Centerm Expansion Project

Draft TSS/Turbidity Monitoring Plan

Vancouver Fraser Port Authority

Project reference: Centerm Expansion Project
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Quality information

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1. Introduction

The Centerm Expansion Project (CEP or the Project) is a proposed series of improvements to the existing Centerm container terminal (Centerm or the Terminal) located on the south shore of Burrard Inlet in the city of Vancouver. The Project will include expansion of the existing Terminal footprint, both westward and eastward. Ocean infilling is required to create the expanded land base, necessitating construction of perimeter dykes to contain the infill material (Figure 1). To establish structurally sound foundations for the perimeter dykes, dredging of fine surficial marine sediments will be necessary.

Dredging and infilling have the potential to affect the marine environment through release of fugitive sediment to the marine water column. The main environmental effects of fugitive sediment are increases in total suspended solids (TSS) and turbidity. In addition to dredging and infilling, construction of the Project will also involve several other in-water work activities that have the potential to release fugitive sediment:

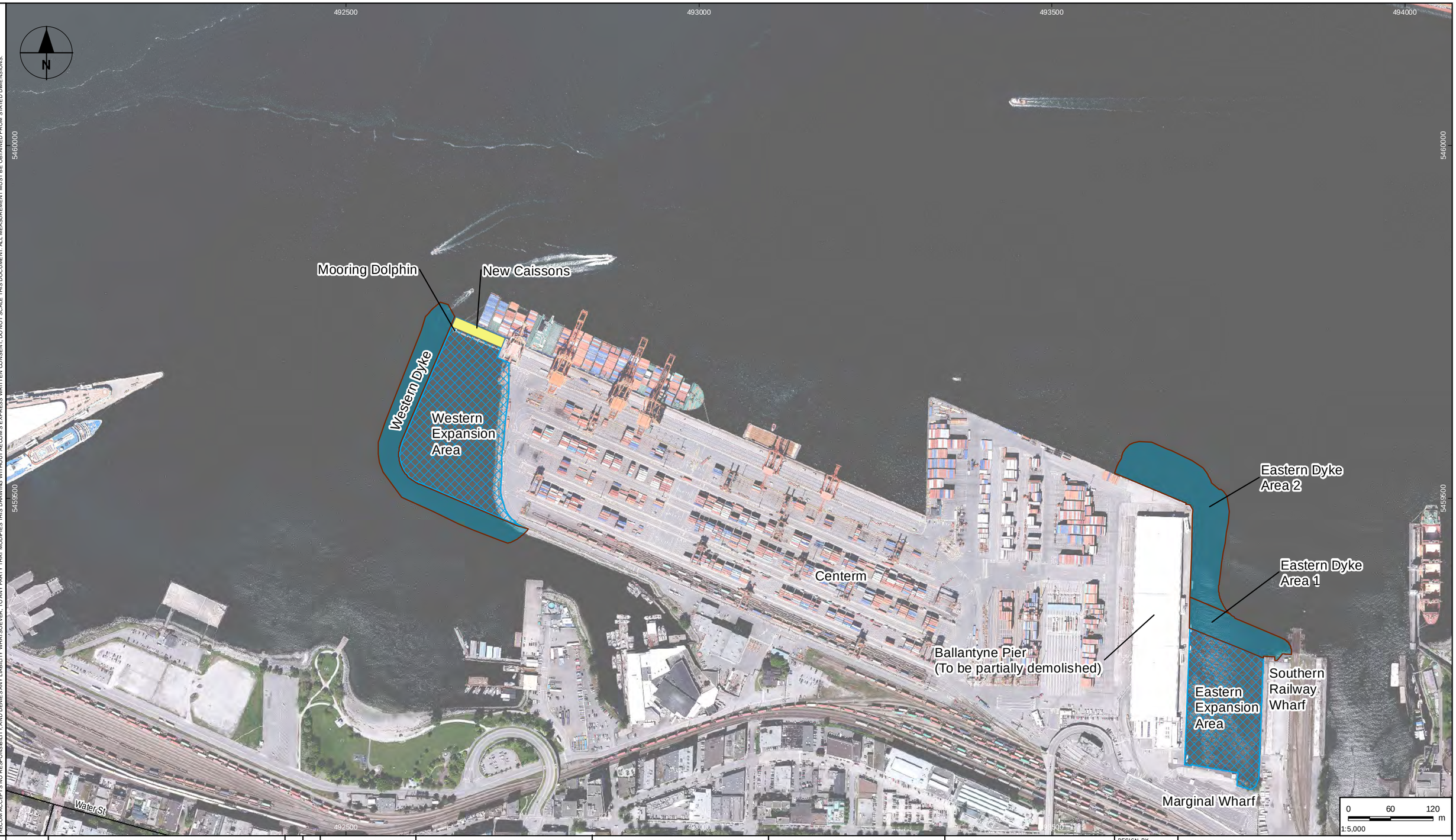
- Building rock dykes for the eastern and western expansion areas.
- Placing two new concrete caissons to extend the existing marine berth.
- Demolishing portions of existing in water structures.

The potential effects and management of sediment releases from in-water work activities are of direct importance to CEP and to three regulatory agencies responsible for review and authorization of different aspects of the Project:

Vancouver Fraser Port Authority (VFPA or the port authority) – The Project site is located on federal land and waters under the jurisdiction of the port authority and is subject to review and approval by the port authority under the Project and Environmental Review (PER) process before it can proceed. The PER application for the Project is currently undergoing review by the VFPA. The effects of fugitive sediment releases and mitigation measures to manage turbidity are part of the port authority's environmental review of the Project.

Environment and Climate Change Canada (ECCC) – The primary role of ECCC in the environmental oversight of the Project is related to dredging, disposal at sea of any dredged materials, and the potential for pollution of the marine environment. Effective management of sediments and limiting their release, during both dredging and disposal of dredged materials, will be part of ECCC's review of the Disposal at Sea Application for the Project. ECCC administers subsection 36(3) of the *Fisheries Act*, under which it is an offence for anyone to deposit or permit the deposit of any type of deleterious substance in water frequented by fish without a permit or under a regulation. Under section 131 of the CEPA 1999, however, if a person disposes of a substance in accordance with conditions of a Disposal at Sea Permit issued under section 130 of CEPA 1999, subsection 36(3) of the *Fisheries Act* is not applicable. When considering dredging associated with the proposed Project, ECCC defines appropriate working conditions and sediment levels. These conditions will be integrated into the DAS permit for the activity.

Department of Fisheries and Oceans – Under section 35(2) of the *Fisheries Act*, authorization from DFO is required for carrying out any work that could result in serious harm to fish that are part of a commercial, recreational, or Aboriginal (CRA) fishery or to fish that support such a fishery. The effects of deposition of sediment on fish and fish habitat will be assessed by DFO as part of their review of the *Fisheries Act* Authorization Application for the Project.



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CENTERM EXPANSION PROJECT
PROPOSED IN-WATER STRUCTURES

Figure 1

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1.1 Purpose

This Draft TSS/turbidity monitoring plan (Monitoring Plan) outlines the procedures for monitoring TSS/turbidity to determine compliance with CCME Canadian Water Quality Guidelines for the Protection of Aquatic Life (WQGs) (CCME 2002) and inform management of in-water work activities. Prior to commencement of in-water works the Design Build Contractor (Design Builder) will update this Monitoring Plan to reflect specific construction methods and operating procedures.

1.2 Applicable Numerical Limits

The CCME WQGs provide numerical concentrations that are recommended as maximum levels that should prevent adverse biological effects on biota, their functions, or any interactions that are integral to sustaining the health of ecosystems.

The CCME WQGs and the provincial Water Quality Ambient Water Quality Guidelines (Criteria) for Turbidity, Suspended and Benthic Sediments Overview Report (BC MOE 2001) have the same numerical limits for fugitive sediments. The TSS numerical limits are measured in milligrams per litre (mg/L) and based on increase from background levels. There are different numerical limits for short term and long term exposure. In-water work activities at CEP that will have the potential to release fugitive sediments will typically be of durations longer than 24 hours (i.e., dredging) and the long term exposure limits will apply. However, there will likely be some activities that last less than 24 hours where the short term exposure limits will apply. The federal (CCME 2002) and the provincial (BC MOE 2001) criteria for the protection of aquatic life that apply to the Project are provided in Table 1.

Table 1 Guidelines on Total Suspended Solids and Turbidity

Parameter	Assessment Criteria at 100 m
Total Suspended Solids clear flows	• Average increase of 5 mg/L from background levels for longer term exposures (i.e., inputs lasting between 24 hours and 30 days). • Change from background of 25 mg/L for any short-term exposure (24 hours or less).

Based on CCME 2002 and BC MOE 2001.

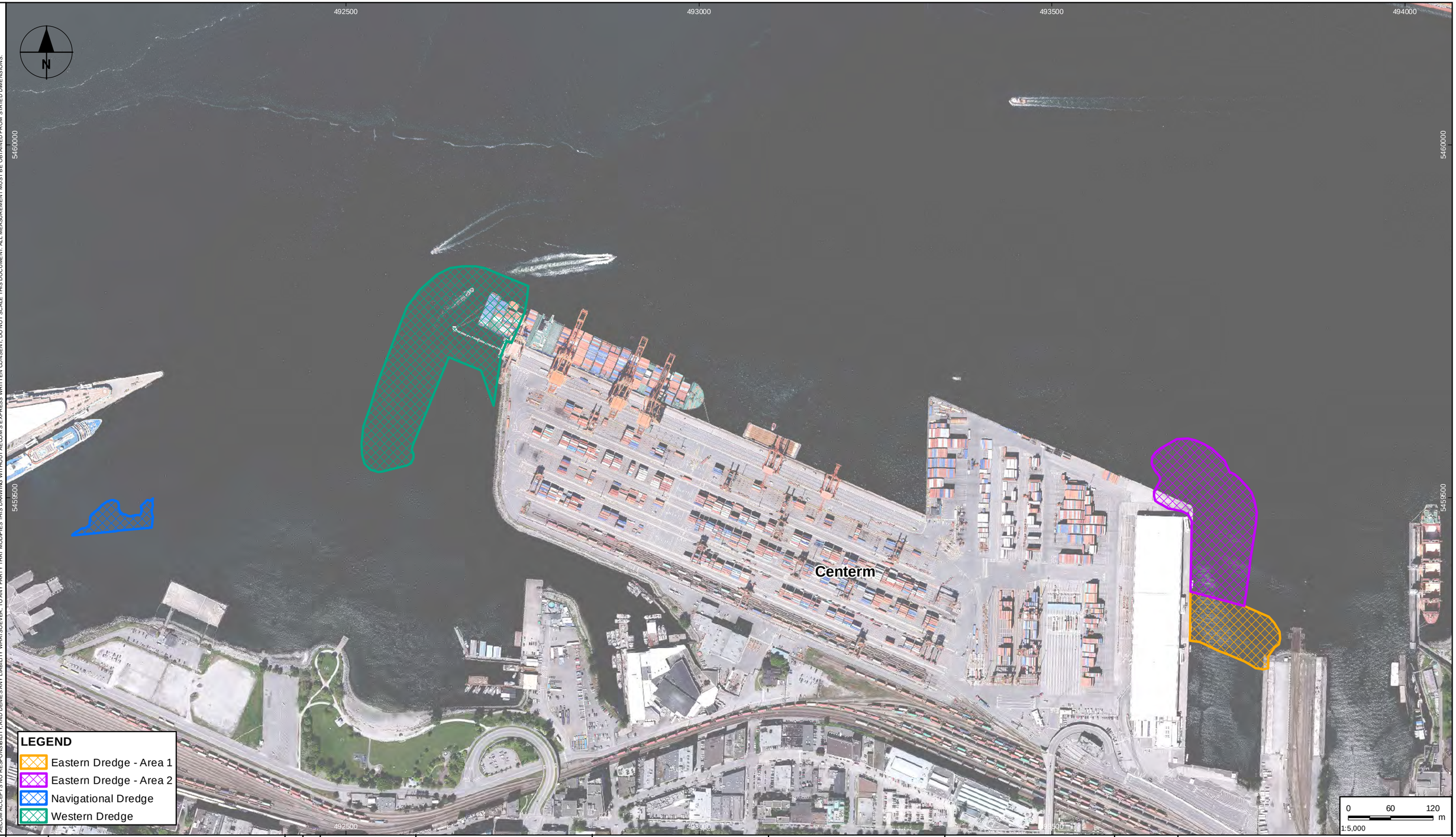
2. Background

2.1 Description of In-Water Work Activities

2.1.1 Dredging

There are three proposed dredge areas associated with the Project: the two dredge areas to support the perimeter dykes and a navigational dredge area for the expansion of Centerm (Figure 2). The total estimated area of dredging to support the eastern and western perimeter dykes is 6.36 ha. The eastern expansion comprises two dredge areas, Area 1 and Area 2 (Figure 2). The western expansion area will affect how cruise ships manoeuvre and berth at the Canada Place cruise ship terminal. As a result, a small area southeast of Canada Place near the SeaBus Terminal will need to be dredged to provide sufficient draft for cruise ships. This navigational dredge area is 0.33 ha. The total volume of material to be dredged from all areas will be approximately 396,800 m^3, consisting of fine sediments.

An initial estimate is that the dredging program will take approximately 4.5 months, with two clamshell dredges operating 24 hours per day, 7 days per week. Dredging work will not be continuous throughout the day and there will be considerable time when no dredging is undertaken. This “down time” is expected to be up to twelve hours per day and includes time for crew changes, manoeuvering the dredge barge, moving the dredgeate scow to stay in position with the dredge, replacing full scows with empty ones, and other activities.



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CENTERM EXPANSION PROJECT
PROPOSED DREDGE AREAS
ASSOCIATED WITH THE PROJECT

Figure 2

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2.1.2 Infilling

Infilling will be required for creating the land base for the western and eastern expansions of the Terminal (Figure 1). The western expansion will result in 2.9 ha of new land area, while the eastern expansion would result in 1.95 ha of new land area. The eastern expansion area comprises two dykes and infill areas, Area 1 and Area 2 (Figure 2) while the western expansion comprises a single dyke and infill area.

The dyke for the western expansion area and Area 2 of the eastern expansion area will be constructed using similar methodology. A stepwise approach will be used during construction of the dykes and infilling. The rock dykes will be constructed in stages. As the dyke is built up, it will be progressively infilled, with sand and gravel material. During periods when the dyke is partially completed, and its top is below the High High Water Level (HHWL), water will flow naturally over the dyke, resulting in sediment releases to marine waters. Once the dyke tops sea surface (at any tidal height), dewatering of the infill area will take place naturally through the sand-gravel barrier as the dyke is being built.

Unlike the dykes for the western expansion area and eastern expansion Area 2, the Area 1 dyke will be constructed to full height before any infilling is undertaken behind the dyke. The design of the Area 1 dyke will comprise a rock fill core, geotextile layer (filter cloth), filter bedding layers, and riprap prior to infilling. This design will prevent release of fugitive particulates to ambient waters because the dyke will be higher than the HHWL before infilling, and the filter layers and geotextile will be impermeable to suspended particulates (AECOM 2017a).

2.1.3 Other In-water Work Activities

Other in-water work activities that have potential to release fugitive sediment are described below and shown in Figure 1.

Building the rock dykes for the eastern and western expansion areas: The dykes will be constructed in layers of imported granular material. There will be a zone of sand and gravel to act as a filter between the dykes and general fill materials. The outer face of the dykes will be faced with riprap.

Placing two new concrete caissons to extend the existing marine berth: To install the caissons, a mattress rock foundation is first placed and densified. The caissons will be floated into place and ballast rock will be added to position them on the mattress rock foundations. Rock fill will be placed around and between the caissons.

Demolishing portions of existing in-water structures: The Ballantyne Pier pile and deck structure, the Marginal Wharf, the west portion of the Southern Railway wharf concrete structure, and the existing mooring dolphin located 76 m west of the existing berth 6.

These other in-water works will release far less sediment, will have shorter durations than infilling and dredging and are encompassed within the dredge footprint. Because the potential effects of these activities will be negligible in comparison to dredging this Monitoring Plan has been planned around dredging.

2.2 Numerical Modelling of Total Suspended Solids

To assess the effects of dredging and infilling on water quality, a three-dimensional time-stepping numerical model (H3D) was used. This model computes the three components of velocity (u,v,w) on a curvilinear grid in three dimensions (x,y,z), as well as scalar fields, such as temperature, salinity and sediments. The most fundamental purposes of the model are to simulate oceanographic processes, such as heat fluxes, mixing, tidal elevations, and tidal, wind driven and density-driven currents. These currents provide the basis for simulating sediment transport, morphologic change and the dispersal of suspended or dissolved material.

H3D was developed and is maintained by Tetra Tech and is implementation derivative of the numerical model developed by Backhaus (1983; 1985) which has had numerous applications across the country and internationally[1]. Locally, H3D has been used throughout the Salish Sea, Fraser River, the north coast of British Columbia and various

[1] Tetra Tech's H3D model has been used to represent conditions at the European continental shelf (Duwe et al. 1983; Backhaus and Meir Reimer 1983), Arctic waters (Kampf and Backhaus 1999; Backhaus and Kampf 1999) and deep estuarine waters (Stronach et al. 1993). H3D forms the basis of the model developed by the St. Lawrence Global Observatory for the Gulf of St. Lawrence (Saucier et al., 2003) and has been applied by Louisiana State University for the Gulf of Mexico (Rego et al. 2008; Rego et al. 2010).

lakes including Quesnel, Seymour, Capilano and Okanagan Lakes and the Site C reservoir (Stronach et al. 2002; Wang and Stronach 2005). The sediment transport and dredging components of H3D have been used to simulate seasonal depositional patterns in the Fraser River, the performance of various land reclamation and beach nourishment projects and the dispersal of dredging-derived sediment from numerous dredging projects.

This model was applied to CEP to predict currents around the berths and to simulate the distribution and concentration of TSS generated during dredging and infilling. This section provides a high-level summary of the model results.

2.2.1 Dispersion Modeling - Dredging

Initial Sediment Dispersion Model (Without Mitigation)

Tetra Tech used the HD3 model to predict the fate of sediments during dredging operations, and the distribution and concentrations of TSS that might be released into the marine environment (Appendix A). The model predicted that, in the west basin, the depth-averaged incremental (i.e., above background level) concentration of TSS[2] was 6.2 mg/L at a point 100 m from the active dredge area, with the incremental depth-averaged concentration of 5 mg/L above background level occurring at a distance of approximately 275 m from the dredge area. In the east basin, the depth-averaged concentration of TSS was 3.6 mg/L above background level at a distance of about 100 m from the active dredge area (Appendix A).

Modelling of the dredging of the navigational channel predicted that the maximum project-derived TSS would drop below 5 mg/L within the dredge area 50% of the time, in part due to the underlying substrate is primarily cobbles overlain with a minimal layer of fine surficial sediments (less than 10 cm thick).

Modelling With Mitigation (Silt Curtains)

Additional modelling was undertaken to determine the effect silt curtains would have on dispersal of fugitive sediment in the eastern and western basins during dredging.

For the navigational dredge zone, it was determined that using a silt curtain would not to be practicable as the area is within an active navigation channel, the volume of sediment is relatively minor, and the dredging is expected to take less than three days. The substrate of the area is predominantly cobble covered by a 10 cm layer of sediment (Appendix A).

Modelling was based on using a US Department of Transportation Type III silt curtain. These silt curtains are constructed from high-strength geotextile fabric, with surface floatation and tension cables running above and below the floatation foam, and chain running along the bottom of the curtain to provide weighting and tension capacity. Owing to the strong tidal currents and deep waters at CEP, a partial height (7 m) silt curtain was modelled. The model accounted for the partial height of the silt curtain, and flaring of the silt curtain that would occur during periods of high tidal currents.

Modelling with silt curtains for the western and eastern dredge areas predicted the depth-averaged concentration of TSS in the west basin to be 3.02 mg/L above background level at a point 100 m from the active dredge area. In the east basin, the depth-averaged concentration of TSS[2] was 2.58 mg/L above background level at a distance of 100 m from the active dredge area (Appendix B).

Deposition Outside the Dredge Areas

The models were also used to predict the thickness of sediment that would be deposited outside the dredge areas. The model predicted that, over the course of the dredging program, the maximum deposited thickness of fugitive sediment would not exceed 10 mm. The maximum thickness at a distance of 100 m away from the dredge areas would be 8 mm. Over the complete dredging program, approximately 70% of the total fugitive sediment volume would settle within 100 m from the dredge areas (Appendix C).

[2] The depth-averaged incremental TSS concentration calculated at 15-minute intervals along a 100 m boundary measured from the edge of the dredge prism and calculated for each of the 25 m by 25 m cells, based on the average of the TSS values predicted at each meter of depth within those cells (Appendix B).

2.2.2 Dispersion Modelling - Infilling

Numerical modelling was conducted to predict the dispersion of sediment during the infilling of the expansion areas. Because the perimeter dykes will be built and infilled in stages, the results vary with each stage or lift.

For the western expansion area the modelling predicted TSS peaks at each stage of infilling; however, the majority (70% to 80%) of sediment would be contained within the boundary of the dyke (Appendix D). The modelling also showed that fugitive sediment dispersal could be minimized by timing of infilling activities, such as avoiding infilling during flood tides.

The modelling results for the eastern expansion predicted TSS peaks at each stage of infilling; however, the majority (60% to 90%) of sediment would be contained within the boundary of the dyke (Appendix D). The results presented for the eastern expansion show higher levels of TSS than are likely to occur since the model was run prior to change in design resulting in splitting the area into separate dredge areas and dykes (Area 1 and Area 2). Based on the updated design, the Area 1 dyke will be built to full height prior to placement of infill material behind the dyke. Therefore, sediment loss during infilling will be significantly reduced, as only the sediment deposited behind the Area 2 dyke will be entrained and flow directly into the harbour when the dyke is below the height of the low tide. Under the updated design, the Area 1 dyke will prevent release of fugitive particulates to waters outside the work area because, before infilling, the dyke will be higher than the HHWL, and the filter layers and geotextile will be impermeable to suspended particulates. Infill modelling also indicated that sediment release can be minimized behind the Area 2 dyke by infilling during slack and ebb tides.

2.3 TSS/Turbidity Compliance Point

The CCME WQGs do not specify a compliance point at which numerical limits for TSS or turbidity in the water column should be applied. Currently, there are no provincial or federal regulations or guidelines that establish a compliance point for the in-water work activities associated with the Project. The Water Quality Turbidity and TSS Management Report (AECOM 2017b) provided the rationale for establishing a compliance point for TSS/turbidity for CEP for all in-water works. The rationale in the report was based on applying the guiding principles outlined by the Canadian Council of Ministers of the Environment (CCME) Guidance on the Site Specific Application in Canada: Procedures for Deriving Numerical Water Quality Objectives (CCME Site Specific Guidance; CCME 2003). The report concluded that a 100 m compliance point from the boundary of the active dredge area (Figure 3) was appropriate for the Project because:

- it accounts for the site-specific tidal velocities and tidal ranges and, based on numerical modelling, the area likely to be affected by the dispersal of fugitive sediment;
- it is protective of existing and future uses of the aquatic ecosystem in accordance with the CCME Site Specific Guidance guiding principles;
- it can be effectively monitored; and,
- it can be operationally achieved with proven mitigation measures.

This Monitoring Plan outlines the rationale and protocol for monitoring TSS/turbidity at the 100 m compliance point.

3. Monitoring

3.1 Rationale

In the case of CEP, the extensive modelling that has been undertaken provides a substantial source of data that can be used to develop an effective TSS monitoring program. The model results provide information on:

- locations where highest concentrations of TSS are likely to be occur over the duration of the dredging and infilling activities;
- average TSS concentrations over a 30-day period expected at these locations; and,
- TSS peaks linked to specific tidal conditions.

Given the quantity and strength of the modelling data it is believed that using the information from the model to define monitoring locations and threshold limits that trigger management actions provides a scientifically sound basis for the monitoring program. The modelling took into account the daily tidal flows and the scale of work activities (i.e., dredging and infilling) to predict both the direction of the dispersion plume and the TSS concentrations across the entire 100 m compliance point boundary. The advantages of using the model data are:

- Sampling will occur at locations where sediment levels are consistently predicted to be highest. This is preferable to simply sampling at a number of points set at equal distances along the compliance boundary since sampling points may be in areas outside the direction of the predicted sediment plume.
- TSS peaks under different tidal conditions can be predicted and therefore the environmental monitor has a benchmark to use as a trigger to recommend appropriate management responses.
- The CCME WQGs numerical TSS limits that apply to longer term exposure (i.e., greater than 24 hours) are based on average increase over background. To determine compliance with the longer term exposure criteria requires collecting sufficient data to calculate a running average of Project induced TSS. The model predicts the TSS levels over a 30-day period thereby providing the reference running average that can be used to assess whether TSS values being observed are within levels that are consistent with achieving compliance with CCME WQGs long term exposure TSS limits of average increase of 5 mg/L over background (Table 1).

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CENTERM EXPANSION PROJECT
WATER QUALITY MONITORING
AND REFERENCE POINTS

Figure 3

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3.2 Monitoring Parameters

Real time monitoring and analysis of sediment levels is necessary to enable CEP to manage in-water work activities to stay in compliance with the CCME WQGs (Table 1). Monitoring of TSS requires laboratory analyses of water samples. Therefore, using TSS as the reference parameter for determining compliance cannot provide real time results during in-water work. Because turbidity can be measured in the field using an optical probe, and because there is typically a strong relationship between TSS and turbidity that can be determined through statistical analysis, turbidity will be used as a surrogate for TSS.

To enable turbidity to be used as a surrogate for TSS, the TSS-turbidity (NTU) relationship must be known so that environmental monitors can convert field measurements of turbidity to TSS estimates. This conversion enables real time comparison of TSS levels to model predictions and compliance with the CCME WQGs. The relationship between turbidity and TSS is site-specific; therefore, if turbidity is to be used as an effective surrogate for TSS, a site-specific relationship between the two variables must be defined before monitoring can commence.

A preliminary TSS/turbidity relationship specific to sediments at CEP has been developed using laboratory analysis of TSS and NTU and then using the data to develop a regression model. The site-specific TSS/turbidity relationship and the methodology used to calculate it are provided in (Appendix E). This preliminary TSS/turbidity relationship will need to be updated at the start of the dredging program with additional site-specific field samples with measured turbidity values between 2 NTUs and 30 NTUs taken from the sediment plume.

3.3 Monitoring Locations

To establish the overall framework for managing turbidity, three areas will be monitored:

Reference Conditions Point(s) (RP) – Reference sites will be used to establish the background levels against which the construction-induced values will be compared. Figure 3 shows the location for three RP points located outside of the predicted area of impact that are expected to be representative of background conditions[3].

Compliance Points (CP) – Five CPs have been established at the perimeter of the compliance boundary for the western area and four for the eastern area (Figure 3). Monitoring results from these points will be used to determine compliance with CCME WQGs and to provide information to manage work activities. The CPs have been established at locations where the modelling predicted elevated TSS/turbidity concentrations over the entire period of model run (31 days). Locating the CPs at these locations has the benefit of allowing detection of spikes in TSS that are of sufficient level above background, to be detectable and along the path of the plume's highest concentration of TSS dispersion.

CRAB Park – The CRAB Park embayment has been identified as an area of concern for First Nations and the public. While modelling shows that the waters near to CRAB Park will not be affected by TSS releases from CEP in-water works, it is considered prudent to establish a monitoring location at CRAB Park to confirm this prediction. One monitoring point will be established in the waters offshore of CRAB Park (Figure 3). Results of monitoring at this point will be used to determine if dredging and infilling activities in the proximity to CRAB Park are generating TSS levels that could affect the beach and tidal area off CRAB Park.

[3] A set of turbidity data was collected continuously from December 2004 to July 2007 on the western side of Canada Place at depths of 1 m and 4.5 m. The average turbidity over the monitoring period was 1.6 NTU at the surface, and 2.0 NTU at depth. However, about once a month, elevated values were recorded of between 10 NTU and 20 NTU, and those levels lasted for less than 1 day. The maximum recorded turbidity was 25 NTU.

3.3.1 TSS/Turbidity Criteria

The model indicated that, with sediment curtains used to contain and reduce the dispersal of sediment during dredging, the average TSS levels would be approximately 3 mg/L above background level at the 100 m compliance boundary (across all CPs). The model output was used to determine the appropriate monitoring locations. The depth-averaged TSS values from the dispersion model have been used to determine threshold values for assessing compliance and estimated TSS levels that would trigger action to further mitigate in-water activities to manage TSS. Output from the model was used to provide the profile of predicted TSS values at each CP.

For the western dredge area, a summary of depth-averaged TSS concentration above background level and corresponding turbidity (NTU) at each CP is presented in Table 2. For the eastern dredge area, a summary of depth-averaged TSS concentration above background level and corresponding NTU levels at each compliance point is presented Table 3.

Table 2 TSS/NTU Concentrations at Western Monitoring Locations

	WCP-1		WCP-2		WCP-3		WCP-4		WCP-5	
Percentile	TSS	NTU	TSS	NTU	TSS	NTU	TSS	NTU	TSS	NTU
Maximum	34.5	25.0	28.6	20.7	8.2	5.9	10.2	7.4	19.1	13.8
95th	8.6	6.2	8.6	6.2	3.7	2.7	5.4	3.9	9.7	7.0
75th	4.4	3.2	4.4	3.2	1.9	1.4	2.7	2.0	4.8	3.5
Median	3.0	2.2	3.0	2.2	1.0	0.7	1.6	1.2	2.5	1.8
25th	2.1	1.5	2.1	1.5	0.5	0.4	0.9	0.7	1.3	0.9
Minimum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5 mg/L Percentile:	82nd		82nd		99th		94th		76th	
Depth (m)	12		11		16		31		24	

Note:
1. NTU value is equal to the TSS/1.38
2. TSS(or NTU) values presented are depth average values i.e., the average value of TSS (or NTU) throughout the water column at the specified CP

Table 3 TSS/NTU Concentrations at Eastern Monitoring Locations

	ECP-1		ECP-2		ECP-3		ECP-4	
Percentile	TSS	NTU	TSS	NTU	TSS	NTU	TSS	NTU
Maximum	20.9	12.7	7.3	4.4	17.3	10.5	29.1	17.7
95th	8.5	5.2	3.5	2.1	8.3	5.1	11.5	7.0
75th	4.1	2.5	1.7	1.0	5.3	3.2	5.6	3.4
Median	1.9	1.2	1.0	0.6	3.6	2.2	3.3	2.0
25th	0.9	0.5	0.5	0.3	2.4	1.5	2.1	1.3
Minimum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5 mg/L Percentile:	83rd		99th		71st		71st	
Depth (m)	21		34		16		11	

Note:
1. NTU value is equal to TSS/1.64
2. TSS (or NTU) values presented are depth average values i.e., the average value of TSS (or NTU) throughout the water column at the specified CP.

If the field samples collected at the CPs indicate that the work induced sediment levels are equal to or less than the 75th percentile values in Table 2 and Table 3, it will be assumed that the work is in compliance with CCME WQGs. Values averaging higher than the 75th percentile would indicate potential failure to meet criteria and the monitoring program includes steps to identify exceedances and subsequent actions to be implemented (i.e., provides for an

"early warning system"). Monitoring data indicating exceedance of the 75th percentile value should provide sufficient time to confirm whether the exceedance is short term (i.e., corrected by adjustment / temporary slow-down of activity) or if it is going to persist for a longer term and additional mitigation needs to be considered.

As shown in Table 2 (the western monitoring locations), WCP-1, WCP-2 and WCP-5 contain 75th percentile values that are close to 5 mg/L concentrations, whereas WCP-3 and WCP-4 are well below, but are included to provide spatial continuity along the compliance boundary and confirm model predictions. Similarly, in Table 3 (the eastern monitoring locations), ECP-2 is well below 5 mg/L, but is included to provide spatial continuity along the compliance boundary and confirm model predictions.

While modelling shows that the waters near to CRAB Park will not be affected by TSS releases from CEP in-water works, it is considered prudent to establish a monitoring location at CRAB Park. If TSS levels at that point exceed the CCME WQGs TSS limit of 5 mg/L over background levels, additional mitigation measures will be applied to limit the sediment transport into the CRAB Park area. Additional mitigation could include installing an additional silt curtain, slowing down work activities or changing the timing of activities to coincide with more favorable tidal conditions.

3.4 Monitoring Protocols

A TSS/turbidity sampling program will be initiated once in-water construction activities begin. The sampling protocols presented below are for a manual sampling program. The Design Builder may opt to automate the process using remote turbidity monitors. There are numerous reliable EPA approved technologies for remote monitoring of turbidity.

3.4.1 Sample Collection Protocol for all In-Water Work Activities

The following sample collection protocols will be followed for all in-water work activities to collect turbidity data:

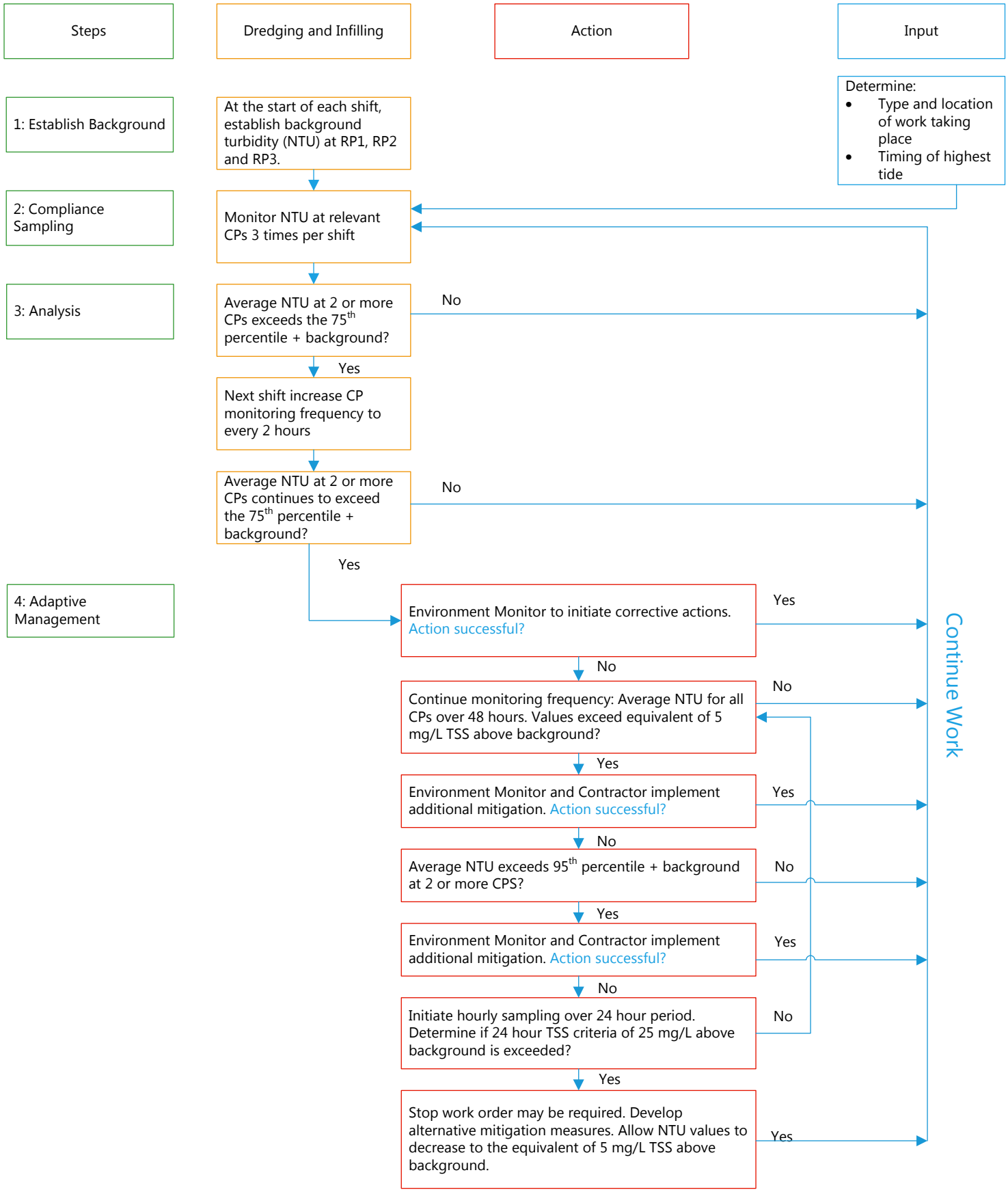
- At each sampling site, collect turbidity data with a turbidity probe (e.g., YSI ProDSS Multiparameter Sampling Instrument or similar) equipped with sufficient cable to reach the ocean bottom.
- Lower the probe to within 1 m of the ocean bottom, without hitting the bottom and disturbing sediment.
- At RPs, collect NTU data at 1 m off the bottom, 1 m below the surface and at a level mid-way between those two depths. Water depth at RP1 is 16 m CD, and at RP2 and RP3 is 50 m CD.
- At CPs, where the water is 11 m deep or less, measure turbidity at 1 m intervals from 1 m above the ocean bottom to the surface. In waters over 11 m deep, turbidity measure turbidity at 2 m intervals starting from 1 m above the bottom. Water depths at the eastern and western CPs range from 11 m to 34 m CD; water depth at the CRAB Park monitoring point is approximately 5.5 m CD. The CPs at the Navigation dredge range in depth from 7 m to 15 m CD.
- Average the NTU values collected over the water column to provide the depth averaged turbidity measurement for that sampling point.

The EM will save all collected field turbidity data (i.e., collected at all depths), and make this data available to the port authority or ECCC, if requested. The EM must also keep track of the depths of NTU values at each sample location and record the data over time and in relation to recorded background values, noting any sustained elevated values. The format of the WQ data reports and the procedure for providing data to PER or ECCC will be developed by the DB Contractor as part of finalizing the WQ TSS/Turbidity Monitoring Plan. The CEP team will coordinate the finalization process, which will include review by VFPA PER, ECCC-DAS and DFO

3.4.2 Monitoring Protocol - Dredging and Infilling

The construction schedule anticipates that, to complete the dredging within DFO's prescribed work window, dredging and infilling will take place 24 hours per day in two shifts. Monitoring will follow the steps illustrated in the flow diagram (Figure 4) as described below.

Figure 4 Centerm Expansion Project Flow Diagram For TSS/Turbidity Monitoring



Monitoring Protocol Steps - Dredging and Infilling

Step 1: Establish Background

1. At the start of each shift the environmental monitor (EM) will measure turbidity levels at the RP sampling sites (Figure 3). The overall average turbidity (i.e., depth average NTU at each RP averaged over the 3 RPs) will be used as the background value for comparison with data from the CPs.

Step 2: Compliance Sampling

1. The EM will document the in-water work activity being conducted, its location, the anticipated duration of the work and the tidal range associated with the duration of the activity.
2. The EM will document the CPs that will be sampled that correlate to the CPs defined for that work area as shown on Figure 3.
3. If there is no in-water work planned during a shift that will generate sediment (i.e., equipment re-positioning only), water sampling will not be required at those CPs.
4. Each relevant CP (i.e., those identified in step 2) will be sampled three times over the course of the work shift, one within 2 hours of the start of work activities, one at mid-shift, and one in the last 2 hours of the shift. At least one of the three samples will be collected at the highest tide level during the shift. This process will require correlating the sampling times with daily tidal cycles and adjusting sampling times accordingly.
5. Samples will be collected as described in Section 3.4.1 or using an automated process and the depth-averaged NTU values will be calculated.
6. The background turbidity values calculated in Step 1 will be added to the predicted NTU values in Table 2 and Table 3 and these values will be compared to the CP values.

Step 3: Analysis

Based on the results of Step 2 one of the following actions will be taken:

1. If the end of shift average CP NTU values do not exceed the 75th percentile NTU value from Table 2 or Table 3 plus background, monitoring will continue as described above. Results in this range will be considered evidence that mitigation measures are effective and the overall sediment release from the site is below the average 5 mg/L of TSS above background (and the NTU equivalent).
2. If end of shift average CP NTU values at two or more CPs are above the 75th percentile (plus background) then sampling frequency will be increased to every two hours for the next 24 hours. If two or more sites still exceed the 75th percentile plus background then Step 4 will be implemented.

Step 4: Adaptive Management

1. EM and construction team to review operation of silt curtains and determine if re-deployment or repair is required to reduce sediment levels. If repair or re-deployment is successful regular monitoring will continue.
2. If the average turbidity of all CPs over 48 hours exceeds the NTU equivalent of 5 mg/L over background, this will be indication that the average 5 mg/L above background could be exceeded. The construction team will work with the EM to determine the appropriate actions to reduce the TSS. Potential strategies may include: avoiding certain tidal conditions, slow dredging activities, or reduce overlapping activities.
3. If NTU values exceed the 95th percentile (provided in Table 2 or Table 3) plus background at two or more CPs, this will be an indication that sediment levels could rise to acute levels and the following steps will be followed:
    a. Additional NTU samples at the CPs will be collected over the tidal cycle to determine the mean NTU value of all CPs.
    b. If the mean value indicates an increase over background greater than an NTU equivalent of 25 mg/L then hourly samples will be collected from the CP sites to determine compliance with the 24 hour criteria.
    c. If the overall average of the NTU data indicates the induced TSS levels are in excess of 25 mg/L over 24 hours, the EM will work with the construction team to determine what additional mitigation measures

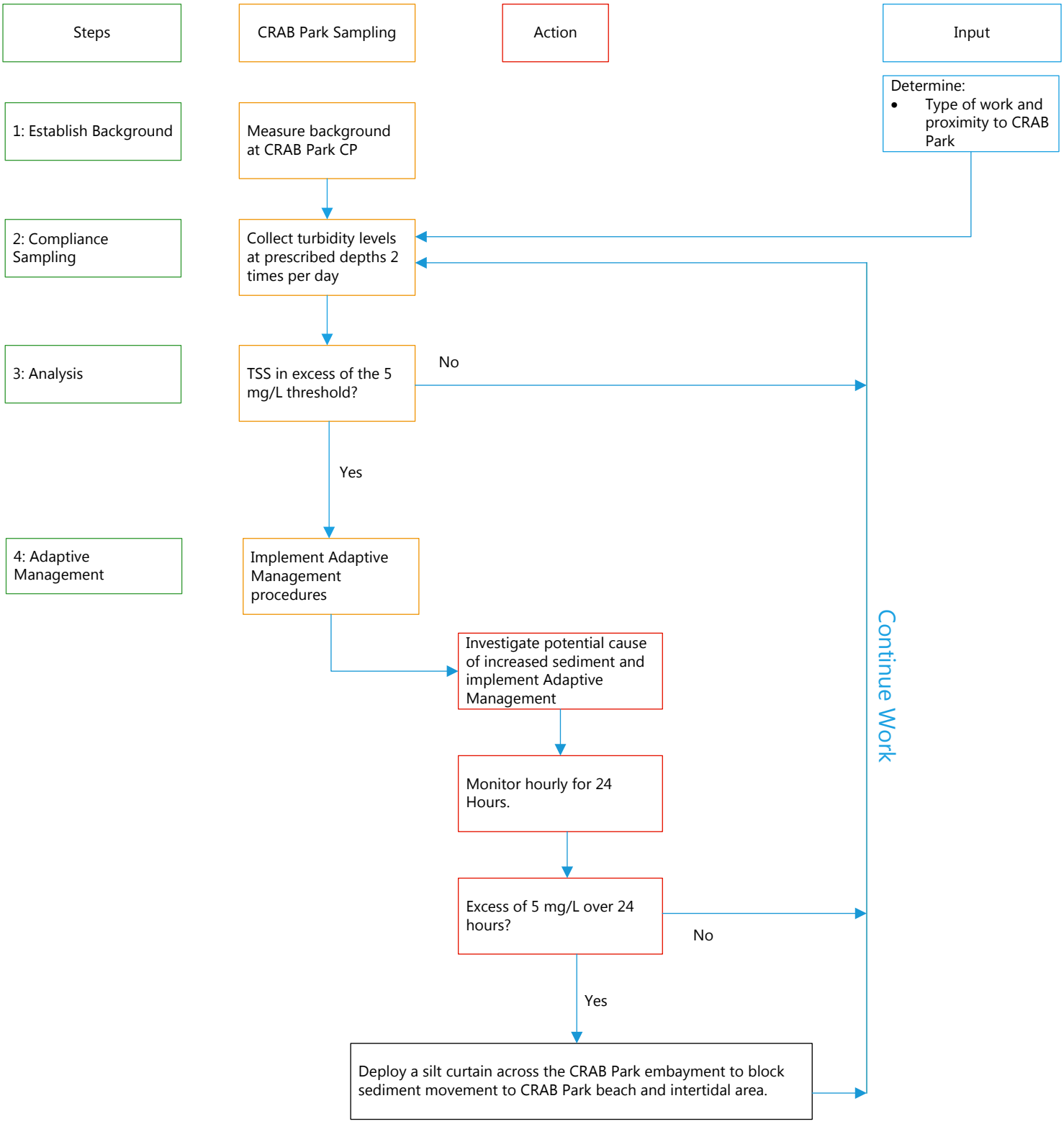
are required. This process would include a reduction or stoppage of work until appropriate solutions are identified and implemented.

d. Once new mitigation measures are implemented the sampling will return to the frequency specified in Step 2.

3.4.3 Monitoring Protocol - CRAB Park

Sampling at CRAB Park will be conducted during work in the area of the navigational dredge area and the western expansion area that have the potential to cause increased TSS in the CRAB Park Embayment. Monitoring will follow the steps illustrated in the flow diagram (Figure 5) as described below.

Figure 5 Centerm Expansion Project CRAB Park Flow Diagram For TSS/Turbidity Monitoring



Monitoring Protocol Steps- CRAB Park

Step 1: Establish Background

1. Prior to the start of work activities NTU will be measured to establish background levels at the CRAB Park CP (Figure 3).

Step 2: Compliance Sampling

1. The EM will document the in-water work activity being conducted, its location, the anticipated duration of the work and the tidal cycle associated with the duration of the activity.
2. CRAB Park Monitoring Point will be sampled at least twice each shift, when work activities are planned in the proximity of CRAB Park (i.e., any dredging or infilling on the west side of Centerm or as directed by the EM.

Step 3: Analysis

1. The NTU/TSS site-specific relationship developed for the Western Dredge area Table 2 will be used.
2. TSS results will be assessed against the CCME WQGs TSS limit of maximum average increase of 5 mg/L over background.

Step 4: Adaptive Management

If the data indicate that work activity induced TSS exceeds the maximum average of 5 mg/L over background and it is likely that this level of TSS will be generated for more than 24 hours, the following action will be taken:

1. The construction team will work with the EM to determine the appropriate actions to reduce the TSS,
2. Hourly monitoring will continue for the next shift.
3. If TSS values return to normal (at or below 5 mg/L over background), normal sampling will resume (2 times per shift).
4. If subsequent monitoring show that TSS levels have not returned to normal, a silt curtain will be deployed to protect the CRAB Park beach intertidal area from further sediment transport.
5. If a silt curtain is deployed, the EM will report the effectiveness of the curtain based on observation or by collecting additional turbidity measurements at the Crab Park CP.

3.4.4 Monitoring Protocol - Other in-Water Work

Other in-water activities include caisson placement dyke construction, vibro-densification and demolition of in-water structures. Sediment sampling for these activities will follow the general procedures in 3.4.1 and the same RPs and CPs will be used. Field measured turbidity will be used as a proxy in order to confirm that elevated TSS levels are at or below the applicable CCME WQGs criteria (Table 1) at the 100 m compliance boundary.

Once the schedule and duration of the other in-water works are determined by the Design Builder, the EM will work with the Design Builder to establish sampling protocols specific to these other in-water work activities and any activities near water. The Draft Construction Environmental Management Plan (AECOM 2017 c) outlines the requirements for monitoring protocols.

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Appendix A Centerm Expansion Project: Dispersal Modelling of Dredging-Derived Fugitive Sediment

Centerm Expansion Project: Dispersal Modelling of Dredging-Derived Fugitive Sediment

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This report and its contents are intended for the sole use of AECOM Canada and their agents. Tetra Tech Canada Inc. (Tetra Tech) does not accept any responsibility for the accuracy of any of the data, the analysis, or the recommendations contained or referenced in the report when the report is used or relied upon by any Party other than AECOM Canada, or for any Project other than the proposed development at the subject site. Any such unauthorized use of this report is at the sole risk of the user. Use of this report is subject to the terms and conditions stated in Tetra Tech Canada Inc.'s Services Agreement. Tetra Tech's General Conditions are provided in Appendix A of this report.

1.0 INTRODUCTION

AECOM Canada (AECOM) retained Tetra Tech Canada Inc. (Tetra Tech) to quantify the release and dispersion of fugitive sediments arising from dredging three sites over the course of the Centerm Expansion Project (CEP). CEP consists of an expansion of the existing Centerm Container Terminal located on the southern shoreline of Vancouver Harbour. The project will consist of two fill expansions to the existing terminal footprint: a westward expansions of approximately 4.2 ha and an eastward expansion of approximately 4 ha. Prior to the construction of perimeter rock dykes and infilling, unstable marine sediments must be removed via dredging. Over the course of CEP additional navigational dredging will take place to the south east of the western expansion to provide a turning basin for ships calling at the East Canada Place cruise ship berth.

This study investigates the behaviour of sediment plumes arising from clamshell dredging operations at the West Basin Dredge Zone, East Basin Dredge Zone and the Navigational Dredge Zone. Dredging will take place using either one clamshell dredge working alone or two clamshell dredges working simultaneously. The entirety of the Navigational Dredge Zone and the surficial sediments of both the East and West Dredge Zones will be dredged with an 8 m^3 capacity environmental dredge bucket. Following removal of surficial sediments at the East and West Dredge Zones, dredging will continue with a 26 m^3 capacity dredge bucket.

The fate and behaviour of the project-derived fugitive sediments has been simulated using an extensively validated three-dimensional numerical model of Vancouver Harbour for a parameterized dredging schedule based on a conceptual plan for dredging, which may be modified by the contractor during the design stage. The predicted concentrations of fugitive sediments reported here reflect unmitigated conditions, with no consideration of mitigation by avoidance of critical tide conditions, or use of silt containment measures.

2.0 METHODS

2.1 Numerical Model

The primary numerical model employed in this study is a 25-m resolution three-dimension numerical model encompassing Burrard Inlet from west of First Narrows to east of Second Narrows. This model is the highest resolution model in a series of nested numerical models extending from the Pacific Ocean to the upper end of Indian Arm:

- Coarse Resolution: 1-km resolution shelf model extending from the mouth of Juan de Fuca Strait to the southern end of Texada Island and the terminus of Indian Arm. The model is driven by tidal constituents and monthly climatology at its boundaries with hourly wind fields and daily river inflows at 13 significant rivers.
- Mid-Resolution: 125-m resolution Burrard Inlet model extending from the entrance to English Bay to the terminus of Indian Arm. The model is driven by water level, temperature and salinity data from the coarse resolution model, with hourly wind fields and daily river inflows.
- High Resolution: 25-m resolution Burrard Inlet model extending from the mid-point of English Bay (near Jericho Beach) to east of Second Narrows (near Berry Point), driven by water level, temperature and salinity data from the mid-resolution model, with hourly wind fields and daily river inflows.

Within the modelling chain, all major rivers in the Salish Sea are included, with Lynne Creek, the Seymour River and the Capilano River feeding directly in the high resolution Burrard Inlet model. Wind fields are interpolated from measured winds at buoys and meteorological stations around coastal British Columbia, with winds for the high resolution Burrard Inlet model based on a dedicated CALMET wind model. Fugitive sediment arising from dredging operations is introduced into the model via a conservatively estimated sediment loss rate specific to clam shell buckets (see Section 3.3). The 25-m resolution model is of sufficient resolution that the near-field (i.e. at a spatial scale smaller than the 25-m grid size) sediment dynamics related to the clam shell dredging operation do not require dedicated simulation to resolve the resulting fugitive sediment dynamics. For each dredging location, the simulation period has been determined based on the dredge prism volume and the estimated production rate of the dredge(s) (see Section 3.3).

The circulation patterns within Vancouver Harbour are tidally dominated, with some baroclinic influence due to seasonal variations in fresh water inflow and heat fluxes at the air/water interface. Streaklines showing the surface currents within western Vancouver Harbour are shown on Figure 1. The most prominent flow features within the harbour are the tidal jets formed at First Narrows and Second Narrows. These jets regularly have peak velocities of over 2.5 m/s, with a maximum velocity nearing 3 m/s possible on occasion. Flood tides result in a strong eastward flowing jet forming at First Narrows that remains coherent well into Vancouver Harbour and establishes a series of eddies and recirculation cells that persist throughout the tidal cycle. The First Narrows jet impinges on the Centerm site resulting in strong eastward flows along the terminal face and generally setting up a clockwise circulation cell between Centerm and Canada Place. On the left panel of Figure 1 two flood-tide circulation cells are shown to the west of Centerm, one clockwise and the other counterclockwise, centered over the Navigation Dredge Zone. Ebb tides result in a strong westward flowing jet forming at Second Narrows (not show on Figure 1), resulting in complex circulation patterns in the vicinity of Centerm. Ebb tidal currents flowing westward in the middle of Vancouver Harbour result in westward flows along the terminal face and set up a counterclockwise eddy between Centerm and Canada Place (Figure 1). Ebb tides generally result in a counter clockwise eddy forming to the west of the East Basin Dredge Zone. Towards the end of ebb tide (not shown on Figure 1) a counterclockwise eddy can be set up in south western Vancouver Harbour which results in eastward flow in the vicinity of Centerm and, somewhat counterintuitively, in the eastward outflow of water from between Centerm and Canada Place during late stages of ebb tide.

2.2 Fugitive Sediment Plume Tracking

Dredging at the three active dredge sites of the CEP will be undertaken with either one clamshell dredge loading a hopper barge or two clamshell dredges simultaneously loading the same hopper barge. It is assumed that the barge will not overflow supernatant dredge water (AECOM 2016). The three dredge zones are displayed on Figure 2, with the Navigation Dredge Zone in blue, the West Basin Dredge Zone in red and East Basin Dredge Zone in green. Around each Dredge Zone, a dilution zone extending 100 m from the edge of the dredge prism is shown. These dilution zones are used later in this report to determine the dilution of the initial dredgeate source strength at 100 m from the dredging area.

