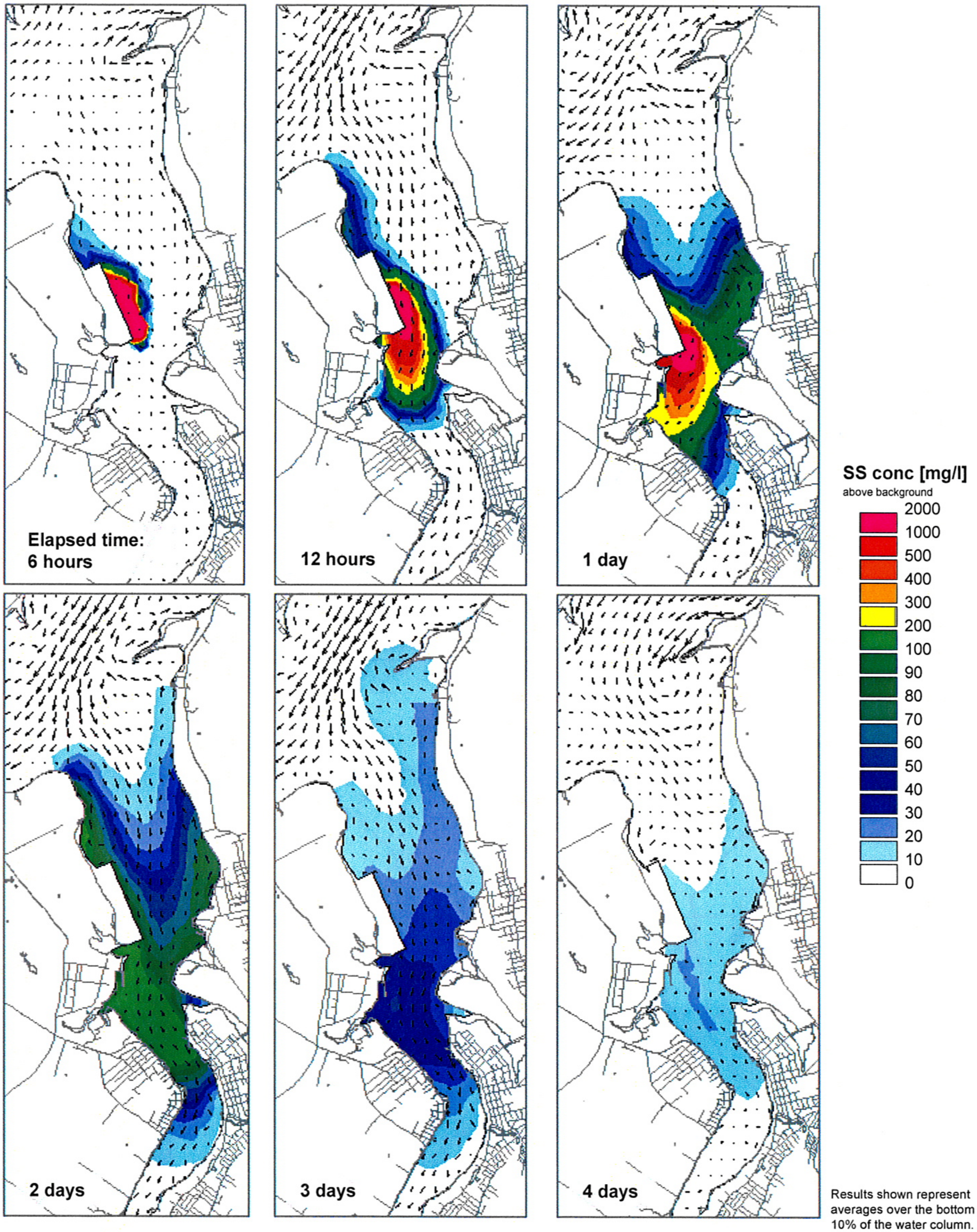
	Modelled Turbidity Plume From Channel Dredging in the Seaward Arm	**Figure 1**