In order to quantify the dispersion of fugitive sediments, the total suspended solids (TSS) content of the fugitive sediment plume is tracked as sediments are released over a simulated dredging program. Two metrics are used to quantify the concentration and extent of the fugitive sediment release:

- **Water Column Maximum TSS Concentration:** At 15 minute intervals, the maximum TSS concentration in the water column (vertical axis) is reported at a 25 m spatial resolution (horizontal axes). This data representation was selected to give a conservative representation of TSS concentration in the water column even though the reported maximum TSS may occur at only one location in the water column.

  The goal of reporting the maximum TSS concentration is to characterize any instantaneous, short lived peaks that would not necessarily be captured by the maximum average concentration discussed below

- **Water Column Average TSS Concentration:** At hourly intervals, the maximum vertically averaged TSS concentration in the water column (vertical axis) is reported on a 25 m by 25 m horizontal grid. In this study, an arithmetic mean is uniformly presented.

  This metric is most comparable to CCME's "maximum average" guidance on Total Particulate Matter concentration and so is the most relevant measure of TSS in the water column.

As an explanatory example, if the water depth is 40 m, with a near bed (e.g. within 1 m of the seabed) TSS concentration of 100 mg/L with the remainder of the water column having a TSS concentration of 2 mg/L, the maximum TSS concentration would be reported as 100 mg/L, while the water column average (arithmetic mean) TSS would be reported as 4.5 mg/L in accordance with CCME guidance.

These two measures of TSS in the water column are then post-processed to determine:

- **Maximum TSS 100 m from source:** The maximum TSS concentration at a 100 m distance from the active dredge zones, computed from the water column maximum TSS concentration. These 100 m boundaries surrounding each dredge zone are presented on Figure 2.
- **Maximum Average TSS 100 m from source:** The maximum average TSS concentration at a 100 m distance from the active dredge zones, computed from the average water column TSS concentration. These 100 m boundaries surrounding each dredge zone are presented on Figure 2.
- **Probability of Maximum TSS Exceeding 5 mg/L:** The probability of the maximum above-background concentration of TSS exceeding 5 mg/L at any given moment during the dredging operation, defined as the commencement of operations to the moment when the above- background concentration drops below 5 mg/L following cessation of dredging. These probabilities are computed from the water column maximum TSS concentration, which is very conservative compared to CCME guidelines.
- **Probability of Maximum TSS Exceeding 25 mg/L:** The probability of the maximum above-background concentration of TSS exceeding 25 mg/L at any given moment during the dredging operation, defined as the commencement of operations to the moment when the above background concentration drops below 25 mg/L following cessation of dredging. These probabilities are computed from the water column maximum TSS concentration, which is very conservative compared to CCME guidelines.
- **Probability of Maximum TSS Exceeding 10% of Source Strength:** The probability of the maximum above-background concentration of TSS exceeding 10% of the initial source strength, defined as the water column averaged TSS immediately below the dredge vessel.

The shaded probability maps presented in Section 4.0 for the three maximum TSS probability metrics described above do not represent the instantaneous TSS plume footprint or a static plume position. Instead, these probability maps represent the likelihood of a given TSS concentration being exceeded at any one location (a block of water 25 m by 25 m in the horizontal and 1 m thick in the vertical) over the entire dredging operation. This likelihood is derived as a composite of maximum TSS concentrations in space and time over the full dredging period and should not be interpreted as a continuous or prevailing condition.

For example, assume that the probability of the maximum TSS concentration exceeding 5 mg/L is given as 1% at a location in Burrard Inlet. This means that if an observer were to check that specific 25 m by 25 m section of Burrard Inlet at a random time over the dredging operation, there is a 1% probability that they would find a TSS concentration exceeding 5 mg/L at that location in the water column. Over an extended dredge operations (e.g. 16 days), this 1% probability indicates that the TSS at that position (and any others similarity classified by the probability map shading) could exceeded 5 mg/L for a total of 3 hours and 50 minutes (i.e. 1% of 16 days).

3.0 SEDIMENT SOURCE TERMS

3.1 Background Suspended Sediment Concentration

The primary source of background suspended sediment concentration in Vancouver Harbour is widely cited as the North Arm of the Fraser River (Davidson 1973, Feely and Lamb 1979, Thomson 1981). A combination of flood currents and the hydraulic head of the river drive a layer of silty fresh water from the North Arm northwards along the edge pf Point Grey, then eastward along the southern shore of English Bay. During certain tidal and wind conditions, this near-surface brackish water can be drawn through First Narrows and into Vancouver Harbour; however the intense tidal mixing of the Narrows mixes out much of the initial stratification. There is, however a general lack of information on background suspended sediment concentrations that result from the influx of brackish water into Vancouver Harbour.

The best source of recent information is a report by Tetra Tech in which turbidity on the western side of Canada Place was monitored continuously from December 2004 to July 2007 (Tetra Tech 2007). Turbidity measured in Nephelometric Turbidity Units (NTU) was monitored at depths of 1.0 m and 4.5 m by YSI 6600EDS-M multi parameter sondes. In general, low turbidity values were recorded throughout the year. Average annual turbidity were 1.6 NTU at 1 m depth and 2.0 NTU at 4.5 m depth. Turbidity levels occasionally (approximately once per month) peaked to between 10 NTU and 20 NTU for a period of less than a day, with the maximum recorded turbidity over the monitoring period of approximately 25 NTU. While these spikes have not been attributed to a specific cause, they do show that there is naturally a factor of 10 range in turbidity in Vancouver Harbour. Turbidity values increased slightly during spring and late summer phytoplankton blooms.

3.2 Sediment Characteristics

The in situ sediments from the west and east dredge basins were characterised using data adapted from the Klohn Crippen Berger (KCB 2016a) site investigation report. CPT and borehole samples collected from within the west and east basin footprints yielded eighteen samples at varying depths. To characterize the sediments of the dredge basins into particle size bins that could be applied within the numerical model, the sand, silt and clay fractions of the east and west basins were determined and are presented in Table 3.1. As there is considerable variation in the relative proportions of sand, silt and clay between samples, the sample from each basin with the highest fines content was selected to represent the entire basin, to generate a conservative sediment source term. For the west dredge basin, this is a fines (silt and clay) content of 56.6% and for the east basin this is a fines content of 19.8%. As no data exists for the Navigation Dredge Zone, the values for the West Basin Dredge Zone are applied there.

Table 3.1 Summary of Grain Size Classification

East Basin					
Sediment Class		**Maximum**	**Minimum**	**Mean**	**Most Fines[1]**
> 2000µm	gravel	83.7%	2.0%	37.2%	2.0%
62µm - 2000µm	sand	88.6%	14.1%	56.4%	78.2%
4µm - 62µm	silt	9.5%	0.7%	4.5%	9.5%
< 4µm	clay	10.3%	0.0%	1.9%	10.3%
West Basin / Navigation					
Sediment Class		**Maximum**	**Minimum**	**Mean**	**Most Fines[1]**
> 2000µm	gravel	71.5%	0.4%	15.5%	2.4%
62µm - 2000µm	sand	82.8%	27.9%	60.7%	40.9%
4µm - 62µm	silt	42.0%	0.6%	17.8%	35.2%
< 4µm	clay	22.4%	0.0%	6.0%	21.4%

[1] Applied in model

Table 3.2 presents the d_{85}, d_{50} and d_{15} for each of the sand, silt and clay sediment classes determined from the four sediment samples that had a full particle size analysis of fines fraction. As the number of samples is limited and there is little variation in size between them, an averaged value across the four samples was applied at the three dredge basins. In situ sediments have a specific gravity of 2.74 and a solid fraction of 0.485 (KCB 2016b).

For simulating the dispersal of fugitive fine sediment, three sediment classes were defined: sand, silt and clay. The relative proportions of each class were proscribed in the modelling based on the sediment fractions presented in Figure 3.1. The specific grain sizes associated with each sediment class were applied based on the particle size information summarized in Table 3.2.

Table 3.2 Summary of Particle Size Distribution

Clay					
Diameter Percentile	**East Basin**	**West Basin**			**Mean[1]**
	DH15-03	DH15-05, 4.7m	DH15-05, 8.5m	DH15-09	
d_{85}, µm	1.14	1.35	2.66	1.40	1.64
d_{50}, µm	0.67	0.79	1.08	0.82	0.84
d_{15}, µm	0.20	0.24	0.32	0.25	0.25
Silt					
Diameter Percentile	**East Basin**	**West Basin**			**Mean[1]**
	DH15-03	DH15-05, 4.7m	DH15-05, 8.5m	DH15-09	
d_{85}, µm	51.5	47.2	51.9	54.6	51.3
d_{50}, µm	20.9	19.1	25.2	31.4	24.2
d_{15}, µm	6.7	5.5	8.0	7.3	6.9
Sand					
Diameter Percentile	**East Basin**	**West Basin**			**Mean[1]**
	DH15-03	DH15-05, 4.7m	DH15-05, 8.5m	DH15-09	
d_{85}, µm	382	251	288	147	267
d_{50}, µm	194	149	118	109	142
d_{15}, µm	104	94	74	72	86

[1] Applied in model

3.3 Sediment Release

The loss rate of sediments from a clamshell dredge is less well defined than for other dredge types, therefore, the loss rate of dredgeate was calculated based on values cited in literature. The loss rate from clamshell dredging largely depends on the operational conditions of the dredge itself, for example, the descent and ascent rate of the bucket, the style of bucket and the swing rate of the dredge arm. Without more detailed information regarding the characteristics of the clamshell dredge to be employed at the CEP, the loss rate from the clamshell has been conservatively estimated as 2%, based on a range of 1% to 2% found in literature (Collins 1995; Hayes et al. 2007; Bridges et al. 2008). The suspended sediment release cloud is generally considered evenly distributed over the water column, though some studies place the volume distribution of the sediment as 40% near bed 30% mid-depth and 30% surface (Lackey et al. 2012). For simplicity, sediment is assumed to be evenly distributed over the volume of water that the dredge bucket passes through, as presented in Table 3.3 below.

An important consideration in clamshell dredging is that the clamshell bucket will not be completely filled with dredgeate. Each seabed material and bucket style has an associated efficiency, with a certain proportion of the bucket filled with dredgeate and the rest, with seawater. The fill efficiency of common clamshell buckets is estimated as 83% for fines, 80% for loose sand and 77% for compact sand, meaning that, for a given bucket volume, approximately 80% of the bucket contains seabed material (including voids) and approximately 20% is seawater (Hayes et al. 2007). Based on local experience, methods and equipment, the 8 m^3 environmental bucket has an anticipated fill factor of 65% and the 26m^3 high capacity bucket has an anticipated fill factor of 60% (AECOM 2017).

In-situ seabed materials have an average solids fraction of 0.485. Therefore each clamshell scoop will transport, for the 8 m^3 and 26 m^3 buckets respectively, 2.52 m^3 and 7.57 m^3 of solids. The dredge buckets are assumed to lose 2% of their content before delivery to the barge, resulting in the fugitive sediment release of 0.050 m^3 and 0.151 m^3 of sediment solids per dredge cycle for the 8 m^3 and 26 m^3 buckets respectively. For each dredge location, the resulting release of each sediment fraction is summarized in Table 3.3.

The fugitive release of sediment during each dredge cycle results in an initial source TSS concentration ranging from 1,989 mg/L to 463 mg/L, as summarized in Table 3.3. The initial dilution volume for the volumetric sediment input is assumed to be equal to the cylindrical volume of water the dredge bucket passes through as it is drawn through the water column. For the 8 m^3 dredge bucket, the diameter of this cylinder has been based on the dimensions of a Ransome YC7000 dredge bucket, while the 26 m^3 dredge bucket dimensions have been interpreted from a variety of 2 and 4 rope clamshell dredge buckets. An additional 0.5 m radial allowance is assumed for the lateral release of slurry from the bucket. The initial source TSS concentration varies from location to location with the depth of water column through which the dredge bucket is pulled. The essential logic underlying this is that any dredgeate that could be mobilized by travel through the water column (i.e. isn't sheltered by larger grains) will be flushed from the bucket relatively quickly compared to the travel time of the bucket from the seabed to the surface. Therefore, for each dredge cycle, the same volume of dredgeate is released, with the initial concentration consequently depending on the water depth via the dilution volume. While it is likely that the blow-off volume has a relationship with the depth of water the bucket is pulled through, in the absence of appropriate literature or data to support a depth dependant blow-off rate, the conservative assumption of a depth-independent blow off rate has been made.

Dredging operations are expected to proceed 24 hours per day with 2 hours per day allocated to maintenance downtime and 10 hours per day spent re-positioning the dredge, resulting in 12 hours per day of effective working time. Dredges operating with an 8 m^3 environmental bucket are estimated to have a 120 second cycle time (i.e. the time between successive bucket grabs), while dredges operating with a 26m^3 high capacity bucket have an estimated 150 second cycle time. Based on an assumed schedule and efficiency, one clamshell dredge with one attending hopper barge has a 1,900 m^3/day production volume (seabed dredged per day) if an 8m^3 dredge bucket is used, compared to a production volume of 4,500m^3/day if a 26 m^3 dredge bucket is employed. Similarly, two clamshell dredges with one attending hopper barge each have a combined production rate of 3,800 m^3/day of seabed with 8m^3 dredge buckets, or 9,000 m^3/day with 26 m^3 dredge buckets. Based on these production rates, the total dredge operation duration is estimated in Table 3.4.

To derive a worst-case sediment TSS concentration, numerical model simulations have been conducted with continuous dredge operation until the completion, such that the total volume of fugitive material is released in as temporally-compressed a manner as possible. The simulations were run until the total volume of fugitive material given in Table 3.4 has been released.

Table 3.3 Summary of Dredge Operation

	Parameter	Navigation	West Basin	East Basin	Unit	Notes
Sediment	Void Ratio	1.0625	1.0625	1.0625	-	KCB Report, 2016
	Porosity	0.515	0.515	0.515	-	η = e/(1+e)
	Solids Fraction	0.485	0.485	0.485		SF = 1 - n
	Specific Gravity	2.74	2.74	2.74	-	KCB Report, 2016
	Sand Fraction	0.434	0.434	0.576	-	KCB Report, 2016
	Silt Fraction	0.352	0.352	0.301	-	KCB Report, 2016
	Clay Fraction	0.214	0.214	0.103	-	KCB Report, 2016
Clam Shell Dredge	Cycle Time	90	90	90	s	Time between bottom grabs
	Bucket Size	8	26	26	m^3	
	Efficiency	0.65	0.60	0.60	-	Factor for partially filled bucket
	Effective Volume	5.20	15.60	15.60	m^3/cycle	Dredgeate per cycle, total
	Solids Volume	2.52	7.57	7.57	m^3/cycle	Dredgeate per cycle, solids
	Loss Rate	0.02	0.02	0.02	-	Portion of dredgeate lost per cycle
	Fugitive Solids	0.05	0.151	0.151	m^3/cycle	Solids volume lost per cycle
	Fugitive Sand	0.022	0.066	0.087	m^3/cycle	Sand volume lost per cycle
	Fugitive Silt	0.018	0.053	0.046	m^3/cycle	Silt volume lost per cycle
	Fugitive Clay	0.011	0.032	0.016	m^3/cycle	Clay volume lost per cycle
Source Strength	Zone Radius	2.3	3.1		m	Based on dredge bucket size
	Depth	Min: 9.0 m Max: 11.5 m	Min: 6.9 m Max: 29.6 m		m	Based on depth in dredge cut
	Volume	Min: 150 m^3 Max: 191m^3	Min: 208 m^3 Max: 894 m^3		m^3	Volume dredge passes through
	TSS Conc.	913 / 717	1,989 / 463	1,989 / 463	mg/L	Max/Min TSS concentration
	Sand Conc.	402 / 316	869 / 202	1,146 / 267	mg/L	Max/Min sand concentration
	Silt Conc.	329 / 258	698 /162	619 / 144	mg/L	Max/Min silt concentration
	Clay Conc.	201 / 158	422 / 98	224 / 52	mg/L	Max/Min clay concentration

Table 3.4 Summary of Dredge Volume, Release Volume and Dredge Operation Duration

	Dredge Prism	8 m^3 Dredge[1]	26 m^3 Dredge[2]	Total Solids	Fugitive Release	Duration 1 Dredge[3]	Duration 2 Dredge[3]
	m^3	m^3	m^3	m^3	m^3	days	days
Navigation	7,000	7,000	0	3,786	76	4	2
West Basin	235,000	33,300	201,700	113,975	2,280	63	31
East Basin	155,000	15,000	124,700	75,175	1,504	36	16
Total	**397,000**	**55,300**	**335,400**	**192,936**	**3,860**	**103**	**49**

[1] Surficial sediments

[2] Deep sediments.

[3] Based on nominal 4,500 m^3/day production volume for a 26 m^3 dredge bucket, 1,900 m^3/day production for a 8 m^3 dredge bucket (AECOM 2017).

4.0 RESULTS

4.1 Navigation Dredge Zone

The Navigation Dredge Zone consists of an approximately 7,000 m^3 dredge prism to be dredged by an 8 m^3 clamshell dredge operating for two (two dredges) or four (one dredge) days including down time and repositioning. Sediments released by an individual clamshell dredge operating in the Navigational Dredge Zone result in a source TSS concentration ranging from approximately 700 mg/L to 900 mg/L depending on the specific location in the dredge cut (Section 3.3). The Navigation Dredge Zone is in a relatively sheltered location, being located in the embayment formed by Centerm and Canada Place. Therefore, the TSS plume originating from the Navigation Dredge Zone, while generally well flushed, has the tendency to build up a background concentration of TSS adjacent to Canada Place over the course of the dredging operation.

Figure 3 presents the fugitive sediment concentration at a 100 m distance from the active dredge zone for 1 and 2 active dredge scenarios. Within 6 hours of the start of dredging the maximum and maximum average TSS concentrations crossing the 100 m boundary from the dredge area exceed 5 mg/L; however, taken along the entire 100 m boundary, 5mg/L represents a 94th and 89th percentile values for one dredge and two dredge scenarios, respectively. The embayment between Canada Place and the SeaBus terminal does not have strong tidal currents and, as a result, TSS concentrations in this area remain elevated above 5 mg/L for 72 hours (one dredge) or 96 hours (two dredges) following the end of dredging operations. During this period, which can be seen on the top and second panels of Figure 3, the isolated pocket of fugitive sediment concentration is attenuated through the processes of bottom deposition and dilution in the receiving environment. Table 4.1 presents the maximum, minimum and percentile concentrations of TSS along the 100 m boundary from the active dredge zone.

Table 4.1 Maximum Average and Maximum Concentration 100 m from Source

Percentile Along 100m Boundary	Maximum Average Concentration[1]		Maximum Concentration[2]		Unit
	1 Dredge	2 Dredges	1 Dredge	2 Dredges	
Maximum	45.13	89.23	68.24	148.47	mg/L
99[3]	15.42	30.18	29.47	58.84	mg/L
95	6.32	13.0	12.56	25.55	mg/L
90	2.58	5.74	7.92	17.31	mg/L
50	0.06	0.18	0.68	1.71	mg/L
10	0.00	0.01	0.07	0.26	mg/L
Minimum	0.00	0.00	0.00	0.00	mg/L

[1] Percentile, maximum and minimum values are calculated from the water column average TSS concentration at 1 hour intervals.

[2] Percentile, maximum and minimum values are calculated from the water column maximum TSS concentration at 15 minute intervals. Therefore, the maximum value occurs for *less than* 15 minutes out of 14 days at a 25 m by 25 m by 1 m parcel of water in Vancouver Harbour.

[3] The 99th percentile concentrations is the TSS concentration at which 99% of all other possible TSS concentrations occurring in time and space will be lower than the 99th percentile. Any concentrations greater than the 99th percentile will occur for only 30 minutes out of a 2 day dredging period.

Figure 4 presents the probability that the maximum instantaneous water column concentration of TSS will be greater than 10% of the source concentration. In all cases, there is less than 1% probability of exceeding 10% of the initial source concentration (hence the appearance of an apparent empty figure due to use of white shading for <1% probability). This is partly due to the modest dredge size and partly due to the dredging period being defined from the commencement of dredging to the moment when the above-background concentration drops below 5 mg/L. The 5 mg/L above background cut-off for the dredge period extends the dredging window up to 96 hours beyond

the end of dredging due of the TSS pocket between the SeaBus terminal and Canada Place and, since there is no active dredging while this pocket attenuates, lowers the probability of the high concentration source TSS occurring over the period of elevated above background TSS concentration.

Figure 5 presents the probability that the above-background maximum instantaneous water column concentration of TSS will exceed 5 mg/L over the duration of the dredging operation. From Figure 5, it can be seen that in the vicinity of the Navigation Dredge Zone the probability of exceeding a TSS concentration of 5 mg/L above background is 30% to 40% for both one and two dredge scenarios, with this probability tapering to 1% at 1,050 m from the source.

Figure 6 presents the probability that the maximum instantaneous water column concentration of TSS will exceed 25 mg/L over the duration of the dredging operation. The footprint of very high probability of this occurrence is larger for the 2 dredge scenario (bottom panel) than the 1 dredge scenario (top panel), however in both cases there is an approximately 30% probability of exceeding 25 mg/L in the Navigation Dredge Zone itself and a short distance westward towards Canada Place, with the probability rapidly tapering outside of this area. Outside of a 625 m radius, the probability is below 1%. Table 4.2 summarizes the decay of TSS with distance for all Navigation Dredge Zone scenarios. For example, Table 4.2 illustrates that with a single dredge sediment concentrations will exceed 5 mg/L less than 20% of the time 225 m from the source but with two dredges the distance for source required to exceed 5 mg/L less than 20% of the time is 250 m.

Table 4.2 Distance from Source to Achieve Maximum TSS of 5 mg/L and 25 mg/L

Probability of Exceedance[1]	1 Dredge		2 Dredges		Unit
	5 mg/L	25 mg/L	5 mg/L	25 mg/L	
90%	Within Dredge Zone	Within Dredge Zone	Within Dredge Zone	Within Dredge Zone	m
80%					m
70%					m
60%					m
50%					m
40%					m
30%	125		125	125	m
20%	225	125	250	175	m
10%	300	150	525	250	m
1%	1,000	325	1,050	625	m

[1] The probability that the instantaneous water-column maximum TSS will exceed a given value over the dredging period. For example, a 1% probability of exceeding 5 mg/L indicates that, over a 2 day dredging period, the maximum TSS in the water column may exceed 5 mg/L for a total of 30 minutes.

4.2 West Basin Dredge Zone

The West Basin Dredge Zone consists of an approximately 235,000 m^3 dredge prism. Surficial sediments will be dredged using an 8 m^3 clamshell dredge, with the vast majority of dredging to be undertaken with a 26 m^3 capacity clamshell dredge. The duration of dredging operations at the West Basin is anticipated to be 31 (two dredges) to 63 (one dredge) days including down time and repositioning. Sediments released by an individual clamshell dredge operating at the West Basin Dredge Zone result in a source TSS concentration ranging from approximately 500 mg/L to 2,000 mg/L depending on the specific location within the dredge cut (Section 3.3). Compared to both the Navigation and East Basin Dredge Zones, the West Basin Dredge Zone is relatively deep, exposed and well flushed. This results in two distinct features of the TSS plume at this location: the initial source concentration is

rapidly diluted; and, the strong ambient currents widely disperse the plume. In particular, during a strong ebb tide fugitive project-derived sediment can very infrequently be entrained into the First Narrows tidal jet. Over a 31 day simulation period (i.e. 62 ebb tides), project derived TSS was transported west of Brockton Point one time at a maximum concentration exceeding 5 mg/L and this was only possible with 2 active 26 m^3 capacity dredges in operation.

Figure 7 presents the fugitive sediment concentration at a 100 m distance from the active dredge zone for 1 and 2 active dredge scenarios. Owing to strong tidal action at the West Basin Dredge Zone the concentration crossing the 100 m boundary rises almost immediately following the commencement of dredging and drops to baseline levels within one tidal cycle of the end of dredging. Figure 7 and Table 4.3 present the source attenuation at the West basin Dredge Zone. Almost immediately following the start of dredging, the maximum and maximum average TSS concentrations crossing the 100 m boundary from the dredge area exceeds 5 mg/L; however, taken along the entire 100 m boundary, 5 mg/L represents 81st and 62nd percentile values of maximum average TSS for one dredge and two dredge scenarios, respectively.

Table 4.3 Maximum Average and Maximum Concentration 100 m from Source

Percentile Along 100m Boundary	Maximum Average Concentration[1]		Maximum Concentration[2]		Unit
	1 Dredge	2 Dredges	1 Dredge	2 Dredges	
Maximum	60.90	139.40	75.65	201.38	mg/L
99[3]	19.72	40.22	27.05	59.47	mg/L
95	11.04	23.36	16.06	34.27	mg/L
90	7.80	16.54	11.48	24.64	mg/L
50	1.70	3.41	2.37	4.73	mg/L
10	0.16	0.34	0.20	0.42	mg/L
Minimum	0.00	0.00	0.00	0.00	mg/L

[1] Percentile, maximum and minimum values are calculated from the water column average TSS concentration at 1 hour intervals.

[2] Percentile, maximum and minimum values are calculated from the water column maximum TSS concentration at 15 minute intervals. Therefore, the maximum value occurs for *less than* 15 minutes out of 31 days at a 25 m by 25 m by 1 m parcel of water in Vancouver Harbour.

[3] The 99th percentile concentrations is the TSS concentration at which 99% of all other possible TSS concentrations occurring in time and space will be lower than the 99th percentile. Any concentrations greater than the 99th percentile will occur for only 7 hours and 30 minutes out of a 31 day dredging period.

On Figure 8 it can be seen that the probability of the maximum instantaneous water column concentration of TSS being greater than 10% of the source concentration is low and confined to the immediate vicinity of the dredge zone. In all cases, the initial source concentration is rapidly diluted by the tidal action in Burrard Inlet.

The probability that the above-background maximum instantaneous water column concentration of TSS will exceed 5 mg/L over the duration of the dredging operation is presented on Figure 9. In this figure the model indicates that the highest probability of the maximum TSS concentration in the water column exceeding 5 mg/L is generally concentrated in the vicinity of the active dredge zones. Also in Figure 9 (lower panel), the model suggests a 3,075 m one-time excursion (during a single ebb tide over 31 days of dredging) of the TSS plume in which the maximum concentration exceeds 5 mg/L above background. This is an extremely rare and short-lived event arising from particularly unfavorable dredge positioning and ebb tidal conditions: it has a 1% occurrence probability, equivalent to a single ebb tide. It should also be noted that the aim of this study is not to forecast a specific dredging operation but to estimate all possible iterations of TSS plume positions, however unlikely or unfavorable. As measure of more typical TSS plume behaviour, the fugitive TSS plume arising from dredging does not exceed 5 mg/L beyond 125 m (one dredge) or 275 m (two dredges) from the West Basin Dredge Zone more than 50% of the time.

The probability that the instantaneous TSS concentration will exceed 25 mg/L above background during the dredging period is much more modest and occurs over a small area (Figure 10). With one active dredge this area is limited to within 275 m of the dredge zone, and with two active dredges, the probability of exceeding a 25 mg/L above background TSS concentration threshold drops to 1% within 750 m of the source. By comparing Figures 9 and 10, it can been seen that the vast majority of the probability footprint displayed in Figure 9 is no longer present in Figure 10. Outside the 1% probability contour shown in Figure 10, there is no significant probability that the maximum water column concentration of TSS will exceed 25 mg/L at any location in Burrard Inlet. Therefore, while the 5 mg/L threshold might theoretically be exceeded over an occasionally wide area, the maximum water column TSS remains well below 25 mg/L and, likely, only slightly exceeds 5 mg/L.

Table 4.4 summarizes the decay of TSS with distance for all West Basin Dredge Zone scenarios. For example, Table 4.4 illustrates that with a single dredge sediment concentrations will exceed 5 mg/L less than 20% of the time 600 m from the source but with two dredges the distance for source required to exceed 5 mg/L less than 20% of the time is 675 m.

Table 4.4 Distance from Source to Achieve Maximum TSS of 5 mg/L and 25 mg/L

Probability of Exceedance[1]	1 Dredge		2 Dredges		Unit
	5 mg/L	25 mg/L	5 mg/L	25 mg/L	
90%	Within Dredge Zone	Within Dredge Zone	Within Dredge Zone	Within Dredge Zone	m
80%					m
70%					m
60%					m
50%	125		275		m
40%	150		450		m
30%	225		525		m
20%	600		675	275	m
10%	800	125	1,150	375	m
1%	1,425	275	3,075	750	m

[1] The probability that the instantaneous water-column maximum TSS will exceed a given value over the dredging period. For example, a 1% probability of exceeding 5 mg/L indicates that, over a 31 day dredging period, the maximum TSS in the water column may exceed 5 mg/L for a total of 7 hours and 30 minutes.

4.3 East Basin Dredge Zone

The East Basin Dredge Zone consists of an approximately 155,000 m^3 dredge prism. Surficial sediments will be dredged using an 8 m^3 clamshell dredge, with the vast majority of dredging to be undertaken with a 26 m^3 capacity clamshell dredge. The duration of dredging operations at the East Basin is anticipated to be 16 (two dredges) to 36 (one dredge) days including down time and repositioning. Sediments released by an individual clamshell dredge operating at the East Basin Dredge Zone result in a source TSS concentration ranging from approximately 500 mg/L to 2,000 mg/L depending on the specific location within the dredge cut (Section 3.3). Dredging operations at the East Basin Dredge Zone are assumed to begin at the shore, near the Southern Railway Pier, and progress northwards along the eastern face of Ballantyne Pier. At the south end of the embayment formed by the Southern Railway and Ballantyne Piers there is relatively poor flushing and there is potential for the build-up of TSS. Towards the north end of Ballantyne Pier, tidal currents increase in magnitude and result in both better dilution of the fugitive sediment plume and a wider dispersal of the sediments.

Figure 11 presents the fugitive sediment concentration at a 100 m distance from the active dredge zone for 1 and 2 active dredge scenarios. The initial period (first 7 days) of elevated TSS concentration is due to the aforementioned poor flushing capacity of the embayment between Southern Railway and Ballantyne Piers. TSS builds up in the embayment and is occasionally flushed by tidal action. As the dredging operation progresses northwards, mixing improves and the concentration of TSS drops (attenuates) significantly before crossing the 100 m boundary. As discussed in Section 3.2, the source concentration is tied to the water depth in which the dredge is operating, which is why the source concentration drops as the dredge moves northwards into deeper water. This also contributes to the gradual decline in TSS concentration at the 100 m boundary from the dredge area.

Exceedance values at a100 m boundary from the East Basin Dredge Zone are presented in Table 4.5. Compared to both the Navigation and West Basin Dredge Zones, high-percentile maximum average TSS concentrations observed at the East Basin 100m boundary are elevated due to the buildup of TSS between the Southern Railway and Ballantyne Piers. Comparing the median and low-percentile concentrations, the East Basin Dredge Zone has generally lower maximum average TSS concentrations at the 100 m boundary, due to the high flushing in the northern dredge area. Taken along the entire 100 m boundary at the East Basin Dredge Zone, 5 mg/L represents 95th and 85th percentile values of maximum average TSS concentration for one dredge and two dredge scenarios, respectively.

Table 4.5 Maximum Average and Maximum Concentration 100 m from Source

Percentile Along 100m Boundary	Maximum Average Concentration[1]		Maximum Concentration[2]		Unit
	1 Dredge	2 Dredges	1 Dredge	2 Dredges	
Maximum	83.44	148.03	85.31	156.16	mg/L
99[3]	17.18	30.06	19.06	33.53	mg/L
95	5.21	13.36	7.82	15.30	mg/L
90	1.91	8.31	5.06	10.28	mg/L
50	0.12	0.44	0.38	0.80	mg/L
10	0.02	0.13	0.07	0.15	mg/L
Minimum	0.00	0.00	0.00	0.00	mg/L

[1] Percentile, maximum and minimum values are calculated from the water column average TSS concentration at 1 hour intervals.

[2] Percentile, maximum and minimum values are calculated from the water column maximum TSS concentration at 15 minute intervals. Therefore, the maximum value occurs for *less than* 15 minutes out of 16 days at a 25 m by 25 m by 1 m parcel of water in Vancouver Harbour.

[3] The 99th percentile concentrations is the TSS concentration at which 99% of all other possible TSS concentrations occurring in time and space will be lower than the 99th percentile. Any concentrations greater than the 99th percentile will occur for only 3 hours and 50 minutes out of a 16 day dredging period.

On Figure 12 it can be seen that the probability of the maximum instantaneous water column concentration of TSS being greater than 10% of the source concentration is very low north of the northern extent of Ballantyne Pier (<10%), but increases towards the southern end of the dredge zone (up to 70%).

The probability that the instantaneous TSS concentration will exceed 5 mg/L over the duration of the dredging operation at the East Basin Dredge Zone (Figure 13) is similar in magnitude but generally smaller in extent compared to the probabilities determined for the West Basin Dredge Zone. The probability of exceeding 5 mg/L in the embayment between Southern Railway and Ballantyne Piers is approximately 70% due to the buildup up TSS during the dredging operation. As the northern extent of the East Basin Dredge Zone is dredged, the fugitive sediment plume is more widely dispersed by tidal action in Burrard Inlet, with a single instance of the TSS concentration exceeding 5 mg/L over background 2,075 m from the source with two operational dredges. This rare and shore-lived event has a 1% probability of occurrence (i.e. approximately 4 hours) and is caused by a concurrence of strong tides and unfavorable dredge positions near the northern edge of the East Basin Dredge

Zone. As measure of more typical TSS plume behaviour, the fugitive TSS plume arising from dredging does not exceed 5 mg/L outside of the East Basin Dredge Zone footprint more than 50% of the time. In all cases, the fugitive TSS plume remains confined to the southern shoreline of Burrard Inlet with the most likely locations for the maximum TSS concentration to exceed 5 mg/L being in the immediate vicinity of Centerm.

The probability of the instantaneous above-background TSS concentration exceeding 25 mg/L over the course of the dredging operation is relatively low (<20%) and is generally confined to a relatively small area in the immediate vicinity of the East Basin Dredge Zone, as shown on Figure 14. Beyond 550 m from the East Basin Dredge Zone there is a less than 1% probability of the instantaneous TSS concentration exceeding 25 mg/L. Similar to at the West Basin Dredge zone, when Figures 13 and 14 are compared, it can been seen that the vast majority of the probability footprint displayed in Figure 13 is no longer present in Figure 14. Outside the 1% probability contour shown in Figure 14, there is no significant probability that the maximum water column concentration of TSS will exceed 25 mg/L at any location in Burrard Inlet. Therefore, while the 5 mg/L threshold might theoretically be exceeded over an occasionally wide area, the maximum water column TSS remains well below 25 mg/L and, likely, only slightly exceeds 5 mg/L.

Table 4.6 summarizes the decay of TSS with distance for all East Basin Dredge Zone scenarios. For example, Table 4.6 illustrates that with a single dredge sediment concentrations will exceed 5 mg/L less than 20% of the time 425 m from the source but with two dredges the distance for source required to exceed 5 mg/L less than 20% of the time is 500 m.

Table 4.6 Distance from Source to Achieve Maximum TSS of 5 mg/L and 25 mg/L

Probability of Exceedance[1]	1 Dredge		2 Dredges		Unit
	5 mg/L	25 mg/L	5 mg/L	25 mg/L	
90%	Within Dredge Zone	Within Dredge Zone	Within Dredge Zone	Within Dredge Zone	m
80%					m
70%					m
60%					m
50%					m
40%	150		350		m
30%	300		475		m
20%	425	150	500	200	m
10%	675	275	875	275	m
1%	1,575	375	2,075	550	m

[1] The probability that the instantaneous water-column maximum TSS will exceed a given value over the dredging period. For example, a 1% probability of exceeding 5 mg/L indicates that, over a 16 day dredging period, the maximum TSS in the water column may exceed 5 mg/L for a total of 3 hours and 50 minutes.

5.0 CONCLUSION

Based on the results of this modelling study:

Navigation Dredge Zone

- **One Dredge:** modeling results of the Navigation Dredge Zone dredging process suggest that the maximum project-derived TSS concentrations above background drop below 5 mg/L 1,000 m from source 99% of the time and drop below 5 mg/L within the dredge zone 50% of the time.
- **One Dredge:** modeling results of the Navigation Dredge Zone dredging process suggest that the maximum project-derived TSS concentrations 5 mg/L above background are attenuated 72 hrs following cessation of dredging.
- **Two Dredges:** modeling results of the Navigation Dredge Zone dredging process suggest that the maximum project-derived TSS concentrations above background drop below 5 mg/L 1,025 m from source 99% of the time and drop below 5 mg/L within the dredge zone 50% of the time.
- **Two Dredges:** modeling results of the Navigation Dredge Zone dredging process suggest that the maximum project-derived TSS concentrations 5 mg/L above background are attenuated 96 hrs following cessation of dredging.

West Basin Dredge Zone

- **One Dredge:** modeling results of the West Basin Dredge Zone dredging process suggest that the maximum project-derived TSS concentrations above background drop below 5 mg/L 1,425 m from source 99% of the time and drop below 5 mg/L 125 m from source 50% of the time.
- **One Dredge:** modeling results of the West Basin Dredge Zone dredging process suggest that the maximum project-derived TSS concentrations 5 mg/L above background are attenuated 12 hrs following cessation of dredging.
- **Two Dredges:** modeling results of the West Basin Dredge Zone dredging process suggest that the maximum project-derived TSS concentrations above background drop below 5mg 3,075 m from source 99% of the time and drop below 5 mg/L 275 m from source 50% of the time.
- **Two Dredges:** modeling results of the West Basin Dredge Zone dredging process suggest that the maximum project-derived TSS concentrations 5 mg/L above background are attenuated 12 hrs following cessation of dredging.

East Basin Dredge Zone

- **One Dredge:** modeling results of the East Basin Dredge Zone dredging process suggest that the maximum project-derived TSS concentrations above background drop below 5mg/L 1,575 m from source 99% of the time and drop below 5 mg/L within the dredge zone 50% of the time.
- **One Dredge:** modeling results of the East Basin Dredge Zone dredging process suggest that the maximum project-derived TSS concentrations 5 mg/L above background are attenuated 12 hrs following cessation of dredging.
- **Two Dredges:** modeling results of the East Basin Dredge Zone dredging process suggest that the maximum project-derived TSS concentrations above background drop below 5 mg/L 2,075 m from source 99% of the time and drop below 5 mg/L 200 m from source 50% of the time.
- **Two Dredges:** modeling results of the East Basin Dredge Zone dredging process suggest that the maximum project-derived TSS concentrations 5 mg/L above background are attenuated 12 hrs following cessation of dredging.

Following from the above analysis, the following locations for turbidity monitoring are recommended during dredging activities:

- **Navigation Dredge Zone:** While dredging is taking place, it is recommended to monitor turbidity in the vicinity of the active dredge(s), in the basin between the Navigation Terminal and Canada Place and along the eastern edge of Canada Place.

- **West Basin Dredge Zone:** It is recommended to monitor turbidity on the down-drift side of the active dredge(s) while dredging is taking place.
- **East Basin Dredge Zone:** While dredging is underway, it is recommended to monitor turbidity in the vicinity of the active dredge(s), in the basin between the Ballantyne and Southern Railway Piers and to periodically check the turbidity levels in the basins between Ballantyne Pier and Vanterm.

6.0 CLOSURE

We trust this report meets your present requirements. If you have any questions or comments, please contact the undersigned.

Respectfully submitted,
Tetra Tech Canada Inc.

Prepared by:
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/db

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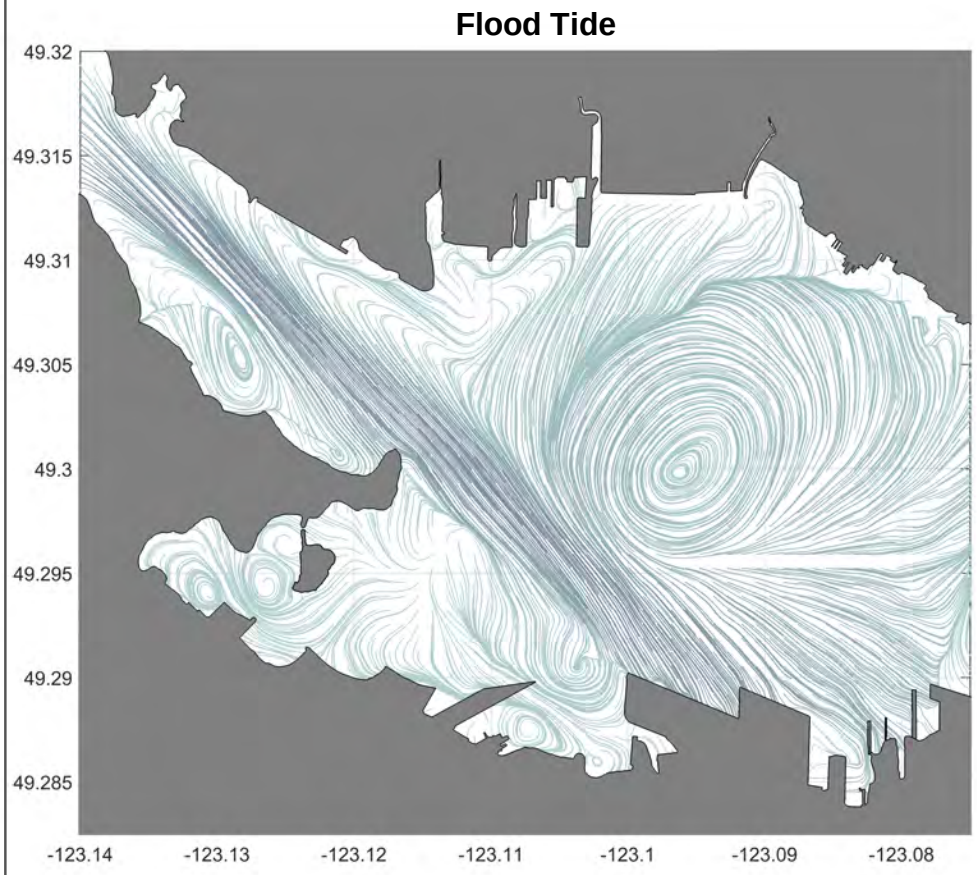
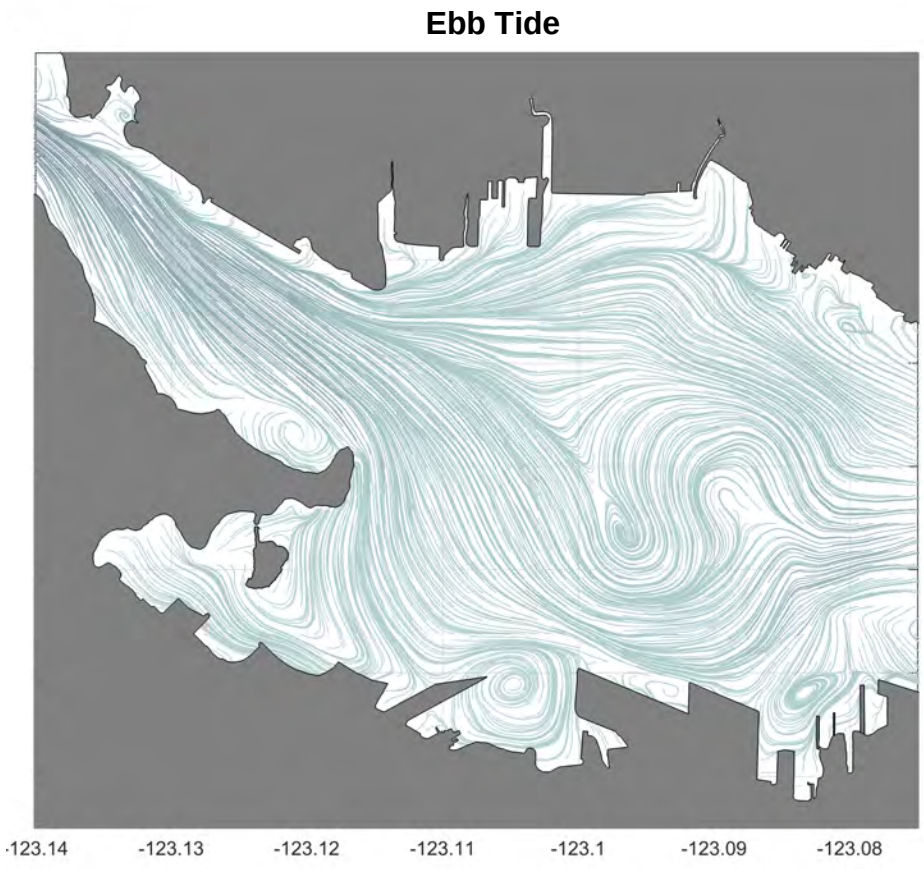
FIGURES





NOTES

Flow fields are presented for the existing Centerm geometry using Tetra Tech's 25-m resolution numerical model of Burrard Inlet.
Flow fields are visualized at peak flood and ebb flow during a moderate tide.

STATUS
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TETRA TECH

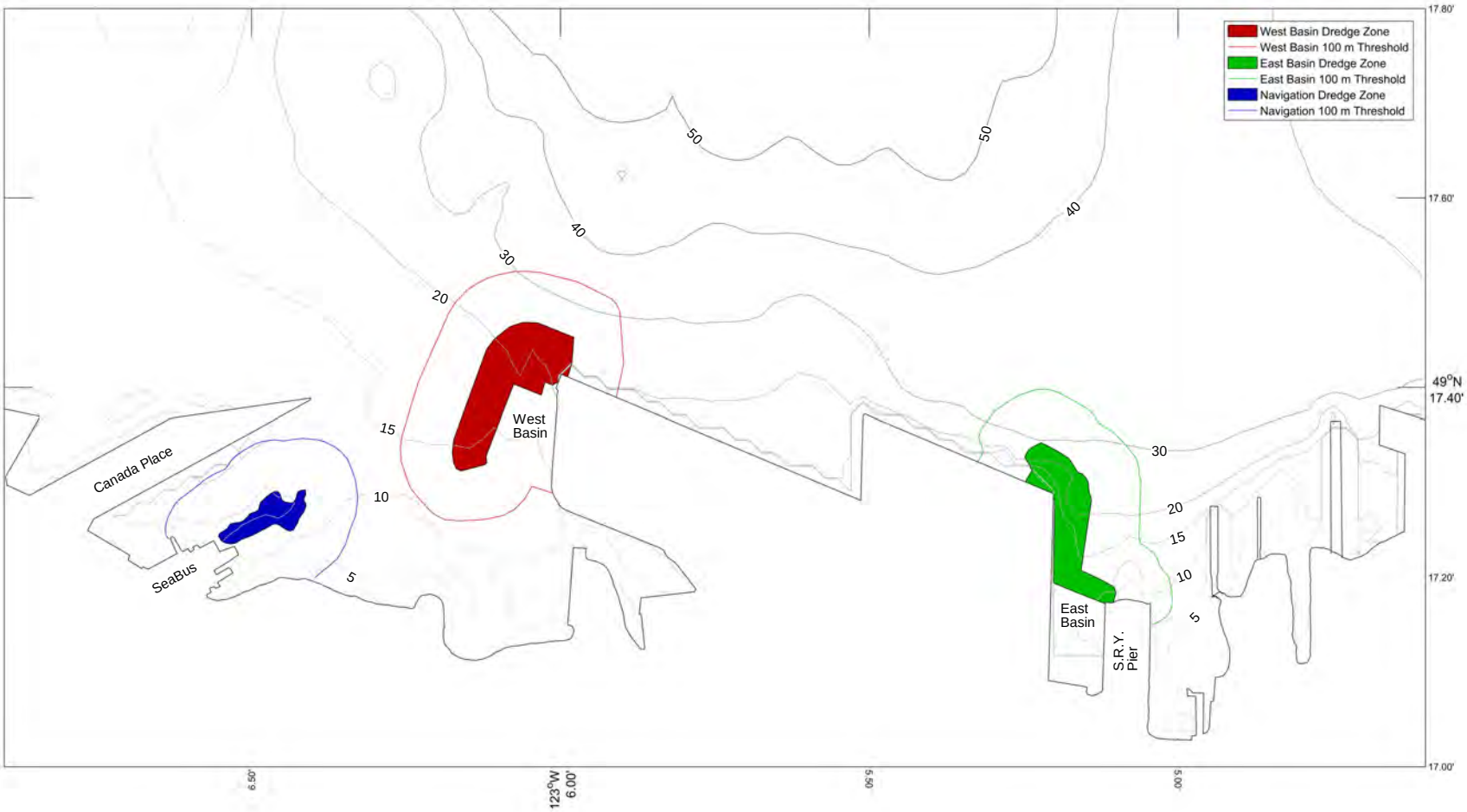
Dispersal Modelling of Dredging Derived Fugitive Sediment

Flow Fields in Western Vancouver Harbour

PROJECT NO.	DWN	CKD	APVD	REV
WTRM.03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech - VANC	March, 2017

Figure 1



NOTES

Dredge prism outlines and 100 m radius boundaries are plotted in the above figure.

STATUS
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CLIENT

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TETRA TECH

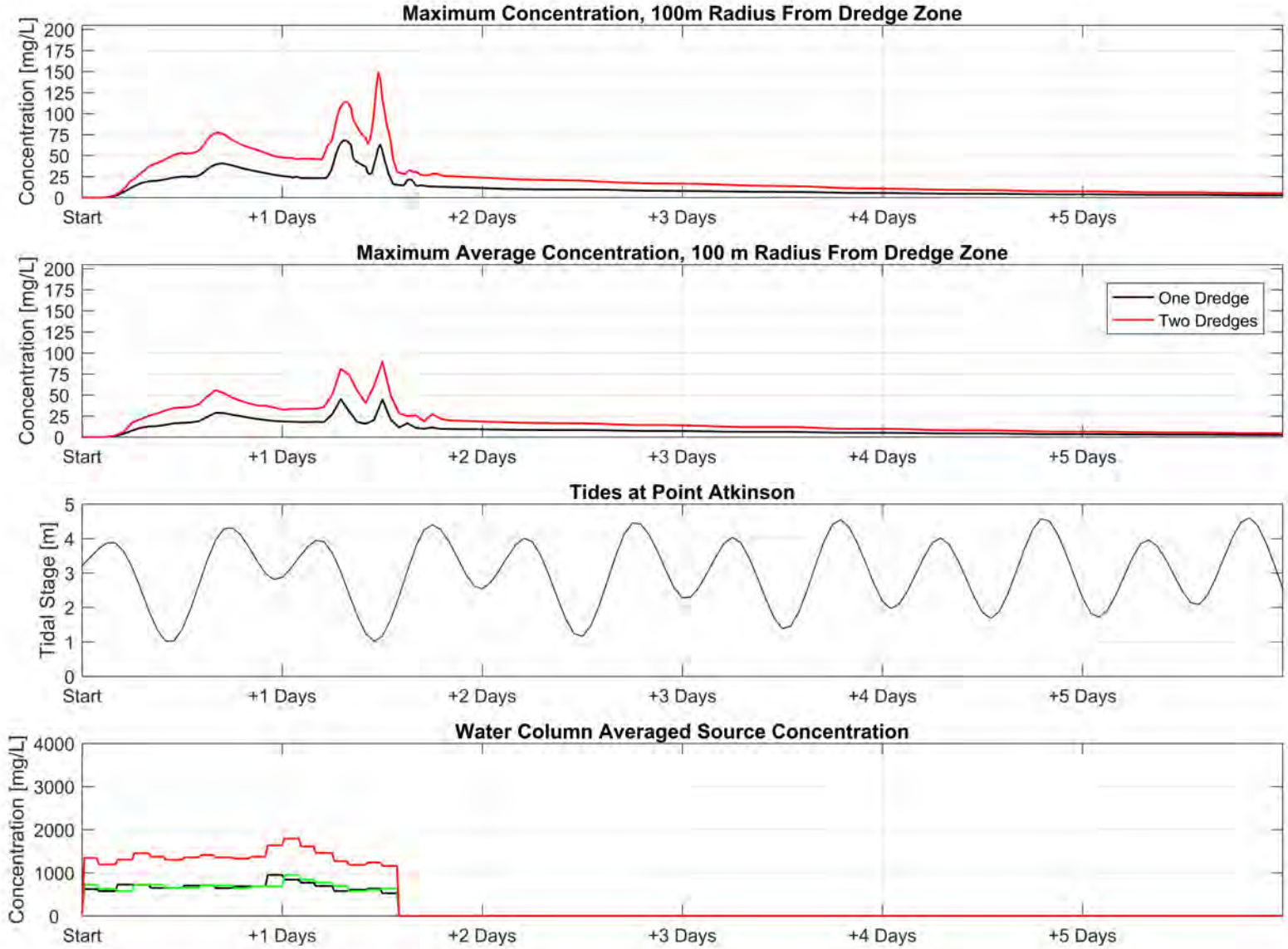
Dispersal Modelling of Dredging Derived Fugitive Sediment

CEP Dredge Zone Overview

PROJECT NO.	DWN	CKD	APVD	REV
WTRM.03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech - VANC	March, 2017

Figure 2



NOTES

1) The concentration axis scale for the Source Concentration plot differs from that of the 100 m Concentration plots.
2) Source concentration varies in time due to depth variations between dredge locations and tidal action.
3) Maximum concentrations are the maximum of the maximum concentration over the water column (seabed to surface) along the 100 m boundary.
4) Maximum average concentrations are the maximum of the average concentration over the water column (seabed to surface) along the 100 m boundary.

STATUS
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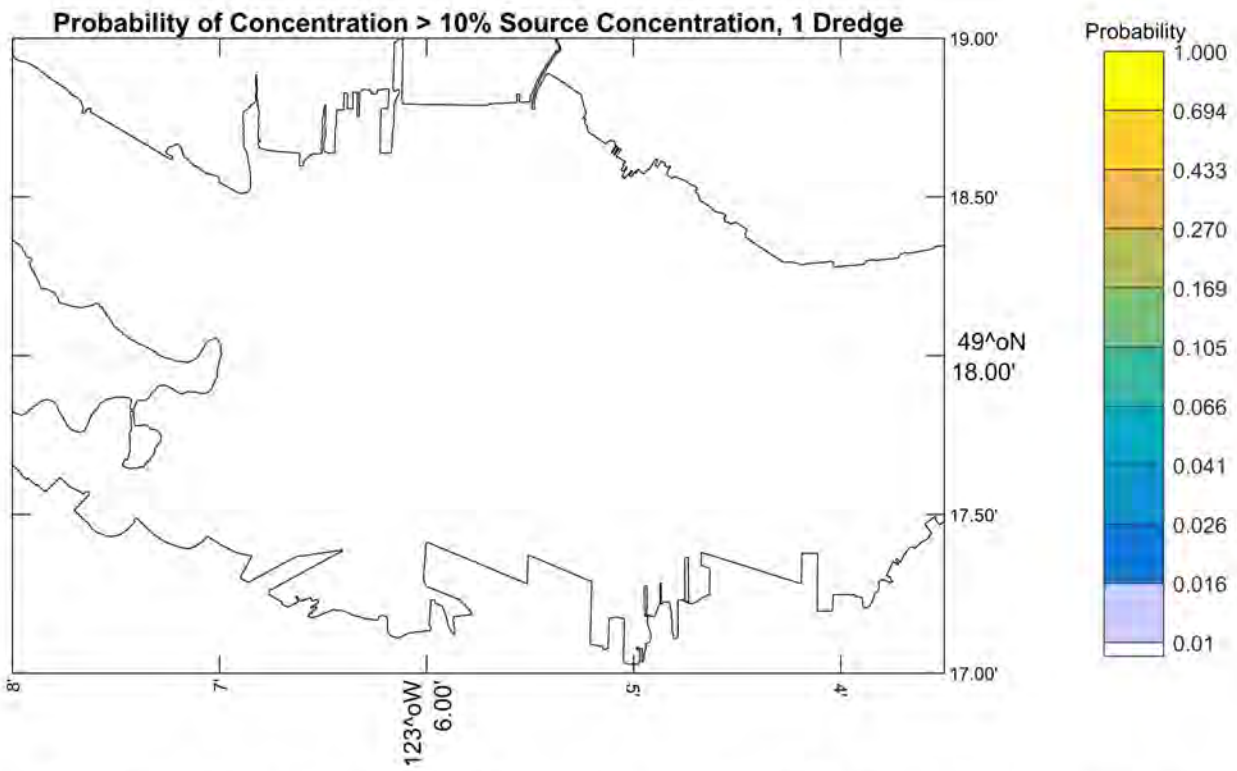
Dispersal Modelling of Dredging Derived Fugitive Sediment

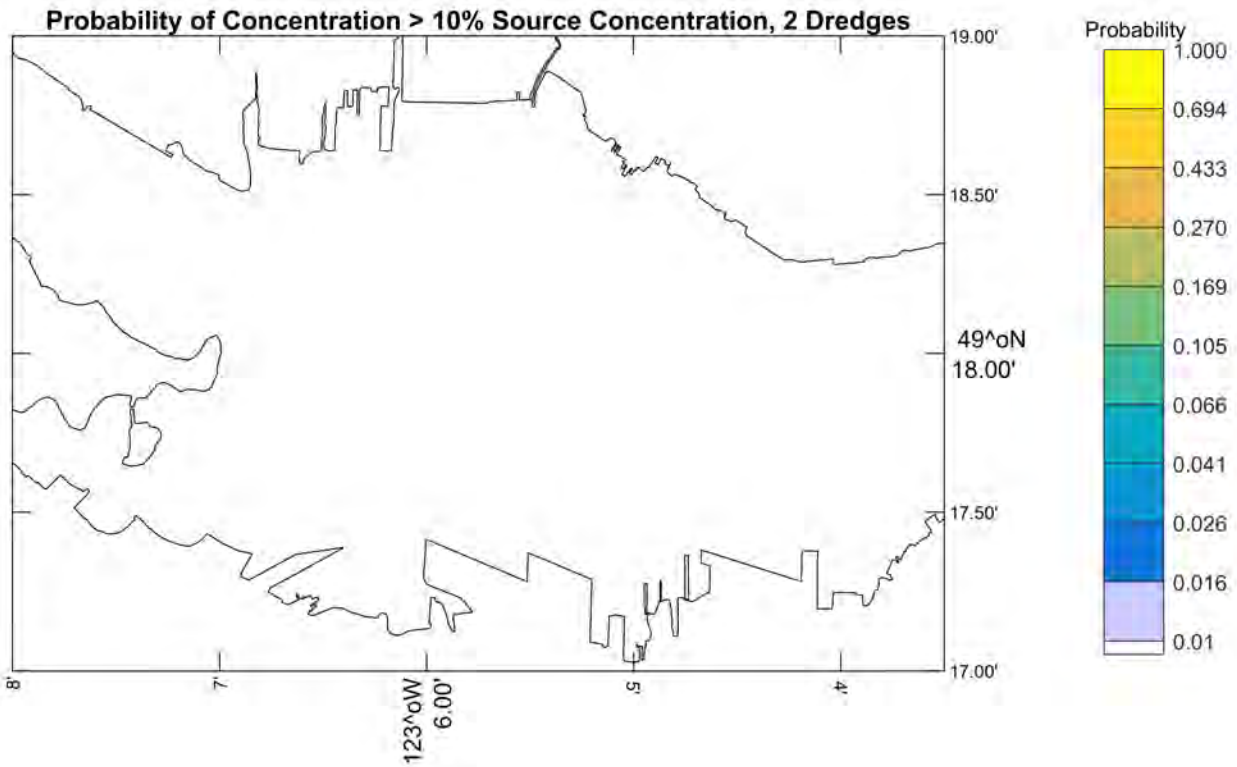
Navigation Dredge Zone TSS Source Attenuation

PROJECT NO.	DWN	CKD	APVD	REV
WTRM.03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech - VANC	March, 2017

Figure 3





NOTES

1) Probability is calculated over the full dredge period and is determined from 15 minute model data.
2) All concentrations are the maximum concentration over the water column (seabed to surface) at a given location.

STATUS
ISSUED FOR USE

CLIENT

AECOM

TETRA TECH

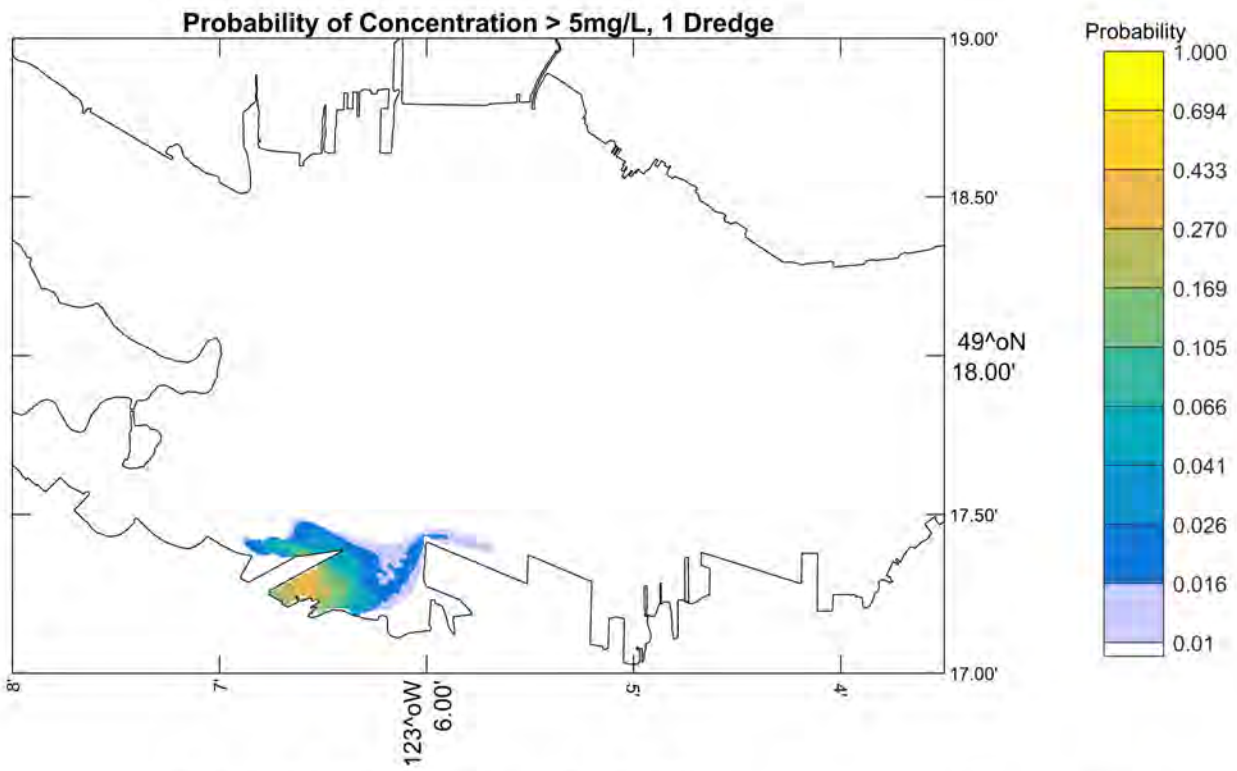
Dispersal Modelling of Dredging Derived Fugitive Sediment

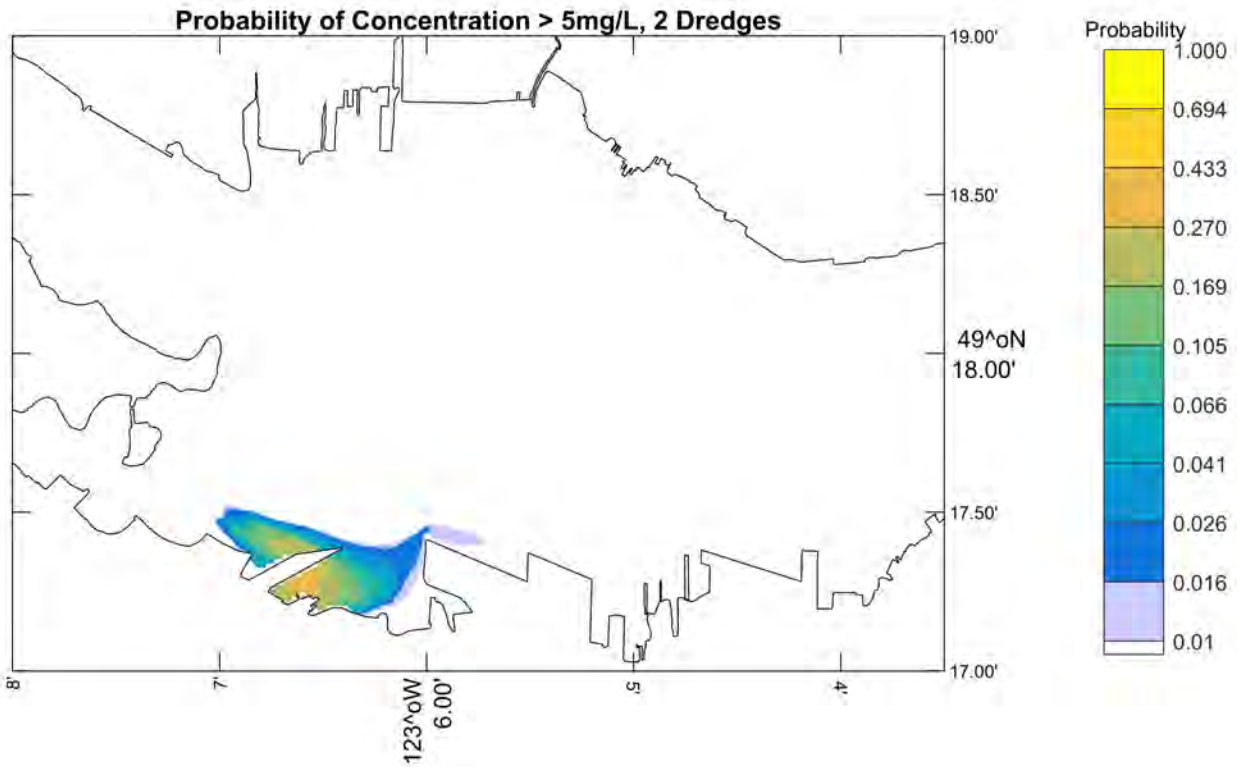
Navigation Dredge Zone Probability Maximum TSS More Than 10% of Source

PROJECT NO.	DWN	CKD	APVD	REV
WTRM03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech - VANC	March, 2017

Figure 4





NOTES

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STATUS
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CLIENT

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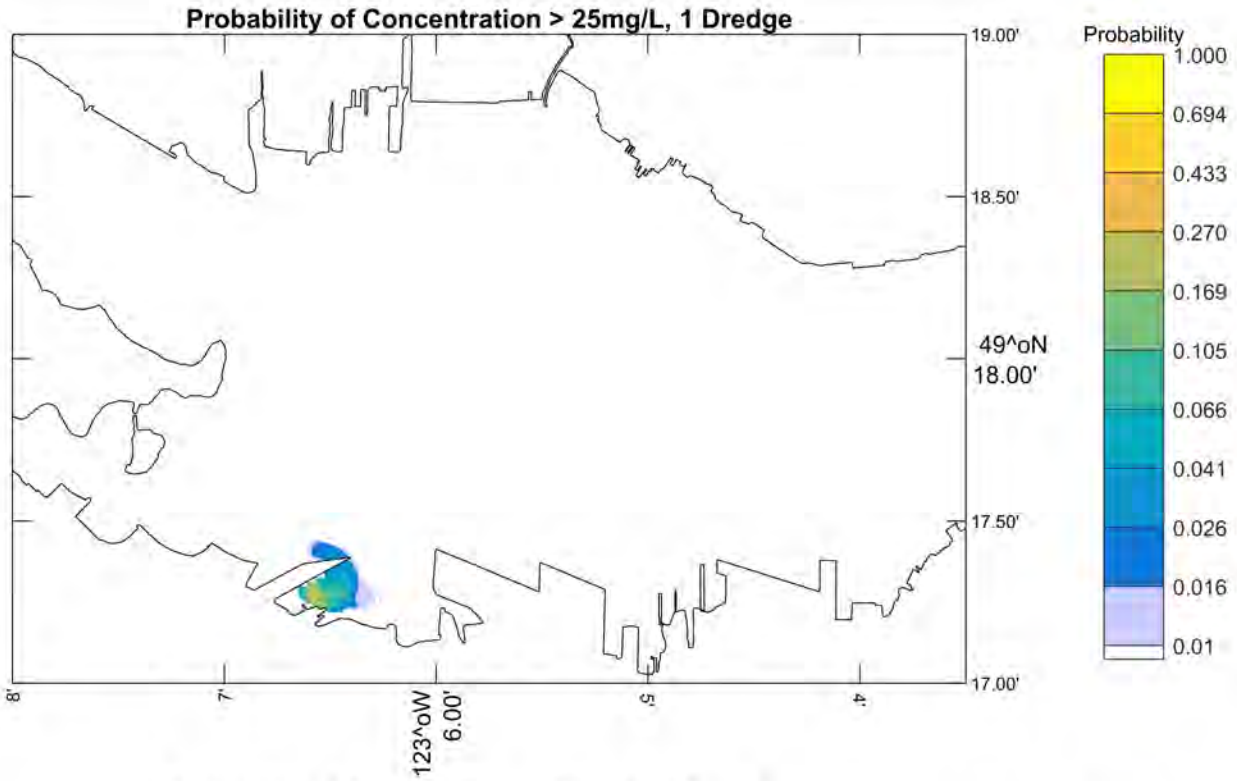
Dispersal Modelling of Dredging Derived Fugitive Sediment

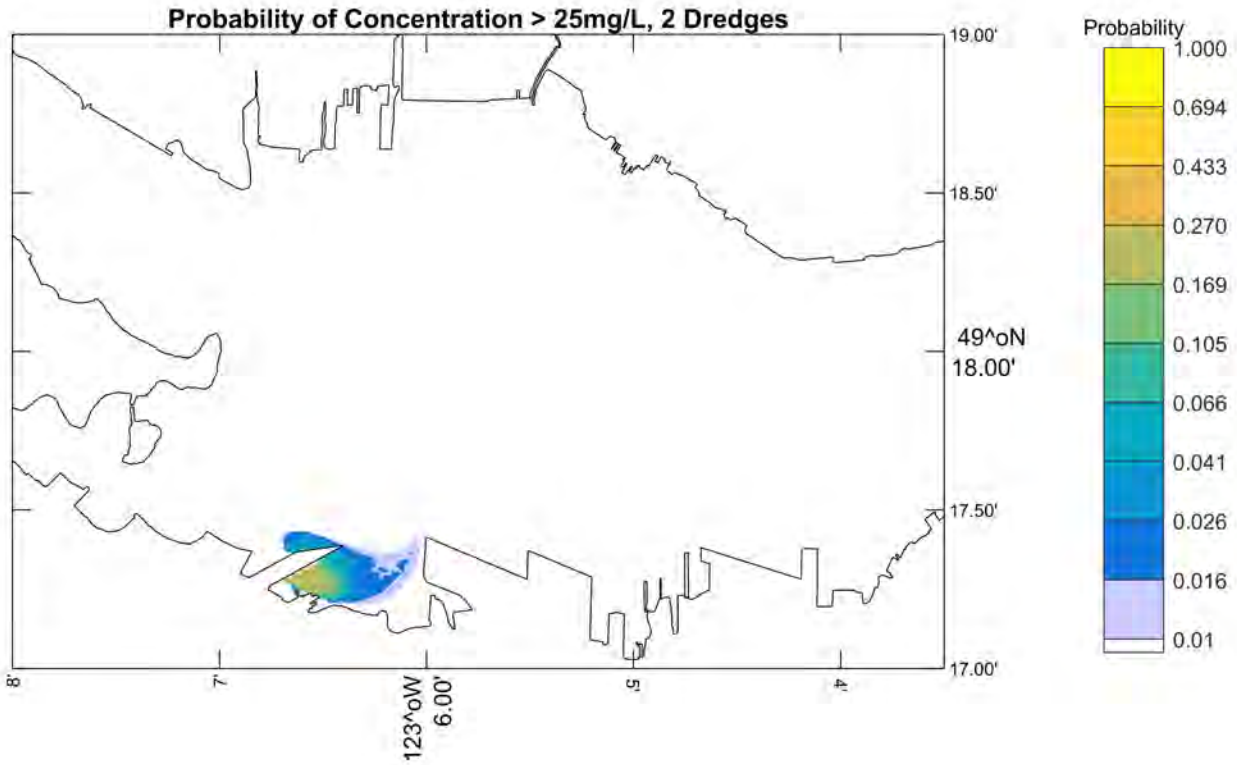
Navigation Dredge Zone Probability of Maximum TSS Exceeding 5 mg/L

PROJECT NO.	DWN	CKD	APVD	REV
WTRM03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech - VANC	March, 2017

Figure 5





NOTES

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2) All concentrations are the maximum concentration over the water column (seabed to surface) at a given location.

STATUS
ISSUED FOR USE

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TETRA TECH

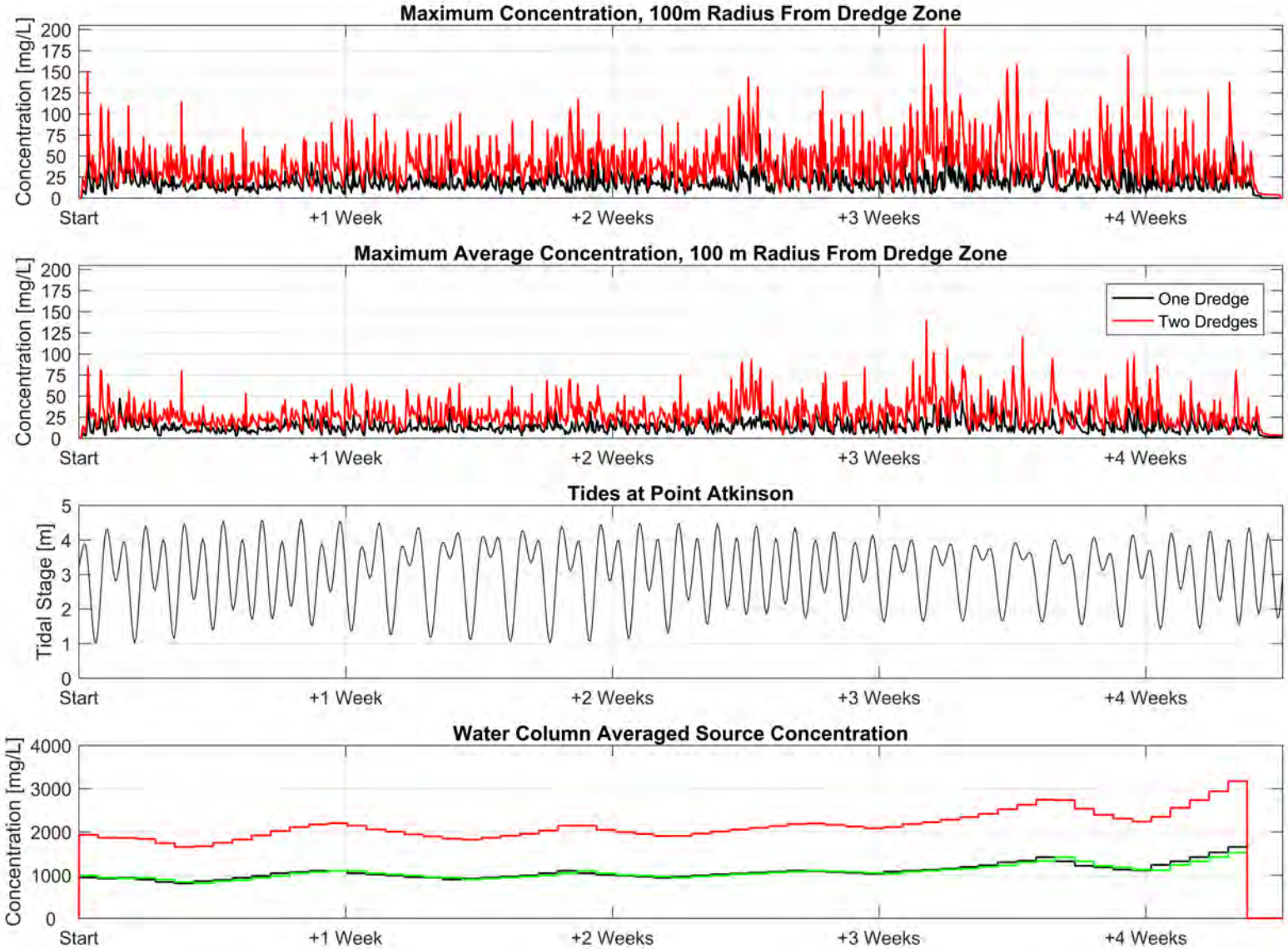
Dispersal Modelling of Dredging Derived Fugitive Sediment

Navigation Dredge Zone Probability of Maximum TSS Exceeding 25 mg/L

PROJECT NO.	DWN	CKD	APVD	REV
WTRM03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech - VANC	March, 2017

Figure 6



NOTES

1) The concentration axis scale for the Source Concentration plot differs from that of the 100 m Concentration plots.
2) Source concentration varies in time due to depth variations between dredge locations and tidal action.
3) Maximum concentrations are the maximum of the maximum concentration over the water column (seabed to surface) along the 100 m boundary.
4) Maximum average concentrations are the maximum of the average concentration over the water column (seabed to surface) along the 100 m boundary.

STATUS
ISSUED FOR USE

CLIENT

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TETRA TECH

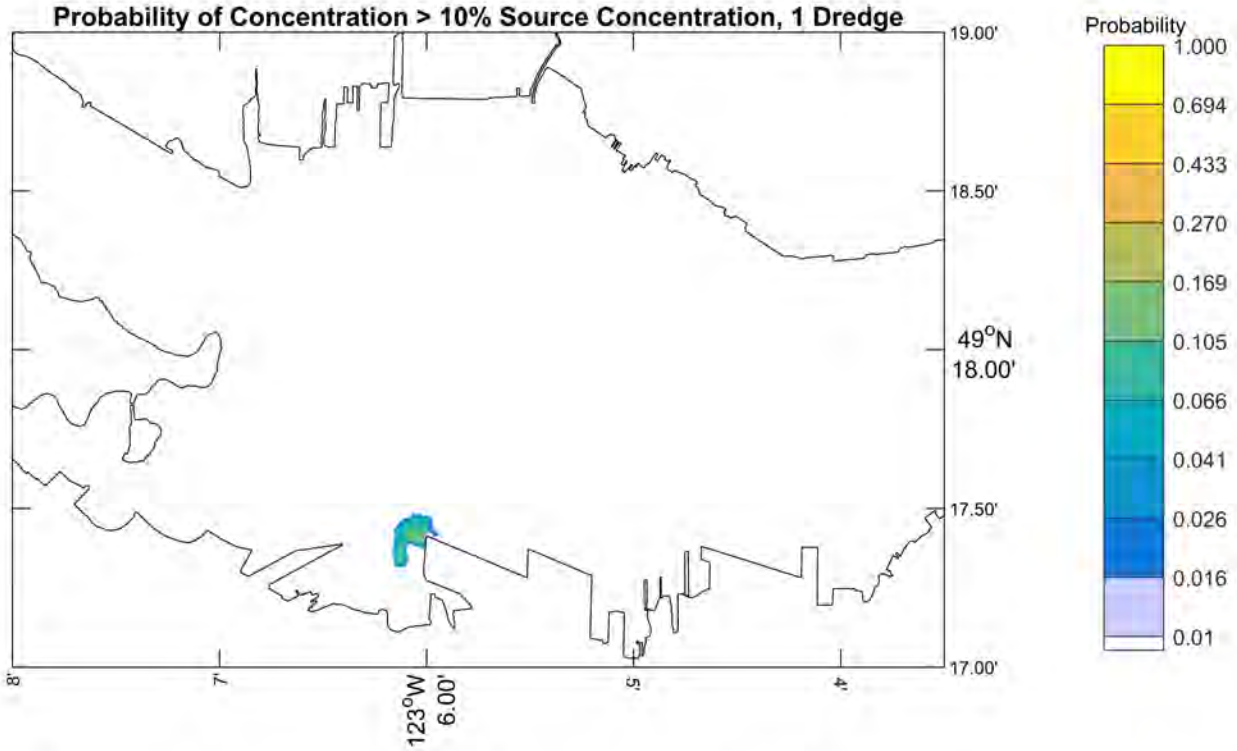
Dispersal Modelling of Dredging Derived Fugitive Sediment

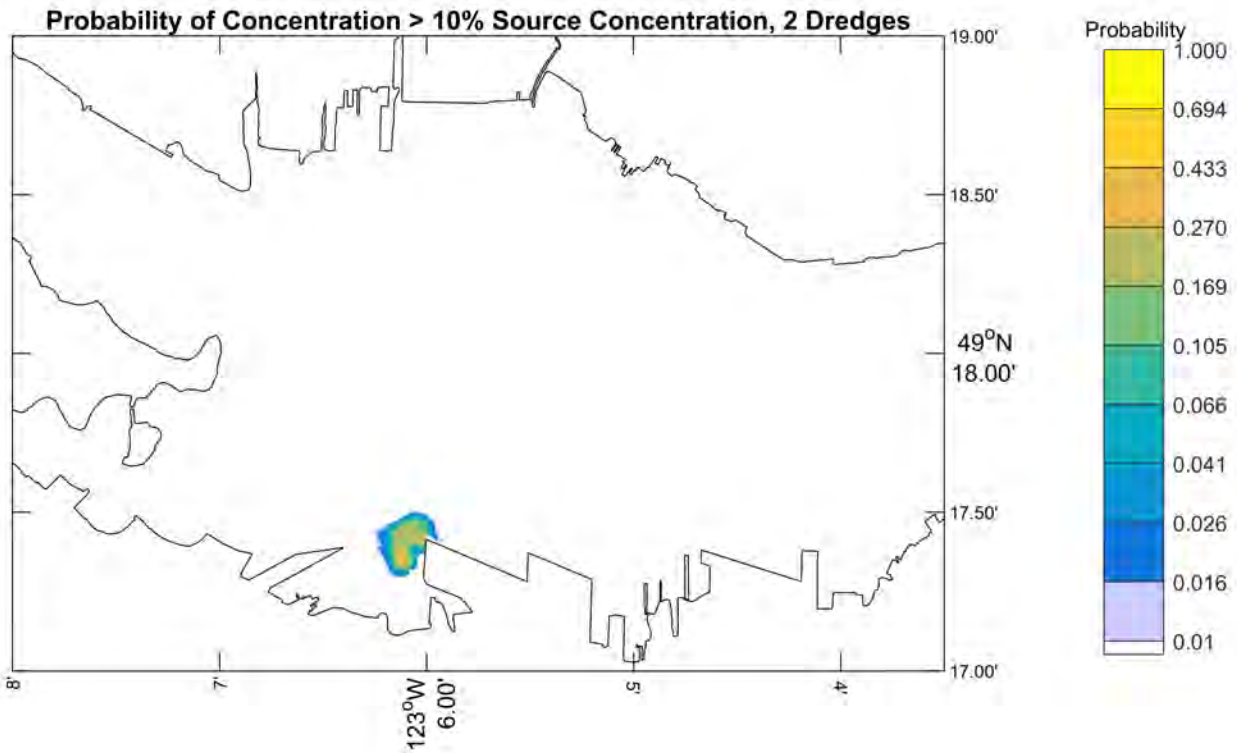
West Basin Dredge Zone TSS Source Attenuation

PROJECT NO.	DWN	CKD	APVD	REV
WTRM.03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech - VANC	March, 2017

Figure 7





NOTES

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2) All concentrations are the maximum concentration over the water column (seabed to surface) at a given location.

STATUS
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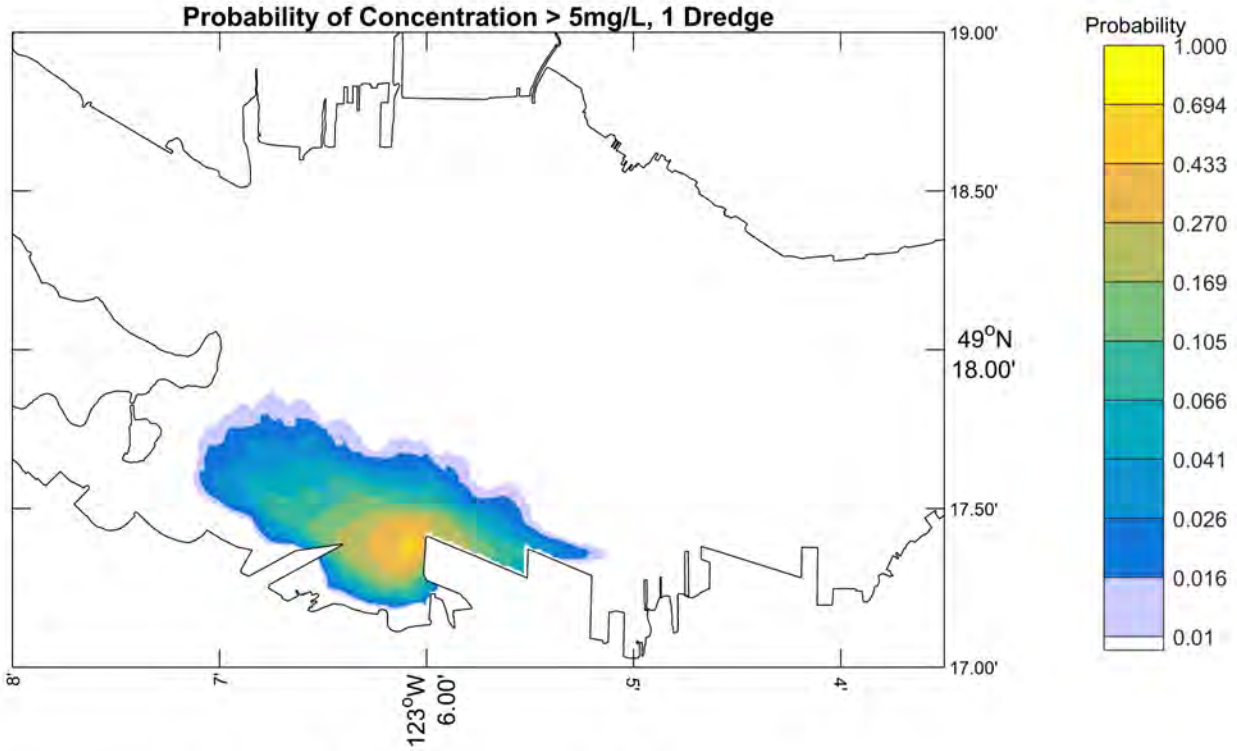
Dispersal Modelling of Dredging Derived Fugitive Sediment

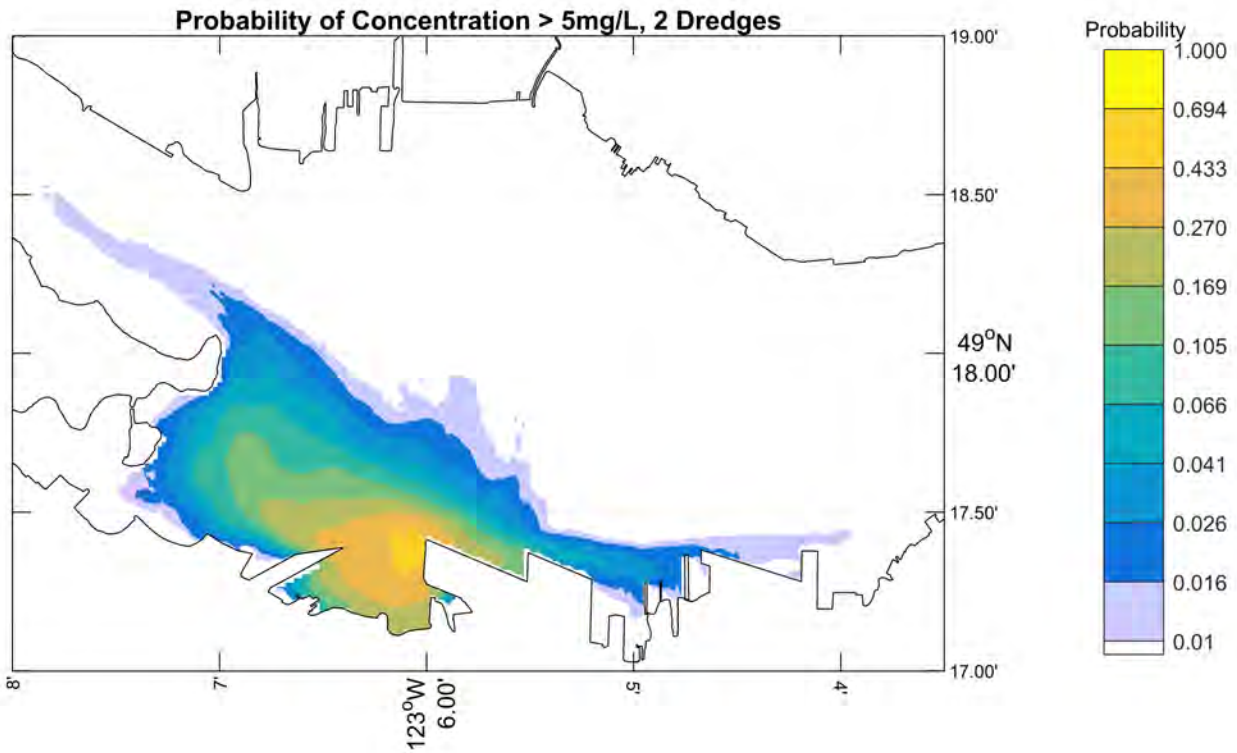
West Basin Dredge Zone Probability of Maximum TSS More Than 10% of Source

PROJECT NO.	DWN	CKD	APVD	REV
WTRM03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech - VANC	March, 2017

Figure 8





NOTES

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2) All concentrations are the maximum concentration over the water column (seabed to surface) at a given location.

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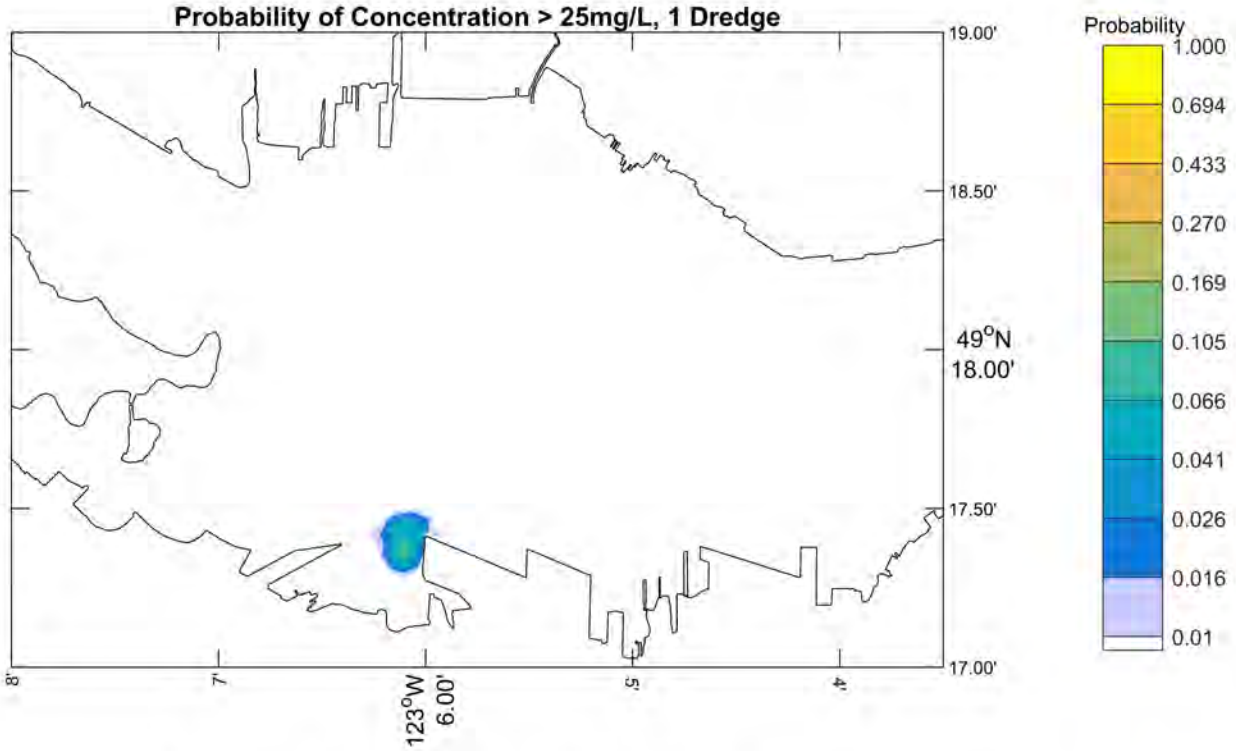
Dispersal Modelling of Dredging Derived Fugitive Sediment

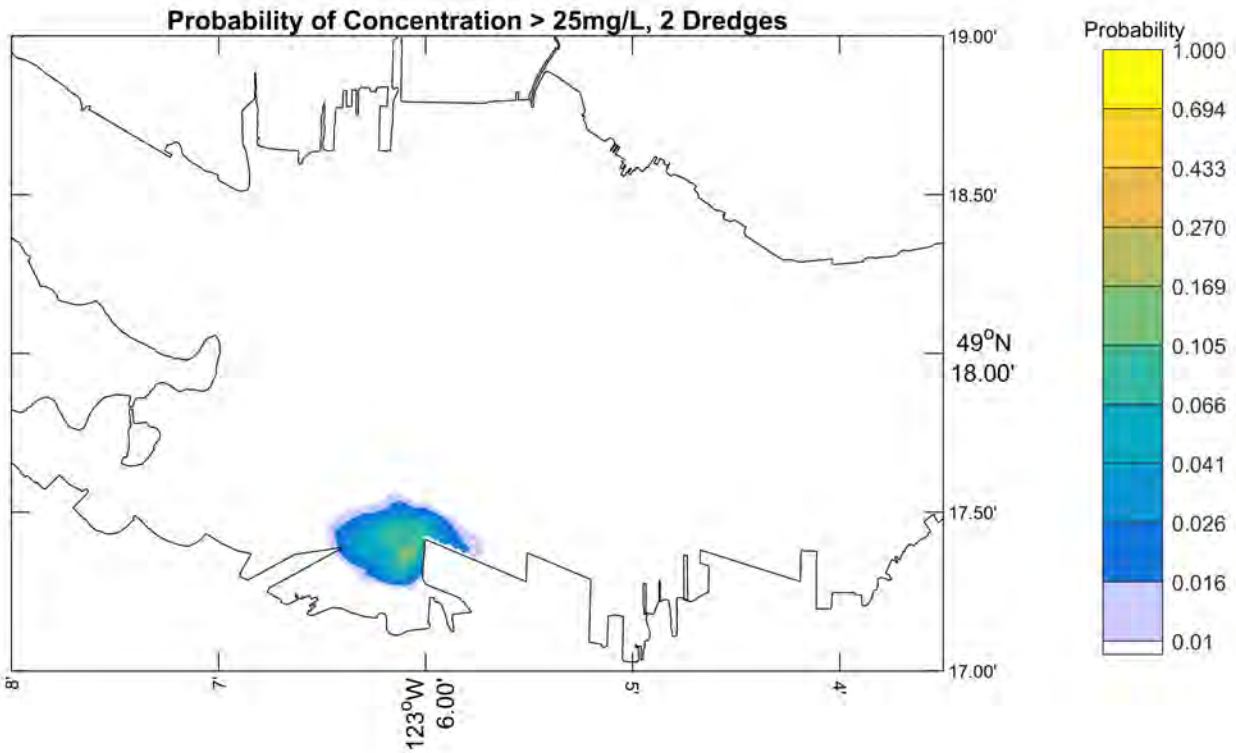
West Basin Dredge Zone Probability of Maximum TSS Exceeding 5 mg/L

PROJECT NO.	DWN	CKD	APVD	REV
WTRM03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech - VANC	March, 2017

Figure 9





NOTES

1) Probability is calculated over the full dredge period and is determined from 15 minute model data.
2) All concentrations are the maximum concentration over the water column (seabed to surface) at a given location.

STATUS
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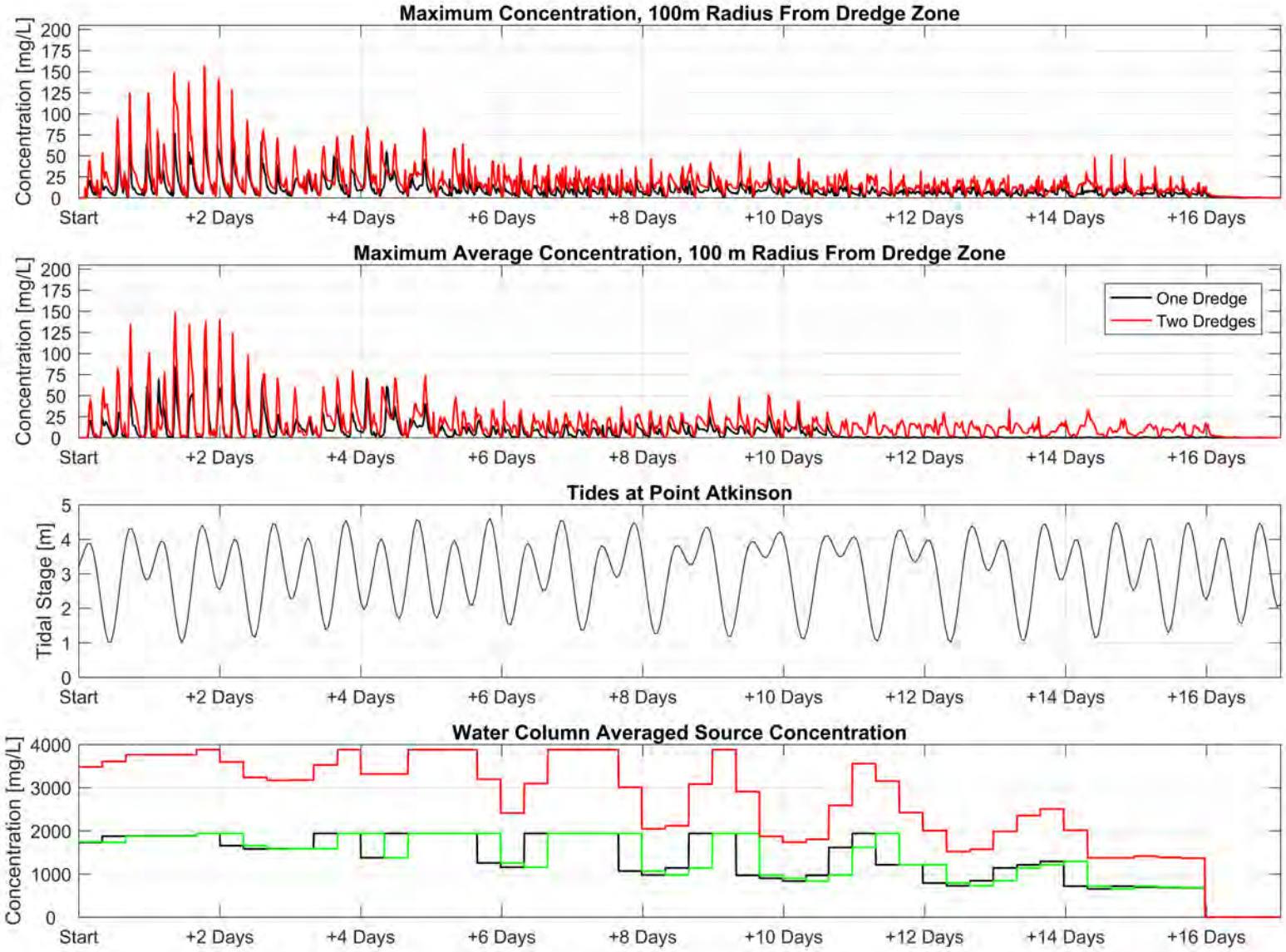
Dispersal Modelling of Dredging Derived Fugitive Sediment

West Basin Dredge Zone Probability of Maximum TSS Exceeding 25 mg/L

PROJECT NO.	DWN	CKD	APVD	REV
WTRM03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech - VANC	March, 2017

Figure 10



NOTES

1) The concentration axis scale for the Source Concentration plot differs from that of the 100 m Concentration plots.
2) Source concentration varies in time due to depth variations between dredge locations and tidal action.
3) Maximum concentrations are the maximum of the maximum concentration over the water column (seabed to surface) along the 100 m boundary.
4) Maximum average concentrations are the maximum of the average concentration over the water column (seabed to surface) along the 100 m boundary.

STATUS
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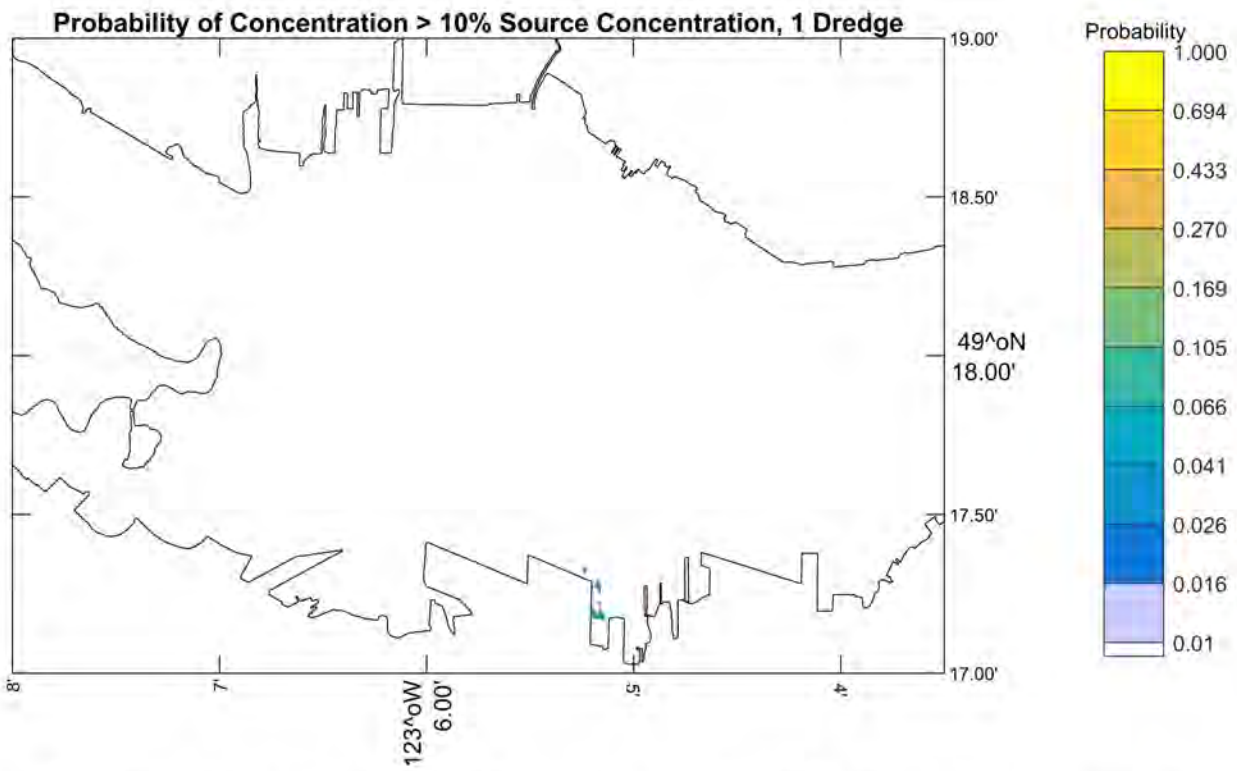
Dispersal Modelling of Dredging Derived Fugitive Sediment

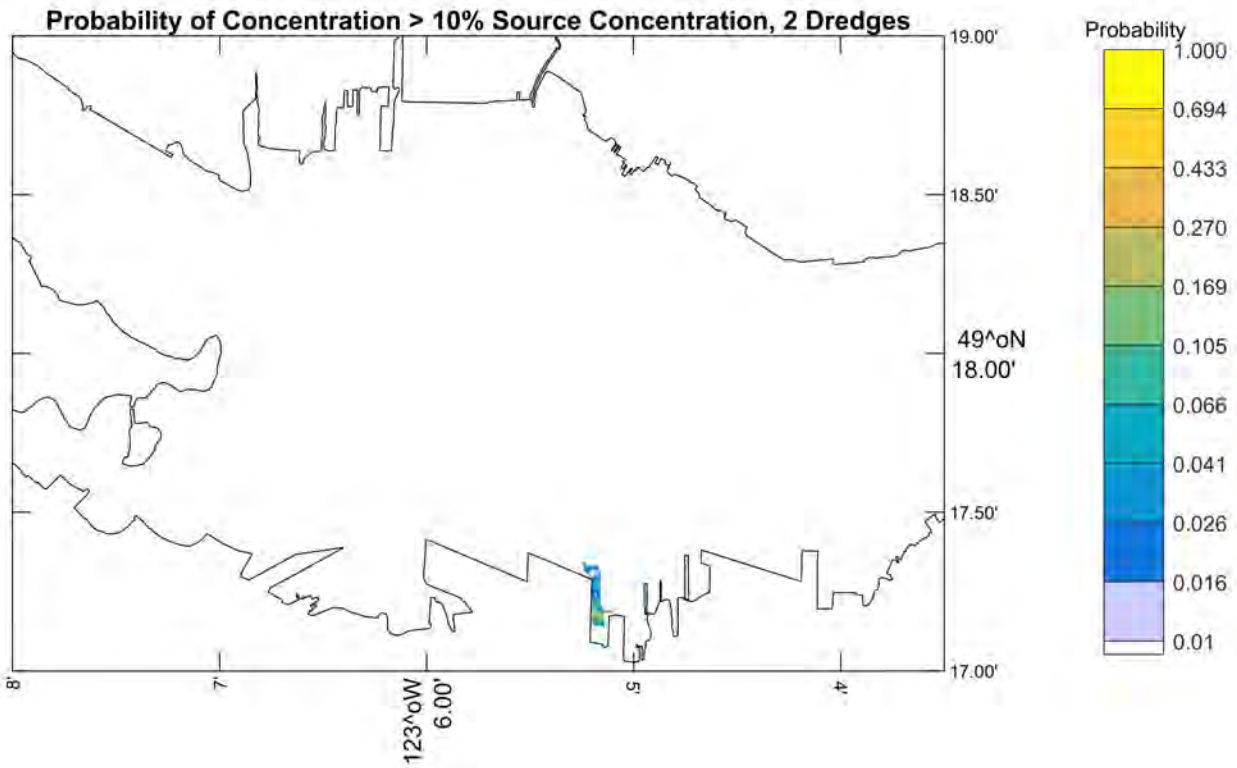
East Basin Dredge Zone TSS Source Attenuation

PROJECT NO.	DWN	CKD	APVD	REV
WTRM.03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech EBA - VANC	March, 2017

Figure 11





NOTES

1) Probability is calculated over the full dredge period and is determined from 15 minute model data.
2) All concentrations are the maximum concentration over the water column (seabed to surface) at a given location.