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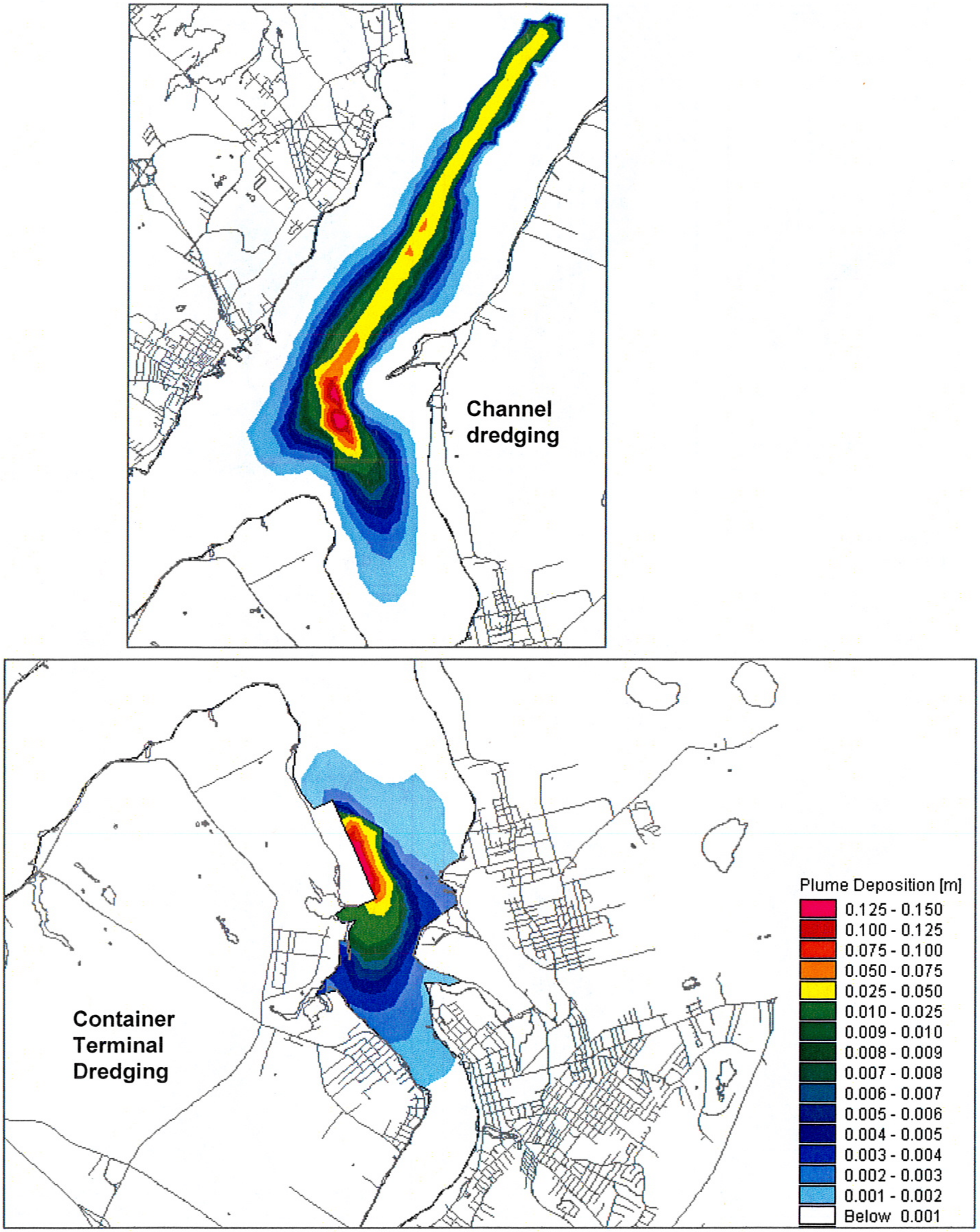
Modelled Turbidity Plume From 24-Hour Continuous Dredging of Fines at the Proposed Container Terminal