STATUS
ISSUED FOR USE

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TETRA TECH

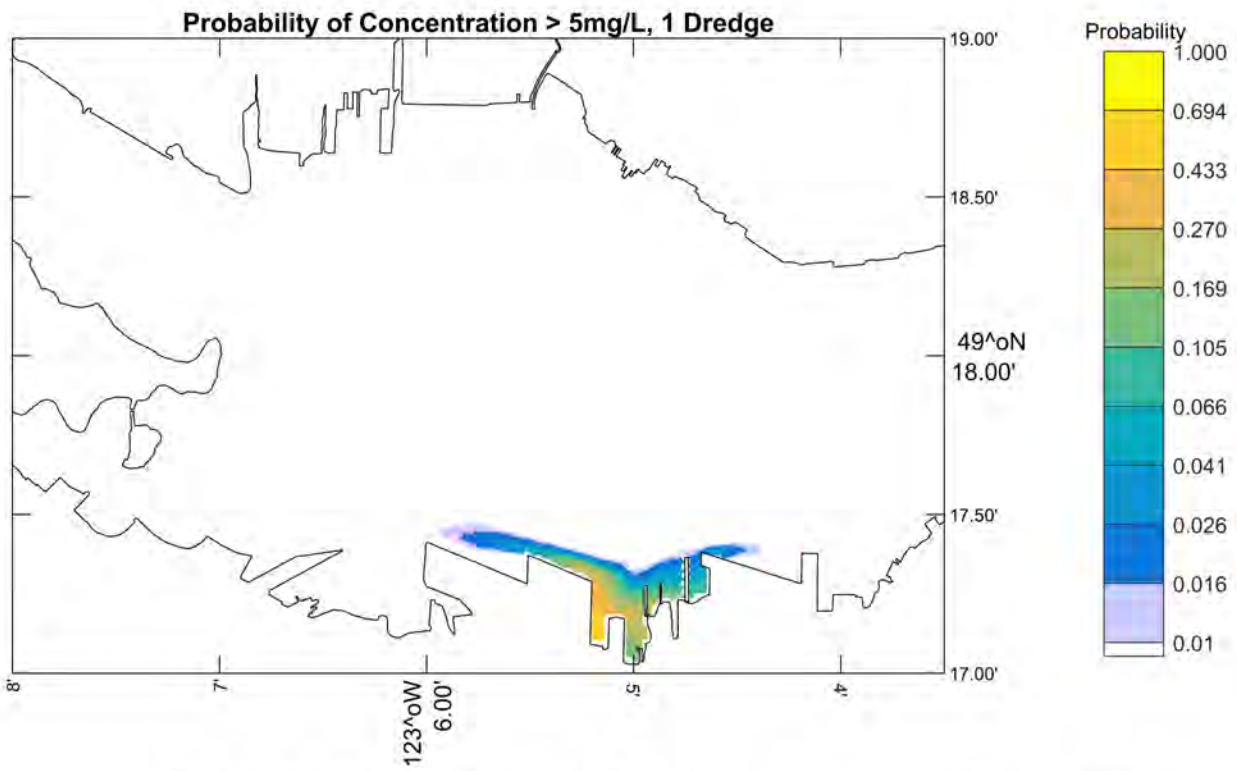
Dispersal Modelling of Dredging Derived Fugitive Sediment

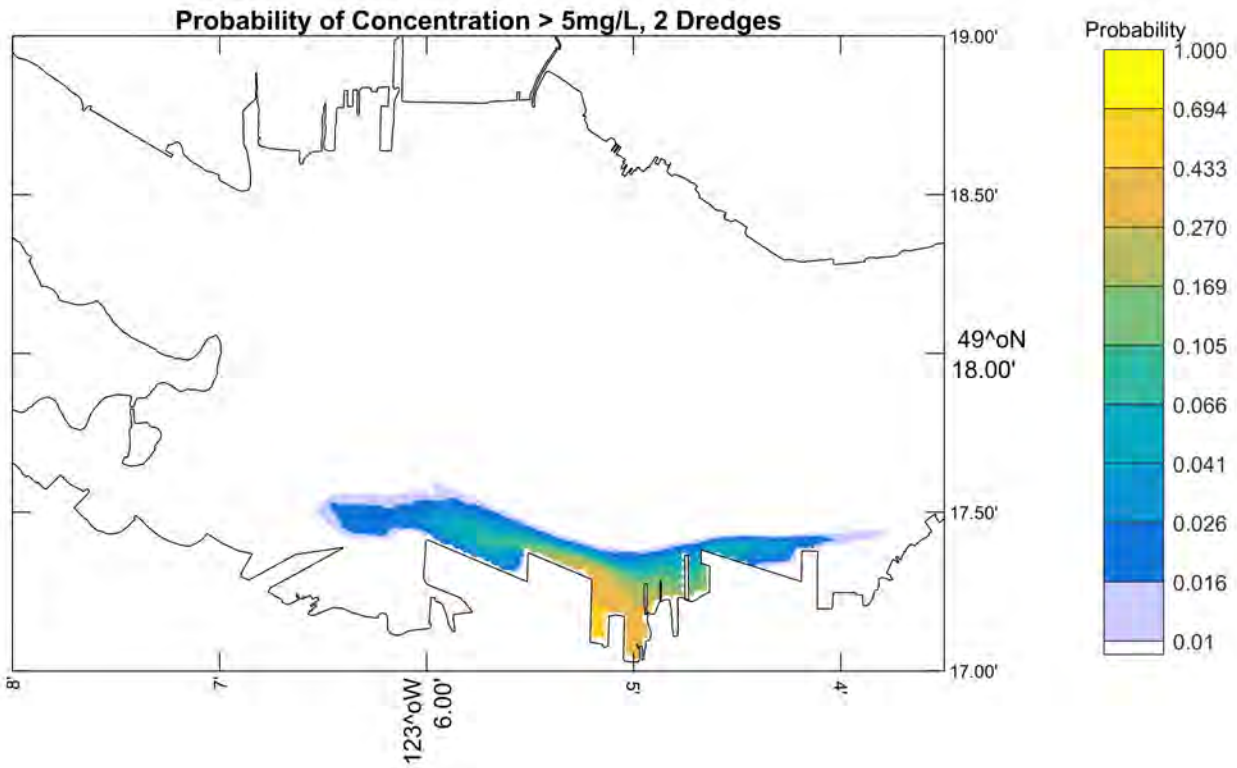
East Basin Dredge Zone Probability of Maximum TSS More Than 10% of Source

PROJECT NO.	DWN	CKD	APVD	REV
WTRM03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech - VANC	March, 2017

Figure 12





NOTES

1) Probability is calculated over the full dredge period and is determined from 15 minute model data.
2) All concentrations are the maximum concentration over the water column (seabed to surface) at a given location.

STATUS
ISSUED FOR USE

CLIENT

AECOM

TETRA TECH

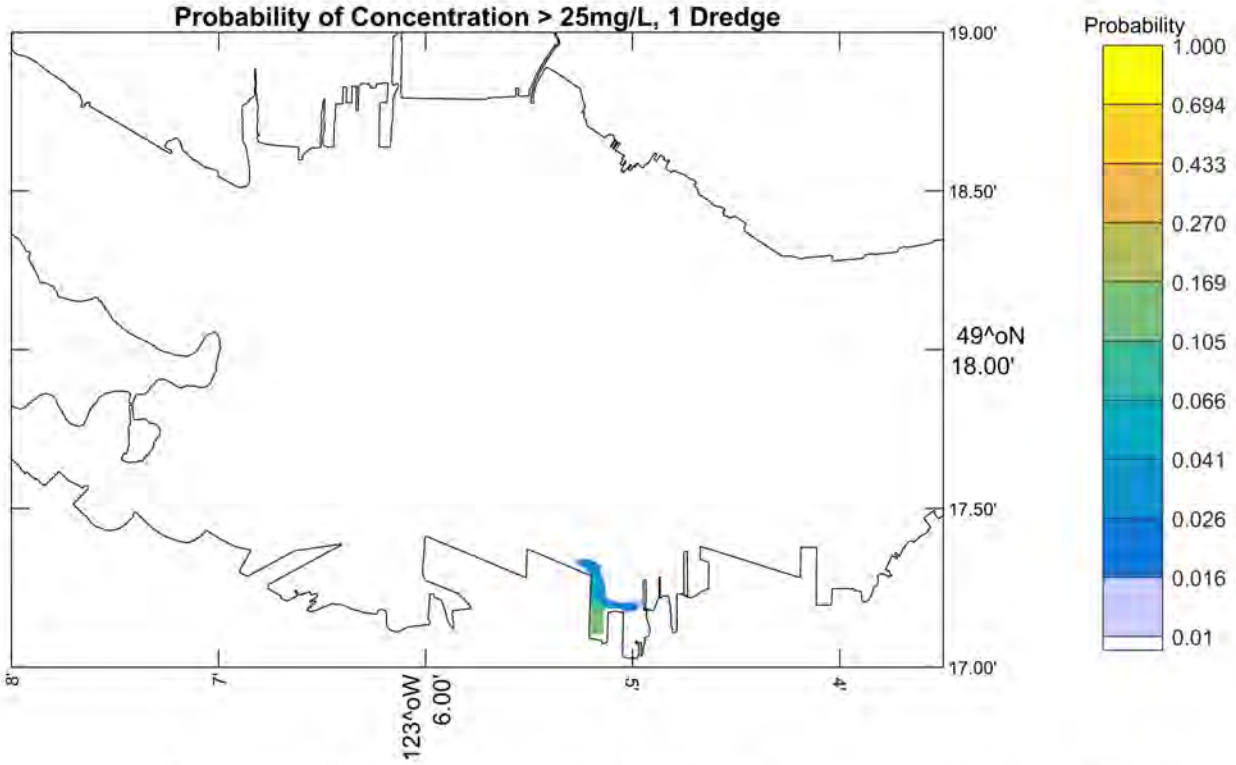
Dispersal Modelling of Dredging Derived Fugitive Sediment

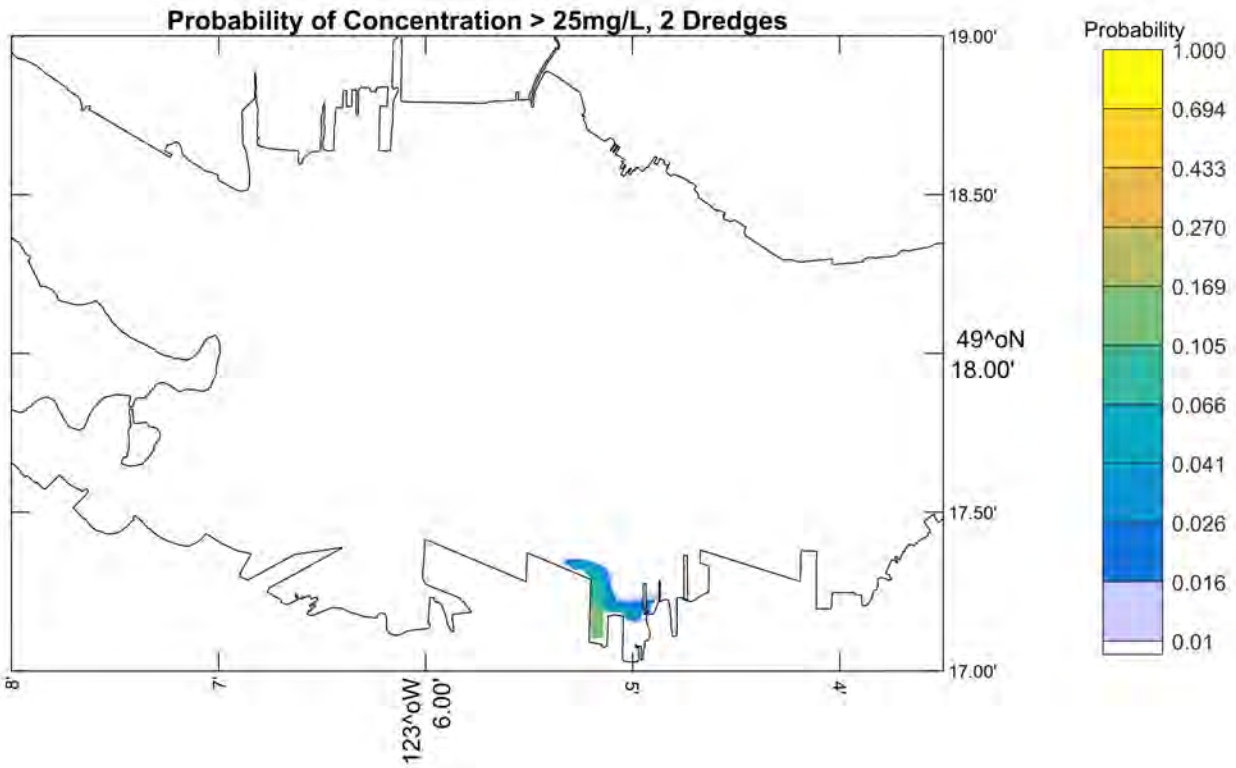
East Basin Dredge Zone Probability of Maximum TSS Exceeding 5 mg/L

PROJECT NO.	DWN	CKD	APVD	REV
WTRM03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech - VANC	March, 2017

Figure 13





NOTES

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2) All concentrations are the maximum concentration over the water column (seabed to surface) at a given location.

STATUS
ISSUED FOR USE

CLIENT

AECOM

TETRA TECH

Dispersal Modelling of Dredging Derived Fugitive Sediment

East Basin Dredge Zone Probability of Maximum TSS Exceeding 25 mg/L

PROJECT NO.	DWN	CKD	APVD	REV
WTRM03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech - VANC	March, 2017

Figure 14

APPENDIX A

TETRA TECH'S GENERAL CONDITIONS

GENERAL CONDITIONS

HYDROTECHNICAL

This report incorporates and is subject to these “General Conditions”.

1.0 USE OF REPORTS AND OWNERSHIP

This report pertains to a specific site, a specific development, and a specific scope of work. The report may include plans, drawings, profiles and other supporting documents that collectively constitute the report (the “Report”).

The Report is intended for the sole use of Tetra Tech EBA’s Client (the “Client”) as specifically identified in the Tetra Tech EBA Services Agreement or other Contract entered into with the Client (either of which is termed the “Services Agreement” herein). Tetra Tech EBA does not accept any responsibility for the accuracy of any of the data, analyses, recommendations or other contents of the Report when it is used or relied upon by any party other than the Client, unless authorized in writing by Tetra Tech EBA.

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2.0 ALTERNATIVE REPORT FORMAT

Where Tetra Tech EBA submits both electronic file and hard copy versions of the Report or any drawings or other project-related documents and deliverables (collectively termed Tetra Tech EBA’s “Instruments of Professional Service”), only the signed and/or sealed versions shall be considered final. The original signed and/or sealed version archived by Tetra Tech EBA shall be deemed to be the original. Tetra Tech EBA will archive the original signed and/or sealed version for a maximum period of 10 years.

Both electronic file and hard copy versions of Tetra Tech EBA’s Instruments of Professional Service shall not, under any circumstances, be altered by any party except Tetra Tech EBA. Tetra Tech EBA’s Instruments of Professional Service will be used only and exactly as submitted by Tetra Tech EBA.

Electronic files submitted by Tetra Tech EBA have been prepared and submitted using specific software and hardware systems. Tetra Tech EBA makes no representation about the compatibility of these files with the Client’s current or future software and hardware systems.

3.0 STANDARD OF CARE

Services performed by Tetra Tech EBA for the Report have been conducted in accordance with the Services Agreement, in a manner consistent with the level of skill ordinarily exercised by members of the profession currently practicing under similar conditions in the jurisdiction in which the services are provided. Professional judgment has been applied in developing the conclusions and/or recommendations provided in this Report. No warranty or guarantee, express or implied, is made concerning the test results, comments, recommendations, or any other portion of the Report.

If any error or omission is detected by the Client or an Authorized Party, the error or omission must be immediately brought to the attention of Tetra Tech EBA.

4.0 ENVIRONMENTAL AND REGULATORY ISSUES

Unless expressly agreed to in the Services Agreement, Tetra Tech EBA was not retained to investigate, address or consider, and has not investigated, addressed or considered any environmental or regulatory issues associated with the project.

5.0 DISCLOSURE OF INFORMATION BY CLIENT

The Client acknowledges that it has fully cooperated with Tetra Tech EBA with respect to the provision of all available information on the past, present, and proposed conditions on the site, including historical information respecting the use of the site. The Client further acknowledges that in order for Tetra Tech EBA to properly provide the services contracted for in the Services Agreement, Tetra Tech EBA has relied upon the Client with respect to both the full disclosure and accuracy of any such information.

6.0 INFORMATION PROVIDED TO TETRA TECH EBA BY OTHERS

During the performance of the work and the preparation of this Report, Tetra Tech EBA may have relied on information provided by persons other than the Client.

While Tetra Tech EBA endeavours to verify the accuracy of such information, Tetra Tech EBA accepts no responsibility for the accuracy or the reliability of such information even where inaccurate or unreliable information impacts any recommendations, design or other deliverables and causes the Client or an Authorized Party loss or damage.

7.0 GENERAL LIMITATIONS OF REPORT

This Report is based solely on the conditions present and the data available to Tetra Tech EBA at the time the Report was prepared.

The Client, and any Authorized Party, acknowledges that the Report is based on limited data and that the conclusions, opinions, and recommendations contained in the Report are the result of the application of professional judgment to such limited data.

The Report is not applicable to any other sites, nor should it be relied upon for types of development other than those to which it refers. Any variation from the site conditions present at or the development proposed as of the date of the Report requires a supplementary investigation and assessment.

It is incumbent upon the Client and any Authorized Party, to be knowledgeable of the level of risk that has been incorporated into the project design, in consideration of the level of the hydrotechnical information that was reasonably acquired to facilitate completion of the design.

The Client acknowledges that Tetra Tech EBA is neither qualified to, nor is it making, any recommendations with respect to the purchase, sale, investment or development of the property, the decisions on which are the sole responsibility of the Client.

8.0 JOB SITE SAFETY

Tetra Tech EBA is only responsible for the activities of its employees on the job site and was not and will not be responsible for the supervision of any other persons whatsoever. The presence of Tetra Tech EBA personnel on site shall not be construed in any way to relieve the Client or any other persons on site from their responsibility for job site safety.

Appendix B Centerm Expansion Project: Numerical Modelling of Silt Curtain Effectiveness in Reducing Dredging-Derived Fugitive Sediment

Centerm Expansion Project: Numerical Modelling of Silt Curtain Effectiveness in Reducing Dredging-Derived Fugitive Sediment

PRESENTED TO

AECOM Canada

SEPTEMBER 14, 2017
ISSUED FOR USE
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This report and its contents are intended for the sole use of AECOM Canada and their agents. Tetra Tech Canada Inc. (Tetra Tech) does not accept any responsibility for the accuracy of any of the data, the analysis, or the recommendations contained or referenced in the report when the report is used or relied upon by any Party other than AECOM Canada, or for any Project other than the proposed development at the subject site. Any such unauthorized use of this report is at the sole risk of the user. Use of this report is subject to the terms and conditions stated in Tetra Tech Canada Inc.'s Services Agreement. Tetra Tech's General Conditions are provided in Appendix A of this report.

1.0 INTRODUCTION

AECOM Canada (AECOM) retained Tetra Tech Canada Inc. (Tetra Tech) to quantify the release and dispersion of fugitive sediments arising from dredging three sites over the course of the Centerm Expansion Project (CEP) and assess the effectiveness of floating silt curtains in controlling the release of fugitive sediment to the marine environment. CEP consists of an expansion of the existing Centerm Container Terminal located on the southern shoreline of Vancouver Harbour. The project will consist of two fill expansions to the existing terminal footprint: a westward expansions of approximately 4.2 ha and an eastward expansion of approximately 4 ha. Prior to the construction of perimeter rock dykes and infilling, unstable marine sediments must be removed via dredging. Over the course of CEP additional navigational dredging will take place to the south west of the western expansion to provide a turning basin for ships calling at the East Canada Place cruise ship berth.

An overview of the project site is presented on Figure 1.1, showing the West Basin Dredge Zone (westward expansion) in red, the East Basin Dredge Zone (eastward expansion) in green and the Navigational Dredge Zone (expanded turning basin) in blue. The dredge prisms are shown in solid colours, while the 100 m initial dilution zone is plotted as a thin line colour matched to its respective dredge prism. Dredging will take place using either one clamshell dredge working alone or two clamshell dredges working simultaneously. The entirety of the Navigational Dredge Zone and the surficial sediments of both the East and West Dredge Zones will be dredged with an 8 m^3 capacity environmental dredge bucket. Following removal of surficial sediments at the East and West Dredge Zones, dredging will continue with a 26 m^3 capacity dredge bucket. The unmitigated behaviour of sediment plumes arising from clamshell dredging operations has previously been quantified in the study *Centerm Expansion Project: Dispersal Modelling of Dredging-Derived Fugitive Sediment* (Tetra Tech 2017a). Fugitive sediment releases during the infilling process have been previously quantified in the report *Centerm Expansion Project: Dispersal Modelling of Infilling-Derived Fugitive Sediment* (Tetra Tech 2017b).

The present study quantifies the effectiveness of floating silt curtains in mitigating the release of fugitive suspended sediments arising from dredging of the West Basin Dredge Zone and East Basin Dredge Zone. Silt curtain mitigation of dredging at the Navigational Dredge Zone is not required as the volume of dredgeate is relatively minor, the dredging duration will be very short (order of days) and a cobble substrate has been found over the course of site investigations. The entirety of the West Basin work area will be enclosed by a 7 m depth Type III silt curtain, while the East Basin will be isolated into southern and northern work areas with a similar 7 m depth Type III silt curtain. With the exception of the silt curtain containment, the dredging scenarios presented in this report are identical to those presented previously in Tetra Tech 2017a.

The fate and behaviour of the project-derived fugitive sediments has been simulated using an extensively validated three-dimensional numerical model of Vancouver Harbour in conjunction with a parameterized dredging schedule based on a conceptual plan for dredging, which may be modified by the contractor during the design stage. The predicted concentrations of fugitive sediments reported here reflect conditions as mitigated by silt curtain enclosure, but with no consideration of mitigation by avoidance of critical tide conditions.

2.0 METHODS

2.1 Numerical Model

The primary numerical model employed in this study is a 25-m resolution three-dimension numerical model encompassing Burrard Inlet from west of First Narrows to east of Second Narrows. This model is the highest resolution model in a series of nested numerical models extending from the Pacific Ocean to the upper end of Indian Arm:

- **Coarse Resolution:** 1-km resolution shelf model extending from the mouth of Juan de Fuca Strait to the southern end of Texada Island and the terminus of Indian Arm. The model is driven by tidal constituents and monthly climatology at its boundaries with hourly wind fields and daily river inflows at 13 significant rivers.

- **Mid-Resolution:** 125-m resolution Burrard Inlet model extending from the entrance to English Bay to the terminus of Indian Arm. The model is driven by water level, temperature and salinity data from the coarse resolution model, with hourly wind fields and daily river inflows.
- **High Resolution:** 25-m resolution Burrard Inlet model extending from the mid-point of English Bay (near Jericho Beach) to east of Second Narrows (near Berry Point), driven by water level, temperature and salinity data from the mid-resolution model, with hourly wind fields and daily river inflows.

Within the modelling chain, all major rivers in the Salish Sea are included, with Lynn Creek, the Seymour River and the Capilano River feeding directly into the high resolution Burrard Inlet model. Wind fields are interpolated from measured winds at buoys and meteorological stations around coastal British Columbia, with winds for the high resolution Burrard Inlet model based on a dedicated CALMET wind model. Fugitive sediment arising from dredging operations is introduced into the model via a conservatively estimated sediment loss rate specific to clam shell buckets (see Section 3.3). The 25-m resolution model is of sufficient resolution that the near-field (i.e. at a spatial scale smaller than the 25-m grid size) sediment dynamics related to the clam shell dredging operation do not require dedicated simulation to resolve the resulting fugitive sediment dynamics. For each dredging location, the simulation period has been determined based on the dredge prism volume and the estimated production rate of the dredge(s) (see Section 3.3).

The circulation patterns within Vancouver Harbour are tidally dominated, with some baroclinic influence due to seasonal variations in fresh water inflow and heat fluxes at the air/water interface. Streaklines showing the surface currents within western Vancouver Harbour are shown on Figure 2.1. The most prominent flow features within the harbour are the tidal jets formed at First Narrows and Second Narrows. These jets regularly have peak velocities of over 2.5 m/s, with a maximum velocity nearing 3 m/s on occasion. Flood tides result in a strong eastward flowing jet forming at First Narrows that remains coherent well into Vancouver Harbour and establishes a series of eddies and recirculation cells that persist throughout the tidal cycle. The First Narrows jet impinges on the Centerm site resulting in strong eastward flows along the terminal face and generally setting up a clockwise circulation cell between Centerm and Canada Place. On the left panel of Figure 2.1 two flood-tide circulation cells are shown to the west of Centerm, one clockwise and the other counterclockwise, centered over the Navigation Dredge Zone. Ebb tides result in a strong westward flowing jet forming at Second Narrows (not show on Figure 2.1), resulting in complex circulation patterns in the vicinity of Centerm. Ebb tidal currents flowing westward in the middle of Vancouver Harbour result in westward flows along the terminal face and set up a counterclockwise eddy between Centerm and Canada Place (Figure 1). Ebb tides generally result in a counter clockwise eddy forming to the west of the East Basin Dredge Zone. Towards the end of ebb tide (not shown on Figure 2.1) a counterclockwise eddy can be set up in south western Vancouver Harbour which results in eastward flow in the vicinity of Centerm and, somewhat counterintuitively, in the eastward outflow of water from between Centerm and Canada Place during late stages of ebb tide.

2.2 Fugitive Sediment Plume Tracking

Dredging at the three active dredge sites of the CEP will be undertaken with either one clamshell dredge loading a hopper barge or two clamshell dredges simultaneously loading the same hopper barge. It is assumed that the barge will not overflow supernatant dredge water (AECOM 2016). The three dredge zones are displayed on Figure 1.1, with the Navigation Dredge Zone in blue, the West Basin Dredge Zone in red and East Basin Dredge Zone in green. Around each Dredge Zone, a dilution zone extending 100 m from the edge of the dredge prism is shown. These dilution zones are used later in this report to determine the dilution of the incidentally released dredgeate at a distance of 100 m from the dredging area.

In order to quantify the dispersion of fugitive sediments, the total suspended solids (TSS) content of the fugitive sediment plume is tracked as sediments are released over a simulated dredging program. Within the numerical model of Burrard Inlet, the position and concentration of the sediment plume is determined in three dimensions every 4 to 8 seconds. This results in a very large data set that must be summarized to meaningfully present the position and concentration of the sediment plume.

The primary metric used to quantify the concentration and extent of the sediment plume is the arithmetic mean of above-background TSS concentration over the water column, referred to in this report as the depth-averaged TSS

concentration**.** At 15 minute intervals, the depth-averaged TSS concentration is calculated from the full three-dimensional model output on a 25 m by 25 m horizontal grid across all of Burrard Inlet.

As an explanatory example: in a water depth of 40 m, there is a TSS concentration of 100 mg/L within 1 m of the seabed and a TSS concentration of 4 mg/L through the rest of the water column. The instantaneous (i.e. occurring right now, not time-averaged) depth-maximum TSS concentration is 100 mg/L, while the instantaneous depth-averaged TSS concentration is 6.4 mg/L. For dredging operations with a duration greater than 24 hours, CCME's guidance on Total Particulate Matter recommends that the average TSS level not exceed 5 mg/L over the duration of the dredging program. Therefore, if a depth-averaged TSS concentration of 6.4 mg/L is present for 3 days out of a 10 day dredging program, the average TSS level calculated as per CCME guidance would be 1.9 mg/L and the dredging program would be in compliance. Conversely, if a depth-averaged TSS concentration of 6.4 mg/L is present for 8 days out of a 10 day dredging program, the average TSS level would be 5.1 mg/L and the dredging program would be out of compliance.

After computing the depth-averaged TSS concentration across all of Burrard Inlet at 15 minute intervals, this data set is then post-processed to produce the following measures of TSS concentration compliance:

- **Instantaneous Depth-Averaged TSS Concentrations, 100 m from the Dredge Prism:** The depth-averaged TSS concentration calculated at 15 minute intervals along the 100 m boundary measured from the edge of the dredge prism. Separate time-series of depth-averaged TSS concentration are computed at all model grid points that lie along the perimeter of the 100 m boundary. These separate time series are then used to calculate the maximum, mean and percentiles of the depth-averaged TSS concentrations at the 100 m boundary that are presented in Section 5.0.
- **Average TSS Concentration, 100 m from the Dredge Prism:** The average TSS concentration along the 100 m boundary measured from the edge of the dredge prism. This average is computed from the depth-averaged TSS in all model grid cells that lie along the perimeter of the 100 m boundary and represents the overall average TSS concentration along the entire 100 m boundary. This metric is most comparable to CCME's guidance on Total Particulate Matter concentration for inputs lasting 24 hours to 30 days, which recommends that the average TSS level not exceed 5 mg/L over the duration of the dredging operation. For works lasting longer than 30 days, a 30 day moving average of TSS concentration is presented. The average TSS concentration is the most relevant measure of TSS in the water column.
- **Probability of Depth-Averaged TSS Exceeding 5 mg/L:** The probability that the depth-averaged TSS concentration will exceed 5 mg/L at any given location in Burrard Inlet over the dredging operation. The probability of exceedance should be interpreted as the chance that an observer would encounter a depth-average TSS concentration over 5 mg/L at any given time over the dredging operation. The duration of the dredging operation is here defined as from the start of dredging to when the depth-averaged TSS concentration drops below 5 mg/L following the end of dredging.

  The shaded probability maps presented in Section 5.0 for the depth-averaged TSS concentration do not represent the instantaneous TSS plume footprint or a static plume position, although they have the appearance of a sediment plume. Instead, these probability maps represent the likelihood of the depth-averaged TSS concentration exceeding 5 mg/L at any one location (represented on a 25 m by 25 m horizontal grid) over the entire dredging operation. This likelihood is derived as a composite of depth-averaged TSS concentrations in space and time over the full dredging period and should not be interpreted as a continuous or prevailing condition.

  For example: assume a 1% probability that the depth-averaged TSS concentration will exceed 5 mg/L a location in Burrard Inlet. This means that if an observer were to check that specific 25 m by 25 m section of Burrard Inlet at a random time over the dredging operation, there is a 1% probability that they would find a depth-averaged TSS concentration exceeding 5 mg/L. Over an extended dredge operations (e.g. 16 days), this 1% probability indicates the TSS at that position (and any others similarity classified by the probability map shading) could exceeded 5 mg/L for a total of 3 hours and 50 minutes (i.e. 1% of 16 days).

3.0 SILT CURTAIN PARAMETERIZATION

3.1 Silt Curtains in the Marine Environment

Silt curtains are flexible barriers that act to partially contain water laden with TSS. Silt curtains as applied in the marine environment are generally constructed from a geotextile material, with a continuous float along the top edge, weighting along the bottom edge (generally consisting of chain) and some form of tensioning wire or reinforcement through the middle of the curtain to decrease current-induced deformation. Silt curtains are generally anchored in place, either using bottom anchors, fixed points (e.g. piles) or dynamically positioned support vessels.

In most marine applications silt curtains are suspended from floats at the surface and secured by anchors to the bottom. Silt curtains can either extend across the entire water column from surface to seabed or, as is more typical in tidal waters, across a portion of the water column. As a partial height curtain does not fully isolate the working area, they serve to reduce TSS releases by promoting the downward migration of suspended sediment, shortening the settling time and reducing the prevalence of TSS at the water surface.

Silt curtains in tidal waters can be exposed to large hydrodynamic loads due to tidal currents. The geotextile material that make up silt curtains, while permeable to water, is not sufficiently permeable, particularly when clogged with fine sediments, to allow the direct flow-through of currents. Therefore, the silt curtains present, for all practical purposes, an impermeable barrier to flow, causing water to flow under and around the isolated work area. As current velocities increase, the loading on the silt curtains rises, resulting in deformation of the silt curtain enclosure. This deformation takes place in the horizontal plane as the silt curtains bend in response to hydrodynamic forces and, more importantly, in the vertical plane as the bottom of the silt curtains flare upwards. As hydrodynamic loading increases, the amount of flare increases, reducing the effective draft of the silt curtain and their resulting effectiveness. At the upper operational range of silt curtains, flare can reduce the effective draft of the silt curtains to essentially zero, completely removing site isolation.

Depending on the strength of the ambient currents, the size of the work area and the type of dredging activity, the silt curtain enclosure may have to be repositioned numerous times over the course of dredging operations. Repositioning can take place either by opening and repositioning the silt curtains and thereby releasing any TSS contained within the silt curtains or by moving the silt curtain isolation in bulk during periods of calm currents, and thereby containing any TSS laden water.

3.2 Model Implementation

Silt curtains have been implemented within Tetra Tech's three dimensional numerical model of Burrard Inlet as a mobile barrier to water motion and scalar transport. As implemented in the numerical model, the silt curtains have the following properties:

- **Permeability:** It is assumed that silt curtains are impermeable. Since the hydraulic resistance of silt curtains is very large, currents will tend to flow under and around the curtains, rather than through, and the amount of through flow is trivial compared to other processes.
- **Temperature and Salinity Transmissivity:** It is assumed that the silt curtains do not allow the transmission of temperature and salinity. Given that the silt curtains are largely impervious, salinity will naturally not be transferred in large quantities. The transmission of temperature through the silt curtain barrier is possible and not represented but is trivial compared to the heat transfer due to mixing.
- **Sediment Transmissivity:** It is assumed that the silt curtains do not allow the transmission of sediments.
- **Silt Curtain Flare:** The flare of the silt curtains in response to hydraulic loading is calculated via the catenary equations presented in JBF Scientific Corporations' 1978 report *An Analysis of the Functional Capabilities and Performance of Silt Curtains*. As these equations are implemented in a three dimensional numerical model, several of the most significant assumptions in JBF 1978 are no longer required: the full vertical current field is used, the silt curtain is no longer assumed uniform in cross section and the gap beneath the curtain can vary

dynamically in response to flare. The assumption that the silt curtains have no capacity for compression or moments has been retained as it is a reasonable approximation.

- **Deformation of the Silt Curtain Enclosure:** It is assumed that the silt curtain enclosure is sufficiently anchored to prevent significant deformation. A deformation greater than one model grid cell (25 m) would be considered significant at the model resolution employed in this study.

The numerical model determines silt curtain behavior at two time levels pertinent to the time scale of each process. Below is a brief outline of the model logic.

Hourly Intervals, Silt Curtain Management:

- At the start of each hour, check the silt curtain position against the dredging schedule
- If the silt curtain requires repositioning, move the curtain to reflect the desired silt curtain arrangement
- If the silt curtain is to be removed, check the TSS levels against any criteria (e.g. return to background levels) and if all criteria for removal are met, remove the silt curtain
- If the silt curtain does not require repositioning or removal there is no change in the model

The flare of the silt curtain is calculated at each time step, approximately every 4 to 8 seconds:

- Determine water density along outer edge of the silt curtain
- Determine water velocity along outer edge of the silt curtain
- Calculate hydrodynamic loading on silt curtain
- Solve catenary equations to determine silt curtain flare
- Adjust silt curtain draft to reflect flare calculation

3.3 Silt Curtains at the Centerm Expansion Project

Owing to the strong tidal currents and large water depths at the CEP project site, partial height silt curtains will be deployed. At the West Basin, these silt curtains will extend 7 m below the water surface, will isolate a working area of approximately 60,000 m^2 and will fully enclose the active dredge zone. At the East Basin, two isolation areas will be used: a southern area between the Southern Railway and Ballantyne Piers with a surface area of approximately 12,400 m^2; and, a northern area along the eastern and northern edge of Ballantyne Pier isolating an area of approximately 25,700 m^2. Each of these three silt curtain enclosures will be situated approximately 25 m from the active dredge equipment and the curtains will be repositioned to expand or contract as need be without opening the containment area. The ultimate layout of the silt curtains is shown on Figure 3.1.

Silt curtains will be in place continuously throughout the active dredging operations at the West and East Basins. If a silt curtain enclosure requires relocation as the dredges move around the project area it will not be opened during repositioning. Barges servicing the dredges will remain outside the silt curtain enclosure, and their overflow water will be pumped into the enclosed work area.

As the project site is exposed to tidal currents at the upper operational range of typical silt curtains, silt curtains corresponding to the US Department of Transportation Type III classification will be deployed. For this study, specifications corresponding to Abasco Type III Turbidity Curtains have been used, however the specifications for Type III curtains are largely similar between manufacturers. These silt curtains are constructed from high strength geotextile fabric, with surface floatation and tension cables running above and below the floatation foam and chain running along the bottom of the curtain to provide weighting and tension capacity. The properties of the simulated silt curtains are summarized in Table 3-1 and the impact of ambient current velocity on the effective depth of the silt curtains is plotted on Figure 3.2. On Figure 3.2, the 7 m draft silt curtain is highlighted in red, with alternate drafts with the same floatation and ballast are plotted in gray. When the varying silt curtain drafts are compared, it is

apparent that as the ambient current velocity rises, the effective draft of the various silt curtains tends to converge due to flare.

Table 3-1: Relevant Silt Curtain Specifications, Abasco Type III Turbidity Curtain

Parameter	Manufacturer's Specification	Model Input	Notes
Fabric	woven/non-woven filter fabric	N/A	Assumed impervious
Flotation	8" to 12" diameter EPS foam	74.1 kg/m	12" diameter, ρ_{foam} 50 kg/m^3
Top Tension	2x 5/16" steel cable	N/A	Top and middle tension included in model
Bottom Tension	1x 3/8" steel chain	N/A	Bottom tension included in model
Ballast	1x 3/8" steel chain,1.41 lb/ft	2.1 kg/m	
Draft	up to 100 ft	7.0 m	AECOM specification

4.0 SEDIMENT SOURCE TERMS

4.1 Background Suspended Sediment Concentration

The primary source of background suspended sediment concentration in Vancouver Harbour is widely cited as the North Arm of the Fraser River (Davidson 1973, Feely and Lamb 1979, Thomson 1981). A combination of flood currents and the hydraulic head of the river drive a layer of silty fresh water from the North Arm northwards along the edge pf Point Grey, then eastward along the southern shore of English Bay. During certain tidal and wind conditions, this near-surface brackish water can be drawn through First Narrows and into Vancouver Harbour; however the intense tidal mixing of the Narrows mixes out much of the initial stratification. There is, however a general lack of information on background suspended sediment concentrations that result from the influx of brackish water into Vancouver Harbour.

The best source of recent information is a report by Tetra Tech in which turbidity on the western side of Canada Place was monitored continuously from December 2004 to July 2007 (Tetra Tech 2007). Turbidity measured in Nephelometric Turbidity Units (NTU) was monitored at depths of 1.0 m and 4.5 m by YSI 6600EDS-M multi parameter sondes. In general, low turbidity values were recorded throughout the year. Average annual turbidity was 1.6 NTU at 1 m depth and 2.0 NTU at 4.5 m depth. Turbidity levels occasionally (approximately once per month) peaked to between 10 NTU and 20 NTU for a period of less than a day, with the maximum recorded turbidity over the monitoring period of approximately 25 NTU. While these spikes have not been attributed to a specific cause, they do show that there is naturally a factor of 10 range in turbidity in Vancouver Harbour. Turbidity values increased slightly during spring and late summer phytoplankton blooms.

4.2 Sediment Characteristics

The in situ sediments from the west and east dredge basins were characterised using data adapted from the Klohn Crippen Berger (KCB 2016a) site investigation report. Cone Penetrating Tests (CPT) and borehole samples collected from within the west and east basin footprints yielded eighteen samples at varying depths. To characterize the sediments of the dredge basins into particle size bins that could be applied within the numerical model, the sand, silt and clay fractions of the east and west basins were determined and are presented in Table 4-1. As there is considerable variation in the relative proportions of sand, silt and clay between samples, the sample from each basin with the highest fines content was selected to represent the entire basin, to generate a conservative sediment source term. For the west dredge basin, this is a fines (silt and clay) content of 56.6% and for the east basin this is a fines content of 19.8%.

Table 4-1: Summary of Grain Size Classification

East Basin					
Sediment Class		**Maximum**	**Minimum**	**Mean**	**Most Fines[1]**
> 2000µm	gravel	83.7%	2.0%	37.2%	2.0%
62µm - 2000µm	sand	88.6%	14.1%	56.4%	78.2%
4µm - 62µm	silt	9.5%	0.7%	4.5%	9.5%
< 4µm	clay	10.3%	0.0%	1.9%	10.3%
West Basin					
Sediment Class		**Maximum**	**Minimum**	**Mean**	**Most Fines[1]**
> 2000µm	gravel	71.5%	0.4%	15.5%	2.4%
62µm - 2000µm	sand	82.8%	27.9%	60.7%	40.9%
4µm - 62µm	silt	42.0%	0.6%	17.8%	35.2%
< 4µm	clay	22.4%	0.0%	6.0%	21.4%

[1] Applied in model

Table 4-2 presents the d_{85}, d_{50} and d_{15} for each of the sand, silt and clay sediment classes determined from the four sediment samples that had a full particle size analysis of fines fraction. As the number of samples is limited and there is little variation in size between them, an averaged value across the four samples was applied at the three dredge basins. In situ sediments have a specific gravity of 2.74 and a solid fraction of 0.485 (KCB 2016b).

For simulating the dispersal of fugitive fine sediment, three sediment classes were defined: sand, silt and clay. The relative proportions of each class were prescribed in the modelling based on the sediment fractions presented in Table 4-1. The specific grain sizes associated with each sediment class were applied based on the particle size information summarized in Table 4-2.

Table 4-2: Summary of Particle Size Distribution

Clay					
Diameter Percentile	**East Basin**	**West Basin**			**Mean[1]**
	DH15-03	DH15-05, 4.7m	DH15-05, 8.5m	DH15-09	
d_{85}, µm	1.14	1.35	2.66	1.40	1.64
d_{50}, µm	0.67	0.79	1.08	0.82	0.84
d_{15}, µm	0.20	0.24	0.32	0.25	0.25
Silt					
Diameter Percentile	**East Basin**	**West Basin**			**Mean[1]**
	DH15-03	DH15-05, 4.7m	DH15-05, 8.5m	DH15-09	
d_{85}, µm	51.5	47.2	51.9	54.6	51.3
d_{50}, µm	20.9	19.1	25.2	31.4	24.2
d_{15}, µm	6.7	5.5	8.0	7.3	6.9
Sand					
Diameter Percentile	**East Basin**	**West Basin**			**Mean[1]**
	DH15-03	DH15-05, 4.7m	DH15-05, 8.5m	DH15-09	
d_{85}, µm	382	251	288	147	267
d_{50}, µm	194	149	118	109	142
d_{15}, µm	104	94	74	72	86

[1] Applied in model

4.3 Sediment Release

The loss rate of sediments from a clamshell dredge is less well defined than for other dredge types, therefore, the loss rate of dredgeate was calculated based on values cited in literature. The loss rate from clamshell dredging largely depends on the operational conditions of the dredge itself, for example, the descent and ascent rate of the bucket, the style of bucket and the swing rate of the dredge arm. Without more detailed information regarding the characteristics of the clamshell dredge to be employed at the CEP, the loss rate from the clamshell has been conservatively estimated as 2%, based on a range of 1% to 2% found in literature (Collins 1995; Hayes et al. 2007; Bridges et al. 2008). The suspended sediment release cloud is generally considered evenly distributed over the water column, though some studies place the volume distribution of the sediment as 40% near bed 30% mid-depth and 30% surface (Lackey et al. 2012). For simplicity, sediment is assumed to be evenly distributed over the volume of water that the dredge bucket passes through, as presented in Table 4-3 below.

An important consideration in clamshell dredging is that the clamshell bucket will not be completely filled with dredgeate. Each seabed material and bucket style has an associated efficiency, with a certain proportion of the bucket filled with dredgeate and the rest, with seawater. The fill efficiency of common clamshell buckets is estimated as 83% for fines, 80% for loose sand and 77% for compact sand, meaning that, for a given bucket volume, approximately 80% of the bucket contains seabed material (including voids) and approximately 20% is seawater (Hayes et al. 2007). Based on local experience, methods and equipment, the 8 m^3 environmental bucket has an anticipated fill factor of 65% and the 26m^3 high capacity bucket has an anticipated fill factor of 60% (AECOM 2017).

In-situ seabed materials have an average solids fraction of 0.485. Therefore each clamshell scoop will transport, for the 8 m^3 and 26 m^3 buckets respectively, 2.52 m^3 and 7.57 m^3 of solids. The dredge buckets are assumed to lose 2% of their content before delivery to the barge, resulting in the fugitive sediment release of 0.050 m^3 and 0.151 m^3 of sediment solids per dredge cycle for the 8 m^3 and 26 m^3 buckets respectively. For each dredge location, the resulting release of each sediment fraction is summarized in Table 4-3.

The fugitive release of sediment during each dredge cycle results in an initial source TSS concentration ranging from 1,989 mg/L to 463 mg/L, as summarized in Table 4-3. The range of concentrations arises because of the range of depths over which dredging occurs, and the assumption that the released sediment is distributed over the water column, as described below. The initial dilution volume for the volumetric sediment input is assumed to be equal to the cylindrical volume of water the dredge bucket passes through as it is drawn through the water column. For the 8 m^3 dredge bucket, the diameter of this cylinder has been based on the dimensions of a Ransome YC7000 dredge bucket, while the 26 m^3 dredge bucket dimensions have been interpreted from a variety of 2 and 4 rope clamshell dredge buckets. An additional 0.5 m radial allowance is assumed for the lateral release of slurry from the bucket. The initial source TSS concentration varies from location to location with the depth of water column through which the dredge bucket is pulled. The essential logic underlying this is that any dredgeate that could be mobilized by travel through the water column (i.e. isn't sheltered by larger grains) will be flushed from the bucket relatively quickly compared to the travel time of the bucket from the seabed to the surface. Therefore, for each dredge cycle, the same volume of dredgeate is released, with the initial concentration consequently depending on the water depth via the dilution volume. While it is likely that the blow-off volume has a relationship with the depth of water the bucket is pulled through, in the absence of appropriate literature or data to support a depth dependant blow-off rate, the conservative assumption of a depth-independent blow off rate has been made.

Dredging operations are expected to proceed 24 hours per day with 2 hours per day allocated to maintenance downtime and 10 hours per day spent re-positioning the dredge, resulting in 12 hours per day of effective working time. Dredges operating with an 8 m^3 environmental bucket are estimated to have a 120 second cycle time (i.e. the time between successive bucket grabs), while dredges operating with a 26m^3 high capacity bucket have an estimated 150 second cycle time. Based on an assumed schedule and efficiency, one clamshell dredge with one attending hopper barge has a 1,900 m^3/day production volume (seabed dredged per day) if an 8 m^3 dredge bucket is used, compared to a production volume of 4,500m^3/day if a 26 m^3 dredge bucket is employed. Similarly, two clamshell dredges with one attending hopper barge each have a combined production rate of 3,800 m^3/day of seabed with 8m^3 dredge buckets, or 9,000 m^3/day with 26 m^3 dredge buckets. Based on these production rates, the total dredge operation duration is estimated in Table 4-4.

To derive a worst-case sediment TSS concentration, numerical model simulations have been conducted with continuous dredge operation until the completion, such that the total volume of fugitive material is released in as

short a time as possible. The simulations were run until the total volume of fugitive material given in Table 4-4 has been released.

Table 4-3: Summary of Dredge Operation

	Parameter	Navigation	West Basin	East Basin	Unit	Notes
Sediment	Void Ratio	1.0625	1.0625	1.0625	-	KCB Report, 2016
	Porosity	0.515	0.515	0.515	-	η = e/(1+e)
	Solids Fraction	0.485	0.485	0.485		SF = 1 - n
	Specific Gravity	2.74	2.74	2.74	-	KCB Report, 2016
	Sand Fraction	0.434	0.434	0.576	-	KCB Report, 2016
	Silt Fraction	0.352	0.352	0.301	-	KCB Report, 2016
	Clay Fraction	0.214	0.214	0.103	-	KCB Report, 2016
Clam Shell Dredge	Cycle Time	120	150	150	s	Time between bottom grabs
	Bucket Size	8	26	26	m^3	
	Efficiency	0.65	0.60	0.60	-	Factor for partially filled bucket
	Effective Volume	5.20	15.60	15.60	m^3/cycle	Dredgeate per cycle, total
	Solids Volume	2.52	7.57	7.57	m^3/cycle	Dredgeate per cycle, solids
	Loss Rate	0.02	0.02	0.02	-	Portion of dredgeate lost per cycle
	Fugitive Solids	0.05	0.151	0.151	m^3/cycle	Solids volume lost per cycle
	Fugitive Sand	0.022	0.066	0.087	m^3/cycle	Sand volume lost per cycle
	Fugitive Silt	0.018	0.053	0.046	m^3/cycle	Silt volume lost per cycle
	Fugitive Clay	0.011	0.032	0.016	m^3/cycle	Clay volume lost per cycle
Source Strength	Zone Radius	2.3	3.1		m	Based on dredge bucket size
	Depth	Min: 9.0 m Max: 11.5 m	Min: 6.9 m Max: 29.6 m		m	Based on depth in dredge cut
	Volume	Min: 150 m^3 Max: 191m^3	Min: 208 m^3 Max: 894 m^3		m^3	Volume dredge passes through
	TSS Conc.	913 / 717	1,989 / 463	1,989 / 463	mg/L	Max/Min TSS concentration
	Sand Conc.	402 / 316	869 / 202	1,146 / 267	mg/L	Max/Min sand concentration
	Silt Conc.	329 / 258	698 /162	619 / 144	mg/L	Max/Min silt concentration
	Clay Conc.	201 / 158	422 / 98	224 / 52	mg/L	Max/Min clay concentration

Table 4-4: Summary of Dredge Volume, Release Volume and Dredge Operation Duration

	Dredge Prism	8 m^3 Dredge[1]	26 m^3 Dredge[2]	Total Solids	Fugitive Release	Duration 1 Dredge[3]	Duration 2 Dredge[3]
	m^3	m^3	m^3	m^3	m^3	days	days
Navigation	7,000	7,000	0	3,786	76	4	2
West Basin	235,000	33,300	201,700	113,975	2,280	63	31
East Basin	155,000	15,000	124,700	75,175	1,504	36	16
Total	**397,000**	**55,300**	**335,400**	**192,936**	**3,860**	**103**	**49**

[1] Surficial sediments

[2] Deep sediments.

[3] Based on nominal 4,500 m^3/day production volume for a 26 m^3 dredge bucket, 1,900 m^3/day production for a 8 m^3 dredge bucket (AECOM 2017).

5.0 RESULTS

5.1 West Basin Dredge Zone

The West Basin Dredge Zone consists of an approximately 235,000 m^3 dredge prism. Surficial sediments will be dredged using an 8 m^3 clamshell dredge, with the vast majority of dredging to be undertaken with a 26 m^3 capacity clamshell dredge. The duration of dredging operations at the West Basin is anticipated to be 31 days (two dredges) to 63 days (one dredge), including down time and repositioning. Sediments released by an individual clamshell dredge operating at the West Basin Dredge Zone result in a source TSS concentration ranging from approximately 500 mg/L to 2,000 mg/L depending on the depth of the dredge cut (Section 4.3). Compared to both the Navigation and East Basin Dredge Zones, the West Basin Dredge Zone is relatively deep, exposed and well flushed.

Without mitigation (i.e. without a silt curtain in place), the TSS plume originating from dredging at the west basin is rapidly diluted and can be widely dispersed. In particular, during strong ebb tides fugitive project-derived sediment can occasionally be entrained into the First Narrows tidal jet. With mitigation (i.e. with a silt curtain in place), both the overall footprint and concentration of the TSS plume is reduced, although the plume itself tends to follow a similar dispersion pattern. Owing to strong tidal action at the West Basin Dredge Zone the TSS concentration crossing the 100 m boundary rises almost immediately with the commencement of dredging. However, because of the silt curtains retain TSS in a relatively contained area, it takes approximately 2 days for TSS concentrations to fall to baseline levels following the end of dredging, compared to approximately 12 hours without the silt curtains in place.

Figure 5.1 presents the fugitive sediment concentration at a 100 m distance from the active dredge zone for 1 and 2 active dredge scenarios. The upper panel presents a time series of the maximum depth-averaged TSS concentration along the 100 m boundary (i.e. the maximum of the depth-averaged TSS concentrations calculated in each model grid cell along the 100 m boundary). The upper-middle panel presents a time series of the average TSS concentration along the 100 m boundary. The middle-bottom panel presents the corresponding tidal elevation at Point Atkinson and the bottom panel presents the dredge source strength, summarized as a depth-averaged TSS concentration. The time series data presented in Figure 5.1, as well as data for the unmitigated case, is summarized in Table 5-1 for depth-averaged TSS concentrations. Table 5-1 presents the maximum and average depth-averaged TSS concentrations along with percentile values, including the percentile associated with 5 mg/L. The presence of the silt curtains serves to significantly reduce the TSS concentration reaching the 100 m threshold and reduces the average TSS concentration ("Average" row in Table 5-1) below 5 mg/L for both 1 and 2 dredge scenarios.

Table 5-1: West Basin, Depth-Averaged[1] Concentration 100 m from Source With and Without Silt Curtains

Percentile Along 100m Boundary[2]	No Silt Curtain		7 m Silt Curtain		Unit
	1 Dredge	2 Dredges	1 Dredge	2 Dredges	
99	19.72	40.22	5.50	11.54	mg/L
95	11.04	23.36	3.62	7.69	mg/L
90	7.80	16.54	2.91	6.13	mg/L
50	1.70	3.41	1.19	2.47	mg/L
10	0.16	0.34	0.40	0.84	mg/L
5 mg/L Percentile	**80.2**	**61.6**	**98.6**	**83.9**	**-**
Maximum[3] at 100m	**60.90**	**139.40**	**19.30**	**34.46**	**mg/L**
Average[4] at 100m	**2.99**	**6.22**	**1.44**	**3.02**	**mg/L**

[1] Average is defined as the depth-averaged TSS concentration, reported at 15 minute intervals, within each 25 m by 25 m grid cell along the 100 m initial dilution boundary.

[2] Percentile values are calculated from the depth-averaged TSS concentration. For example, the 99th percentile is the depth-averaged TSS concentration greater than 99% of all other possible depth-averaged TSS concentrations occurring in time and space. Concentrations exceeding the 99th percentile will occur for only 7 hours and 30 minutes out of a 31 day dredging period.

[3] Maximum is the maximum recorded depth-averaged TSS concentration along the 100 m initial dilution boundary and occurs for less than 15 minutes out of the 31 day dredging period.

[4] Average is a 30 day moving average of the depth-averaged TSS concentration along the 100 m initial dilution boundary and represents the global 30 day average of concentration on this 100 m threshold.

The probability that the above-background depth-averaged TSS concentration will exceed 5 mg/L over the duration of the dredging operation is presented on Figure 5.2 for one active dredge and Figure 5.3 for two active dredges. The top panel of Figures 5.2 and 5.3 presents a shaded probability map showing the probability that the depth-averaged TSS concentration at any one location will exceed 5 mg/L over the course of the dredging operation. This probability can be interpreted as the overall duration of 5 mg/L exceedance, with 1% indicating that 5 mg/L is exceeded for a total of 1% of the 31 day dredge operation, or 7 hours and 30 minutes. The bottom panel of Figures 5.2 and 5.3 presents a histogram of depth-averaged TSS concentration along the 100 m boundary plotted in red in the upper panel. This histogram displays the probability (y-axis) of a given depth-averaged TSS concentration (x-axis) occurring along the 100 m boundary. The vertical red line show the 5 mg/L exceedance threshold, the green vertical line shows the average TSS concentration over the dredging operation and the dashed and dotted black vertical lines show the 95th percentile and maximum depth-averaged TSS concentrations, respectively.

The largest probability of the depth-averaged TSS concentration exceeding 5 mg/L is highly concentrated in the vicinity of the active dredge zone, with very modest excursions outside of the 100 m boundary, as can be seen on lower panels of Figures 5.2 and 5.3. With one active dredge, there is a 98.6% probability of depth-averaged TSS concentrations being below 5 mg/L at the 100 m boundary, while with two active dredges there is an 83.9% probability of depth-averaged TSS concentrations being below 5 mg/L at the 100 m boundary. The data plotted on Figures 5.2 and 5.3 is summarized in Table 5-2, which presents the distance to achieve a given probability of 5 mg/L exceedance, alongside matching data for the unmitigated case. Comparing the mitigated and unmitigated scenarios, the presence of the silt curtains reduces the maximum excursion length of the TSS plume by a factor of 3 to 5. With silt curtains in place, there is a maximum 30% probability that a depth-averaged TSS concentration exceeding 5 mg/L will be present outside of the 100 m boundary at any given time during the dredge operation with two active dredges and maximum 10% probability with a single active dredge.

Table 5-2: West Basin, Distance from Source to Achieve Depth-Averaged TSS Concentration of 5 mg/L With and Without Silt Curtains

Probability of Exceedance[1]	No Silt Curtain		7 m Silt Curtain		Unit
	1 Dredge	2 Dredges	1 Dredge	2 Dredges	
90%	Within 100 m Boundary	Within 100 m Boundary	Within 100 m Boundary	Within 100 m Boundary	m
80%					m
70%					m
60%					m
50%					m
40%					m
30%		275			m
20%	200	450		150	m
10%	375	675		175	m
1%	825	1,000	175	375	m

[1] The probability that the instantaneous depth-averaged TSS concentration will exceed 5 mg/L over the dredging period. For example, a 1% probability of exceeding 5 mg/L indicates that, over a 31 day dredging period, the depth-averaged TSS concentration may exceed 5 mg/L for a total of 7 hours and 30 minutes

5.2 East Basin Dredge Zone

The East Basin Dredge Zone consists of an approximately 155,000 m^3 dredge prism. Surficial sediments will be dredged using an 8 m^3 clamshell dredge, with the vast majority of dredging to be undertaken with a 26 m^3 clamshell dredge. The duration of dredging operations at the East Basin is anticipated to be 16 (two dredges) to 36 (one dredge) days including down time and repositioning. Sediments released by an individual clamshell dredge operating at the East Basin Dredge Zone result in a source TSS concentration ranging from approximately 500 mg/L to 2,000 mg/L depending on the specific location within the dredge cut (Section 4.3).

Dredging operations at the East Basin Dredge Zone are assumed to begin at the shore, near the Southern Railway Pier, and progress northwards along the eastern face of Ballantyne Pier. At the south end of the embayment formed by the Southern Railway and Ballantyne Piers there is relatively poor flushing and there is potential for the build-up of TSS, which is occasionally flushed by tidal action resulting in periodic spikes of TSS dispersing from the dredge area. As the dredging operation progresses northwards towards the north end of Ballantyne Pier, mixing improves and the TSS concentration exiting the dredge area drops significantly due to dilution.

Figure 5.3 presents the fugitive sediment concentration at a 100 m distance from the active dredge zone for 1 and 2 active dredge scenarios. The upper panel presents a time series of the maximum depth-averaged TSS concentration along the 100 m boundary (i.e. the maximum of the depth-averaged TSS concentrations calculated in each model grid cell along the 100 m boundary). The upper-middle panel presents a time series of the average TSS concentration along the 100 m boundary. The middle-bottom panel presents the corresponding tidal elevation at Point Atkinson and the bottom panel presents the dredge source strength, summarized as a depth-averaged TSS concentration. The time series data presented in Figure 5.4, as well as data for the unmitigated case, is summarized in Table 5-3 for depth-averaged TSS concentrations. Table 5-3 presents the absolute maximum and overall average depth-averaged TSS concentrations along with percentile values including the percentile associated with 5 mg/L.

Comparing the depth-averaged TSS concentrations in Table 5-3, silt curtains act to significantly reduce the depth-averaged TSS concentration exiting the 100 m boundary. The average TSS concentration, here taken as the average over the 16 day dredge period, is below 5 mg/L for both one and two active dredge scenarios ("average" row of Table 5-3). Comparing mitigated and unmitigated depth-averaged TSS concentrations in Table 5-3, however, it is apparent that the presence of silt curtains at the East Basin tends to increase the depth-averaged TSS concentration at lower concentrations (e.g. below the 50th percentile and well below 5 mg/L). This is because the silt curtains tend to contain the sediment plume and concentrate its release to near the seabed, which results in a comparatively thinner layer of suspended sediment with a more constant (i.e. lacking some of the large TSS peaks) concentration passing the 100 m boundary.

Table 5-3: East Basin, Depth-Averaged[1] Concentration 100 m from Source With and Without Silt Curtains

Percentile Along 100m Boundary[2]	No Silt Curtain		7 m Silt Curtain		Unit
	1 Dredge	2 Dredges	1 Dredge	2 Dredges	
99	17.18	30.06	5.79	12.16	mg/L
95	5.21	13.36	3.57	7.37	mg/L
90	1.91	8.31	2.75	5.66	mg/L
50	0.12	0.44	0.88	1.86	mg/L
10	0.02	0.13	0.20	0.43	mg/L
5 mg/L Percentile	**93.1**	**82.7**	**98.3**	**86.7**	**-**
Maximum[3] at 100m	**83.44**	**148.03**	**17.78**	**30.88**	**mg/L**
Average[4] at 100m	**1.80**	**3.61**	**1.25**	**2.58**	**mg/L**

[1] Average is defined as the depth-averaged TSS concentration, reported at 15 minute intervals, within each 25 m by 25 m grid cell along the 100 m initial dilution boundary.

[2] Percentile values are calculated from the depth-averaged TSS concentration. For example, the 99th percentile is the depth-averaged TSS concentration greater than 99% of all other possible depth-averaged TSS concentrations occurring in time and space Any concentrations greater than the 99th percentile will occur for only 3 hours and 50 minutes out of a 16 day dredging period.

[3] Maximum is the maximum recorded depth-averaged TSS concentration along the 100 m initial dilution boundary and occurs for less than 15 minutes out of the 16 day dredging period

[4] Average is taken over the 16 day dredge period.

The probability that the above-background depth-averaged TSS concentration will exceed 5 mg/L over the duration of the dredging operation is presented on Figure 5.5 for one active dredge and Figure 5.6 for two active dredges. The top panel of Figures 5.5 and 5.6 presents a shaded probability map showing the probability that the depth-averaged TSS concentration at any one location will exceed 5 mg/L over the course of the dredging operation. This probability can be interpreted as the overall duration of 5 mg/L exceedance, with 1% indicating that 5 mg/L is exceeded for a total of 1% of the 16 day dredge operation, or 3 hours and 50 minutes. The bottom panel of Figures 5.5 and 5.6 presents a histogram of depth-averaged TSS concentration along the 100 m boundary plotted in red in the upper panel. This histogram displays the probability (y-axis) of a given depth-averaged TSS concentration (x-axis) occurring along the 100 m boundary. The vertical red line show the 5 mg/L exceedance threshold, the green vertical line shows the average TSS concentration over the dredging operation and the dashed and dotted black vertical lines show the 95th percentile and maximum depth-averaged TSS concentrations, respectively.

The largest probability of the depth-averaged TSS concentration in the water column exceeding 5 mg/L is highly concentrated in the vicinity of the active dredge zone and the embayment between Ballantyne and Southern Railway Piers that was included within the southern silt curtain isolation area. With one active dredge, the TSS plume excursion outside of the 100 m boundary is very modest and the plume associated with two active dredges is largely confined to the immediate vicinity of the project area. With one active dredge, there a 98.3% probability of depth-averaged TSS concentrations below 5 mg/L at the 100 m boundary, while with two active dredges there is an 86.7% probability of depth-averaged TSS concentrations below 5 mg/L at the 100 m boundary. The data plotted on Figures 5.5 and 5.6 is summarized in Table 5-4, which presents the distance to achieve a given probability of 5 mg/L exceedance, alongside matching data for the unmitigated case. Comparing the mitigated and unmitigated scenarios, the presence of the silt curtains reduces the maximum excursion length of the TSS plume by a factor of 1.3 to 2.0. With silt curtains in place, there is a maximum 30% probability that a depth-averaged TSS concentration exceeding 5 mg/L will be present outside of the 100 m boundary at any given time during the dredge operation with two active dredges and maximum 20% probability with a single active dredge.

Table 5-4: Distance from Source to Achieve Depth-Averaged TSS Concentration of 5 mg/L With and Without Silt Curtains

Probability of Exceedance[1]	No Silt Curtain		7 m Silt Curtain		Unit
	1 Dredge	2 Dredges	1 Dredge	2 Dredges	
90%	Within 100 m Boundary	Within 100 m Boundary	Within 100 m Boundary	Within 100 m Boundary	m
80%					m
70%					m
60%					m
50%					m
40%		275			m
30%	150	300			m
20%	325	375		175	m
10%	600	650	125	400	m
1%	950	1,000	400	775	m

[1] The probability that the instantaneous depth-averaged TSS concentration will exceed 5 mg/L over the dredging period. For example, a 1% probability of exceeding 5 mg/L indicates that, over a 16 day dredging period, the depth-averaged TSS concentration may exceed 5 mg/L for a total of 3 hours and 50 minutes.

6.0 CONCLUSION

To quantify the release of fugitive (i.e. incidental) fine sediment arising from dredging activities at CEP, a three dimensional numerical model of Burrard Inlet was used to simulate the fate and behaviour of the fugitive sediment plume. Using this validated numerical model as a starting point, the dredging program was parameterized to generate a series of sediment sources that were introduced into the model to represent fugitive sediment releases. To help contain these sediment releases, silt curtains have been proposed for the West Basin and East Basin dredge operations. In this study, the effectiveness of these silt curtains in mitigating the release of suspended sediment has been investigated by including the proposed silt curtain containment in the numerical model.

The modelling approach represents a balance between conservatism and accurately representing the physical processes at work in the dredging operation and in Burrard Inlet as a whole. Conservatism enters the model through several assumptions related to the dredging operation:

- The dredging operation has been simulated as taking place 24 hours per day when, in fact, there is up to 12 hours per day of down time. This assumption does not give the suspended sediment concentration the chance to attenuate while the dredge is being repositioned or during crew changes. Therefore, the simulations presented in this report represent a worst-case dredging scenario.
- A sediment loss rate of 2% has been assumed for the clam shell dredges operating at CEP. Literature suggest that a loss rate of 1% to 2% is typical, which means an upper bound value has been used in this study.
- A great deal of effort has been put into accurately representing the deformation of the silt curtains in response to tidal currents. The results presented in this study include the deformation of the silt curtains due to currents and any potential loss of containment due to currents above the rated capacity of the silt curtains.

Based on the results of this modelling study, silt curtains are an effective means of reducing the depth-averaged TSS concentration arising from dredging activities at the western and eastern dredge prisms of CEP. At the West Basin, silt curtains serve to significantly reduce the average TSS concentration of TSS, resulting in a 30-day moving average TSS concentration below 5 mg/L, 100 m from the edge of the dredge prism. At the East Basin, silt curtains similarly serve to significantly reduce depth-averaged TSS concentrations, resulting in an average TSS concentration over the dredge period below 5 mg/L, 100 m from the edge of the dredge prism. The presence of silt curtains at the East Basin may slightly increase the low concentration (below 5 mg/L) depth-averaged TSS concentration by enhancing settling and concentrating TSS near the seabed.

7.0 CLOSURE

We trust this report meets your present requirements. If you have any questions or comments, please contact the undersigned.

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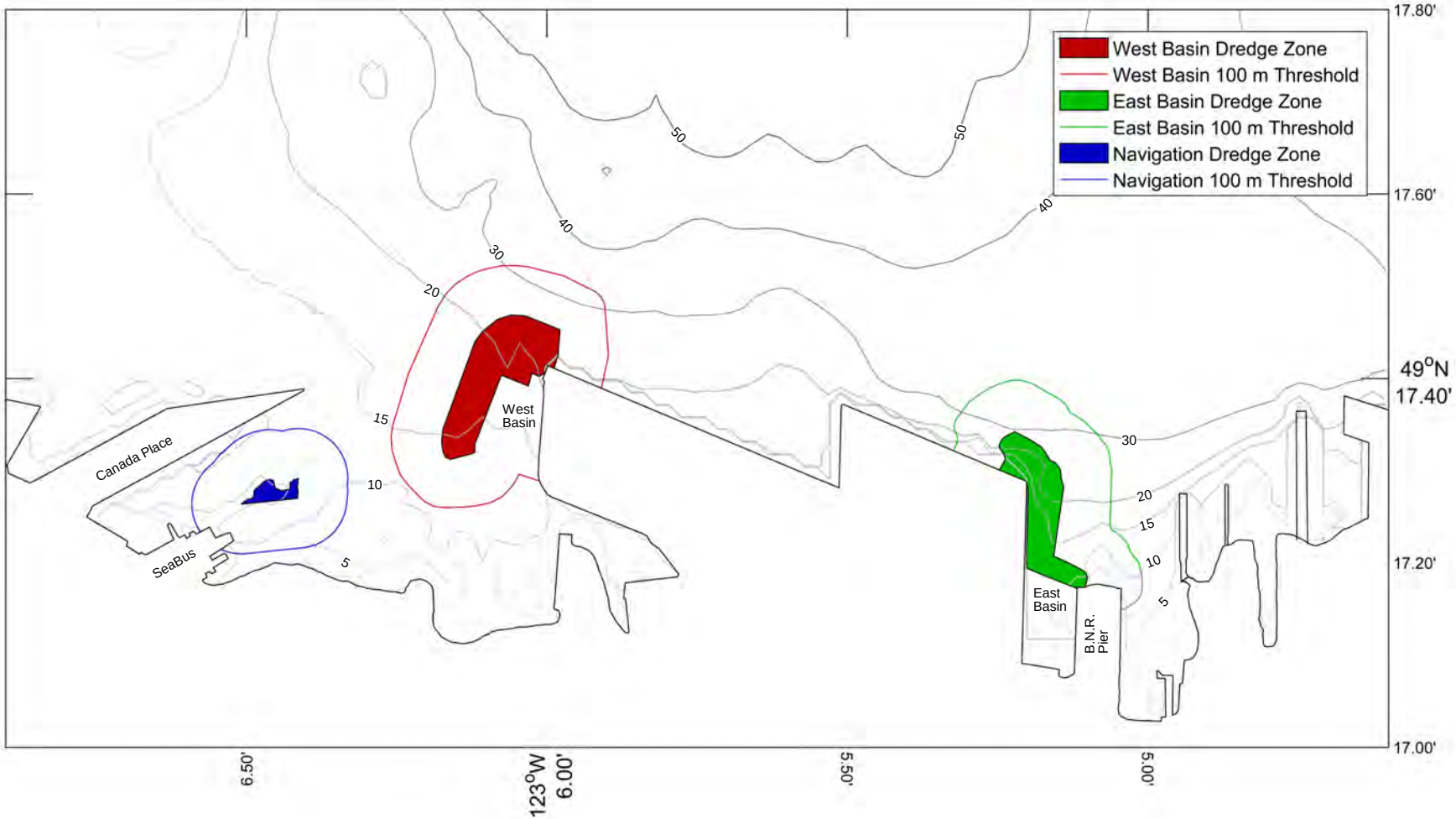
Yasui, A., Deguchi, I., Ono, M., 1999. “Performance of Silt Protector in Three Dimensional Flow”. Proceedings 9th International Offshore and Polar Engineering Conference, Brest, France.

FIGURES



NOTES

Dredge prism outlines and 100 m radius boundaries are plotted in the above figure.

STATUS
ISSUED FOR REVIEW

CLIENT

AECOM

TETRA TECH

Numerical Modelling of Silt Curtain Performance

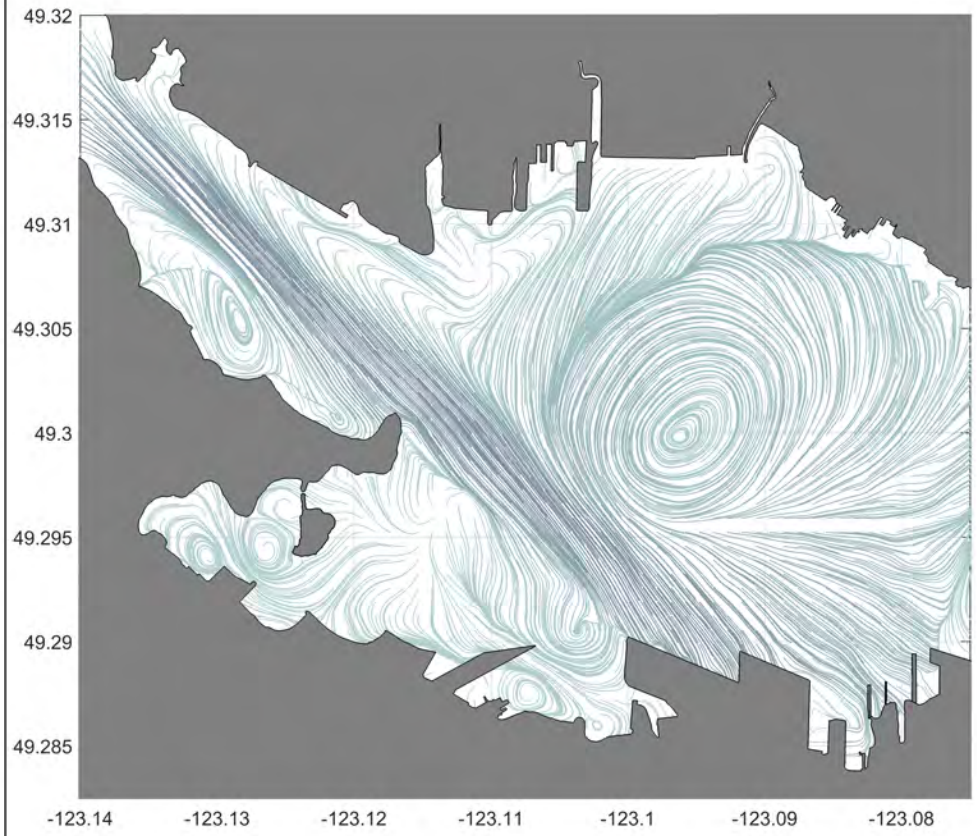
CEP Dredge Zone Overview

PROJECT NO.	DWN	CKD	APVD	REV
WTRM.03017	JM	JM	JAS	0

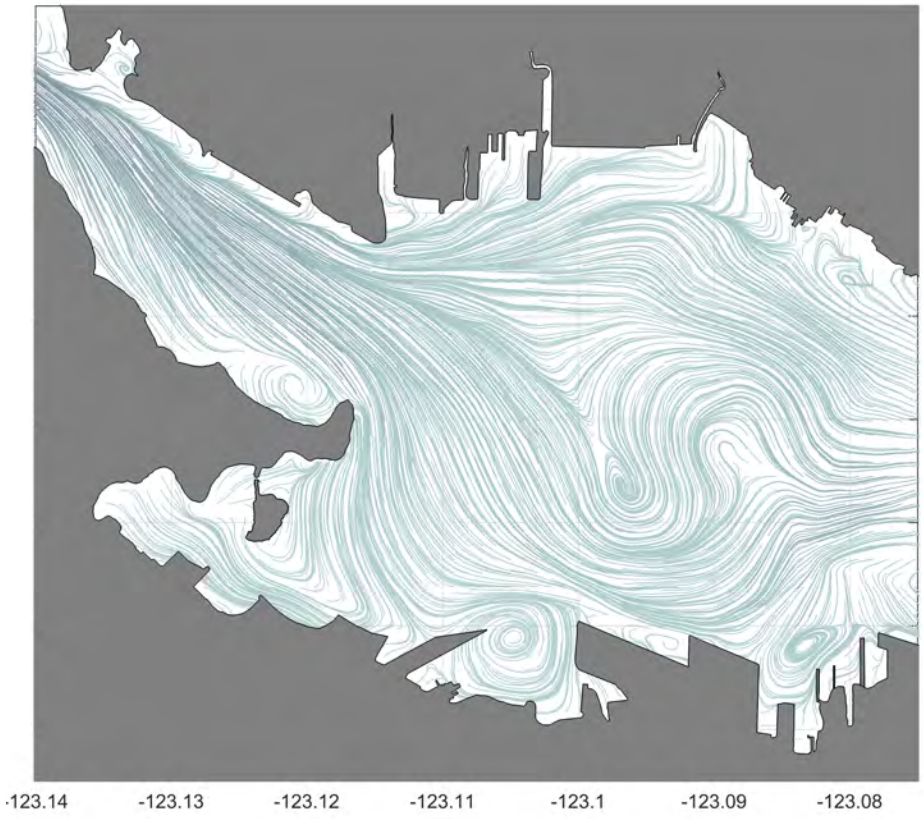
OFFICE	DATE
Tetra Tech EBA - VANC	August, 2017

Figure 1.1

Flood Tide



Ebb Tide



NOTES

Flow fields are presented for the existing Centerm geometry using Tetra Tech's 25-m resolution numeical model of Burrard Inlet.
Flow fields are visualized at peak flood and ebb flow during a moderate tide.

STATUS
ISSUED FOR USE

CLIENT

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Numerical Modelling of Silt Curtain Performance

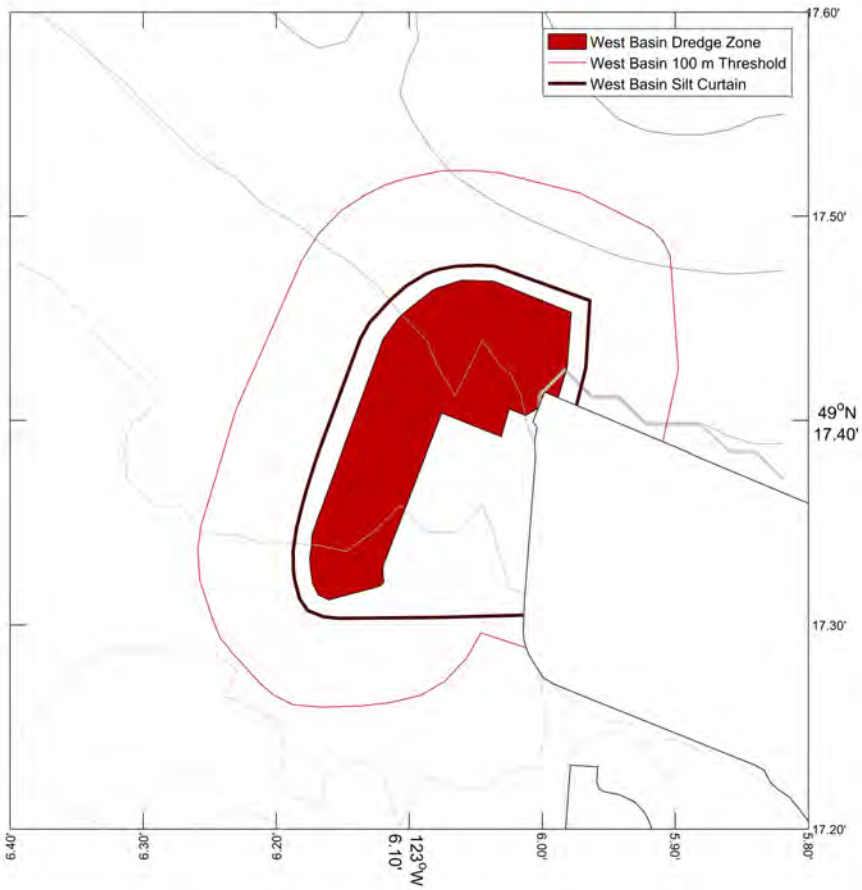
Flow Fields in Western Vancouver Harbour

PROJECT NO.	DWN	CKD	APVD	REV
WTRM.03017	JM	JM	JAS	0

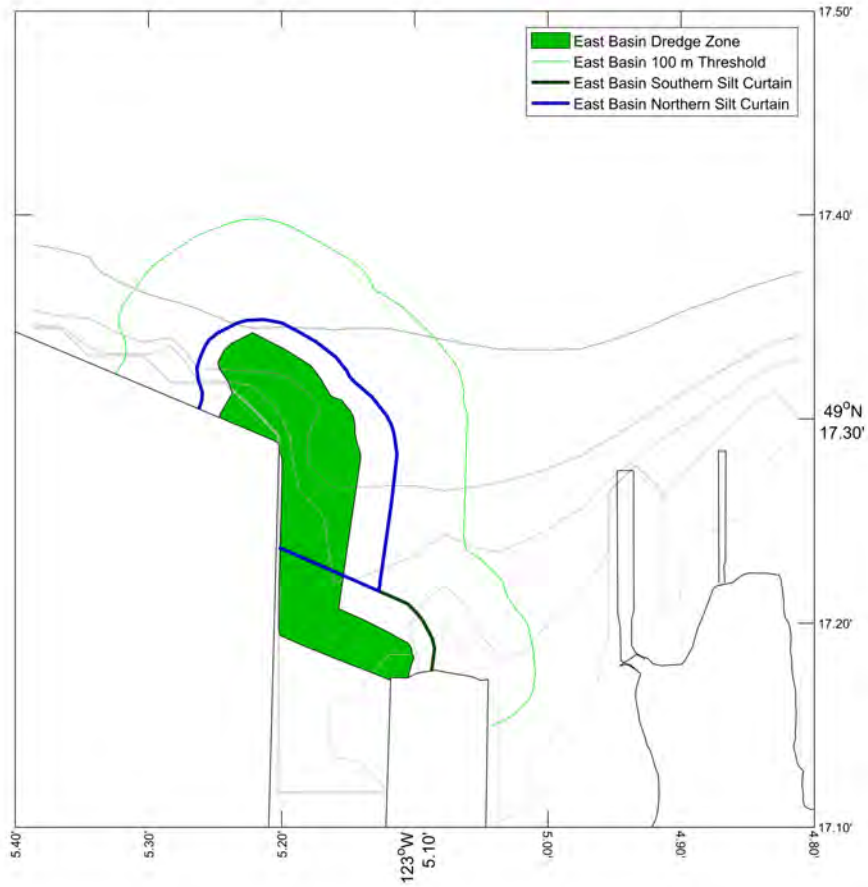
OFFICE	DATE
Tetra Tech EBA - VANC	August, 2017

Figure 2.1

West Basin Silt Curtain Arrangement



East Basin Silt Curtain Arrangement



NOTES

Dredge prism outlines, silt curtains and 100 m radius boundaries are plotted in the above figures.

STATUS
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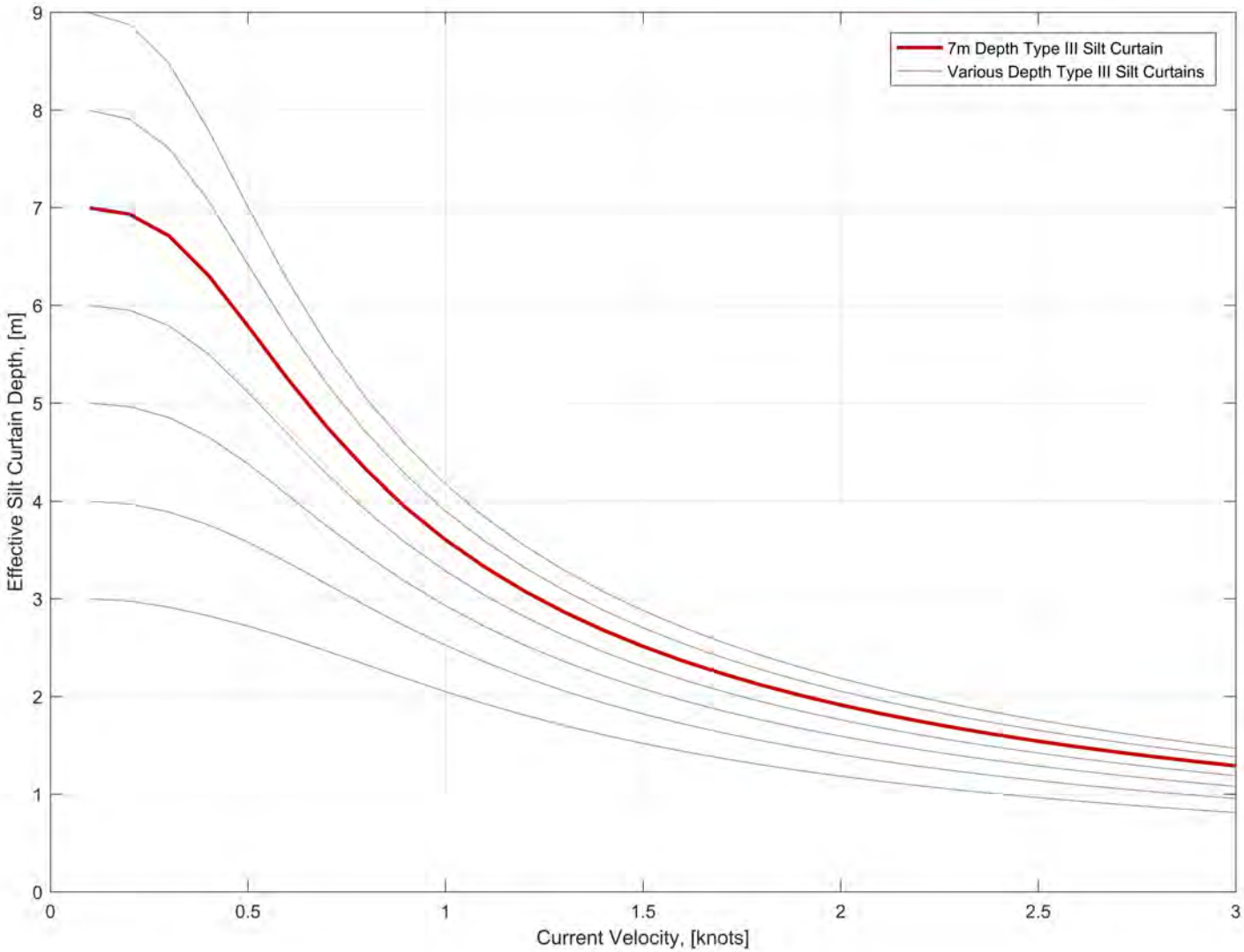
Numerical Modelling of Silt Curtain Performance

Arrangement of East and West Basin Silt Curtains

PROJECT NO.	DWN	CKD	APVD	REV
WTRM.03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech EBA - VANC	August, 2017

Figure 3.1



NOTES

Type III Silt Curtain Specifications:

Fabric:	woven/non-woven filter fabric
Flotation:	12" diameter EPS foam, 74.1 kg/m of floatation
Top Tension:	2 x 5/16" steel cable, above and below floatation
Bottom Tension:	3/8" steel chain
Ballast:	3/8" steel chain, 2.1 kg/m
Draft:	7.0 m

STATUS
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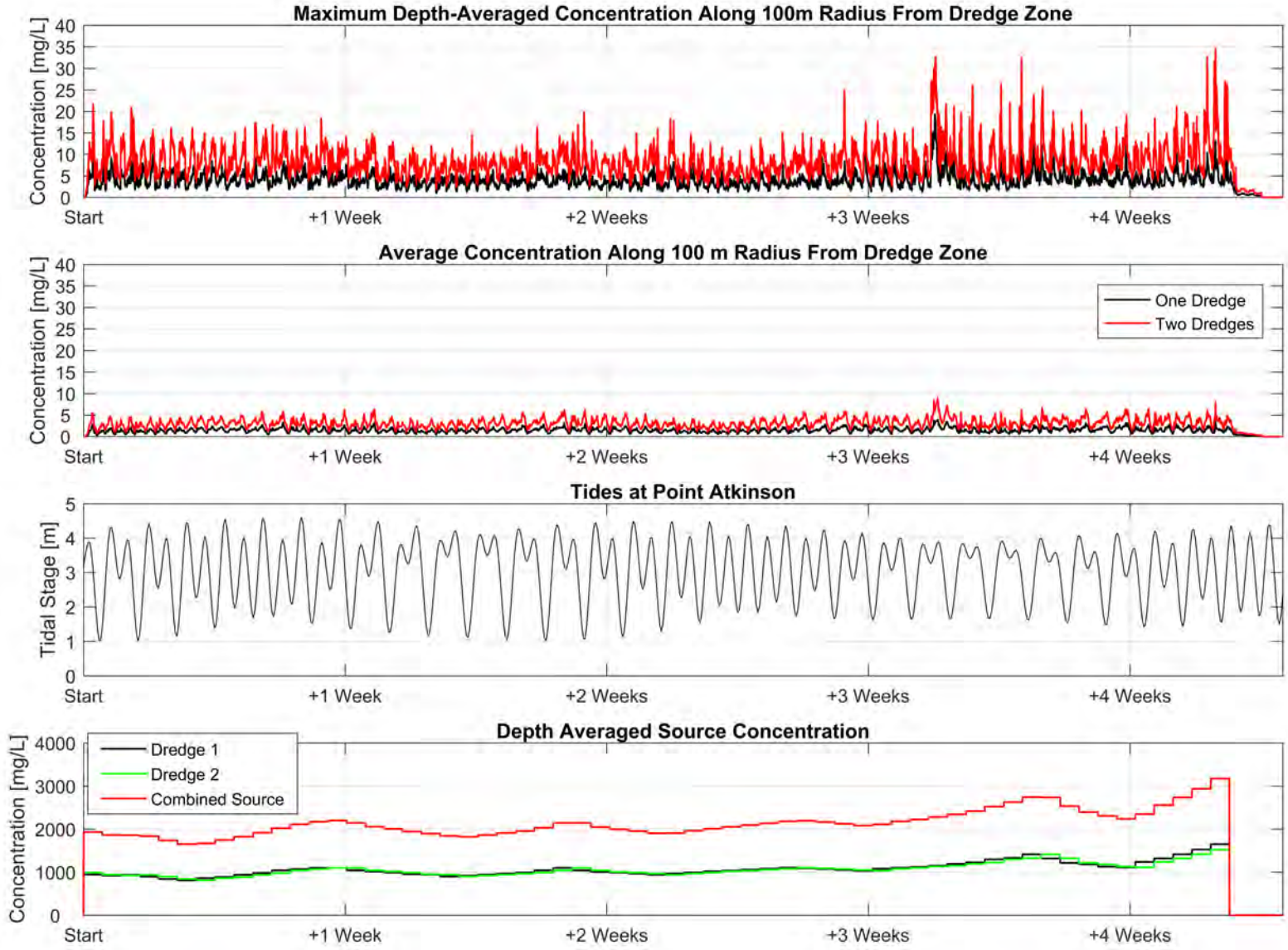
Numerical Modelling of Silt Curtain Performance

Performance of Type III Silt Curtain in Response to Currents

PROJECT NO.	DWN	CKD	APVD	REV
WTRM.03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech EBA - VANC	August, 2017

Figure 3.2



NOTES

1) Maximum depth-averaged concentration is the maximum of the depth-averaged concentration (seabed to surface) along the 100 m boundary.
2) Average concentration is the average concentration along the 100 m boundary.
3) The y-axis scale for the Source Concentration plot differs from that of the concentration time series plots.
4) Source concentration varies in time due to depth variations between dredge locations and tidal action.

STATUS
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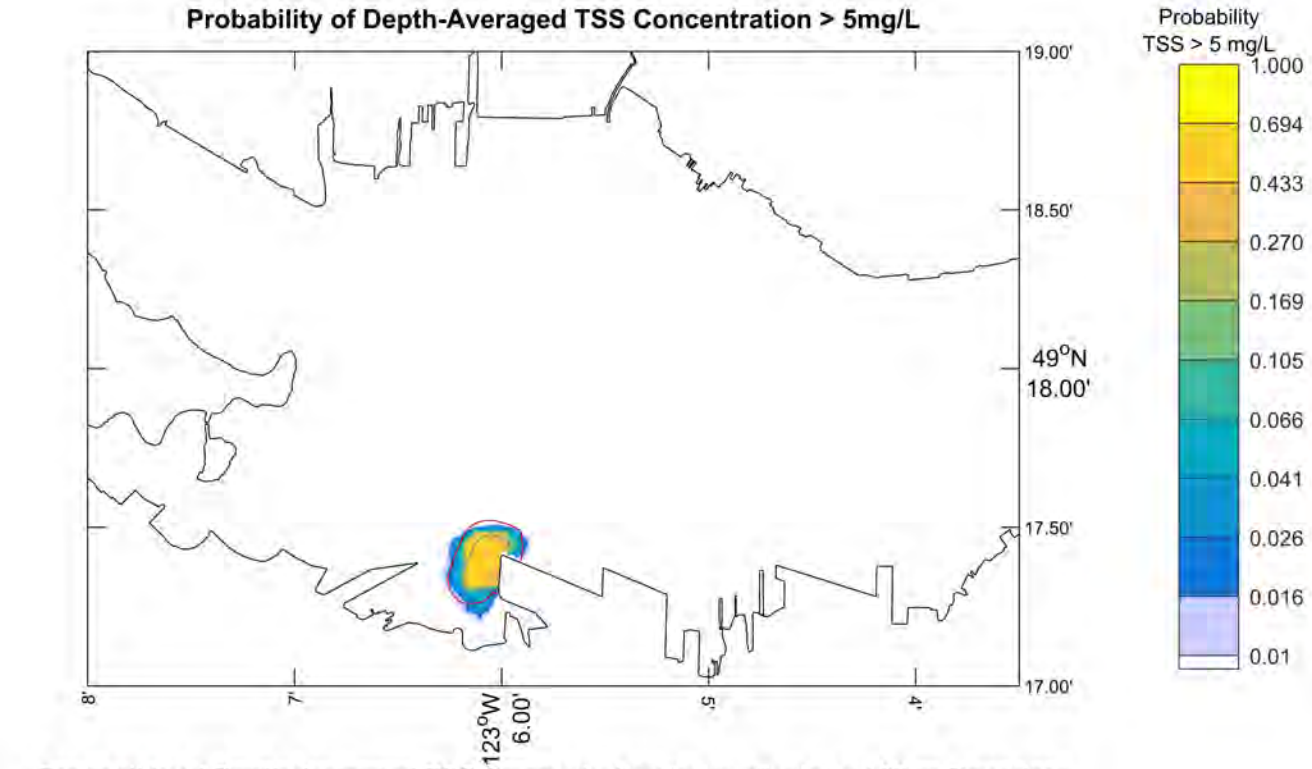
Numerical Modelling of Silt Curtain Performance

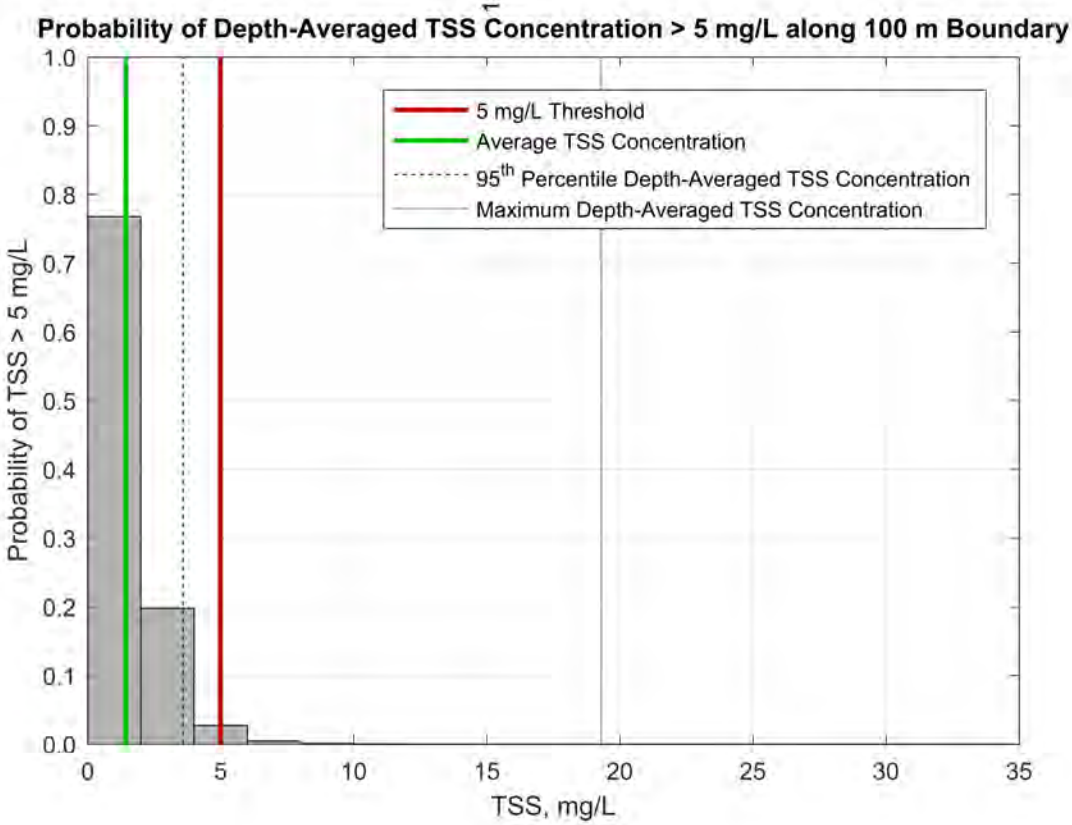
West Basin Dredge Zone TSS Source Attenuation With Silt Curtain Mitigation

PROJECT NO.	DWN	CKD	APVD	REV
WTRM.03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech EBA - VANC	September, 2017

Figure 5.1





NOTES

1) Probability is calculated over the full dredge period and is determined from 15 minute model data.
2) All concentrations are the depth averaged concentration over the water column (seabed to surface) at a given location.

100 m Initial Dilution Zone
Silt Curtain Containment Area

STATUS
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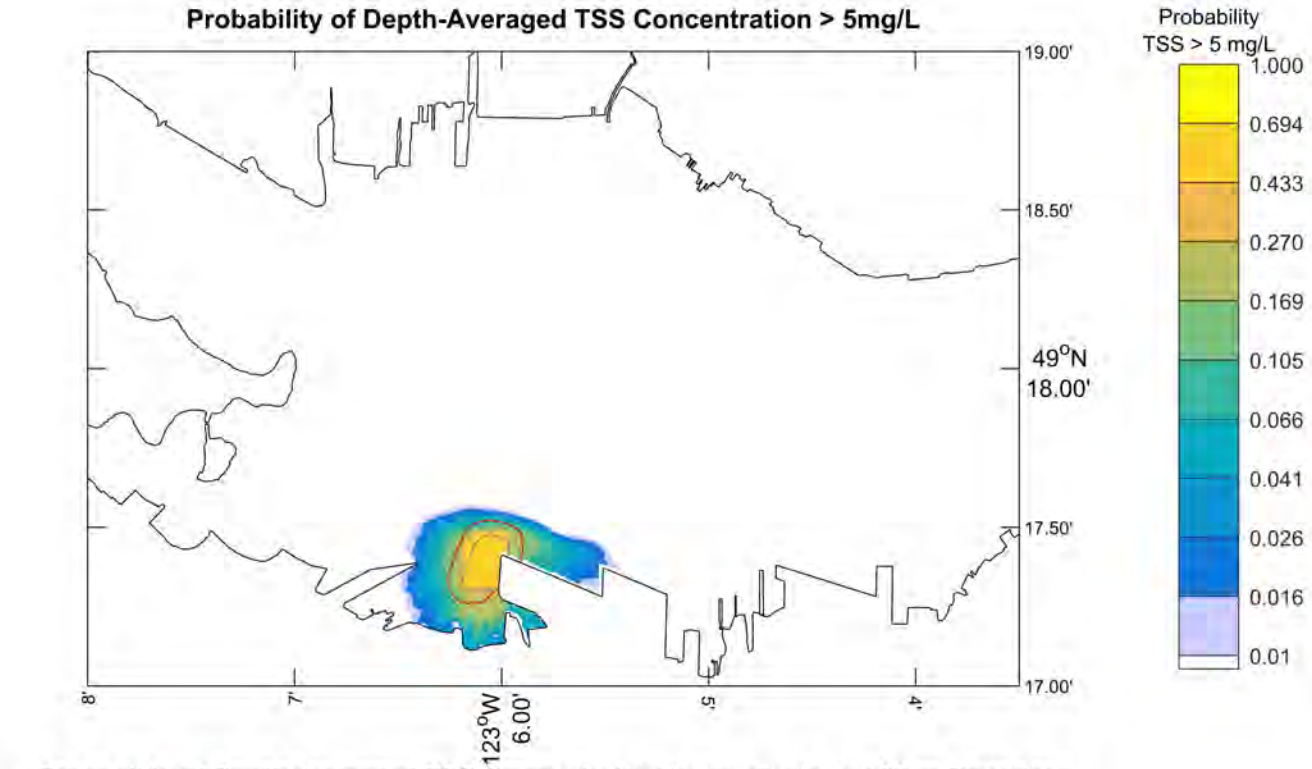
Dispersal Modelling of Silt Curtain Performance

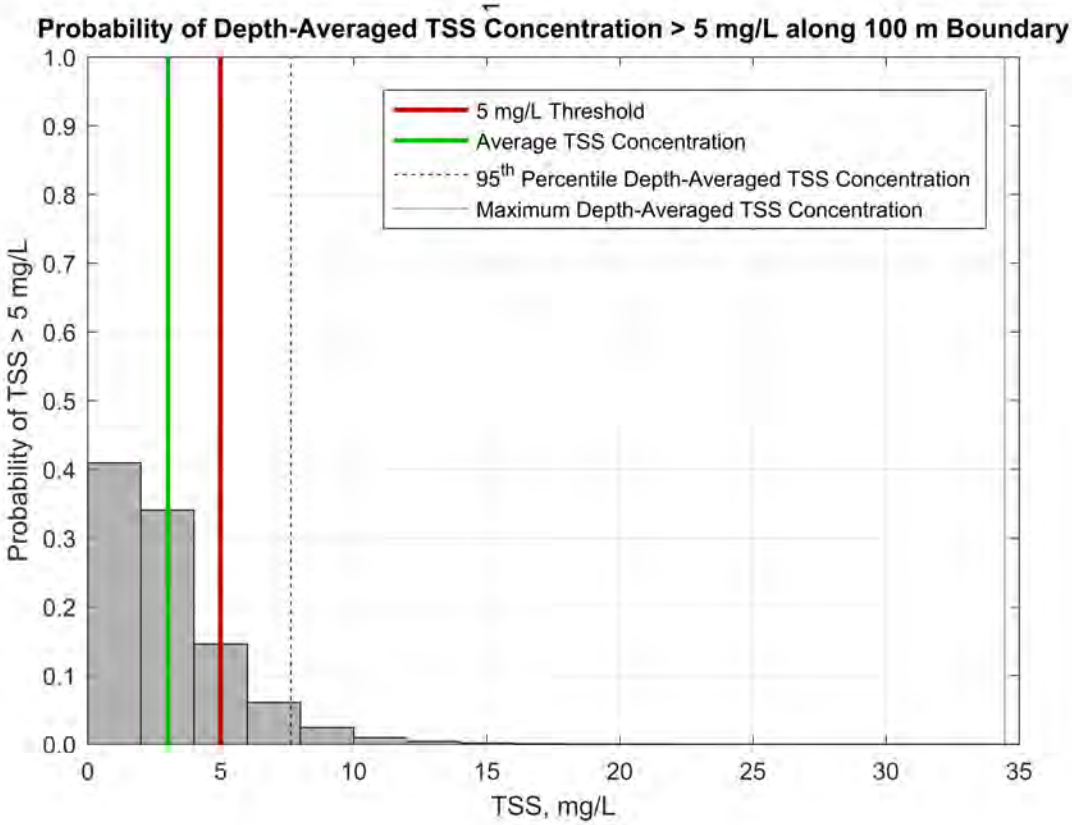
West Basin, One Dredge Probability of Depth-Averaged TSS Concentration Exceeding 5 mg/L

PROJECT NO.	DWN	CKD	APVD	REV
WTRM03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech EBA - VANC	Septmeber, 2017

Figure 5.2





NOTES

1) Probability is calculated over the full dredge period and is determined from 15 minute model data.
2) All concentrations are the depth averaged concentration over the water column (seabed to surface) at a given location.

100 m Initial Dilution Zone
Silt Curtain Containment Area

STATUS
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CLIENT

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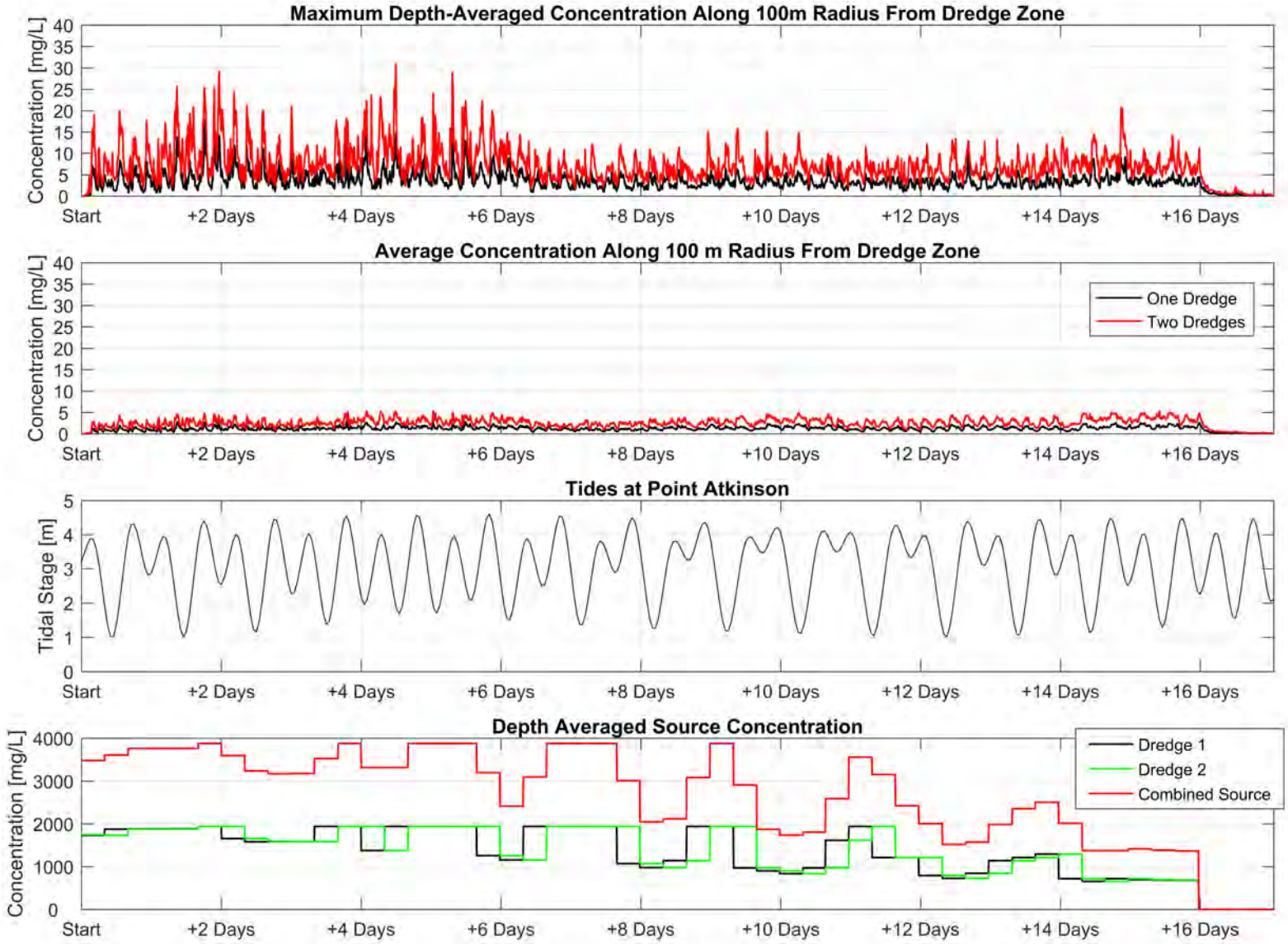
Dispersal Modelling of Silt Curtain Performance

West Basin, Two Dredges Probability of Depth-Averaged TSS Concentration Exceeding 5 mg/L

PROJECT NO.	DWN	CKD	APVD	REV
WTRM03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech EBA - VANC	September, 2017

Figure 5.3



NOTES

1) Maximum depth-averaged concentration is the maximum of the depth-averaged concentration (seabed to surface) along the 100 m boundary.
2) Average concentration is the average concentration along the 100 m boundary.
3) The y-axis scale for the Source Concentration plot differs from that of the concentration time series plots.
4) Source concentration varies in time due to depth variations between dredge locations and tidal action.