Figure 2



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	Sydney Harbour Dredge Plume Modelling	October 2008 Job No. 082466
	Modelled Re-deposition from Turbidity Plume	**Figure 3**

3. Storm-Induced Turbidity Peaks

In terms of environmental impacts, it is important to compare the dredging-induced turbidity with natural background levels that would peak during storms. In the Seaward Arm, the higher SS peaks would be primarily due to resuspension by waves as there are no major river discharges. The existing SS measurements only provide typical background values and are do not include large storms, so there are no calibration data available for storms.

3.1. Existing Data

As detailed in the oceanographic summary, TSS samples were collected by ASA at 8 sites throughout the South Arm and at current meter sites 4 and 5 off New Victoria and Sydney Mines on several occasions in August and December 1992. All SS concentrations at the top and bottom of the water column were below 10 mg/l, except for two isolated occurrences at the bottom where the sampling mechanism may have stirred up bottom material. The values are typical for lower-energy coastal waters with limited river inputs. It is interesting to compare these values to Halifax Harbour data, where an extensive water quality dataset is currently being collected as part of the Halifax Harbour Water Quality Monitoring Project (COA 2006). Like Sydney Harbour, Halifax Harbour is a relatively deep inlet on the Atlantic Ocean with relatively few sediment inputs, and the mean TSS levels are comparable – ranging from 2 to 11 mg/l for Halifax in 2006, depending on the time of year. Higher values may be attributed to passing storms and phytoplankton blooms. Out of 364 samples for 2006 (26 weeks x 7 sites x 2 depths), the maximum value observed was 41 mg/l at 1m below surface, and 34 mg/l at 10m. The dataset does not include shallow water results during a major storm.

3.2. Inputs and assumptions

As for the dredge plume modelling exercise, the mud transport module of MIKE3 was used over the same model domain. Sediment re-suspension and transport was activated based on bottom shear stresses and currents, using the hydrodynamic results and wave fields computed using the spectral wave module MIKE21 SW driven by 1-year return offshore wave conditions at the boundary.

Sediment characteristics -

Assumed bottom sediment characteristics are as measured in the Seaward Arm, i.e. 80% sand and 20% fines. The sand fraction was assigned a 0.1 N/m^2 critical shear stress for erosion, a 1mm/s settling velocity, and is primarily transported as bedload. Most of the modelled turbidity would therefore come from suspended transport of the fine fraction, which was assigned 0.07 N/m^2 critical shear stress and a conservatively low settling velocity of 0.1mm/s.

Erosion -

Erosion formulations and coefficients constitute the most sensitive calibration parameter, which can influence the modelled SS values by several orders of magnitude. Erosion was modelled using the formula and values suggested by DHI (2008):

$E = Eo * \exp(\alpha (\tau - \tau_{critical}))$ in $kg/m^2/s$,

with τ bed shear stress and Eo and α key factors governing the speed of erosion. For soft beds Eo can range from 5.10^{-6} to 2.10^{-5}. The factor α adds more uncertainty in the form of potentially exponential variation. Fig 4 illustrates the 10-fold variability in resulting SS values from just the variation in Eo, assuming the exponential factor is equal to one (and not accounting for settling). It also shows how SS concentrations can be much higher in shallow water during storms.