STATUS
ISSUED FOR USE

CLIENT

AECOM

TETRA TECH

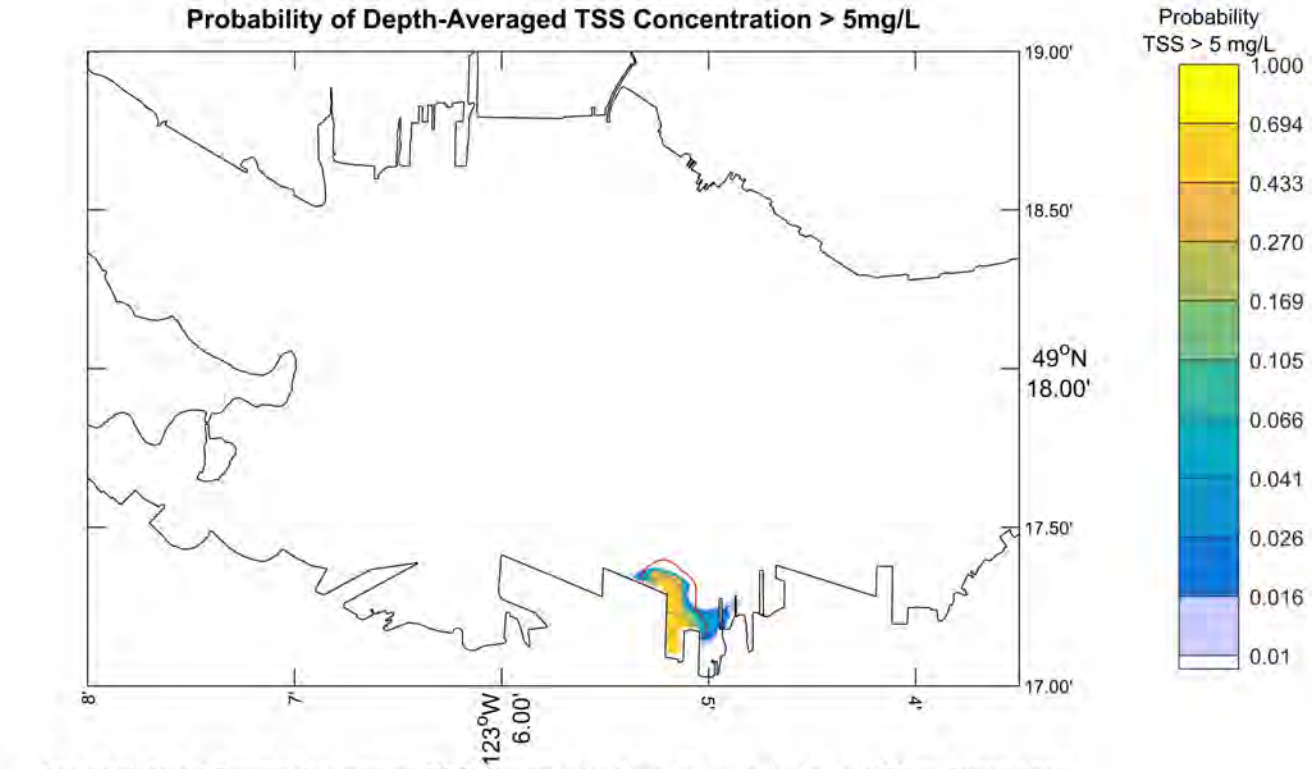
Numerical Modelling of Silt Curtain Performance

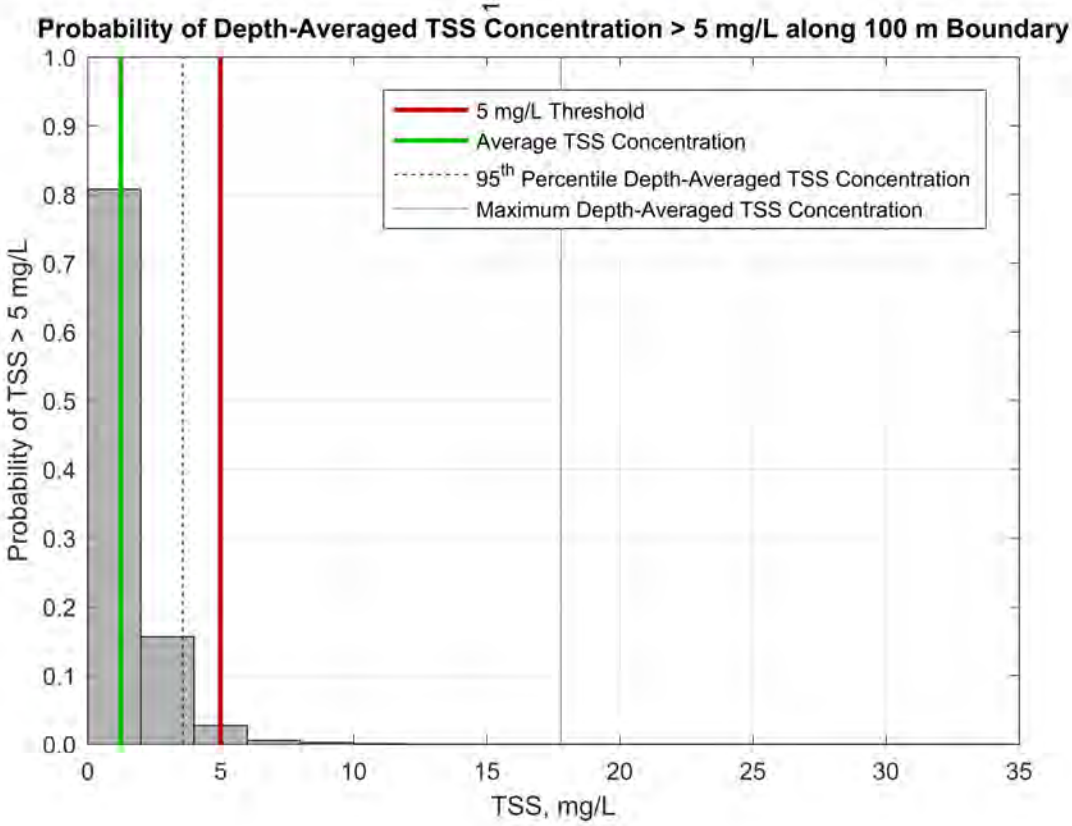
East Basin Dredge Zone TSS Source Attenuation With Silt Curtain Mitigation

PROJECT NO.	DWN	CKD	APVD	REV
WTRM.03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech EBA - VANC	September, 2017

Figure 5.4





NOTES

1) Probability is calculated over the full dredge period and is determined from 15 minute model data.
2) All concentrations are the depth averaged concentration over the water column (seabed to surface) at a given location.

100 m Initial Dilution Zone
Silt Curtain Containment Area

STATUS
ISSUED FOR USE

CLIENT

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TETRA TECH

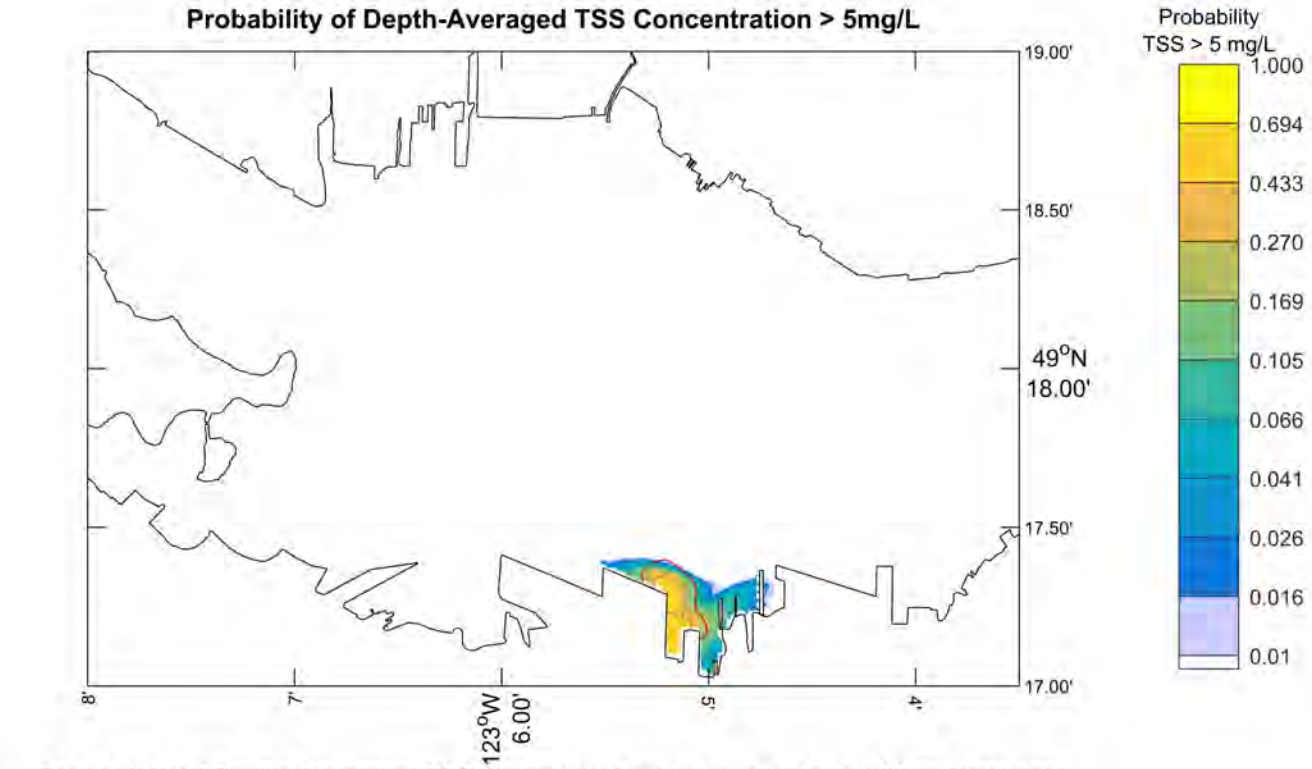
Dispersal Modelling of Silt Curtain Performance

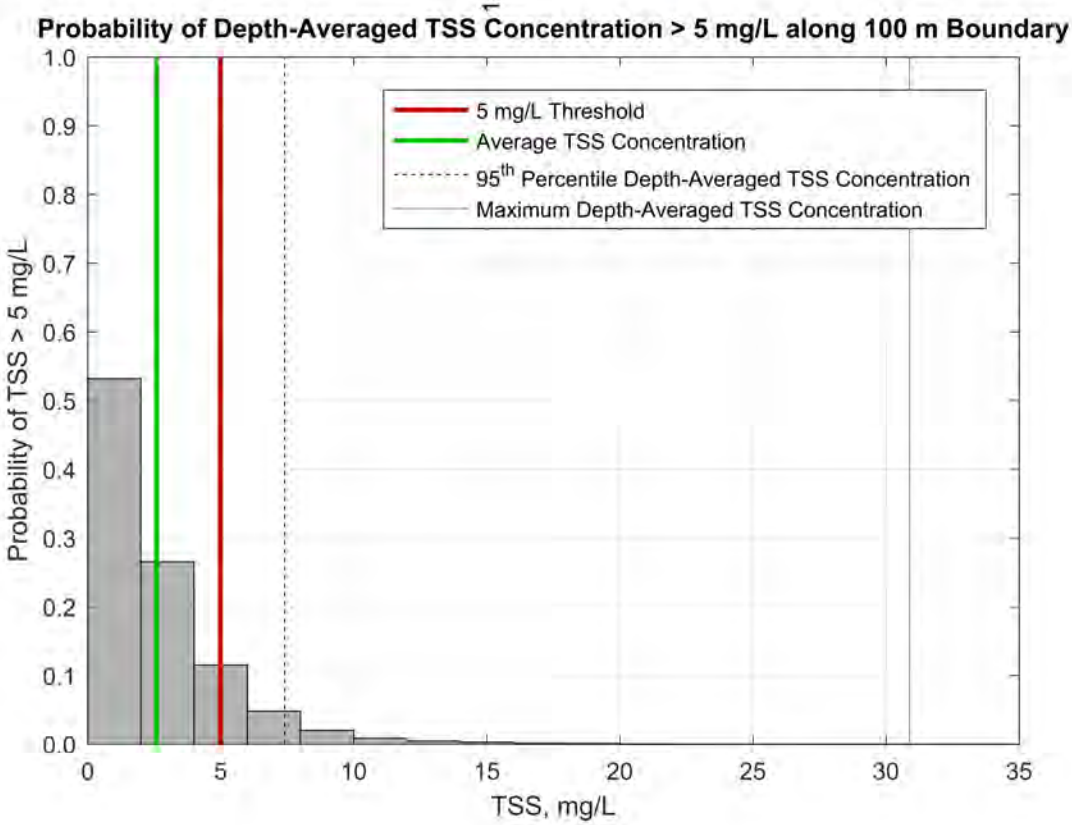
East Basin, One Dredge Probability of Depth-Averaged TSS Concentration Exceeding 5 mg/L

PROJECT NO.	DWN	CKD	APVD	REV
WTRM03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech EBA - VANC	September, 2017

Figure 5.5





NOTES

1) Probability is calculated over the full dredge period and is determined from 15 minute model data.
2) All concentrations are the depth averaged concentration over the water column (seabed to surface) at a given location.

100 m Initial Dilution Zone
Silt Curtain Containment Area

STATUS
ISSUED FOR USE

CLIENT

AECOM

TETRA TECH

Dispersal Modelling of Silt Curtain Performance

East Basin, Two Dredges Probability of Depth-Averaged TSS Concentration Exceeding 5 mg/L

PROJECT NO.	DWN	CKD	APVD	REV
WTRM03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech EBA - VANC	September, 2017

Figure 5.6

APPENDIX A

TETRA TECH'S GENERAL CONDITIONS

GENERAL CONDITIONS

HYDROTECHNICAL

This report incorporates and is subject to these “General Conditions”.

1.0 USE OF REPORTS AND OWNERSHIP

This report pertains to a specific site, a specific development, and a specific scope of work. The report may include plans, drawings, profiles and other supporting documents that collectively constitute the report (the “Report”).

The Report is intended for the sole use of Tetra Tech EBA’s Client (the “Client”) as specifically identified in the Tetra Tech EBA Services Agreement or other Contract entered into with the Client (either of which is termed the “Services Agreement” herein). Tetra Tech EBA does not accept any responsibility for the accuracy of any of the data, analyses, recommendations or other contents of the Report when it is used or relied upon by any party other than the Client, unless authorized in writing by Tetra Tech EBA.

Any unauthorized use of the Report is at the sole risk of the user. Tetra Tech EBA accepts no responsibility whatsoever for any loss or damage where such loss or damage is alleged to be or, is in fact, caused by the unauthorized use of the Report.

Where Tetra Tech EBA has expressly authorized the use of the Report by a third party (an “Authorized Party”), consideration for such authorization is the Authorized Party’s acceptance of these General Conditions as well as any limitations on liability contained in the Services Agreement with the Client (all of which is collectively termed the “Limitations on Liability”). The Authorized Party should carefully review both these General Conditions and the Services Agreement prior to making any use of the Report. Any use made of the Report by an Authorized Party constitutes the Authorized Party’s express acceptance of, and agreement to, the Limitations on Liability.

The Report and any other form or type of data or documents generated by Tetra Tech EBA during the performance of the work are Tetra Tech EBA’s professional work product and shall remain the copyright property of Tetra Tech EBA.

The Report is subject to copyright and shall not be reproduced either wholly or in part without the prior, written permission of Tetra Tech EBA. Additional copies of the Report, if required, may be obtained upon request.

2.0 ALTERNATIVE REPORT FORMAT

Where Tetra Tech EBA submits both electronic file and hard copy versions of the Report or any drawings or other project-related documents and deliverables (collectively termed Tetra Tech EBA’s “Instruments of Professional Service”), only the signed and/or sealed versions shall be considered final. The original signed and/or sealed version archived by Tetra Tech EBA shall be deemed to be the original. Tetra Tech EBA will archive the original signed and/or sealed version for a maximum period of 10 years.

Both electronic file and hard copy versions of Tetra Tech EBA’s Instruments of Professional Service shall not, under any circumstances, be altered by any party except Tetra Tech EBA. Tetra Tech EBA’s Instruments of Professional Service will be used only and exactly as submitted by Tetra Tech EBA.

Electronic files submitted by Tetra Tech EBA have been prepared and submitted using specific software and hardware systems. Tetra Tech EBA makes no representation about the compatibility of these files with the Client’s current or future software and hardware systems.

3.0 STANDARD OF CARE

Services performed by Tetra Tech EBA for the Report have been conducted in accordance with the Services Agreement, in a manner consistent with the level of skill ordinarily exercised by members of the profession currently practicing under similar conditions in the jurisdiction in which the services are provided. Professional judgment has been applied in developing the conclusions and/or recommendations provided in this Report. No warranty or guarantee, express or implied, is made concerning the test results, comments, recommendations, or any other portion of the Report.

If any error or omission is detected by the Client or an Authorized Party, the error or omission must be immediately brought to the attention of Tetra Tech EBA.

4.0 ENVIRONMENTAL AND REGULATORY ISSUES

Unless expressly agreed to in the Services Agreement, Tetra Tech EBA was not retained to investigate, address or consider, and has not investigated, addressed or considered any environmental or regulatory issues associated with the project.

5.0 DISCLOSURE OF INFORMATION BY CLIENT

The Client acknowledges that it has fully cooperated with Tetra Tech EBA with respect to the provision of all available information on the past, present, and proposed conditions on the site, including historical information respecting the use of the site. The Client further acknowledges that in order for Tetra Tech EBA to properly provide the services contracted for in the Services Agreement, Tetra Tech EBA has relied upon the Client with respect to both the full disclosure and accuracy of any such information.

6.0 INFORMATION PROVIDED TO TETRA TECH EBA BY OTHERS

During the performance of the work and the preparation of this Report, Tetra Tech EBA may have relied on information provided by persons other than the Client.

While Tetra Tech EBA endeavours to verify the accuracy of such information, Tetra Tech EBA accepts no responsibility for the accuracy or the reliability of such information even where inaccurate or unreliable information impacts any recommendations, design or other deliverables and causes the Client or an Authorized Party loss or damage.

7.0 GENERAL LIMITATIONS OF REPORT

This Report is based solely on the conditions present and the data available to Tetra Tech EBA at the time the Report was prepared.

The Client, and any Authorized Party, acknowledges that the Report is based on limited data and that the conclusions, opinions, and recommendations contained in the Report are the result of the application of professional judgment to such limited data.

The Report is not applicable to any other sites, nor should it be relied upon for types of development other than those to which it refers. Any variation from the site conditions present at or the development proposed as of the date of the Report requires a supplementary investigation and assessment.

It is incumbent upon the Client and any Authorized Party, to be knowledgeable of the level of risk that has been incorporated into the project design, in consideration of the level of the hydrotechnical information that was reasonably acquired to facilitate completion of the design.

The Client acknowledges that Tetra Tech EBA is neither qualified to, nor is it making, any recommendations with respect to the purchase, sale, investment or development of the property, the decisions on which are the sole responsibility of the Client.

8.0 JOB SITE SAFETY

Tetra Tech EBA is only responsible for the activities of its employees on the job site and was not and will not be responsible for the supervision of any other persons whatsoever. The presence of Tetra Tech EBA personnel on site shall not be construed in any way to relieve the Client or any other persons on site from their responsibility for job site safety.

Appendix C Centerm Expansion Project: Deposition Thickness of Dredging Derived Fugitive Sediment

TETRA TECH

TECHNICAL MEMO

ISSUED FOR USE

To:	Bruce Ford	**Date:**	September 1, 2017
c:	Neil Snowball, Jim Stronach	**Memo No.:**	4
From:	Jordan Matthieu	**File:**	704-WTR.WTRM03017
Subject:	Depositional Thickness of Dredging Derived Fugitive Sediment		

1.0 INTRODUCTION

AECOM Canada (AECOM) previously retained Tetra Tech Canada Inc. (Tetra Tech) to quantify the release and dispersion of fugitive sediments arising from dredging three sites over the course of the Centerm Expansion Project (CEP) and infilling of two land reclamation areas (Tetra Tech 2017a, 2017b). In this follow up study, AECOM has retained Tetra Tech to estimate the depositional thickness of fugitive sediment arising from the excavation of the three dredging sites.

CEP consists of an expansion of the existing Centerm Container Terminal located on the southern shoreline of Vancouver Harbour. The project will consist of two fill expansions to the existing terminal footprint: a westward expansion of approximately 4.2 ha and an eastward expansion of approximately 4 ha. Prior to the construction of perimeter rock dykes and infilling, unstable marine sediments must be removed via dredging. Over the course of CEP additional navigational dredging will take place to the south east of the western expansion to provide a turning basin for ships calling at the East Canada Place cruise ship berth.

This study presents the depositional thickness of fugitive sediment arising from clamshell dredging operations at the West Basin Dredge Zone, East Basin Dredge Zone and the Navigational Dredge Zone. Dredging will take place using either one clamshell dredge working alone or two clamshell dredges working simultaneously. The entirety of the Navigational Dredge Zone and the surficial sediments of both the East and West Dredge Zones will be dredged with an 8 m^3 capacity environmental dredge bucket. Following removal of surficial sediments at the East and West Dredge Zones, dredging will continue with a 26 m^3 capacity dredge bucket.

The fate and behaviour of the project-derived fugitive sediments has been simulated using an extensively validated three-dimensional numerical model of Vancouver Harbour for a parameterized dredging schedule based on a conceptual plan for dredging, which may be modified by the contractor during the final design stage. The predicted depositional thickness of fugitive sediments reported here reflect unmitigated conditions, with no consideration of mitigation by avoidance of critical tide conditions, or use of silt containment measures.

2.0 METHODS

2.1 Numerical Model

The primary numerical model employed in this study is a 25-m resolution three-dimension numerical model encompassing Burrard Inlet from west of First Narrows to east of Second Narrows. This model is the highest resolution model in a series of nested numerical models extending from the Pacific Ocean to the upper end of Indian Arm:

- **Coarse Resolution:** 1-km resolution shelf model extending from the mouth of Juan de Fuca Strait to the southern end of Texada Island and the terminus of Indian Arm. The model is driven by tidal constituents and monthly climatology at its boundaries with hourly wind fields and daily river inflows at 13 significant rivers.

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- **Mid-Resolution:** 125-m resolution Burrard Inlet model extending from the entrance to English Bay to the terminus of Indian Arm. The model is driven by water level, temperature and salinity data from the coarse resolution model, with hourly wind fields and daily river inflows.
- **High Resolution:** 25-m resolution Burrard Inlet model extending from the mid-point of English Bay (near Jericho Beach) to east of Second Narrows (near Berry Point), driven by water level, temperature and salinity data from the mid-resolution model, with hourly wind fields and daily river inflows.

Within the modelling chain, all major rivers in the Salish Sea are included, with Lynne Creek, the Seymour River and the Capilano River feeding directly in the high resolution Burrard Inlet model. Wind fields are interpolated from measured winds at buoys and meteorological stations around coastal British Columbia, with winds for the high resolution Burrard Inlet model based on a dedicated CALMET wind model. Fugitive sediment arising from dredging operations is introduced into the model via a conservatively estimated sediment loss rate specific to clam shell buckets. The 25-m resolution model is of sufficient resolution that the near-field (i.e. at a spatial scale smaller than the 25-m grid size) sediment dynamics related to the clam shell dredging operation do not require dedicated simulation to resolve the resulting fugitive sediment dynamics. For each dredging location, the simulation period has been determined based on the dredge prism volume and the estimated production rate of the dredge(s).

A more complete description of the numerical models used in this study can be found in Tetra Tech's 2017 report *Centerm Expansion Project: Dispersal Modelling of Dredging-Derived Fugitive Sediment* (Tetra Tech 2017a).

2.2 Depositional Footprint Determination

Dredging at the three active dredge sites of the CEP will be undertaken with either one clamshell dredge loading a hopper barge or two clamshell dredges simultaneously loading the same hopper barge. It is assumed that the barge will not overflow supernatant dredge water (AECOM 2016, 2017). The three dredge zones are displayed on Figure 1, with the Navigation Dredge Zone in blue, the West Basin Dredge Zone in red and East Basin Dredge Zone in green. Around each Dredge Zone, a dilution zone extending 100 m from the edge of the dredge prism is shown. These dilution zones are used later in this report to determine the depositional thickness of fugitive sediment outside of the active project area. In all cases the depositional thickness is presented in millimeters over the pre-project seabed and over the complete dredging operation (e.g. West Basin dredging), which is defined as the start of dredging to the point at which the maximum project derived above background TSS concentration drops below 5 mg/L. Depositional thicknesses at given distances from the dredging source are relative to the 100 m dilution zones presented on Figure 1, rather than the dredge prism or dredge vessel(s).

A complete description of the sediment characteristics, fugitive sediment release rates and the behaviour of the dredging derived sediment plumes can be found in Tetra Tech's 2017 report *Centerm Expansion Project: Dispersal Modelling of Dredging-Derived Fugitive Sediment* (Tetra Tech 2017a).

3.0 DEPOSITIONAL THICKNESS

The depositional footprint of fugitive sediments is generally small and is of limited spatial extent. The depositional patterns largely match those of the most common (highest probability) TSS plume trajectories shown in Tetra Tech 2017a, but with a much smaller overall extent. The depositional footprint outside of the 100 m dilution boundary never exceeds 10 mm.

Figure 2 presents the deposited thickness of fugitive sediments following the dredging operation at the West Basin. The maximum deposited thickness outside of the 100 m dilution boundary is 4.1 mm and 7.9 mm for one and two active dredge cases, respectively. The depositional footprint of fugitive sediment following East Basin dredging, shown on Figure 3, is comparatively smaller than at the West Basin; however, the maximum deposited thickness is similar for both the one and two dredge cases at 5.8 mm and 6.6 mm, respectively. The depositional footprint of fugitive sediments from the Navigation Basin, shown on Figure 4, does not extend outside of the 100 m dilution zone at a thickness greater than 1 mm. Over the complete dredging operation, presented on Figure 5, the maximum depositional thickness does not increase significantly beyond the maximum thickness of each individual dredging

operation. This is because there is not a significant overlap in the depositional footprints associated with the three dredging operations.

Table 1 summarizes the depositional thickness of fugitive sediments at different radii from the 100 m dilution zones for West, East and Navigation Basin dredging, as well as the combined footprint of all three dredging activities. From this table, it is apparent that the depositional thicknesses associated with one and two dredge cases quickly converge to within a fraction of a millimetre at all dredge locations. This is because the total volume of fugitive sediment released during either the one or two dredge case is the same, since the total dredge volume is identical. Therefore, outside of the near field variations due to differences in dredge placement that can be seen at the 100 m dilution boundary, there is little reason for variation in the far field depositional thickness between the one and two dredge cases. The larger variation in depositional thickness at the 100 m boundary for the West Basin, as compared to the East and Navigation Basins, is attributable to the more intense tidal currents at this site: the slower release of fugitive sediment during excavation with a single dredge results in better TSS dilution and lower deposition.

Table 1 also provides a summary of the percentage of the fugitive sediment that settles outside of either of the three 100 m dilution boundaries. Over the total dredging operation, 28% to 30% of the total fugitive sediment volume settles outside the boundaries of the three dredge basins with the remaining sediment either settled within the dilution boundaries or flushed out of Vancouver Harbour. At the Navigation Basin, which is the most quiescent of the three sites, only 8% to 9% of the fugitive sediment settles outside of the 100 m dilution boundary. At the comparatively more exposed East Basin, approximately 27% of the fugitive sediment settles outside of the 100 m dilution boundary, while at the most exposed West Basin 29% to 33% of the fugitive sediment settles outside of this boundary.

Table 1: Summary of Fugitive Sediment Depositional Thickness

Distance from 100m Boundary	West Basin Deposition [mm]		East Basin Deposition [mm]		Navigation Basin Deposition [mm]		Total Dredging Deposition [mm]	
	1 Dredge	2 Dredges	1 Dredge	2 Dredges	1 Dredge	2 Dredges	1 Dredge	2 Dredges
0	4.1	7.9	5.8	6.6	0.5	0.5	6.1	8.1
100	2.5	2.5	3.2	3.4	0.1	0.1	2.9	3.2
200	1.6	1.6	1.5	1.5	<0.1	<0.1	1.9	1.9
300	1.2	1.1	0.9	0.9	<0.1	<0.1	1.5	1.5
400	0.9	0.9	0.8	0.8	<0.1	<0.1	0.9	0.8
500	0.8	0.7	0.6	0.6	<0.1	<0.1	0.7	0.7
600	0.6	0.6	0.4	0.4	<0.1	<0.1	0.6	0.6
700	0.5	0.6	0.3	0.3	<0.1	<0.1	0.5	0.6
800	0.5	0.5	0.2	0.3	<0.1	<0.1	0.4	0.5
900	0.4	0.4	0.2	0.3	<0.1	<0.1	0.4	0.4
1,000	0.3	0.4	0.2	0.2	<0.1	<0.1	0.3	0.4
% Settled Outside of Boundaries[1]	**28.6%**	**32.7%**	**26.6%**	**27.3%**	**8.9%**	**8.1%**	**27.5%**	**30.2%**

[1] Defined as the percentage of fugitive sediment that settles on the seabed outside of the 100 m dilution boundaries of all three dredge basins calculated as:
[% Fugitive Sediment Settled Outside Boundaries] = [Volume Outside Boundaries] / [Total Released Fugitive Sediment Volume] x 100%

4.0 CONCLUSION

Over the complete dredging program at CEP, the maximum deposited thickness of dredging-derived fugitive sediment does not exceed 10 mm. The maximum thickness outside of the 100 m dilution zone for a single active dredge is 6.1 mm and is 8.1 mm for two active dredges. The near field depositional thickness is somewhat sensitive to variations in dredge placement, as can be seen by comparing the depositional thickness of the one and two dredge cases at the 100 m dilution boundary. These minor variations, however, largely disappear within 100 m of the 100 m dilution boundary and the far-field depositional thickness does not depend on whether one or two dredges are active. This is because the total dredge volume, and hence the released sediment available to settle, remains the same regardless of the number of dredges employed. Beyond 300 m to 400 m from the 100 m dilution boundary of any of the three Basins, the total depositional thickness of dredging-derived fugitive sediment is less than 1 mm. Over the complete dredging operation, approximately 28% to 30% of the total fugitive sediment volume settles outside of the three 100 m initial dilution boundaries.

5.0 CLOSURE

We trust this technical memo meets your present requirements. If you have any questions or comments, please contact the undersigned.

Respectfully submitted,
Tetra Tech Canada Inc.

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JS/JM

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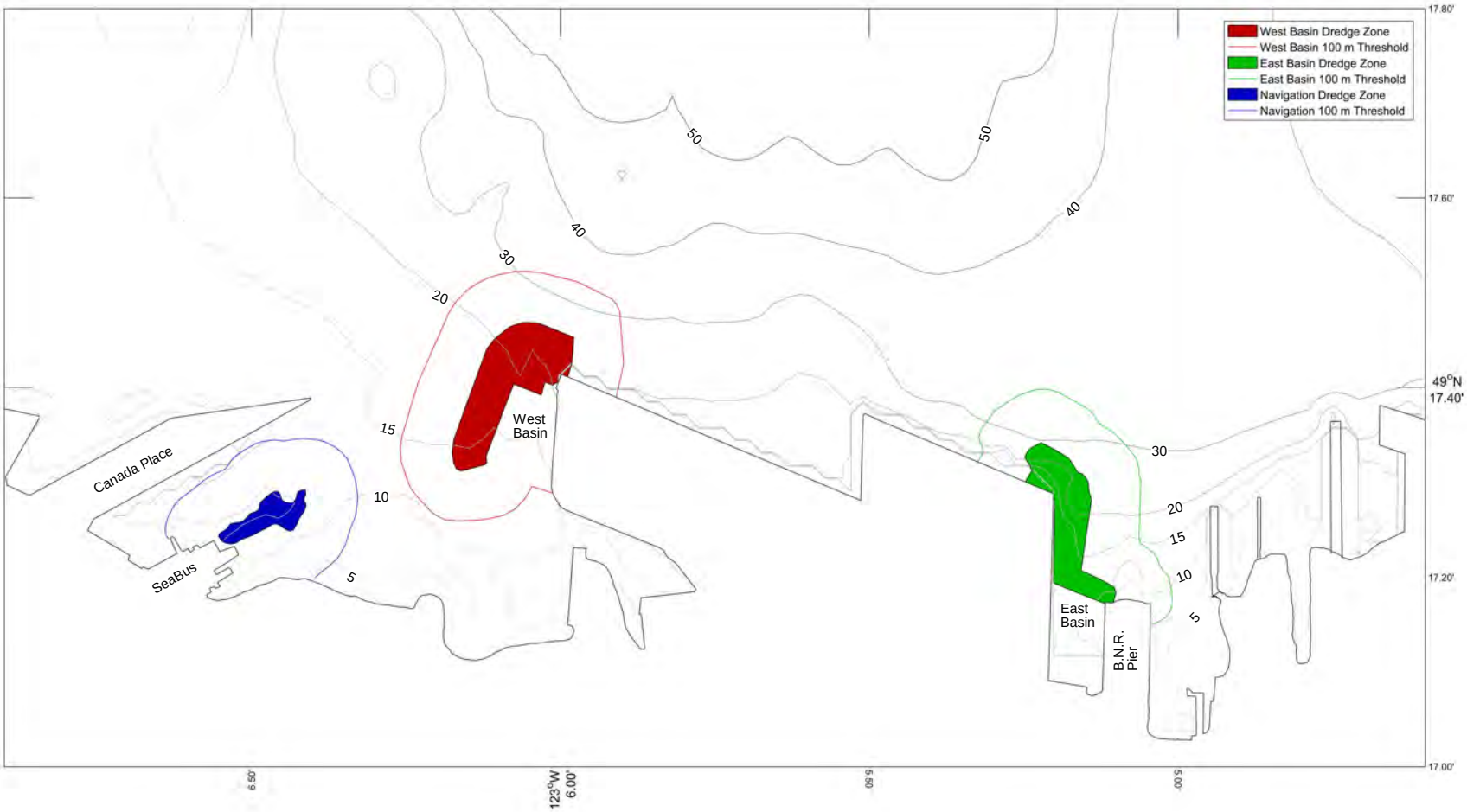
Tetra Tech Canada, 2017a. Centerm Expansion Project: Dispersal Modelling of Dredging Derived Fugitive Sediment. April 13, 2017, File: 704-WTR.WTRM03017, Client: AECOM Canada.

Tetra Tech Canada, 2017b. Centerm Expansion Project: Dispersal Modelling of Infilling Derived Fugitive Sediment. April 21, 2017, File: 704-WTR.WTRM03017, Client: AECOM Canada.

FIGURES



NOTES

Dredge prism outlines and 100 m radius boundaries are plotted in the above figure.

STATUS
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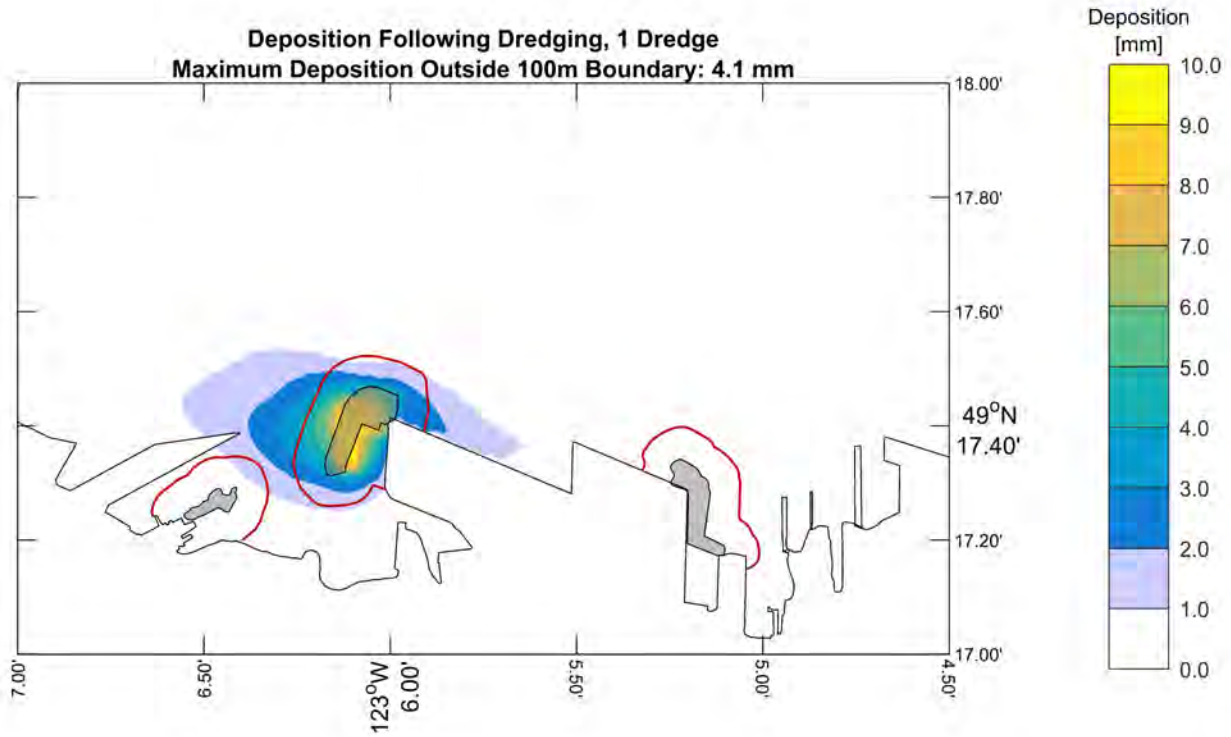
Depositional Thickness of Dredging Derived Fugitive Sediment

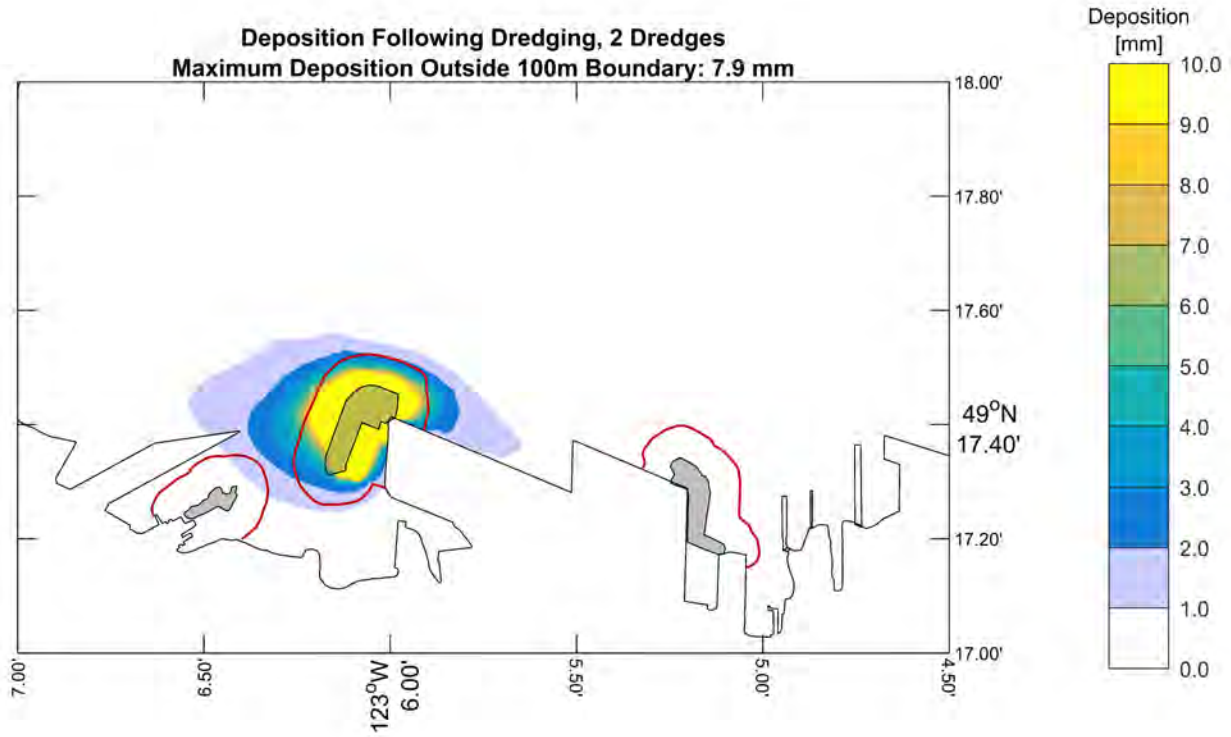
CEP Dredge Zone Overview

PROJECT NO.	DWN	CKD	APVD	REV
WTRM.03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech EBA - VANC	July, 2017

Figure 1





NOTES

Dredge Prism

100 m Threshold

Deposition is the total depth of settled fugitive sediment following the end of the dredging operation.

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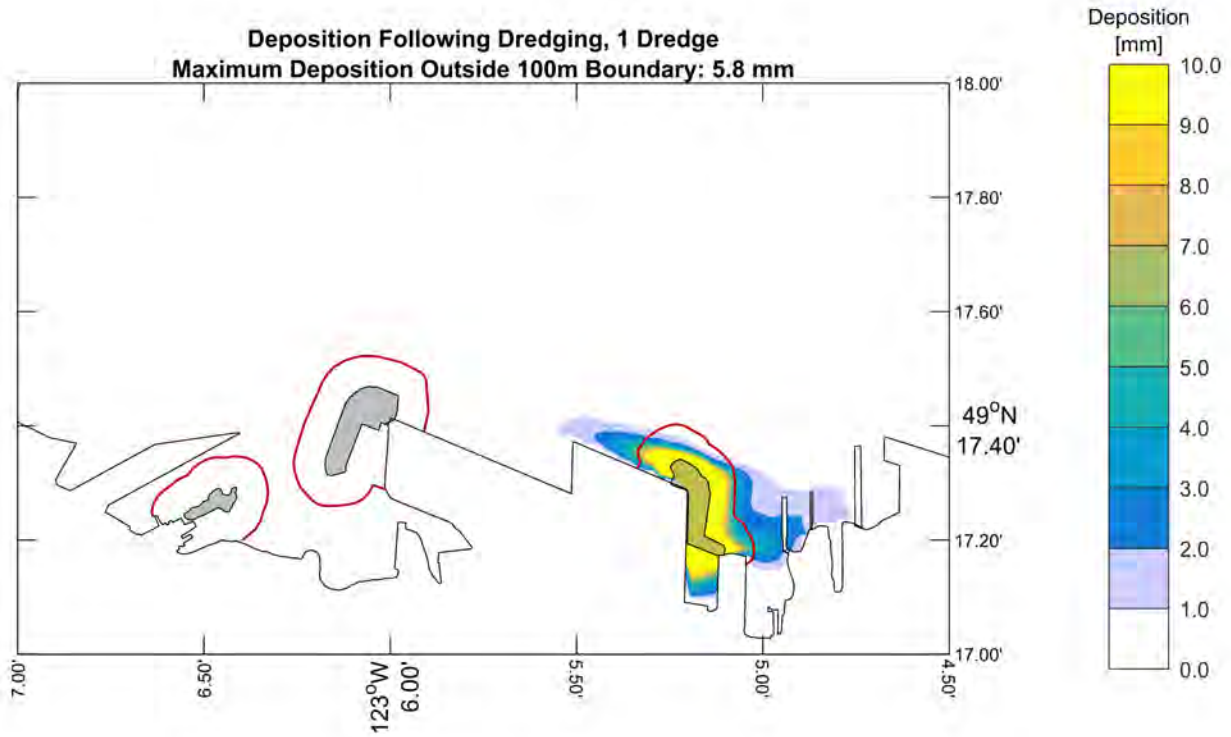
Depositional Thickness of Dredging Derived Fugitive Sediment

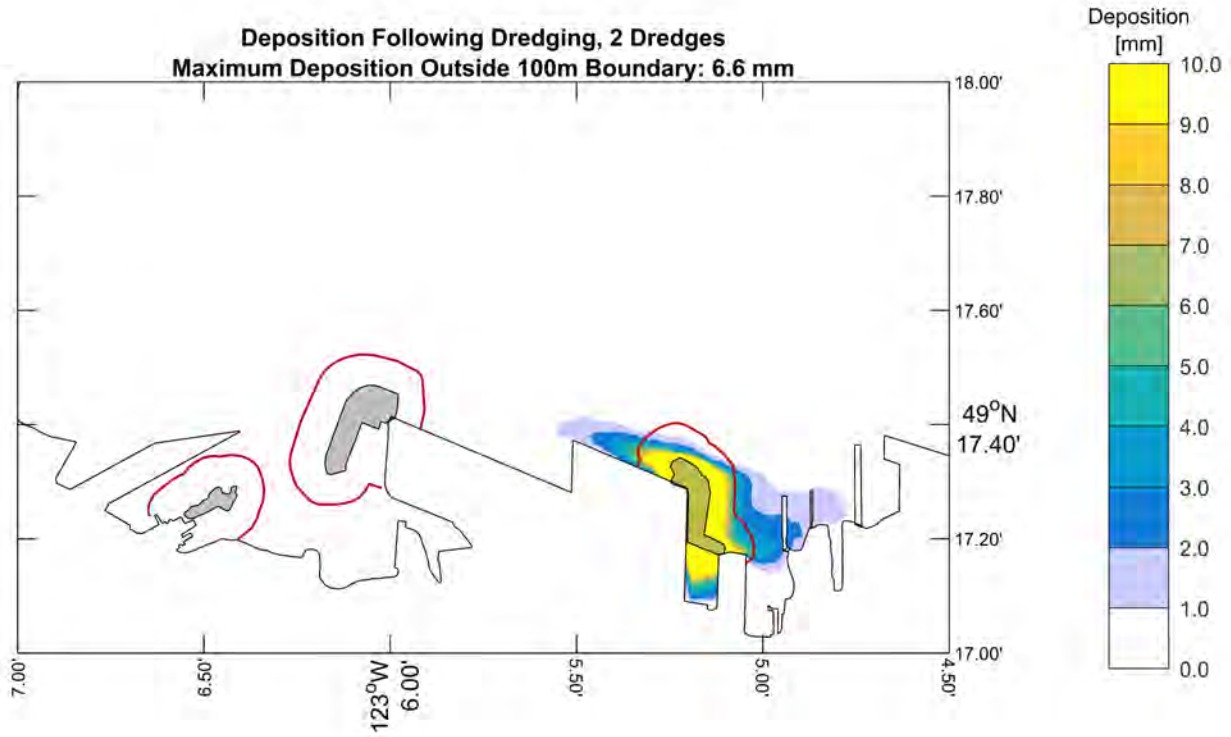
West Basin: Depositional Thickness of Fugitive Sediment

PROJECT NO.	DWN	CKD	APVD	REV
WTRM03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech EBA - VANC	July, 2017

Figure 2





NOTES

Dredge Prism

100 m Threshold

Deposition is the total depth of settled fugitive sediment following the end of the dredging operation.

STATUS
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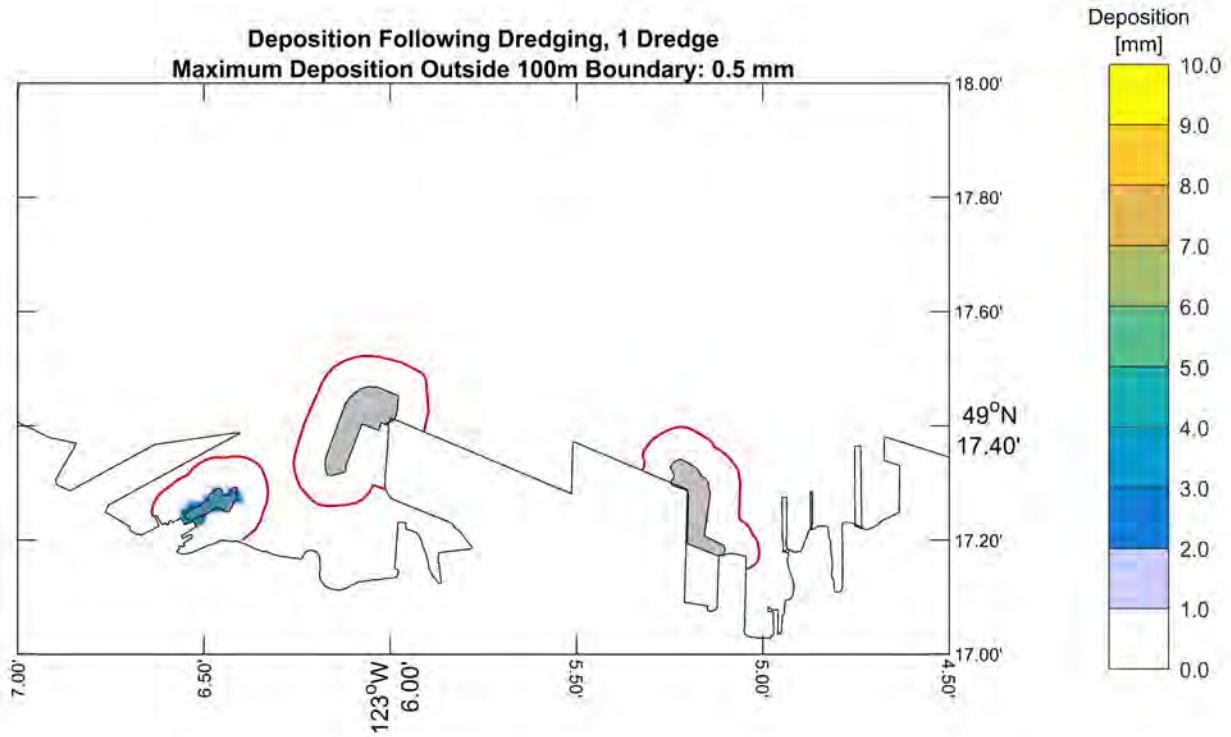
Depositional Thickness of Dredging Derived Fugitive Sediment

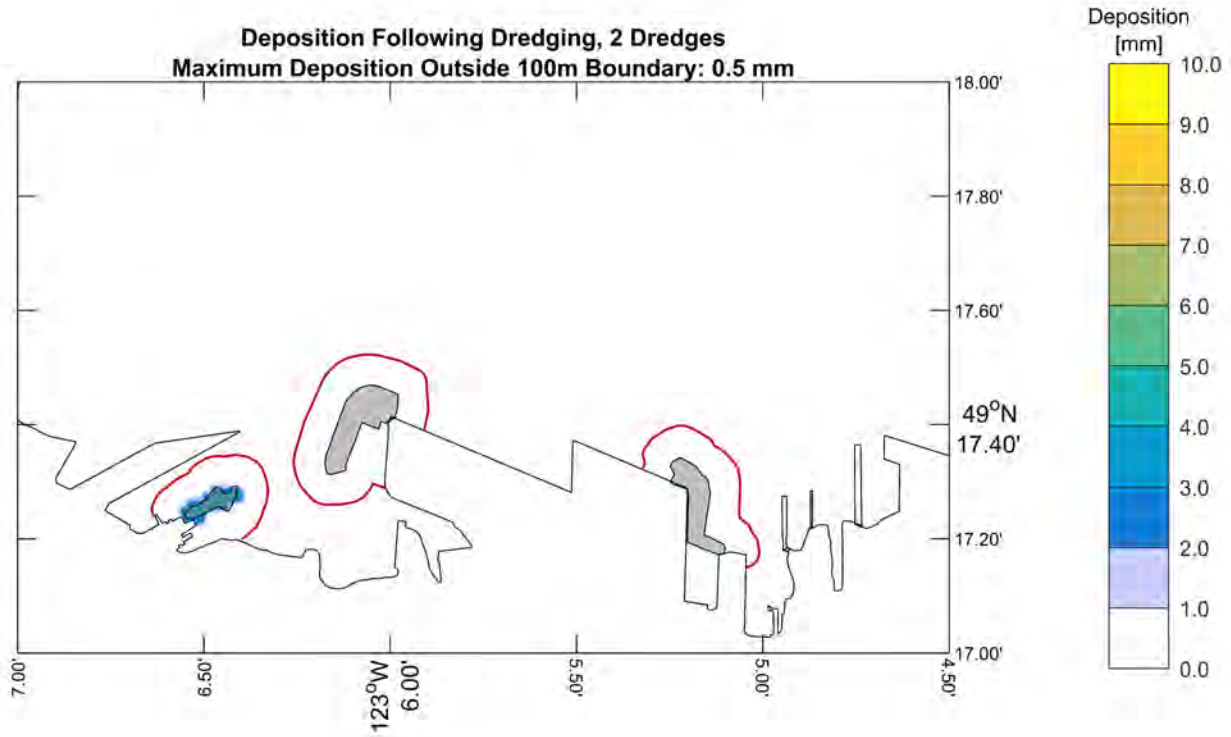
East Basin: Depositional Thickness of Fugitive Sediment

PROJECT NO.	DWN	CKD	APVD	REV
WTRM03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech EBA - VANC	July, 2017

Figure 3





NOTES

Dredge Prism

100 m Threshold

Deposition is the total depth of settled fugitive sediment following the end of the dredging operation.

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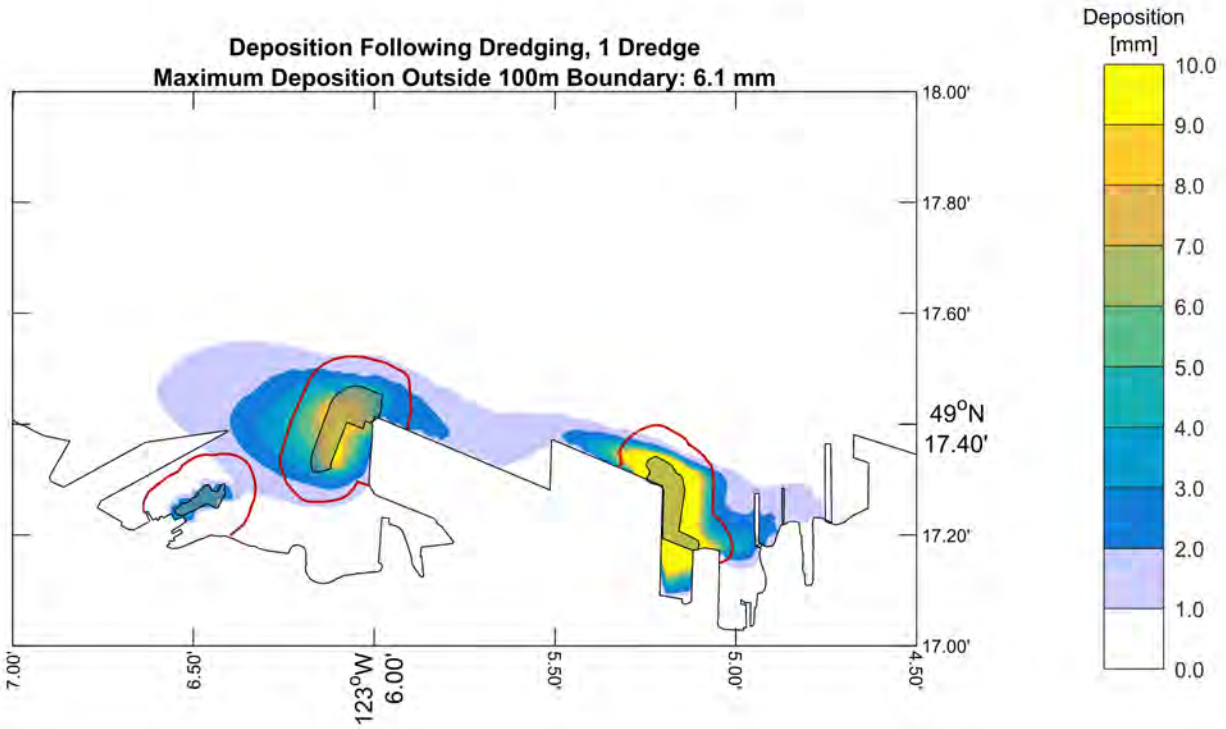
Depositional Thickness of Dredging Derived Fugitive Sediment

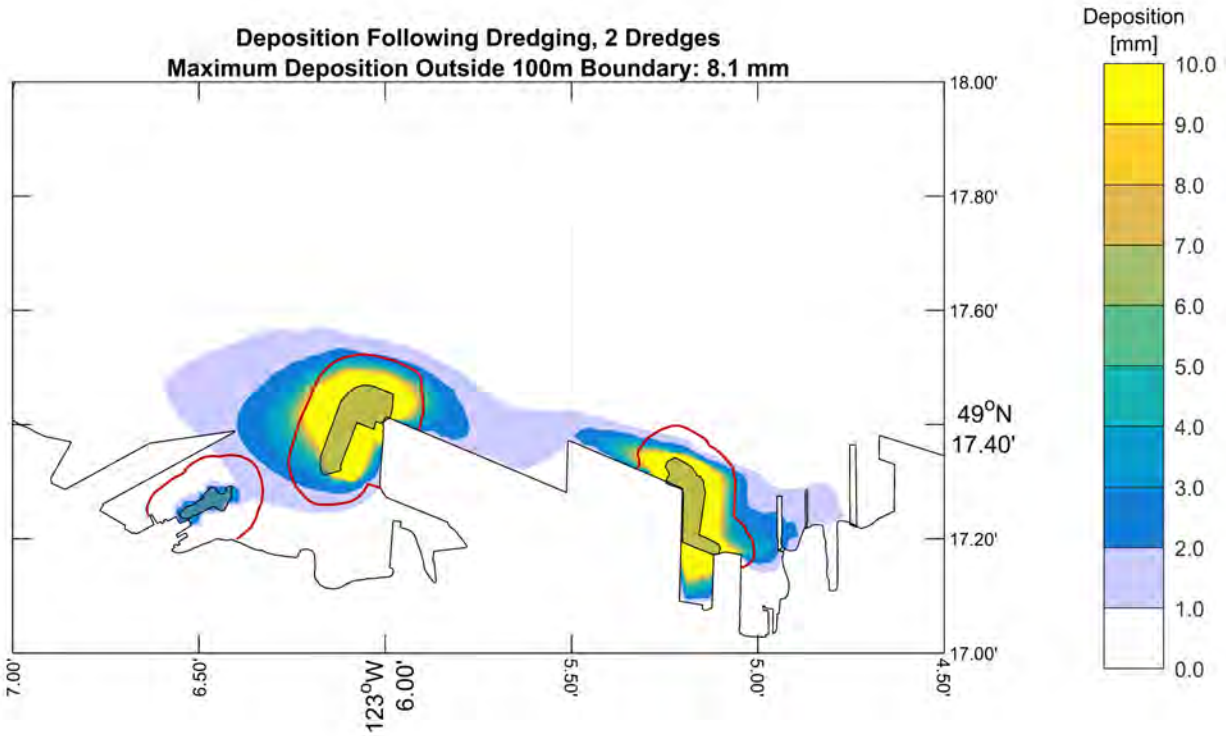
Navigation Basin: Depositional Thickness of Fugitive Sediment

PROJECT NO.	DWN	CKD	APVD	REV
WTRM03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech EBA - VANC	July, 2017

Figure 4





NOTES

Dredge Prism

100 m Threshold

Deposition is the total depth of settled fugitive sediment following the end of the dredging operation.

STATUS
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Depositional Thickness of Dredging Derived Fugitive Sediment

Total Depositional Thickness of Fugitive Sediment Following Dredging

PROJECT NO.	DWN	CKD	APVD	REV
WTRM03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech EBA - VANC	July, 2017

Figure 5

APPENDIX A: TETRA TECH CANADA'S GENERAL CONDITIONS

GENERAL CONDITIONS

HYDROTECHNICAL

This report incorporates and is subject to these “General Conditions”.

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Both electronic file and hard copy versions of Tetra Tech EBA’s Instruments of Professional Service shall not, under any circumstances, be altered by any party except Tetra Tech EBA. Tetra Tech EBA’s Instruments of Professional Service will be used only and exactly as submitted by Tetra Tech EBA.

Electronic files submitted by Tetra Tech EBA have been prepared and submitted using specific software and hardware systems. Tetra Tech EBA makes no representation about the compatibility of these files with the Client’s current or future software and hardware systems.

3.0 STANDARD OF CARE

Services performed by Tetra Tech EBA for the Report have been conducted in accordance with the Services Agreement, in a manner consistent with the level of skill ordinarily exercised by members of the profession currently practicing under similar conditions in the jurisdiction in which the services are provided. Professional judgment has been applied in developing the conclusions and/or recommendations provided in this Report. No warranty or guarantee, express or implied, is made concerning the test results, comments, recommendations, or any other portion of the Report.

If any error or omission is detected by the Client or an Authorized Party, the error or omission must be immediately brought to the attention of Tetra Tech EBA.

4.0 ENVIRONMENTAL AND REGULATORY ISSUES

Unless expressly agreed to in the Services Agreement, Tetra Tech EBA was not retained to investigate, address or consider, and has not investigated, addressed or considered any environmental or regulatory issues associated with the project.

5.0 DISCLOSURE OF INFORMATION BY CLIENT

The Client acknowledges that it has fully cooperated with Tetra Tech EBA with respect to the provision of all available information on the past, present, and proposed conditions on the site, including historical information respecting the use of the site. The Client further acknowledges that in order for Tetra Tech EBA to properly provide the services contracted for in the Services Agreement, Tetra Tech EBA has relied upon the Client with respect to both the full disclosure and accuracy of any such information.

6.0 INFORMATION PROVIDED TO TETRA TECH EBA BY OTHERS

During the performance of the work and the preparation of this Report, Tetra Tech EBA may have relied on information provided by persons other than the Client.

While Tetra Tech EBA endeavours to verify the accuracy of such information, Tetra Tech EBA accepts no responsibility for the accuracy or the reliability of such information even where inaccurate or unreliable information impacts any recommendations, design or other deliverables and causes the Client or an Authorized Party loss or damage.

7.0 GENERAL LIMITATIONS OF REPORT

This Report is based solely on the conditions present and the data available to Tetra Tech EBA at the time the Report was prepared.

The Client, and any Authorized Party, acknowledges that the Report is based on limited data and that the conclusions, opinions, and recommendations contained in the Report are the result of the application of professional judgment to such limited data.

The Report is not applicable to any other sites, nor should it be relied upon for types of development other than those to which it refers. Any variation from the site conditions present at or the development proposed as of the date of the Report requires a supplementary investigation and assessment.

It is incumbent upon the Client and any Authorized Party, to be knowledgeable of the level of risk that has been incorporated into the project design, in consideration of the level of the hydrotechnical information that was reasonably acquired to facilitate completion of the design.

The Client acknowledges that Tetra Tech EBA is neither qualified to, nor is it making, any recommendations with respect to the purchase, sale, investment or development of the property, the decisions on which are the sole responsibility of the Client.

8.0 JOB SITE SAFETY

Tetra Tech EBA is only responsible for the activities of its employees on the job site and was not and will not be responsible for the supervision of any other persons whatsoever. The presence of Tetra Tech EBA personnel on site shall not be construed in any way to relieve the Client or any other persons on site from their responsibility for job site safety.

Appendix D Centerm Expansion Project: Dispersal Modelling of Infilling-Derived Fugitive Sediment

TETRA TECH

OQM | Organizational Quality Management Program

Centerm Expansion Project - Dispersal Modelling of Infilling-Derived Fugitive Sediment

PRESENTED TO

AECOM Canada

APRIL 21, 2017
ISSUED FOR USE
FILE: 704-WTR.WTRM03017-01

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This report and its contents are intended for the sole use of AECOM Canada and their agents. Tetra Tech Canada Inc. (Tetra Tech) does not accept any responsibility for the accuracy of any of the data, the analysis, or the recommendations contained or referenced in the report when the report is used or relied upon by any Party other than AECOM Canada, or for any Project other than the proposed development at the subject site. Any such unauthorized use of this report is at the sole risk of the user. Use of this report is subject to the terms and conditions stated in Tetra Tech Canada Inc.'s Services Agreement. Tetra Tech's General Conditions are provided in Appendix A of this report.

1.0 INTRODUCTION

AECOM Canada (AECOM) retained Tetra Tech Canada Inc. (Tetra Tech) to quantify release and dispersion of fugitive sediments arising from infilling two sites over the course of the Centerm Expansion Project (CEP). CEP consists of an expansion of the existing Centerm Container Terminal located on the southern shoreline of Vancouver Harbour. The project will consist of two fill expansions to the existing terminal footprint: a westward expansion of approximately 4.2 ha and an eastward expansion of approximately 4 ha.

This study investigates the behaviour of total suspended sediment (TSS) plumes arising from infilling operations at the West Basin Infill and East Basin Infill. This study is based on conceptual plan for infilling and dyke construction, and may be modified by the contractor during the design stage. Each infill zone will be contained behind perimeter rock dykes, raised in a series of trapezoidal 4.5 m lifts until the final fill elevation of +7.0 m CD is reached. Bulk fill material consisting of imported sand-gravel with a small fines fraction will be placed behind the perimeter dykes using a combination of bottom-dumping hopper and flat-deck barges with minor fill, reshaping and some aspects of perimeter dyke construction being undertaken with a clamshell derrick. Mattress, berm rock and lower perimeter dyke lifts will be primarily placed with hopper barges, while upper perimeter dyke lifts will be placed with flat-deck barges offloaded with front-end-loader equipment. When there is sufficient water depth over the perimeter dykes, general infill will be performed by hopper or flat-deck barges floated over the perimeter dyke (AECOM/KCB 2016). Once there is insufficient depth over the infill to safely operate barges, infill will be largely complete using pumped granular materials. Prior to the construction of perimeter rock dykes and infilling, unstable marine sediments will be removed via dredging; the associated fugitive sediment behaviour from dredging was reported in *Centerm Expansion Project: Dispersal Modelling of Dredging-Derived Fugitive Sediment* (Tetra Tech 2017).

The present study uses a high resolution three-dimensional oceanographic model to simulate the dispersion of fugitive sediments arising from infilling the East and West Basins of CEP. Two primary phases of filling will take place: submarine placement of fill using hopper and flat-deck barges; and, surficial infill using pumped slurry fill. Submarine fill placement was simulated for two cases: “empty” perimeter dykes, in which the fill level is several meters below the crest of the dykes forming the outer edge of the infill zones; and, “full” perimeter dykes, in which the fill level is at the crest elevation of these dykes. TSS releases arising from pumped slurry fill material have not been simulated as it has been assumed that supernatant water resulting from the pumped fill material will drain through a sand filter abutting the inner surface of the perimeter dykes, with all sediment being contained by the dykes (i.e. no flow-through of suspended sediment).

Maps, tables and time series are presented to describe the spatial variation in the maximum and average suspended sediment concentration in the water column arising from infilling operations. Data are therefore presented for both a “maximum” approach in which all statistics are presented for the *maximum* suspended sediment concentration in the water column and a “maximum average” approach in which statistics are presented for the *average* suspended sediment concentration in the water column. The “maximum average” metric is referenced in the Canadian Council of Ministers of the Environment (CCME) water quality standard for *Total Particulate Matter* and is therefore the main point of reference for this study. The maximum values are presented to characterize instantaneous and short lived TSS peaks that may not be accounted for by the CCME guidelines.

2.0 METHODOLOGY

2.1 Numerical Model

The fate and behaviour of the project-derived fugitive sediments has been simulated using an extensively validated three-dimensional numerical model of Vancouver Harbour along with a parameterized infilling schedule based on the best available information at the time of writing. The primary numerical model employed in this study is a 10-m resolution three-dimension numerical model focussed on the south-western shore of Vancouver Harbour. This model is the highest resolution model in a series of numerical models extending from the Pacific Ocean to the upper end of Indian Arm:

- Coarse Resolution: 1-km resolution shelf model extending from the mouth of Juan de Fuca Strait to the southern end of Texada Island and the terminus of Indian Arm. The model is driven by tidal constituents and monthly climatology at its boundaries with hourly wind fields and daily river inflows at 13 significant rivers.
- Mid-Resolution: 125-m resolution Burrard Inlet model extending from the entrance to English Bay to the terminus of Indian Arm. The model is driven by water level, temperature and salinity data from the coarse resolution model, with hourly wind fields and daily river inflows.
- High Resolution: 25-m resolution Burrard Inlet model extending from the mid-point of English Bay (near Jericho Beach) to east of Second Narrows (near Cates Park), driven by water level, temperature and salinity data from the mid-resolution model, with hourly wind fields and daily river inflows.
- Project Specific: 10-m resolution model of the Centerm site spanning Canada Place, Deadman Island, Burnaby Shoal and Vanterm. Driven by water level, temperature and salinity data from the high-resolution model.

Within the modelling chain, all major rivers in the Salish Sea are included, with Lynne Creek, the Seymour River and the Capilano River feeding directly in the high resolution Burrard Inlet model. Wind fields are interpolated from measured winds at buoys and meteorological stations around coastal British Columbia, with winds for the high resolution Burrard Inlet model based on a dedicated CALMET wind model.

The layout of the 25-m and 10-m resolution numerical models of Vancouver Harbour are presented on Figure 2.1. This figure presents a map of speeds during a moderate flood tide for the existing Centerm geometry. Water level, velocity, salinity, temperature and sediment information is passed from the 1000-m resolution model to the 125-m resolution model to the 25-m resolution model (across the black boundary in Figure 2.1) and, ultimately, across the red boundary in Figure 2.1 into the 10-m resolution numerical model. In general, the model nesting procedure results in a very high fidelity across model domains, as can be seen in Figure 2.1. Fugitive sediment arising from infilling operations is introduced into the model via a coupled version of the STFATE (Short-Term FATE of dredged sediments) model developed by the U.S. Army Corps of Engineers. This model simulates the near-field (i.e. at a spatial scale smaller than the 10-m grid size) sediment dynamics, before passing its results through to the 10-m resolution hydrodynamic model (see Section 3.4). A simulation period of 14 days has been selected to determine the behaviour of the fugitive sediments over a full spring-neap cycle and because it approximately aligns with the time to complete one full perimeter dyke lift (see Section 3.3).

The circulation patterns within Vancouver Harbour are tidally dominated, with some baroclinic influence due to seasonal variations in fresh water inflow and temperature. Streamlines showing the surface currents within western Vancouver Harbour are shown on Figure 2.2. The most prominent flow features within the harbour are the tidal jets formed at First Narrows and Second Narrows. These jets regularly have peak velocities over 2.5 m/s, with a maximum velocity nearing 3 m/s possible on occasion. Flood tides result in a strong eastward flowing jet forming at First Narrows that remains coherent well into Vancouver Harbour and establishes a series of eddies and recirculation cells that persist throughout the tidal cycle. The First Narrows jet impinges on the Centerm site resulting

in strong eastward flows along the terminal face and generally setting up a clockwise circulation cell between Centerm and Canada Place. On the left panel of Figure 2.2 two flood-tide circulation cells are shown to the west of Centerm, one clockwise and the other counterclockwise, centered over the Navigation Dredge Zone. Ebb tides result in a strong westward flowing jet forming at Second Narrows (not show on Figure 2.2), resulting in complex circulation patterns in the vicinity of Centerm. Ebb tidal currents flowing westward in the middle of Vancouver Harbour result in westward flows along the terminal face and set up a counterclockwise eddy between Centerm and Canada Place (Figure 2.2). Ebb tides generally result in a counterclockwise eddy forming to the west of the East Basin Dredge Zone. Towards the end of ebb tide (not shown on Figure 2.2) a counterclockwise eddy can be set up in south western Vancouver Harbour which results in eastward flow in the vicinity of Centerm and, somewhat counterintuitively, in the eastward outflow of water from between Centerm and Canada Place during late stages of ebb tide.

2.2 Fugitive Sediment Plume Tracking

The eastern and western infill zones are displayed on Figure 2.3 with a 100 m dilution boundary plotted for each infill zone. Dilution zones of these dimensions are used later in this report to determine the dilution of the initial fugitive sediment source strength at 100 m from the infill zone “source”.

In order to quantify the dispersion of fugitive sediments, the TSS content of the fugitive sediment plume is tracked as sediments are released over a simulated infill program. In order to quantify the dispersion of fugitive sediments, the total suspended solids (TSS) content of the fugitive sediment plume is tracked as sediments are released over a simulated infilling program. Two metrics are used to quantify the concentration and extent of the fugitive sediment release:

- **Water Column Maximum TSS Concentration:** At 15 minute intervals, the maximum TSS concentration in the water column (vertical axis) is reported on a 10 m by 10 m horizontal grid. This data representation was selected to give a conservative representation of TSS concentration in the water column even though the reported maximum TSS may occur at only one location in the water column.

  The goal of reporting the maximum TSS concentration is to characterize any instantaneous, short lived peaks that would not necessarily be captured by the maximum average concentration discussed below

- **Water Column Average TSS Concentration:** At hourly intervals, the maximum vertically averaged TSS concentration in the water column (vertical axis) is reported on a 10 m by 10 m horizontal grid. In this study, an arithmetic mean is uniformly presented.

  This metric is most comparable to CCME’s “maximum average” guidance on Total Particulate Matter concentration and so is the most relevant measure of TSS in the water column.

As an explanatory example, if the water depth is 40 m, with a near bed (e.g. within 1 m of the seabed) TSS concentration of 100 mg/L with the remainder of the water column having a TSS concentration of 2 mg/L, the maximum TSS concentration would be reported as 100 mg/L, while the water column average TSS would be reported as 4.5 mg/L in accordance with CCME guidance.

These two measures of TSS in the water column are then post-processed to determine:

- **Maximum TSS 100 m from source:** The maximum TSS concentration at a 100 m distance from the active dredge zones, computed from the water column maximum TSS concentration. These 100 m boundaries surrounding each dredge zone are presented on Figure 2.3.

- **Maximum Average TSS 100 m from source:** The maximum average TSS concentration at a 100 m distance from the active dredge zones, computed from the average water column TSS concentration. These 100 m boundary surrounding each dredge zone are presented on Figure 2.3.

- **Probability of Maximum TSS Exceeding 5 mg/L:** The probability of the maximum above-background concentration of TSS exceeding 5 mg/L at any given moment during the dredging operation, defined as the commencement of operations to the moment when the above- background concentration drops below 5 mg/L following cessation of dredging. These probabilities are computed from the water column maximum TSS concentration, which is very conservative compared to CCME guidelines.
- **Probability of Maximum TSS Exceeding 25 mg/L:** The probability of the maximum above-background concentration of TSS exceeding 25 mg/L at any given moment during the dredging operation, defined as the commencement of operations to the moment when the above background concentration drops below 25 mg/L following cessation of dredging. These probabilities are computed from the water column maximum TSS concentration, which is very conservative compared to CCME guidelines.
- **Probability of Maximum TSS Exceeding 10% of Source Strength:** The probability of the maximum above-background concentration of TSS exceeding 10% of the initial source strength, defined as the water column averaged TSS immediately below the dredge vessel.

3.0 SEDIMENT SOURCE TERMS

3.1 Background Suspended Sediment Concentration

The primary source of background suspended sediment concentration in Vancouver Harbour is widely cited as the North Arm of the Fraser River (Davidson 1973, Feely and Lamb 1979, Thomson 1981). A combination of flood currents and the hydraulic head of the river drive a layer of silty fresh water from the North Arm northwards along the edge of Point Grey, then eastward along the southern shore of English Bay. During certain tidal and wind conditions, this near-surface brackish water can be drawn through First Narrows and into Vancouver Harbour; however the intense tidal mixing of the Narrows mixes out much of the initial stratification. There is, however a general lack of information on background suspended sediment concentrations that result from the influx of brackish water into Vancouver Harbour.

The best source of recent information is a report by Tetra Tech in which turbidity on the western side of Canada Place was monitored continuously from December 2004 to July 2007 (Tetra Tech 2007). Turbidity measured in Nephelometric Turbidity Units (NTU) was monitored at depths of 1.0 m and 4.5 m by YSI 6600EDS-M multi parameter sondes. In general, low turbidity values were recorded throughout the year. Average annual turbidity were 1.6 NTU at 1 m depth and 2.0 NTU at 4.5 m depth. Turbidity levels occasionally (approximately once per month) peaked to between 10 NTU and 20 NTU for a period of less than a day, with the maximum recorded turbidity over the monitoring period of approximately 25 NTU. While these spikes have not been attributed to a specific cause, they do show that there is naturally a factor of 10 range in turbidity in Vancouver Harbour. Turbidity values increased slightly during spring and late summer phytoplankton blooms.

3.2 Infill Sediment Characteristics

The properties of the infill materials have been characterised using data adapted from data provided by Klohn Crippen Berger and AECOM (AECOM/KCB 2017). A summary of these data is presented in Table 3.1 for each of the four primary sources of infill sediment. Importantly, the General Fill material and Berm Filter material have a similar fines content, while the Mattress Rock and Dyke Core Rock have a negligible content of any sediment smaller than fine gravel. Therefore, the placement of the General Fill and Berm Filter material (which are contiguous) will result in the fugitive release of TSS, while the placement of the Mattress Rock and Dyke Core Rock can be safely assumed to generate a comparatively negligible TSS plume. Consequently, only the placement of General Fill and Berm Filter material is considered in this study.

Table 3.1: Summary of Infill Material Grain Size Classification

		General Fill[1]		Berm Filter[2]		Mattress Rock[3]		Dyke Core Rock[4]
Sediment Properties		**% Passing**		**% Passing**		**% Passing**		**% Passing**
Class	**mm**	**Lower**	**Upper**	**Lower**	**Upper**	**Lower**	**Upper**	
Boulder	600	100	100	100	100	100	100	100
Small Cobbles	100-150	100	100	100	100	100	100	50
Small Cobbles	75	100	60	100	100	100	60	35
Coarse Gravel	19	100	10	100	75	50	10	19
Medium Gravel	9.5	100	0	100	60	35	0	16
Fine Gravel	4.75	90	0	90	40	20	0	15
Very Coarse Sand	0.425	40	0	15	0	0	0	1
Fine Sand	0.075	5	0	5	0	0	0	0
Medium-Fine Clay	0.001	0	0	0	0	0	0	0

[1] quarry rock and/or river gravels and sands, comprise the vast majority of infill materials
[2] quarry rock to be installed behind caissons
[3] quarry rock to be installed beneath caissons
[4] quarry rock, comprises bulk of dyke material
Source: AECOM 2017

The particle size distributions presented in Table 3.1 have been parameterized into five particle size classes ranging from a very coarse sand to a very fine silt. As the General Fill material presented in Table 3.1 has the largest fines and sand content, its lower bound has been used to derive the particle size classes used in simulating infill operation.

Table 3.2 presents the median (d_{50}), upper bound and lower bound values proscribed in each sediment class bin. In deriving these bins, the focus was on fine sediments and, therefore, sediment classes were not created for materials greater than a small gravel as this material is neither mobilized by ambient currents nor, in the case of a hopper dump, does it travel more than a few meters from its release location.

Table 3.2: Summary of Particle Size Distribution

Sediment Class	Lower Bound	d_{50}	Upper Bound	% Passing	% Retained
	µm	µm	µm	%	%
Very Coarse Sand	425	1795.70	4750.00	90.00	50.00
Fine Sand	75	201.78	425.00	40.00	35.00
Silt	25.49	43.72	75.00	5.00	3.35
Fine Silt	8.66	14.86	25.49	1.70	1.14
Very Fine Silt / Clay	2.94	5.05	8.66	0	0.52

3.3 Volume and Infill Schedule

To complete the infilling operation, approximately 432,000 m^3 of infill material (as distinct from other construction materials) will be required at the West Basin, with 528,000 m^3 required at the East Basin. These material volumes exclude the Perimeter Dyke, Caisson Mattress Rock, Dredge Trench Infill and Caisson Fill, as discussed in Section 3.2. The total volume of material is taken as the sum of sand and gravel infill and general fill based on information provided in the AECOM-KCB dredging and infill statement (AECOM 2017). Table 3-3 summarizes the relative volumes of each sediment class and the total infill material volume with a significant fines fraction (excluding the perimeter dykes rock and mattress rock) at each of the East and West Infill.

Table 3.3: Summary of Infill Volume by Sediment Class

Sediment Class	% of Total	West Basin Infill[2] Volume	East Basin Infill Volume
		m^3	m^3
Gravel and Cobble[1]	10.00	43,157	52,800
Very Coarse Sand	50.00	216,000	264,000
Fine Sand	35.00	151,200	184,800
Silt	3.35	14,472	18,480
Fine Silt	1.14	4,925	6,019
Very Fine Silt / Clay	0.52	2,246	2,746
Total	**100**	**432,000**	**528,000**

[1] Gravel and cobble not subject to dispersion and therefore not simulated.
[2] Excluding Perimeter Dyke, Caisson Mattress Rock, Dredge Trench Infill and Caisson Fill

Infilling is assumed to take place using a 1,500 m^3 capacity hopper and flat deck barge(s) operating with four deliveries per day (AECOM 2017). Minor infill work using a clam shell derrick have not been simulated in this study as this topic was: 1) extensively covered in previous reports (Tetra Tech 2017); and, 2) initial tests demonstrated that TSS concentration originating from clam shell derrick operations we much lower than either the hopper and flat-deck barge scenarios. The East and West Basin infill operations consist of a maximum of five dyke lifts above the native seabed elevation. Due to the uneven and sloping seabed, the infill following the first dyke life will be smaller than subsequent infills. These subsequent infills will vary slightly in volume (hence infill time) depending on the perimeter dyke elevation. To allow for direct comparison between different lift cases, a 14 day infill period for each lift at both the East and West Basins has been simulated. A 14-day cycle allows for simulation over a complete spring-neap tidal cycle and is approximately the average duration of the four submarine infill operations at each Basin.

3.4 Sediment Release

3.4.1 Hopper Barge

The majority of infill material placement is assumed to be carried out via a hopper dredge. A dredge ship of this design transports dredgeate in several internal bins (hoppers) which empty via doors in the ship's bottom. Upon reaching a dump-site, the bottom doors are opened, typically in a specific sequence to ensure even trim of the ship, releasing the dredgeate in a descending cloud.

Sediments released from a hopper dredge generally escape into the surrounding water body in two main phases which, depending on water depth, can be viewed as either independent or concurrent. Firstly, as material leaves the dredge ship, an initial stripping of fine material occurs as the dredgeate accelerates and segregates. This generates a near-surface cloud of material near the release point. Provided the water depth is great enough (and depending on the specific dredgeate composition), all readily removable fine material is stripped during dredgeate descent towards the seafloor. Some fine material, and possibly the bulk of the fine material, can remain entrained in this descending plume, shielded by the larger sediment fractions. When the plume contacts the seafloor, a second cloud of fine material is released as the plume collapses. In shallow depths, the two phases of plume behaviour occur almost simultaneously, while in deeper waters two distinct clouds of fine materials are generated.

With the complete representation of this conceptual model in mind, the release of fines during the infilling operation was modelled with an updated version of the STFATE (Short-Term FATE of dredged sediments) model developed by the U.S. Army Corps of Engineers. The model is based on work by Johnson and Fong (1994), which in turn is developed from the DIFID (Disposal from Instantaneous Discharge) model by Koh and Chang (1973). The model simulates discrete discharge events from dredging vessels – essentially a single delivery operation – and models the complete life-cycle of the discharged dredgeate. For this study, the underlying equations and framework of STFATE were retained; however, large sections of the code were re-worked to allow the model to operate on the time and spatial scales required to simulate the infilling operations.

The released material is modelled in three distinct phases:

- **Convective Descent:** The material falls under the influence of gravity and the initial momentum imposed by discharge from the dredging vessel. In deep water, the dredgeate plume is parameterised as an ellipsoid (roughly egg-shaped) descending mass, while in depth-limited conditions, a column of descending dredgeate results. Based on the initial momentum of the descending plume and the sediment constituents of the dredgeate, the initial blow-off of suspended sediments is calculated.

- **Dynamic Collapse:** The descending cloud of dredgeate either impacts the seafloor or achieves neutral buoyancy with the surrounding water mass. In the event of seafloor impact, the dredgeate plume forms an approximately Gaussian depositional pattern centred on the release point (subject to horizontal advection during the decent phase). Again, based on the momentum of the descending cloud and sediment properties, the blow-off of suspended sediment on impact is calculated.

- **Advection-Diffusion:** Following dynamic collapse, spreading by ambient currents and diffusion disperse any suspended dredgeate. In this application, this functionality of the model is unused and the cloud of suspended sediment generated by STFATE is superimposed on the 10-m resolution hydrodynamic model of CEP (generally over 10 to 12 horizontal grid cells and across the full depth of vertical grid cells). By coupling the models in this way, each of the models is used in its strongest capacity; the detailed and calibrated dredgeate plume formulae of STFATE are applied at a sub-grid scale (with respect to the 10-m resolution model) until the dredgeate plume is dominated by advection-diffusion, at which point the hydrodynamic model takes over the dispersal of the dredgeate.

Calculations of the TSS plume released during the infilling operation are based on information provided by AECOM (AECOM 2017). Dredge dimensions and operating conditions are provided by, or inferred from, this information, and are summarised in Table 3-4.

Table 3.4: Summary of STFATE Input Parameters

Property	Value	Unit
Ship Properties		
Ship Length	60	m
Ship Beam	12.8	m
Loaded Draft	3.6	m
Unloaded Draft	2.2	m
Dredgeate Release Time	60	s
Capacity	1,500	m^3
Release Volumes		
Gravel/Cobble[1]	150.0	m3
Very Coarse Sand	750.0	m^3
Fine Sand	525.0	m^3
Silt	50.3	m^3
Fine Silt	17.1	m^3
Very Fine Silt / Clay	7.8	m^3

[1] Gravel and cobble not subject to dispersion and so not transferred to hydrodynamic model

Sample simulation output of hopper barge dumps at water depths ranging from 7.0 m to 20.0 m are presented on Figure 3.1. In general, the fugitive release of sediments can be summarized as follows:

- The vast majority of fugitive TSS release occurs near the seabed as the descending cloud of dredgeate contacts the bottom. Typically, 16% to 35% of the total fugitive TSS is generated within a meter of the seabed, with 62% to 100% of the fugitive TSS generated within 3 m of the seabed.
- In shallower water (e.g. less than 10 m), fugitive TSS is generated relatively uniformly in the lower half of the water column, while in deeper water (e.g. 20 m), TSS is concentrated near the seabed.
- The initial release of finer fugitive sediment spans several meters of the water column as these sediments (very fine silt, fine silt, silt) tend to get striped from the dredgeate plume during descent.
- The initial release of coarser fugitive sediment tends to be concentrated near the bed as these sediments (fine sand, very coarse sand) tend to be released by the impact of the dredgeate plume on the seabed.
- Very coarse sand is only released as a fugitive sediment in water depths greater than 14 m and less than 20 m as this sediment requires a minimum amount of energy to be released when the dredgeate plume impacts the seabed. At depths shallower than 14 m, the dredgeate plume has not accelerated sufficiently to release the very coarse sand. At depths greater than 20 m, the dredgeate plume decelerates due to water entrainment and, similarly, is not descending fast enough to release the very coarse sand on impact.

3.4.2 Flat-Deck Barge

Adequate literature describing the fugitive sediment release process for offloading a flat-deck barge could not be found. Therefore, it was assumed that the release patterns and rates associated with hopper barge dumping were approximately representative. The offloading of a flat-deck barge was parameterized in the following way:

- It was assumed that the inverse of the release patterns for a hopper barge operating in shallow water (i.e. with low plume acceleration or water entrainment) are applicable. Therefore, the largest fugitive TSS release was assumed to be in the top 3 m of the water column, with the 16% of the fugitive TSS released in the top 1 m, the remaining 62% released in the top 3 m and the remaining 38% evenly distributed between 3 m below the surface and the bed.

- It was assumed that one hour was needed to fully offload the flat-deck barge with the offloading occurring relatively continuously. Therefore, rather than a 60 s release time as was assumed for the hopper barge dump, the release was spread uniformly over 3,600 s.

4.0 FUGITIVE TSS RELEASE

Table 4.1 provides a high level overview of the general construction sequence, summarizes the as-simulated construction cases and gives the associated report section number. The placement of Mattress Rock and Dyke Core Rock was not simulated as neither of these materials have a significant fines fraction and there was a worst-case analogue (i.e. a similar activity taking place with a material having a higher fines content) being simulated. In all cases, the infilling of the perimeter dykes with only General Fill and Berm Filter material has been simulated. It has been assumed that materials placed below perimeter dyke lift 3 will be placed using a bottom dump hopper barge, with the infill of perimeter dyke lift 4 being placed with a flat deck barge due to depth limitations associated with the opening of the hopper doors. Infill of perimeter dyke lift 5 is above mean water and, therefore is assumed to be filled using hydraulically pumped materials and, hence, not subject to fugitive TSS release. It has been assumed that supernatant water resulting from the hydraulically placed fill material will drain through a sand filter lining the inside of the perimeter dykes, with all sediment being contained behind the dykes (i.e. no flow-through of suspended sediment).

Table 4.1: Summary of As-Simulated Construction Activity

Construction Activity	Material	Placement Method	Worst-Case Analogue	Report Section
Dredge Cut Back Fill	Mattress Rock	Hopper	Berm Infill 1	
Dyke Lift 1	Dyke Core Rock	Hopper	Berm Infill 1	
Infill 1	General Fill and Berm Filter	Hopper	Directly Simulated	West: Section 4.1 East: Section 4.3
Dyke Lift 2	Dyke Core Rock	Hopper	Berm Infill 2	
Infill 2	General Fill and Berm Filter	Hopper	Directly Simulated	West: Section 4.1 East: Section 4.3
Dyke Lift 3	Dyke Core Rock	Hopper	Berm Infill 3	
Infill 3	General Fill and Berm Filter	Hopper	Directly Simulated	West: Section 4.1 East: Section 4.3
Dyke Lift 4[1]	Dyke Core Rock	Flat-Deck/ Mechanical	Berm Infill 4	
Infill 4[1]	General Fill and Berm Filter	Flat-Deck	Directly Simulated	West: Section 4.1 East: Section 4.3
Dyke Lifts 5[1]	Dyke Core Rock	Mechanical	Not applicable	
Infill 5[1]	General Fill and Berm Filter	Hydraulic	Not applicable	

[1] Partially or fully above water

4.1 West Basin Perimeter Dyke Lifts 1 to 4: Hopper and Flat-Deck Operations

The West Basin Infill consists of approximately 681,600 m^3 of total material (i.e. including dykes, mattress, etc.) of which 432,000 m^3 is general fill and berm filter material that contains an approximately 5% fines content and is, hence, simulated in this study. The modelling presented in this section is based on conceptual plan for infilling and dyke construction, and may be modified by the contractor during the design stage. Infill will proceed in a series of five 4.5 m trapezoidal perimeter dyke lifts, with infill contained behind the rising dykes. Infill of the perimeter dykes will proceed with hopper and flat-deck barge placement of fill material, with the barges floated over the perimeter dykes while there is sufficient clearance. For perimeter dyke lifts 1, 2 and 3 there will be clearance to allow direct placement of the fill material. Following perimeter dyke lift 4, the dyke crest will penetrate the water surface at low tide and, therefore, the entire basin footprint will regularly dry as the infilling operation progresses from empty to full. A simulation of the infill of perimeter dyke lift 4 using a flat deck barge for an empty berm condition is included in this section but not a full berm as filling mechanism for this condition was not established at the time of writing. The following dyke crest elevations at the West Basin Infill have been assumed:

- Perimeter Dyke Lift 1: crest elevation -11.0 m CD, toe elevation variable
- Perimeter Dyke Lift 2: crest elevation -6.5 m CD, toe elevation -11.0 m CD
- Perimeter Dyke Lift 3: crest elevation -2.0 m CD, toe elevation -6.5 m CD
- Perimeter Dyke Lift 4: crest elevation +2.5 m CD, toe elevation +2.5 m CD
- Perimeter Dyke Lift 5: crest elevation: +7.0 m CD, toe elevation +2.5 m CD

The West Basin is in a relatively exposed location, being located in the path of the flood tide jet originating in First Narrows. During ebb tides, complex flow patterns along the face of Centerm result from the ebb tide jet from Second Narrows entering central Vancouver Harbour. The proposed construction sequence of the West Basin Infill, however, provides effective sheltering and serves to mitigate the worst effects of fugitive TSS loss:

- **Caisson Installation:** by installing the caissons fronting the western infill of CEP, a relatively sheltered infill zone is created, limiting flushing of the infill zone and, hence, the potential for far-field TSS plume dispersal.
- **Perimeter Dyke Lift Sequence:** the highest concentration of TSS released by hopper barge filling is within a few meters of the seabed. This sediment laden water is denser than then surrounding seawater and tends to remains near the bed. As the Perimeter Dykes are typically several meters above the infill level, they provide a barrier to the dispersal of TSS, effectively damming the TSS as a lens of dense near bed water.

This relationship between caisson sheltering and the dyke containment of TSS laden water results in relatively modest TSS losses to Vancouver Harbour as the perimeter dykes typically contain the TSS plume while the sheltered environments behind the caissons enables far more settling that would otherwise be possible.

The concentration of fugitive TSS arising from infilling at the West Basin is governed the plume's interaction with ambient currents which are, in turn, mediated by the perimeter dyke elevation and fill level behind the dykes. As the TSS plume is transported by the currents away from its source location, the concentration of the plume is reduced by mixing with the ambient waters of Burrard Inlet. The faster the plume is transported away from its source location, higher concentration it will tend to be as there has been less time for settling and dispersion, however, faster currents tend to mix the plume more efficiently with the surround water, lowering its concentration. Therefore, at any given location the concentration of the plume reflects a balance between mixing and transport caused by the ambient currents. During periods of lower ambient currents within the perimeter dykes, which are more prevalent at the West Basin at low dyke elevations and low fill levels, the TSS plume tends to be 'transport governed' meaning that

the plume is transported away from its source as a relatively higher concentration. At higher dyke elevations and at high fill levels, currents within the perimeter dykes tend to be higher, leading to a 'dilution governed' plume that is diluted to a relatively low concentration as it is being transported away from its source.

Figures 4.1, 4.4, 4.7 and 4.10 present the fugitive TSS plumes resulting from infilling operations following Perimeter Dyke Lifts 1, 2, 3 and 4, respectively. These figures present the fugitive TSS pattern resulting from an empty Perimeter Dyke (i.e. dyke crest 4.5 m above fill level) immediately following the dyke lift. Figures 4.2, 4.5, and 4.8 present the fugitive TSS plumes resulting from infilling operations immediately prior to perimeter dyke Lifts 2, 3 and 4, respectively. These figures present the fugitive TSS pattern resulting from a full Perimeter Dyke (i.e. dyke crest at fill level) immediately prior to the next dyke lift.

On these figures, the top panel presents the probability of the water column maximum TSS exceeding 5 mg/L during the infill operation. For example, a 5% probability indicates that for a 14 day infill cycle, the maximum above-background concentration of TSS will exceed 5 mg/L for approximately 17 hours over the entire infill period or, alternatively, 1 hour and 12 minutes per day. The middle panel of these figures shows this same information for an exceedance threshold of 25 mg/L, while the bottom panel shows the probability that the maximum above background TSS concentration will be greater than 10% of the initial source strength. Based on these figures, the following generalizations can be made:

- With the exception of Dyke Lift 3, "empty" perimeter dyke cases have a larger maximum TSS plume above 5 mg/L and 25 mg/L as compared to the "Full" perimeter dyke cases. This is because the TSS plume generated during the full perimeter dyke condition is diluted comparatively faster below 5/25 mg/L than during the empty case when the TSS plumes are sheltered from the strongest currents and, hence, mixing by the dykes.

- The full condition of Dyke Lift 3 has a larger TSS plume footprint than the empty condition because a combination of the sheltering that is provided by the caissons (which is independent of dyke elevation) and the near-surface position of the TSS plume due to its shallow initial release depth. Because the plume is initially confined to the near-surface waters by the shallow depth of the full Dyke Lift 3, when it exits the shadow of the caissons it is exposed to relatively high velocity surface currents which transport the plume comparatively farther than the slightly deeper empty Dyke Lift 3 case.

- As the dykes are built progressively higher (Perimeter Dyke 1 is the lowest, Perimeter Dyke 4 is the highest) the footprint of the TSS plume above 5 mg/L and 25 mg/L becomes smaller. This is because the more modest currents present at deeper depths (e.g. Perimeter Dyke 1) transport the TSS plume away from its source with much less dilution than the stronger near-surface currents that are present as the dykes rise through the water column (e.g. Perimeter Dyke 3). Therefore, as the dykes are built upwards, dilution increases and, hence, the faster the maximum TSS concentration drops below 5/25 mg/L.

- For the 25 mg/L plots for Perimeter Dykes 2 and 3, there is a blocky edge that is apparent. This edge traces the outline of the hopper barge dump location, hence the blockiness.

- For all cases except dyke lift 4, the probability of exceeding 10% of the source concentration at any given instant is always << 1% as the initial TSS concentration associated with the infilling operation is very high and attenuates rapidly. During infilling following dyke Lift 4 the maximum TSS concentration often exceeds 10% of the source concentration, mainly because infilling the perimeter dyke elevation following lift 4 penetrates the water's surface at low tide, occasionally trapping TSS in a perched pool of water behind the dykes.

Tables 4.2 and 4.3 present a summary of the data underlying the above figures for full and empty perimeter dyke cases, respectively. From these tables it is apparent that the probability of exceeding either 5 mg/L or 25 mg/L outside of the perimeter dyke footprint is relatively small, never exceeding 10% beyond 100 m from the dykes and rarely exceeding 1% beyond 150 m from the dykes.

Table 4.2: Distance from Infill Boundary to Achieve Maximum TSS of 5 mg/L and 25 mg/L, Empty Perimeter Dyke

Probability of Exceedance[1]	Infill 1		Infill 2		Infill 3		Infill 4		Unit
	5 mg/L	25 mg/L	5 mg/L	25 mg/L	5 mg/L	25 mg/L	5 mg/L	25 mg/L	
90%	Contained within Perimeter Dykes	Contained within Perimeter Dykes	Contained within Perimeter Dykes	Contained within Perimeter Dykes	Contained within Perimeter Dykes	Contained within Perimeter Dykes	Within Per. Dykes	Contained within Perimeter Dykes	m
80%									m
70%									m
60%									m
50%									m
40%									m
30%									m
20%							50		m
10%	60		50		25		60		m
1%	190	40	150		50		70	30	m

[1] The probability that the instantaneous water-column maximum TSS will exceed a given value over the infill period. For example, a 1% probability of exceeding 5 mg/L indicates that, over a 14 day infill period, the maximum TSS in the water column may exceed 5 mg/L for a total of 3 hours and 20 minutes.

Table 4.3: Distance from Infill Boundary to Achieve Maximum TSS of 5 mg/L and 25 mg/L, Full Perimeter Dyke

Probability of Exceedance[1]	Infill 1		Infill 2		Infill 3		Infill 4		Unit
	5 mg/L	25 mg/L	5 mg/L	25 mg/L	5 mg/L	25 mg/L	5 mg/L	25 mg/L	
90%	Contained within Perimeter Dykes	Contained within Perimeter Dykes	Contained within Perimeter Dykes	Contained within Perimeter Dykes	Contained within Perimeter Dykes	Contained within Perimeter Dykes			m
80%									m
70%									m
60%									m
50%									m
40%									m
30%									m
20%	50								m
10%	60		60		25				m
1%	90		70		100	30			m

[1] The probability that the instantaneous water-column maximum TSS will exceed a given value over the infill period. For example, a 1% probability of exceeding 5 mg/L indicates that, over a 14 day infill period, the maximum TSS in the water column may exceed 5 mg/L for a total of 3 hours and 20 minutes.

Figures 4.3, 4.6, 4.9, 4.11 present time-series of the fugitive TSS concentration crossing a 100 m threshold from the crest of the perimeter dykes for Perimeter Dyke Lifts 1, 2, 3 and 4, respectively. The top panel of these figures presents the maximum fugitive TSS concentration exiting a 100 m perimeter around the infill zone, the second from the top panel presents the maximum average fugitive TSS concentration crossing this boundary (this is most directly applicable to CCME guidelines), the second from the bottom panel presents the tidal level at Point Atkinson and the bottom panel presents the source TSS concentration. Note the difference in the vertical axis scale between the top and the second from the top panel graphs.

From these plots it is apparent that for the vast majority of the infilling operation the maximum concentration of fugitive TSS exiting a 100 m threshold from the perimeter dykes is below 5 mg/L, with episodic spikes with a duration typically less than 4 hours with a typical concentration between 50 mg/L and 100 mg/L. The maximum average TSS concentration rarely exceeds 5 mg/L, and only does so during episodic spikes to a typical concentration between 5 mg/L and 10 mg/L with a similar duration of less than 4 hours. Tables 4.4 and 4.5 summarize the data presented in these figures for empty and full perimeter dyke cases, respectively. Taken over all perimeter dyke elevations, the CCME standard for TSS (5 mg/L) may be exceeded 1% of the time beyond 100 m from the dyke crest. When the 5 mg/L is exceeded, however, maximum TSS concentrations as high as 231 mg/L are possible, with a maximum average concentrations as high as 11 mg/L 100 m from the edge of the dyke crest.

Table 4.4: Maximum Average and Maximum Concentration 100 m Infill Boundary, Empty Berm

Percentile	Infill 1		Infill 2		Infill 3		Infill 4		Unit
	Maximum Average [1]	Maximum[2]	Maximum Average [1]	Maximum[2]	Maximum Average [1]	Maximum[2]	Maximum Average [1]	Maximum[2]	
Maximum	8.7	81.6	10.8	110.3	6.9	230.6	3.2	13.8	mg/L
99[3]	1.8	6.9	1.2	4.3	1.7	2.2	1.5	2.6	mg/L
95	0.7	1.6	0.5	1.1	0.8	0.5	1.0	0.7	mg/L
90	0.4	0.7	0.3	0.5	0.5	0.3	0.7	0.3	mg/L
50	0.1	0.1	0.1	0	0.1	0	0.2	0	mg/L
10	0	0	0	0	0	0	0	0	mg/L
Minimum	0	0	0	0	0	0	0	0	mg/L

[1] Percentile, maximum and minimum values are calculated from the water column average TSS concentration at 1 hour intervals.
[2] Percentile, maximum and minimum values are calculated from the water column maximum TSS concentration at 15 minute intervals. Therefore, the Maximum value occurs for *less than* 15 minutes out of 14 days at a 10 m by 10 m by 1 m parcel of water in Vancouver Harbour.
[3] The 99th percentile concentrations is the TSS concentration at which 99% of all other possible TSS concentrations occurring in time and space will be lower than the 99th percentile. Any concentrations greater than the 99th percentile will occur for only 3 hours and 20 minutes out of a 14 day infill period.

Table 4.5: Maximum Average and Maximum Concentration 100 m Infill Boundary, Full Berm

Percentile	Infill 1		Infill 2		Infill 3		Infill 4		Unit
	Maximum Average [1]	Maximum[2]	Maximum Average [1]	Maximum[2]	Maximum Average [1]	Maximum[2]	Maximum Average [1]	Maximum[2]	
Maximum	6.0	166.0	5.3	209.9	3.4	20.1			mg/L
99[3]	1.6	3.1	1.6	2.9	0.8	3.5			mg/L
95	0.8	0.8	0.8	0.9	0.3	0.7			mg/L
90	0.6	0.4	0.6	0.4	0.2	0.3			mg/L
50	0.1	0	0.1	0	0	0			mg/L
10	0	0	0	0	0	0			mg/L
Minimum	0	0	0	0	0	0			mg/L

[1] Percentile, maximum and minimum values are calculated from the water column average TSS concentration at 1 hour intervals.
[2] Percentile, maximum and minimum values are calculated from the water column maximum TSS concentration at 15 minute intervals. Therefore, the Maximum value occurs for *less than* 15 minutes out of 14 days at a 10 m by 10 m by 1 m parcel of water in Vancouver Harbour.
[3] The 99th percentile concentrations is the TSS concentration at which 99% of all other possible TSS concentrations occurring in time and space will be lower than the 99th percentile. Any concentrations greater than the 99th percentile will occur for only 3 hours and 20 minutes out of a 14 day infill period.

4.2 East Basin Perimeter Dyke Lifts 1 to 4: Hopper and Flat-Deck Operations

The East Basin Infill consists of approximately 900,000 m^3 of total material (i.e. including dykes, mattress, etc.) of which 528,000 m^3 is general fill material that contains an approximately 5% fines content and is, hence, simulated in this study. The modelling presented in this section is based on conceptual plan for infilling and dyke construction, and may be modified by the contractor during the design stage. Infill will proceed in a series of five 4.5 m trapezoidal perimeter dyke lifts, with infill contained behind the rising dykes. Infill of the perimeter dykes will proceed with hopper and flat-deck barge placement of fill material, with the barges floated over the perimeter dykes while there is sufficient clearance. For perimeter dyke lifts 1, 2 and 3 there will almost certainly be clearance to allow direct placement of the fill material. Following perimeter dyke lift 4, the dyke crest will penetrate the water surface at low tide and, therefore, the entire basin footprint will regularly dry as the infilling operation progresses from empty to full. A simulation of the infill of perimeter dyke lift 4 using a flat deck barge for an empty berm condition is included in this section but not a full berm as filling mechanism for this condition was not established at the time of writing. The following dyke crest elevations at the East Basin Infill have been assumed:

- Perimeter Dyke Lift 1: crest elevation -11.5 m CD, toe elevation variable
- Perimeter Dyke Lift 2: crest elevation -6.0 m CD, toe elevation -11.5 m CD
- Perimeter Dyke Lift 3: crest elevation -2.5 m CD, toe elevation -6.0 m CD
- Perimeter Dyke Lift 4: crest elevation +2.0 m CD, toe elevation -2.5 m CD
- Perimeter Dyke Lift 5: crest elevation: +6.5 m CD, toe elevation +2.0 m CD

The East Basin Infill is in a relatively sheltered location, being located in an embayment between Ballantyne Pier and Southern Railway Pier. The location of the East Basin within Vancouver Harbour and the surrounding currents generally act to supress the dispersion of fugitive TSS releases from the infill operation:

- **Tidal Currents:** the East Basin Infill is generally subject to mild currents with flood tides producing a weak clockwise circulation offshore of the infill location and ebb tides producing a counter-clockwise gyre between Ballantyne Pier and Vanterm. As a result of these generally constrained circulation patterns, TSS released during the East Basin Infilling operation does not tend to disperse far beyond the northern edge of Centerm.
- **Basin Confinement:** The East Basin Infill is constrained by the shoreline on three sides, limiting tidal agitation to simple exchange flows as the water level of Vancouver Harbour rises and falls, rather than the strong tidal currents generated by First and Second Narrows. Therefore the dispersion potential of sediments from the East Basin Infill is relatively low.

The concentration of fugitive TSS arising from infilling at the East Basin is governed the tidal exchange in the confined basin between the Ballantyne and Southern Railway Piers and the plume's interaction with ambient currents once outside of this embayment. At low perimeter dyke elevations where the dykes present little obstacle to TSS transport, the TSS plume is transported by ambient currents away from its source location and the concentration of the plume is reduced by mixing with the waters of Burrard Inlet. As the perimeter dykes are build upwards through the water column, at mid-depth elevations they present a barrier to plume transport and act to confine TSS in the East Basin footprint. As the perimeter dykes approach the surface, the tidal velocities over the dyke crest becomes stronger because the same tidal prism (i.e. tidal exchange volume) is flowing through a smaller cross-sectional area. These more vigorous tidal currents lead to a larger TSS plume footprint as the dykes approach the surface.

Figures 4.12, 4.15, 4.18 and 4.21 present the maximum fugitive TSS plumes resulting from infilling operations following Perimeter Dyke Lifts 1, 2, 3 and 4, respectively. This condition is representative of an empty Perimeter Dyke (i.e. dyke crest 4.5 m above fill level) immediately following the dyke lift. Figures 4.13, 4.16, and 4.19 present the fugitive TSS plumes resulting from infilling operations immediately prior to Perimeter Dyke Lifts 2, 3 and 4, respectively. This condition is representative of a full Perimeter Dyke (i.e. dyke crest at fill level) immediately prior to the next dyke lift.

On these figures, the top panel presents the probability of the water column maximum TSS exceeding 5 mg/L during the infill operation. For example, a 5% probability indicates that for a 14 day infill cycle, the maximum above-background concentration of TSS will exceed 5 mg/L for approximately 17 hours over 14 days or, alternatively, 1 hour and 12 minutes per day. The middle panel of these figures shows this same information for an exceedance threshold of 25 mg/L, while the bottom panel shows the probability that the maximum above background TSS concentration will be greater than 10% of the initial source strength. Based on these figures, the following comparisons between the TSS behaviour at rising dyke elevations can be made:

- **Perimeter Dyke Lift 1:** The perimeter dyke crest is essentially at grade along much of the infill footprint between Ballantyne and Southern Railway Piers and, as a result, presents little impediment to the dispersal of TSS. Hence, there is no clear trend between the “empty” and “full” cases as there is always an escape path for the TSS, regardless of the fill level behind the berm.

- **Perimeter Dyke Lift 2:** The perimeter dyke crest is up to 4.5m above the surrounding grade and, therefore, presents an impediment to TSS dispersal. This is why the TSS plume resulting from the infill of perimeter dyke lift 2 is significantly smaller than for lift 1.