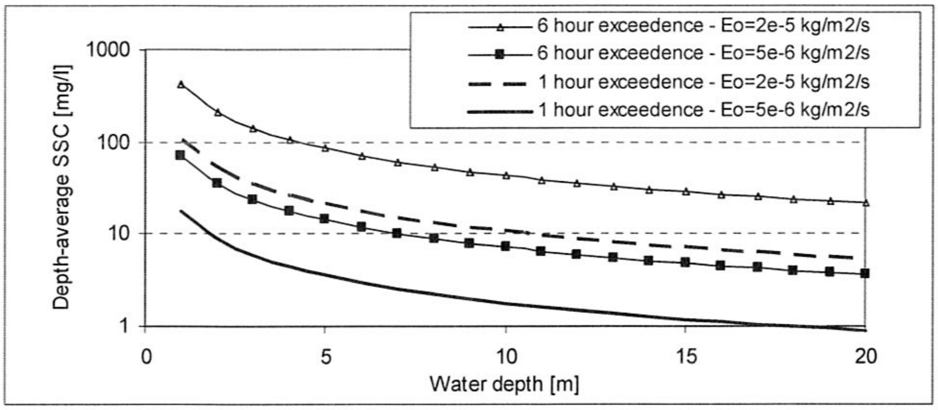


Figure 4 Suspended sediment concentration as a function of erosion coefficient and duration of exceedence of critical bottom shear stress - Note: Possible exponential variations due to bottom type are not represented

The model was tested using a range of values for Eo and α. Results are given for a particular combination ($Eo = 1.25.10^{-5}$ and $\alpha = 1$) that provides a reasonable fit to typical calm conditions where background TSS are below 10 mg/l. The modelled peaks storm values could not be verified.

Considerations on suspended concentration profiles -

The model calculates average concentrations over each horizontal layer. As with the dredge plume model runs, the bottom layer in the model represents the lower 10% of the water depth, i.e. up to 1.5m above bottom in the Seaward Arm. The results can therefore be compared on a similar basis between dredging and storm simulations. It is noted that the actual concentrations will be much greater than shown very close to the bottom.

3.3. Results

The model results are shown on Fig. 5. Under calm conditions (i.e. no wave agitation), the model reproduces the observed background levels, generally below 10 mg/l except for a few peaks between 10 and 20 mg/l under higher currents. The model indicates that one-year return storm waves may cause levels up to several hundred mg/l in the shallower areas along the coastline. Over the channel centerline, peak values may be in the order of 10 to 100 mg/l. Based on the assumed settling velocities, the values would return to background levels typically 5 to 10 days after the peak of the storm. Again, it is cautioned that depending on the assumptions and input coefficients, results for the peak of the storm may vary by an order of magnitude. More field data is needed to increase confidence in these results.

In term of turbidity levels, a 1-year storm would have a greater footprint than that generated during dredging in the Seaward Arm, except along the narrow centerline of the channel where turbidity may be up to 10 times higher during dredging. However, a storm would cause a much greater spreading of suspended sediment with peak concentrations occurring along the shorelines. For the marine organisms whose habitat spans both the shallow and deeper waters of the harbour, turbidity from the dredging operations in the channel (depending on their duration) may be comparable to that from an extended period of back-to-back storms with the exception of much lower turbidity close to the shoreline.

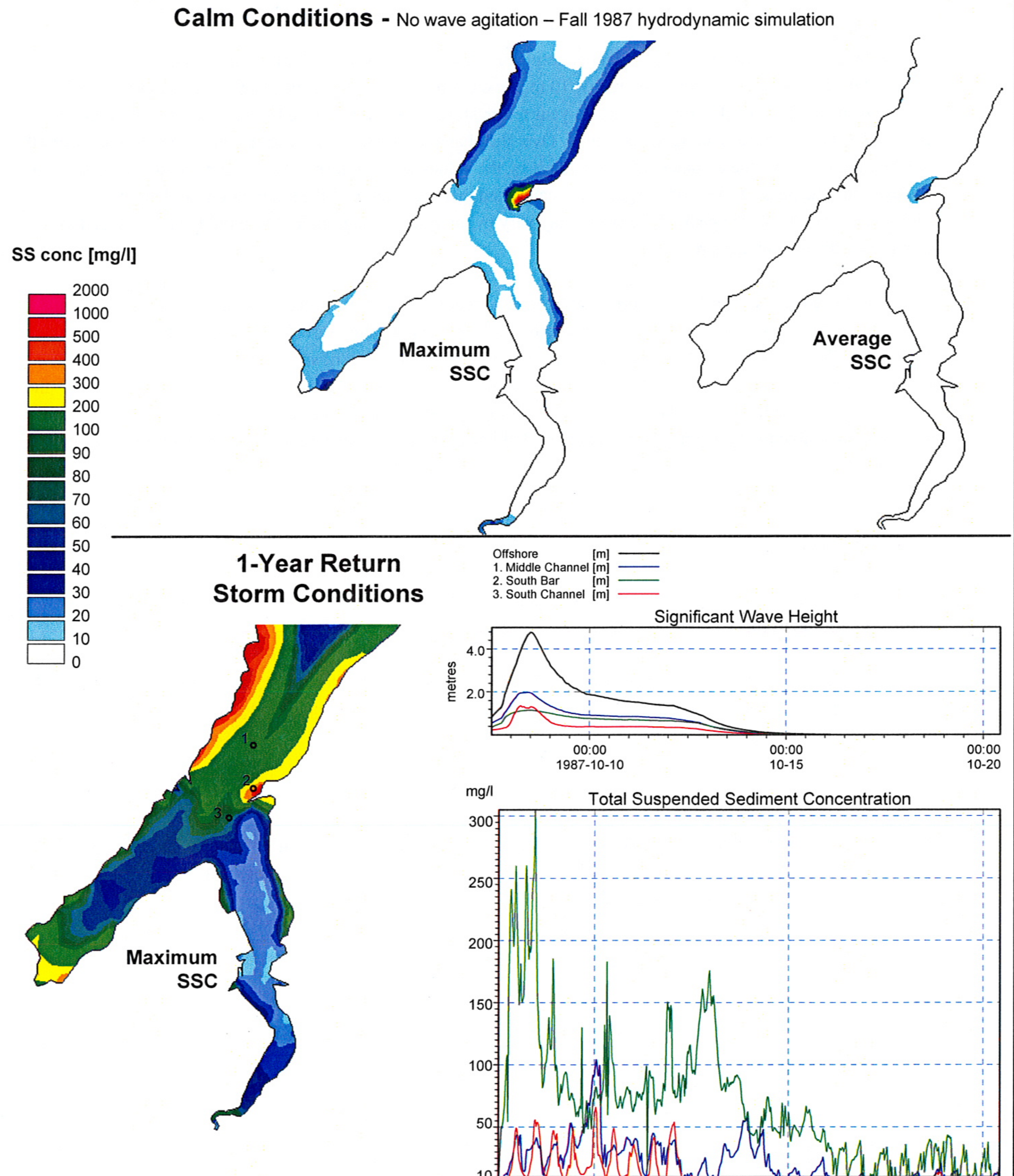
4. References

CBCL Limited, 2008. Sydney Harbour Hydrodynamic Coastal Study. *In Preparation* for Sydney Ports Corporation Inc.

Coastal Ocean Associates Inc., 2006. Halifax Harbour Water Quality Monitoring Program – Quarterly Report #4. Prepared for Jacques Whitford Limited. http://www.halifax.ca/harboursol/waterqualitydata.html - accessed 20 Oct 2008.

DHI Software, 2008. MIKE3, Coastal Hydraulics and Oceanography – User Guide. Danish Hydraulic Institute.

Johnson, B. H., and Parchure, T.M. 2000. Estimating dredging sediment resuspension sources. DOER Technical Notes Collection (TN DOER-E6). U.S. Army Engineer Research and Development Center, Vicksburg, MS. www.wes.army.mil/el/dots/doer



Results shown represent averages over the bottom 10% of the water column.
Potential variability = 1 order of magnitude, depending primarily on erosion coefficients and depth above bottom being considered.

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	Modelled Natural Suspended Sediment Concentrations	**Figure 5**