- **Perimeter Dyke Lift 3:** Since the perimeter dyke crest is now approaching the surface, TSS dispersal is enhanced by flow acceleration over the dyke crest and the generally higher near surface velocities in Vancouver Harbour. Therefore, the TSS plume resulting from the infill of perimeter dyke lift 3 is larger than that of both lift 1 and lift 2. Consistent with the results of the West Basin Infill, as the dyke crest approaches the surface there is a more marked difference in the shape of the TSS plume based on whether the dyke is “empty” or “full”.

- **Perimeter Dyke Lift 4:** The trend of increasing TSS plume footprint with increasing dyke elevation identified at Perimeter Dyke Lift 3 continues, with the increased tidal flow velocity over the dyke crests leading to enhanced plume transport.

Tables 4.6 and 4.7 present a summary of the data underlying the above figures for full and empty perimeter dyke cases, respectively. From these tables it is apparent that the probability of the maximum TSS exceeding either 5 mg/L or 25 mg/L outside of the perimeter dyke footprint is relatively small, never exceeding 30% beyond 20 m from the dykes and rarely exceeding 1% beyond 380 m from the dykes. From these tables, it is apparent that Dyke Lift 2 has much lower maximum TSS levels compared to all other dyke lifts. This is because, at this mid-depth elevation, the dykes present an effective barrier to plume transport while, at the same time, do not rise high enough in the water column to significantly accelerate tidal exchange flows over the dykes and, hence, draw the TSS plume into Burrard Inlet.

Table 4.6: Distance from Infill Boundary to Achieve Maximum TSS of 5 mg/L and 25 mg/L, Empty Perimeter Dyke

Probability of Exceedance	Infill 1		Infill 2		Infill 3		Infill 4		Unit
	5 mg/L	25 mg/L	5 mg/L	25 mg/L	5 mg/L	25 mg/L	5 mg/L	25 mg/L	
90%	Contained within Perimeter Dykes	Contained within Perimeter Dykes	Contained within Perimeter Dykes	Contained within Perimeter Dykes	Contained within Perimeter Dykes	Contained within Perimeter Dykes	Within Dykes	Contained within Perimeter Dykes	m
80%									m
70%									m
60%									m
50%									m
40%									m
30%							20		m
20%							50		m
10%	40	20	10		40		90	50	m
1%	170	60	40		290	40	380	130	m

[1] The probability that the instantaneous water-column maximum TSS will exceed a given value over the infill period. For example, a 1% probability of exceeding 5 mg/L indicates that, over a 14 day infill period, the maximum TSS in the water column may exceed 5 mg/L for a total of 3 hours and 20 minutes.

Table 4.7: Distance from Infill Boundary to Achieve Maximum TSS of 5 mg/L and 25 mg/L, Full Perimeter Dyke

Probability of Exceedance	Infill 1		Infill 2		Infill 3		Infill 4		Unit
	5 mg/L	25 mg/L	5 mg/L	25 mg/L	5 mg/L	25 mg/L	5 mg/L	25 mg/L	
90%	Contained within Perimeter Dykes	Contained within Perimeter Dykes	Contained within Perimeter Dykes	Contained within Perimeter Dykes	Within Per. Dykes	Contained within Perimeter Dykes			m
80%									m
70%									m
60%									m
50%									m
40%									m
30%									m
20%									m
10%	50	20	10		50				m
1%	100	60	50		330	40			m

[1] The probability that the instantaneous water-column maximum TSS will exceed a given value over the infill period. For example, a 1% probability of exceeding 5 mg/L indicates that, over a 14 day infill period, the maximum TSS in the water column may exceed 5 mg/L for a total of 3 hours and 20 minutes.

Figures 4.14, 4.17, 4.20, 4.22 present the fugitive TSS concentration crossing a 100 m threshold from the crest of the perimeter dykes for perimeter dyke lifts 1, 2, 3 and 4, respectively. The top panel of these figures presents the maximum fugitive TSS concentration exiting a 100 m perimeter around the infill zone, the second from the top panel presents the maximum average fugitive TSS concentration crossing this boundary (this is most directly applicable to CCME guidelines), the second from the bottom panel presents the tidal level at Point Atkinson and the bottom panel presents the source TSS concentration..

From these plots it is apparent that for the vast majority of the infilling operation the maximum concentration of fugitive TSS exiting a 100 m threshold from the perimeter dykes is below 5mg/L, with episodic spikes with a duration typically less than 4 hours with a typical concentration less than 100 mg/L. The maximum average TSS concentration above background rarely exceeds 5 mg/L, and only does so during episodic spikes to a concentration typically less than 10 mg/L and never more than 20 mg/L, with a duration less than 4 hours. Tables 4.8 and 4.9 summarize the data presented in these figures for empty and full perimeter dyke cases, respectively. Taken over all perimeter dyke elevations, the above background fugitive TSS concentration of 5 mg/L will be exceeded 2% of the time beyond 100 m from the dyke crest. When the 5 mg/L is exceeded, however, maximum TSS concentrations as high as 207 mg/L and maximum average concentrations as high as 20 mg/L are possible 100 m from the dyke crest.

Table 4.8: Maximum Average and Maximum Concentration 100 m Infill Boundary, Empty Berm

Percentile	Infill 1		Infill 2		Infill 3		Infill 4		Unit
	Maximum Average [1]	Maximum[2]	Maximum Average [1]	Maximum[2]	Maximum Average [1]	Maximum[2]	Maximum Average [1]	Maximum[2]	
Maximum	19.8	207.1	8.7	9.4	9.3	45.5	14.8	137.6	mg/L
99[3]	4.2	6.3	2.0	1.9	2.5	8.0	3.7	13.2	mg/L
95	2.1	1.8	1.0	0.7	1.2	2.3	2.0	4.0	mg/L
90	1.4	0.9	0.7	0.3	0.8	0.9	1.4	2.0	mg/L
50	0.3	0	0.1	0	0.1	0.1	0.3	0.1	mg/L
10	0	0	0	0	0	0	0	0	mg/L
Minimum	0	0	0	0	0	0	0	0	mg/L

[1] Percentile, maximum and minimum values are calculated from the water column average TSS concentration at 1 hour intervals.

[2] Percentile, maximum and minimum values are calculated from the water column maximum TSS concentration at 15 minute intervals. Therefore, the Maximum value occurs for *less than* 15 minutes out of 14 days at a 10 m by 10 m by 1 m parcel of water in Vancouver Harbour.

[3] The 99th percentile concentrations is the TSS concentration at which 99% of all other possible TSS concentrations occurring in time and space will be lower than the 99th percentile. Any concentrations greater than the 99th percentile will occur for only 3 hours and 20 minutes out of a 14 day infill period.

Table 4.9: Maximum Average and Maximum Concentration 100 m Infill Boundary, Full Berm

Percentile	Infill 1		Infill 2		Infill 3		Infill 4		Unit
	Maximum Average [1]	Maximum[2]	Maximum Average [1]	Maximum[2]	Maximum Average [1]	Maximum[2]	Maximum Average [1]	Maximum[2]	
Maximum	10.1	84.0	7.4	13.7	7.6	97.8			mg/L
99[3]	3.8	4.9	2.2	2.5	2.6	8.8			mg/L
95	1.8	1.4	1.1	0.8	1.1	1.9			mg/L
90	1.1	0.7	0.7	0.4	0.7	0.9			mg/L
50	0.2	0	0.1	0	0.1	0.1			mg/L
10	0	0	0	0	0	0			mg/L
Minimum	0	0	0	0	0	0			mg/L

[1] Percentile, maximum and minimum values are calculated from the water column average TSS concentration at 1 hour intervals.

[2] Percentile, maximum and minimum values are calculated from the water column maximum TSS concentration at 15 minute intervals. Therefore, the Maximum value occurs for *less than* 15 minutes out of 14 days at a 10 m by 10 m by 1 m parcel of water in Vancouver Harbour.

[3] The 99th percentile concentrations is the TSS concentration at which 99% of all other possible TSS concentrations occurring in time and space will be lower than the 99th percentile. Any concentrations greater than the 99th percentile will occur for only 3 hours and 20 minutes out of a 14 day infill period.

4.3 Fugitive TSS Peaks

The concentration of TSS resulting from individual hopper barge deliveries to the east and west basins is tied to the tidal phase and hopper dump location: certain locations within the infill basins are more prone to fugitive TSS release under specific tidal conditions. For each perimeter dyke elevation, TSS peaks have been investigated to determine the mechanisms that may generate the largest TSS peaks and recommendations been developed to potentially reduce the largest simulated peaks.

An example of the influence of tidal conditions that drives this spatial and temporal variation in TSS peak formation can be found by comparing Figures 4.23 and 4.24. The top panel of these figures shows the hopper barge position at the time of the dump resulting in a TSS peak (red) and a subsequent dump (green) that does not. The second panel shows the maximum of the water column maximum TSS concentration along the 100 m boundary from the perimeter dykes. The red line shows the TSS resulting from dumps occurring behind full perimeter dykes and the black line shows the TSS resulting from dumps occurring behind empty perimeter dykes. The “red” hopper dump plotted in the top panel occurs at time -1:15 and the “green” hopper dump occurs at time +4:45. The third panel shows the equivalent maximum of the water column average TSS concentration along the 100 m boundary. The fourth panel shows the concurrent tidal level at Point Atkinson and the fifth panel shows the water column averaged source concentration with the red point indicating the hopper dump resulting in the TSS spike (matching the red barge position) and the green point indicating a subsequent hopper dump (batching the green barge position).

Figure 4.23 presents the TSS peak resulting from a hopper barge dump occurring near the perimeter dyke edge during a flood time, while Figure 4.24 presents a very similar hopper dump occurring during an ebb tide. By comparing these figures, it is apparent that the same hopper dump operation can result in radically different fugitive TSS concentrations, depending on whether it occurs during flood or ebb tide. The subsequent summary and recommendations presented in Sections 4.3.1 and 4.3.2 are based on this observation and similar observations of peak TSS events at the both basins for all perimeter dyke elevations.

4.3.1 West Basin TSS Peaks

Filling of the eastern edge of the west basin rarely results in high concentration fugitive TSS releases, while filling of the north-east corner almost never results in significant fugitive TSS releases beyond the perimeter dykes. The most release-prone area of the west basin is the north-west corner. Below is a summary of the timing and potential mitigation measures for each perimeter dyke lift of the west basin.

- **Perimeter Dyke Lift 1:** the largest TSS peaks are associated with flood tide and are relatively insensitive to the position of the barge within the infill footprint.

  To minimize fugitive TSS release, infilling during flood tides should be avoided and barge deliveries should be timed to coincide with ebb tide and slack water.

- **Perimeter Dyke Lift 2:** the largest TSS peaks do not show a clear pattern between flood tide and high slack water, but in general flood tide and barge positions near the north-west infill corner result in larger TSS peaks.

  To minimize fugitive TSS release, infilling near the perimeter dyke edge and in the north-west corner of the basin should be avoided during flood tides.

- **Perimeter Dyke Lift 3:** the largest TSS peaks are associated with peak flood and ebb velocities and vessel positions near the edge of the perimeter dyke. Whether the tide is flooding or ebbing is less significant than the tidal current velocity and vessel position within the perimeter dykes.

To minimize fugitive TSS release, infilling near the perimeter dyke edges should occur during slack water or during the minor tide of the day.

- **Perimeter Dyke Lift 4:** the largest TSS peaks are associated with high tide and barge positions near the edge of the perimeter dyke.

  To minimize fugitive TSS release, infilling operations should be conducted when the perimeter dyke crest is dry and, otherwise, towards the east and north-east sections of the basin while the perimeter dyke crests are submerged.

4.3.2 East Basin TSS Peaks

Infilling of the southern end of the east basin rarely results in high concentration fugitive TSS releases, with fugitive releases occurring from this area at high berm elevations and during ebb tides. Infilling the northern side of the east basin, near the perimeter dyke edge, is prone to producing fugitive TSS releases, particularly at high berm elevations during ebb tide. Below is a summary of the timing and potential mitigation measures for each perimeter dyke lift of the east basin.

- **Perimeter Dyke Lift 1:** the largest TSS peaks are associated with flood tide infilling occurring near the edge of the perimeter dykes.

  To minimize fugitive TSS release infilling during slack and ebb tides is preferred.

- **Perimeter Dyke Lift 2:** the largest TSS peaks are associated with flood tide infilling occurring near the edge of the perimeter dykes.

  To minimize fugitive TSS release infilling during slack and flood tides is preferred.

- **Perimeter Dyke Lift 3:** The largest TSS peaks are strongly associated with infilling during ebb tide near the edge of the perimeter dykes.

  To minimize fugitive TSS release infilling during slack and flood tides is preferred.

- **Perimeter Dyke Lift 4:** The largest TSS peaks are associated with high tide, with a slight bias towards the high water turn to ebb.

  To minimize fugitive TSS release infilling during slack and flood tides is preferred.

5.0 CONCLUSION

Based on the results of this modelling study, it is apparent that the concentration and dispersal distance of the TSS plume arising from the infill operation can vary significantly depending on the elevation of the perimeter dyke crest and the specific type of equipment being used. The fugitive TSS concentrations arising from the East and West Basin Infills are approximately equal when all configurations are considered; however, the interaction between the local hydrodynamics, dyke crest elevation and TSS dispersal is complex and, while trends are present, the resulting TSS concentration is highly site specific. Section 5.1 presents site specific results for the West Basin Infill Zone and Section 5.2 presents results for the East Basin Infill Zone, followed by general recommendations for TSS monitoring locations.

5.1 West Basin Infill Zone

At the West Basin, the TSS plume footprint tends to shrink as the perimeter dykes are constructed higher in the water column. This is because at high dyke elevations the relatively fast currents near the surface tend to dilute the TSS plume as it is transported away from the West Basin. Comparatively, the relatively weak near bed currents present at low dyke elevations tend to transport the TSS plume with much lower mixing and dilution resulting in a larger plume footprint. Below, a specific summary for each dyke elevation is given:

- **Perimeter Dyke Lift 1:** modelling results of the West Basin Infill Zone infilling process suggest that project-derived maximum TSS concentration above background drops below 5 mg/L 190 m from source 99% of the time and is contained within the perimeter dyke footprint 70% to 80% of the time. The CCME standard for TSS (5 mg/L) may be exceeded 1% of the time beyond 100 m from the dyke crest at a peak maximum average concentration of 8.7 mg/L. To minimize fugitive TSS release, infilling during flood tides should be avoided and barge deliveries should be timed to coincide with ebb tide and slack water.

- **Perimeter Dyke Lift 2:** modelling results of the West Basin Infill Zone infilling process suggest that project-derived maximum TSS concentration above background drops below 5 mg/L 150 m from source 99% of the time and is contained within the perimeter dyke footprint 80% to 90% of the time. The CCME standard for TSS (5 mg/L) may be exceeded 1% of the time beyond 100 m from the dyke crest at a peak maximum average concentration of 10.8 mg/L. To minimize fugitive TSS release, infilling near the perimeter dyke edge and in the north-west corner of the basin should be avoided during flood tides.

- **Perimeter Dyke Lift 3:** modelling results of the West Basin Infill Zone infilling process suggest that project-derived maximum TSS concentration above background drops below 5 mg/L 100 m from source 99% of the time and is contained within the perimeter dyke footprint 80% to 90% of the time. The CCME standard for TSS (5 mg/L) may be exceeded 1% of the time beyond 100 m from the dyke crest at a peak maximum average concentration of 6.9 mg/L. To minimize fugitive TSS release, infilling near the perimeter dyke edges should occur during slack water or during the minor tide of the day.

- **Perimeter Dyke Lift 4:** modelling results of the West Basin Infill Zone infilling process suggest that project-derived maximum TSS concentration above background drops below 5 mg/L 70 m from source 99% of the time and is contained within the perimeter dyke footprint 70% to 80% of the time. The CCME standard for TSS (5 mg/L) is likely not to be exceeded beyond 100 m from the dyke crest; peak maximum average concentration is 3.2 mg/L. To minimize fugitive TSS release, infilling operations should be conducted when the perimeter dyke crest is dry and, otherwise, towards the east and north-east sections of the basin while the perimeter dyke crests are submerged.

5.2 East Basin Infill Zone

At the East Basin, as the perimeter dykes rise higher in the water column the TSS plume footprint grows in size due to the more vigorous tidal exchange over the perimeter dykes and the lower initial dilution volume as the basin shallows. The East Basin Infill has a generally larger TSS plume footprint compared to the West Basin because the weaker current velocities at the East Basin lead to lower mixing (hence dilution) with ambient waters. In all cases, TSS released at or near high water tends to disperse farther than releases at low water due to the outflow of sediment laden water over the perimeter dykes. Below, a specific summary for each dyke elevation is given:

- **Perimeter Dyke Lift 1:** modelling results of the East Basin Infill Zone infilling process suggest that project-derived maximum TSS concentration above background drops below 5 mg/L 170 m from source 99% of the time and is contained within the perimeter dyke footprint 80% to 90% of the time. The CCME standard for TSS (5 mg/L) may be exceeded 1% of the time beyond 100 m from the dyke crest at a peak maximum average concentration of 19.8 mg/L. To minimize fugitive TSS release infilling during slack and ebb tides is preferred.

- **Perimeter Dyke Lift 2:** modelling results of the East Basin Infill Zone infilling process suggest that project-derived maximum TSS concentration above background drops below 5 mg/L 60 m from source 99% of the time and is contained within the perimeter dyke footprint 80% to 90% of the time. The CCME standard for TSS (5 mg/L) may be exceeded 1% of the time beyond 100 m from the dyke crest at a peak maximum average concentration of 8.7 mg/L. To minimize fugitive TSS release infilling during slack and flood tides is preferred.

- **Perimeter Dyke Lift 3:** modelling results of the East Basin Infill Zone infilling process suggest that project-derived maximum TSS concentration above background drops below 5 mg/L 330 m from source 99% of the time and is contained within the perimeter dyke footprint 80% to 90% of the time. The CCME standard for TSS (5 mg/L) may be exceeded 1% of the time beyond 100 m from the dyke crest at a peak maximum average concentration of 9.3 mg/L. To minimize fugitive TSS release infilling during slack and flood tides is preferred.

- **Perimeter Dyke Lift 4:** modelling results of the East Basin Infill Zone infilling process suggest that project-derived maximum TSS concentration above background drops below 5 mg/L 380 m from source 99% of the time and is contained within the perimeter dyke footprint 60% to 70% of the time. The CCME standard for TSS (5 mg/L) may be exceeded 1% of the time beyond 100 m from the dyke crest at a peak maximum average concentration of 14.8 mg/L. To minimize fugitive TSS release infilling during slack and flood tides is preferred.

Following from the above analysis, the following locations for turbidity monitoring are recommended during dredging activities:

- **General Comments:** the highest TSS concentration tends to be concentrated near the bed, therefore, to capture high-turbidity events arising from construction a bottom-mounted monitoring station is recommended.

- **West Basin Infill Zone:** It is recommended to monitor turbidity on the west side of the caissons where they meet the perimeter dyke and on the southeast side of the infill where the perimeter dykes meet the existing Centerm fill. These two locations are the most consistent places where fugitive TSS exits the perimeter dyke footprint. The northeastern end of Canada Place and the northern tip of Main Street Dock would be effective far-field monitoring locations.

- **East Basin Infill Zone:** It is recommended to monitor turbidity at several locations along the perimeter dyke crest, particularly between Ballantyne and Southern Railway Piers. The eastern face of Centerm and the dock structures immediately north-east of Southern Railway Pier would be effective far-field monitoring locations.

6.0 CLOSURE

We trust this report meets your present requirements. If you have any questions or comments, please contact the undersigned.

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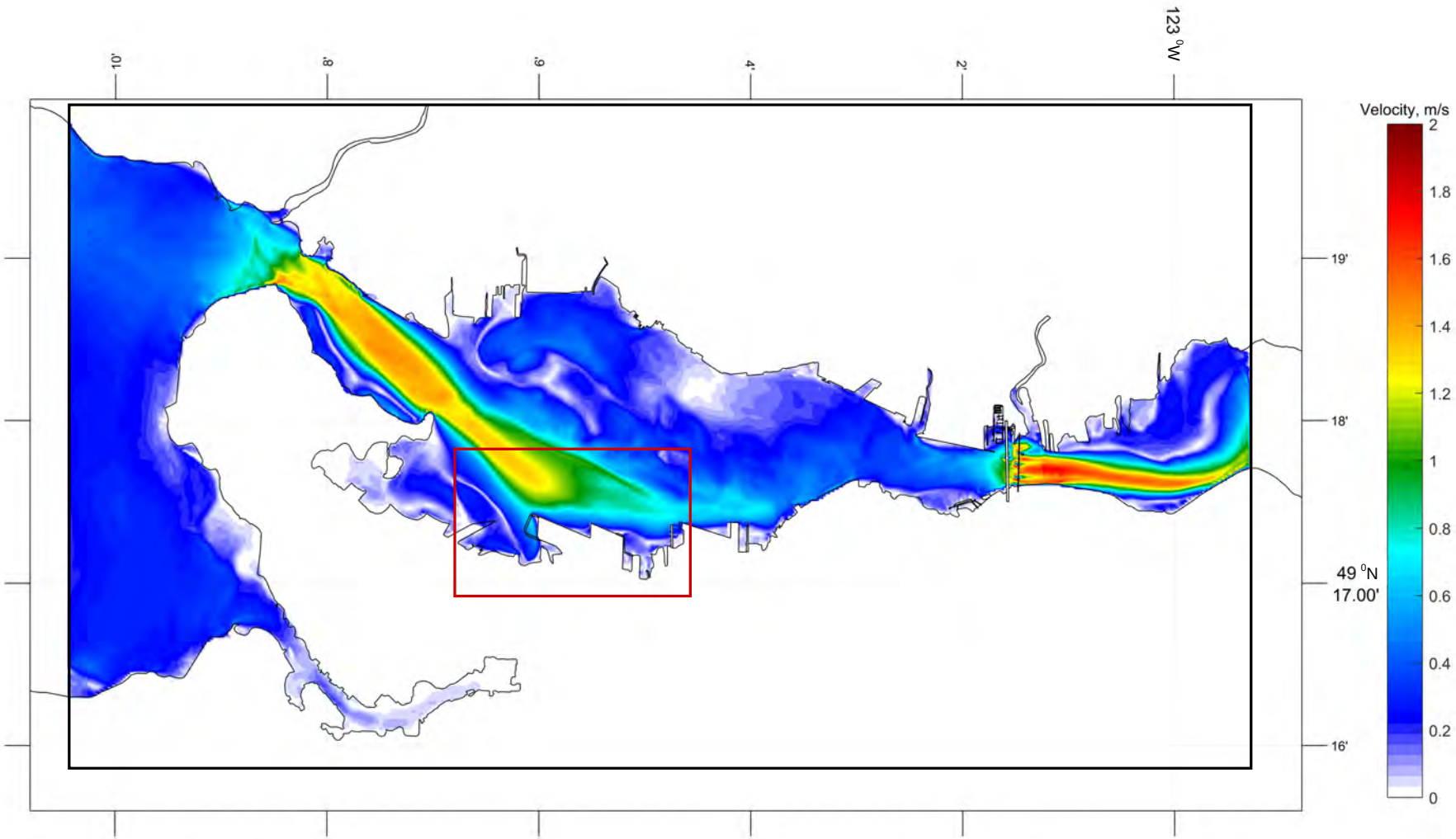
FIGURES



NOTES

1) Flow fields are presented for the existing Centerm geometry using Tetra Tech's 25-m and 10-m resolution models of Burrard Inlet.
2) Flow fields are visualized at during a moderate flood tide

25-m model boundary, nested into larger scale 125-m and 1000-m oceanographic models

10-m model boundary, nested into 25-m resolution model

STATUS
ISSUED FOR USE

CLIENT

AECOM

TETRA TECH

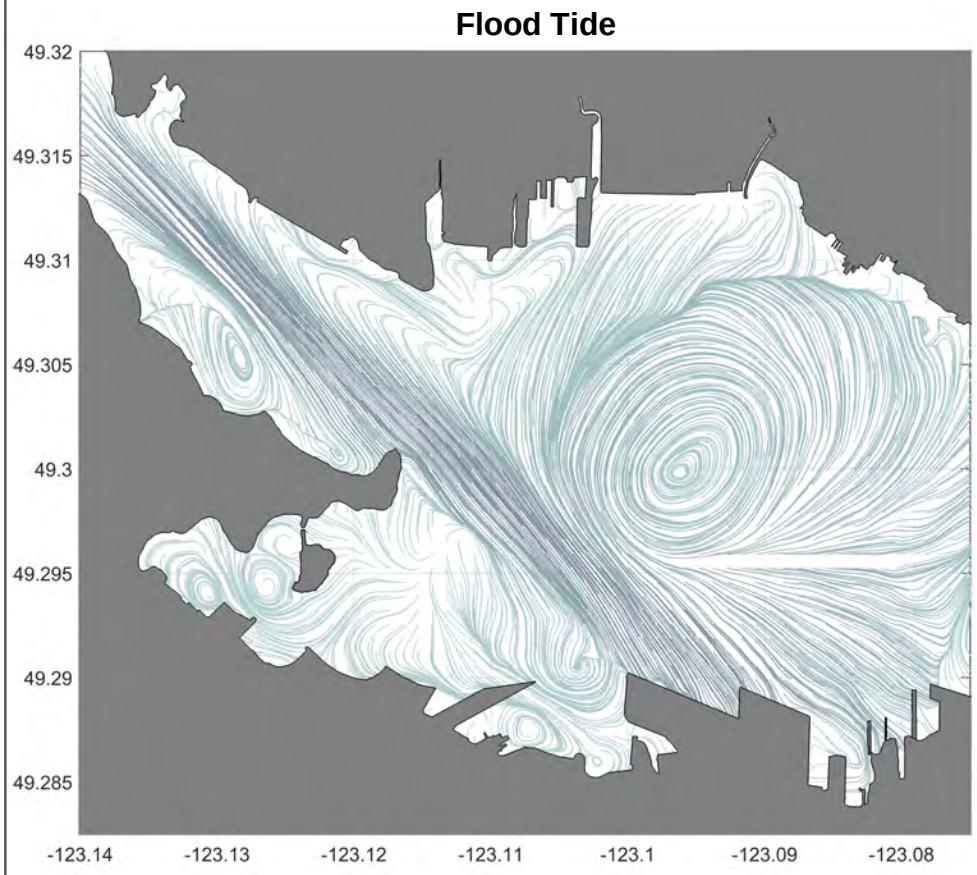
Dispersal Modelling of Infill Derived Fugitive Sediment

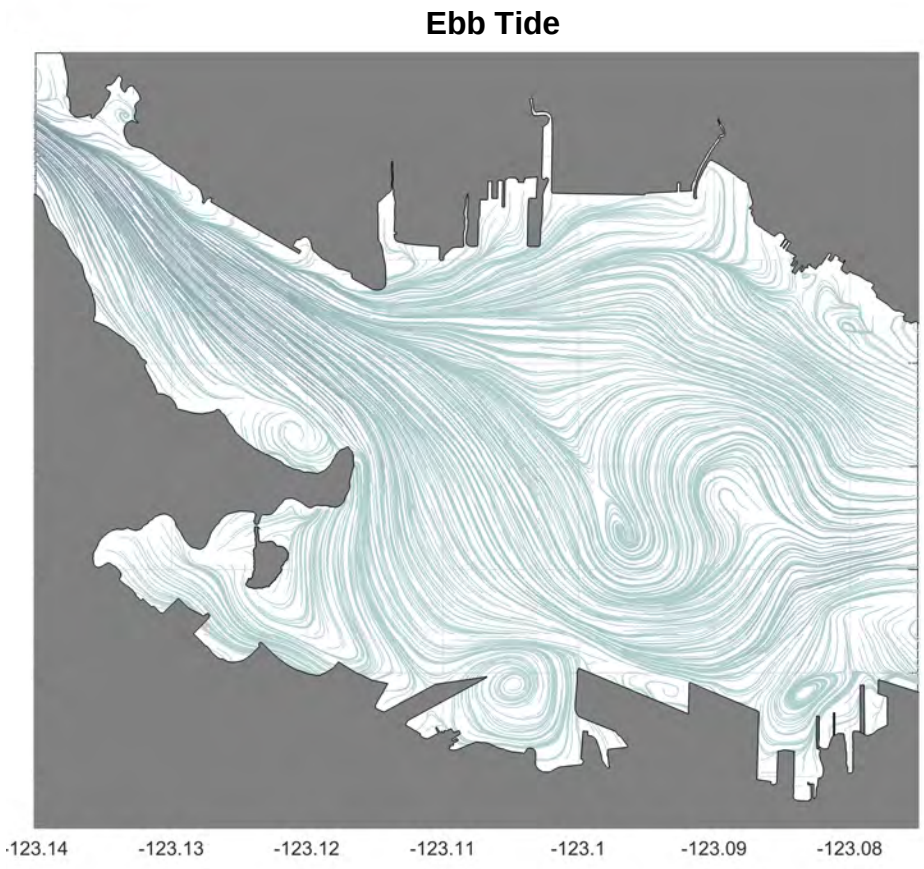
25-m and 10-m Resultion Models of Vancouver Harbour

PROJECT NO.	DWN	CKD	APVD	REV
WTRM.03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech - VANC	March, 2017

Figure 2.1





NOTES

Flow fields are presented for the existing Centerm geometry using Tetra Tech's 25-m resolution numeical model of Burrard Inlet.
Flow fields are visualized at peak flood and ebb flow during a moderate tide.

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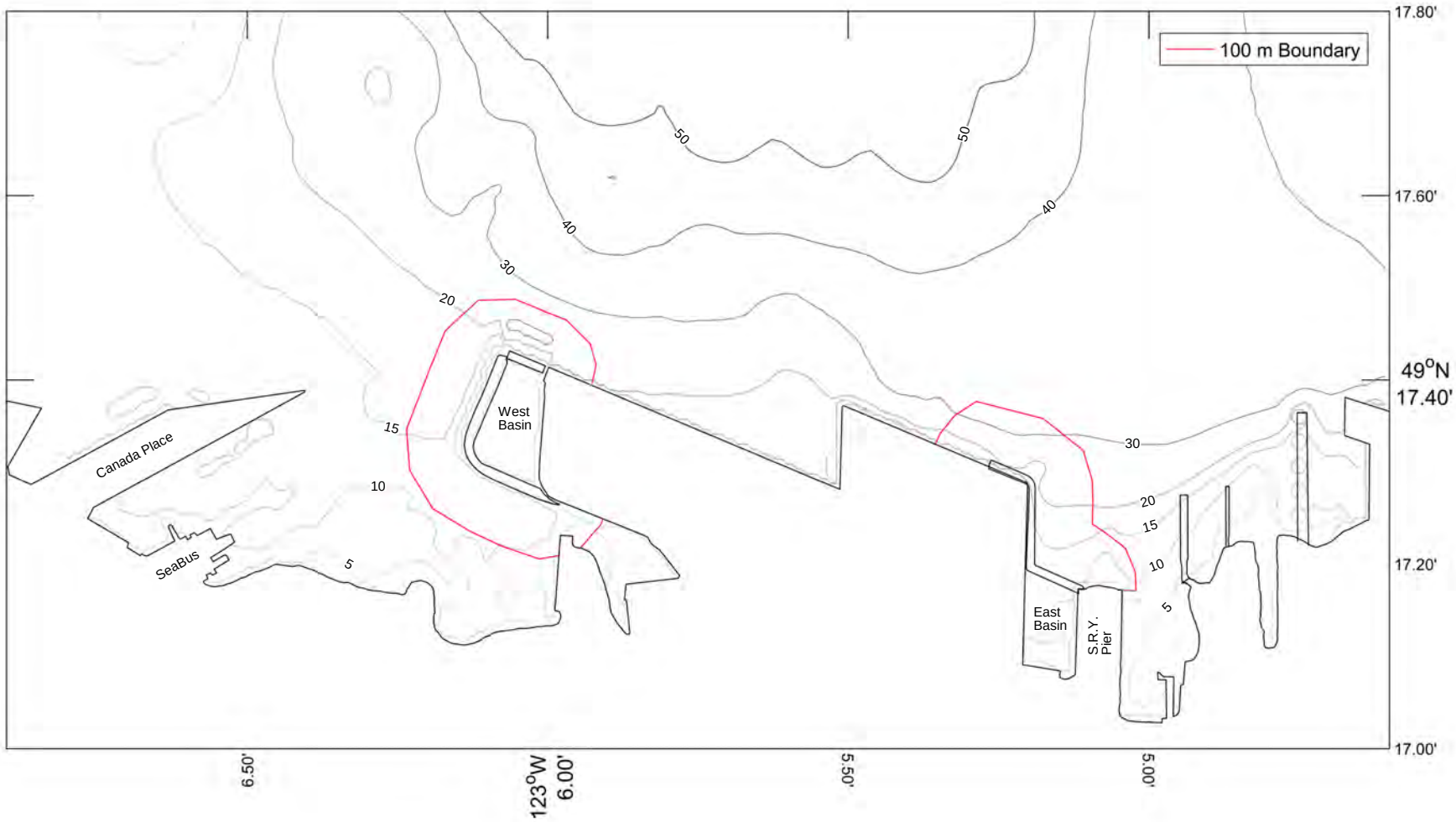
Dispersal Modelling of Infill Derived Fugitive Sediment

Flow Fields in Western Vancouver Harbour

PROJECT NO.	DWN	CKD	APVD	REV
WTRM.03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech - VANC	March, 2017

Figure 2.2



NOTES

1) West Basin is presented with perimeter dyke lift 3 in place and the northern caissons installed
2) East Basin in presented with perimeter dyke lift 3 in place and the current Ballantyne Pier outline

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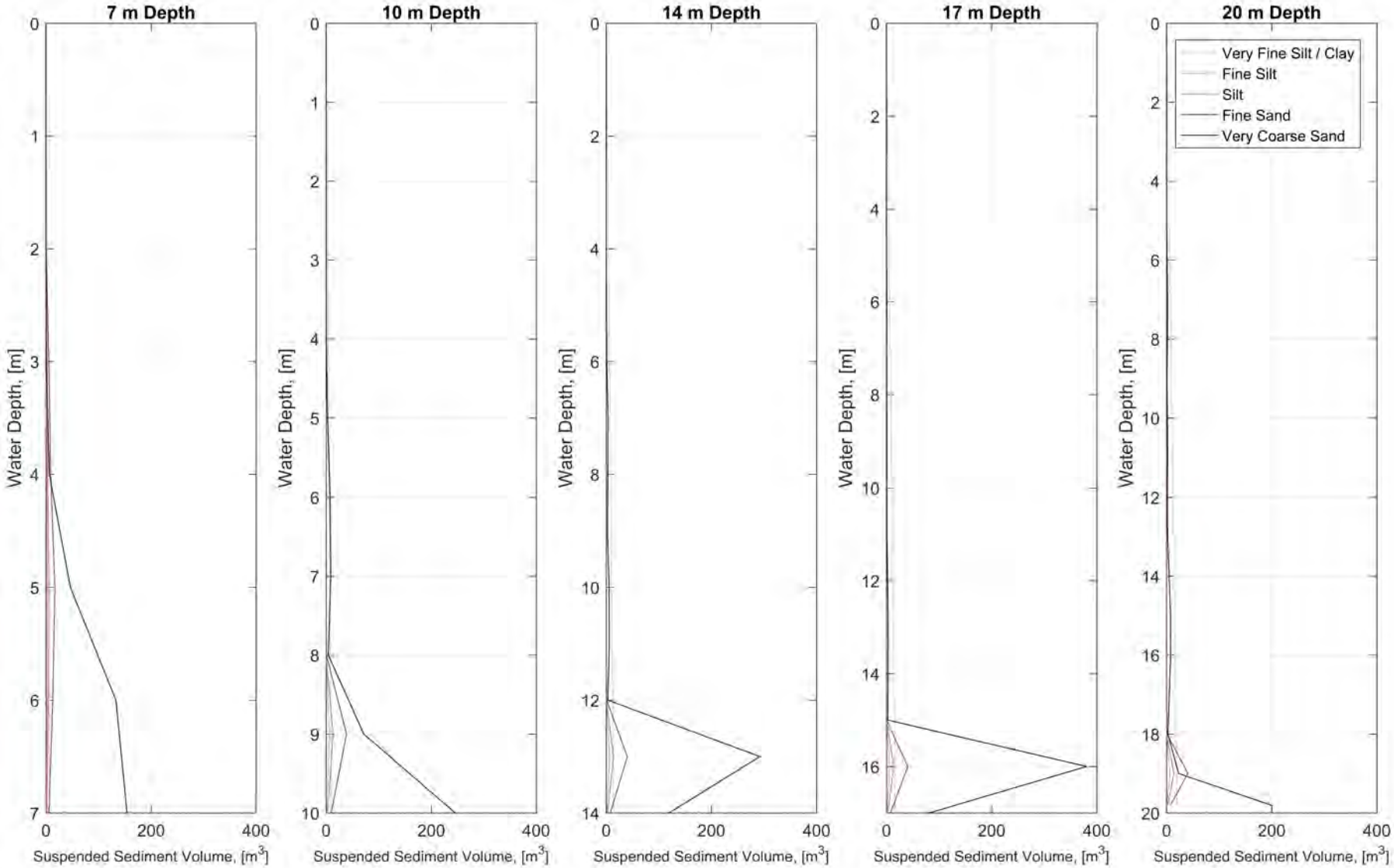
Dispersal Modelling of Infill Derived Fugitive Sediment

CEP Infill Overview

PROJECT NO.	DWN	CKD	APVD	REV
WTRM.03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech - VANC	March, 2017

Figure 2.3



NOTES

1) Suspended sediment concentration as simulated by STFATE, visualized 5 seconds after the dredgeage plume contacts the seabed
2) Suspended sediment is presented as the total volume of sediment at a given depth level.
3) Note that the vertical scale between panels is not constant

STATUS
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TETRA TECH

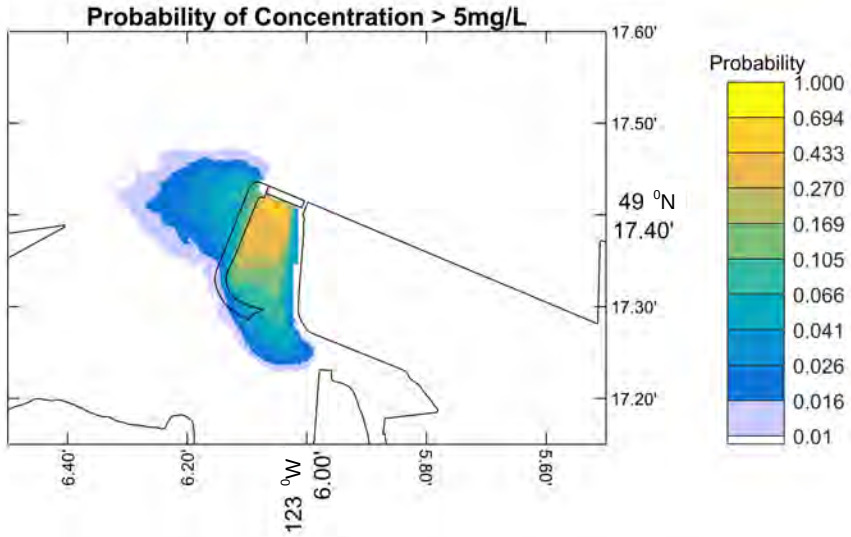
Dispersal Modelling of Infill Derived Fugitive Sediment

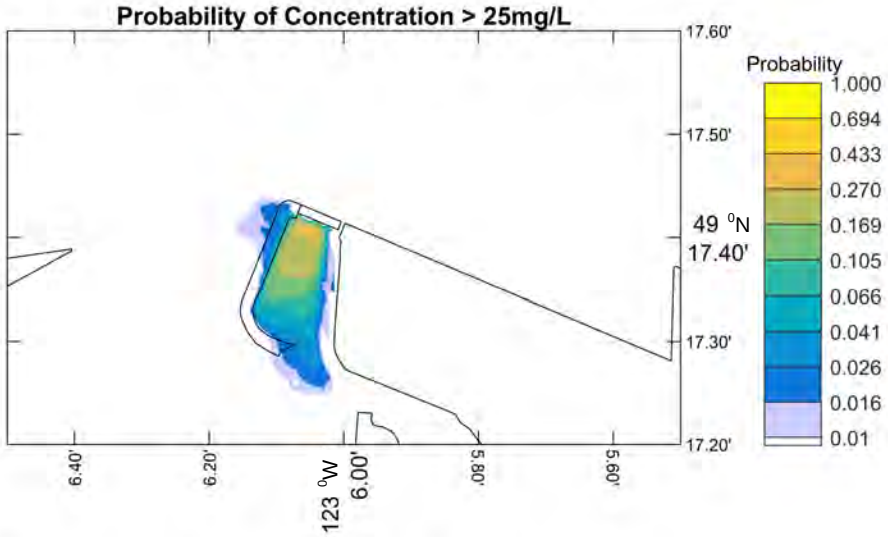
Hopper Barge Dump Suspended Sediment Concentration

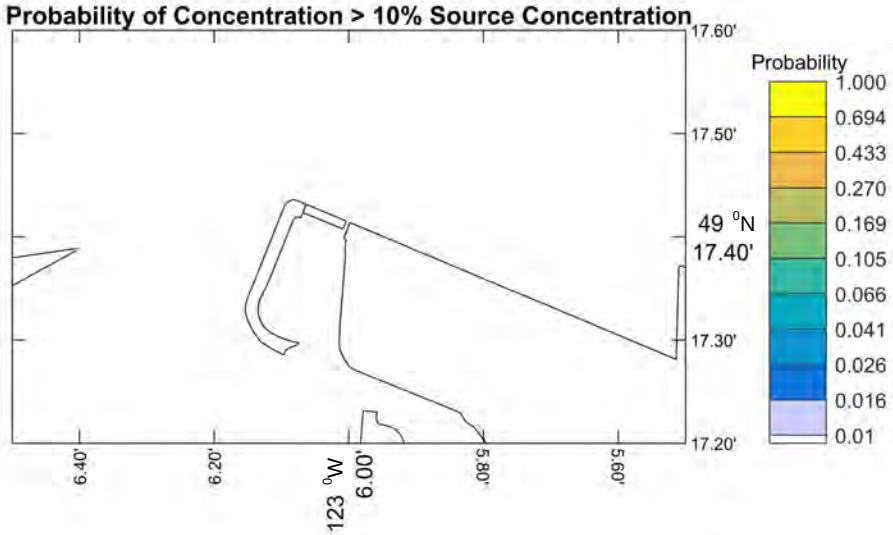
PROJECT NO.	DWN	CKD	APVD	REV
WTRM.03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech - VANC	March, 2017

Figure 3.1







NOTES

1) Probability is calculated over the full dredge period and is determined from 15 minute model data.
2) All concentrations are the maximum concentration over the water column (seabed to surface) at a given location.

STATUS
ISSUED FOR USE V:

CLIENT

AECOM

TETRA TECH

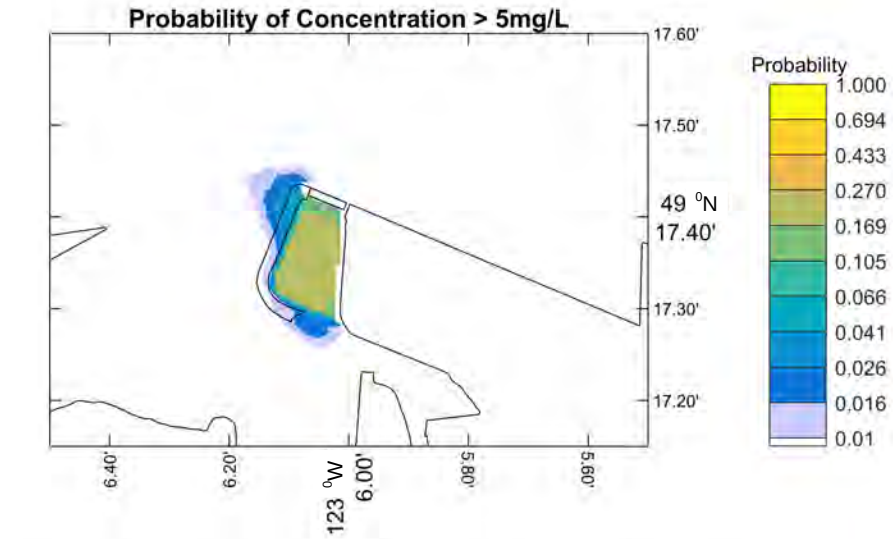
Dispersal Modelling of Infill Derived Fugitive Sediment

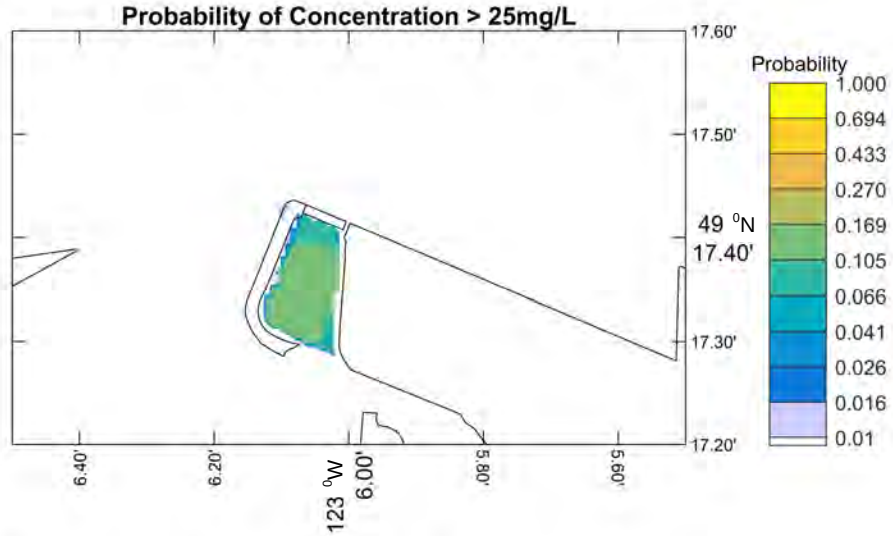
West Basin Infill Zone, Lift 1 Empty Maximum TSS Exceedance Probabilities

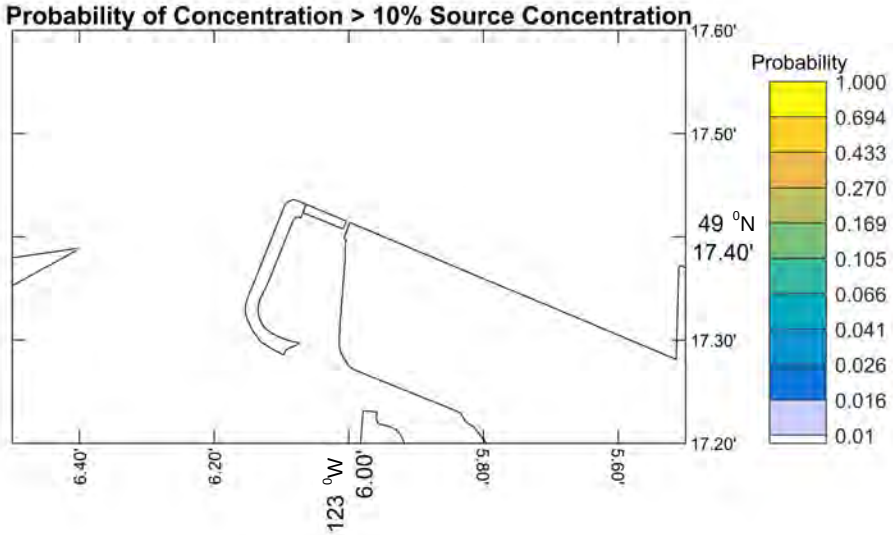
PROJECT NO.	DWN	CKD	APVD	REV
WTRM03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech EBA - VANC	March, 2017

Figure 4.1







NOTES

1) Probability is calculated over the full dredge period and is determined from 15 minute model data.
2) All concentrations are the maximum concentration over the water column (seabed to surface) at a given location.

STATUS
ISSUED FOR USE

CLIENT

AECOM

TETRA TECH

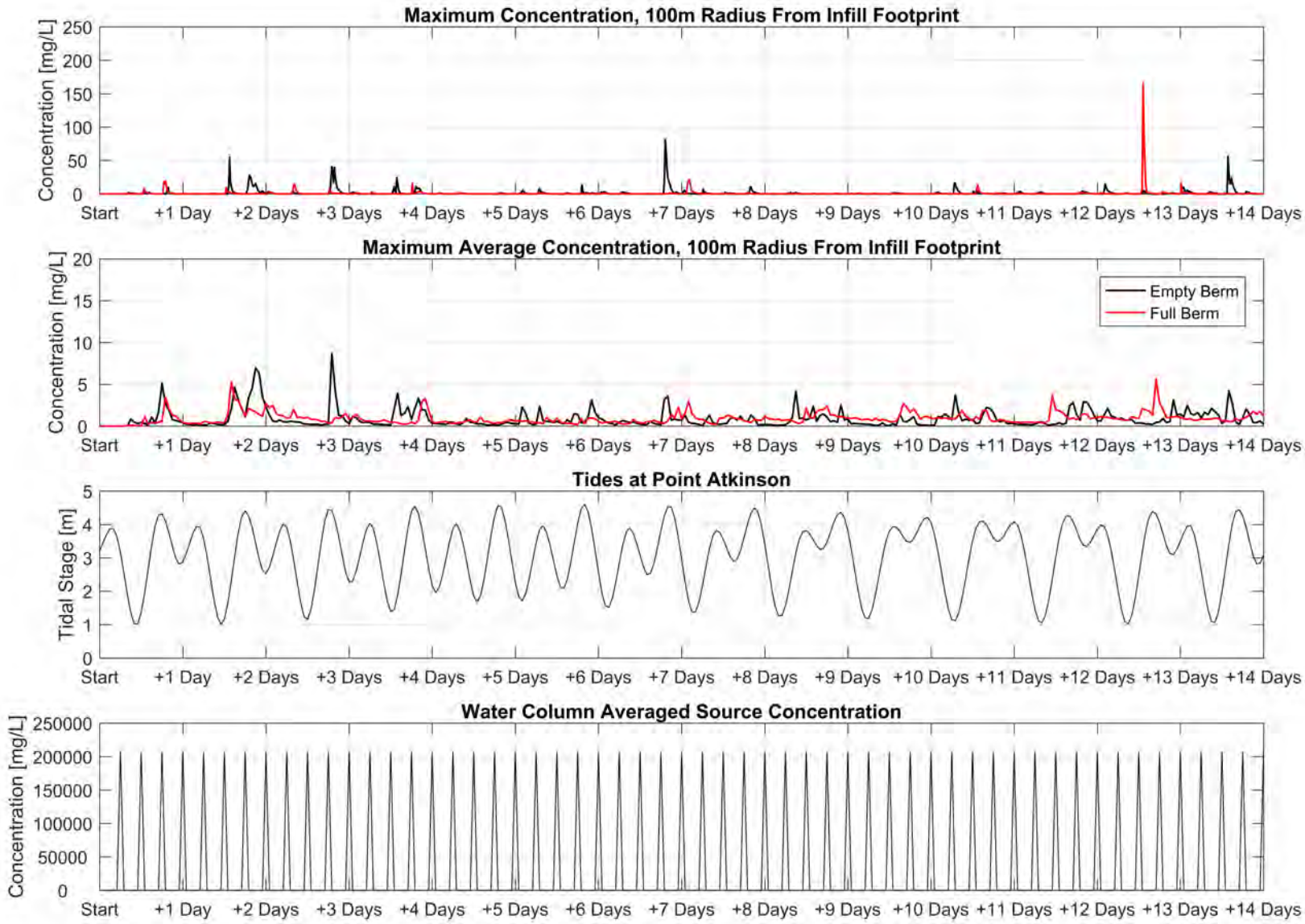
Dispersal Modelling of Infill Derived Fugitive Sediment

West Basin Infill Zone, Lift 1 Full Maximum TSS Exceedance Probabilities

PROJECT NO.	DWN	CKD	APVD	REV
WTRM03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech - VANC	March, 2017

Figure 4.2



NOTES

1) The concentration axis scale differs between plots.
2) Maximum concentration is the maximum of the maximum TSS over the water column (seabed to surface) along a boundary 100 m from the edge of the infill footprint.
3) Maximum Average concentration is the maximum of the average TSS over the water column (seabed to surface) along a boundary 100 m from the edge of the infill footprint.

STATUS
ISSUED FOR USE

CLIENT

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TETRA TECH

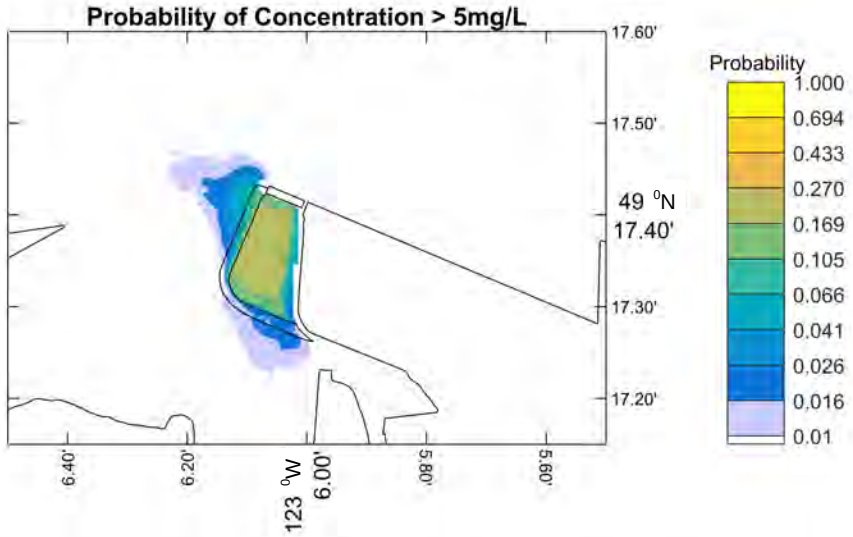
Dispersal Modelling of Infill Derived Fugitive Sediment

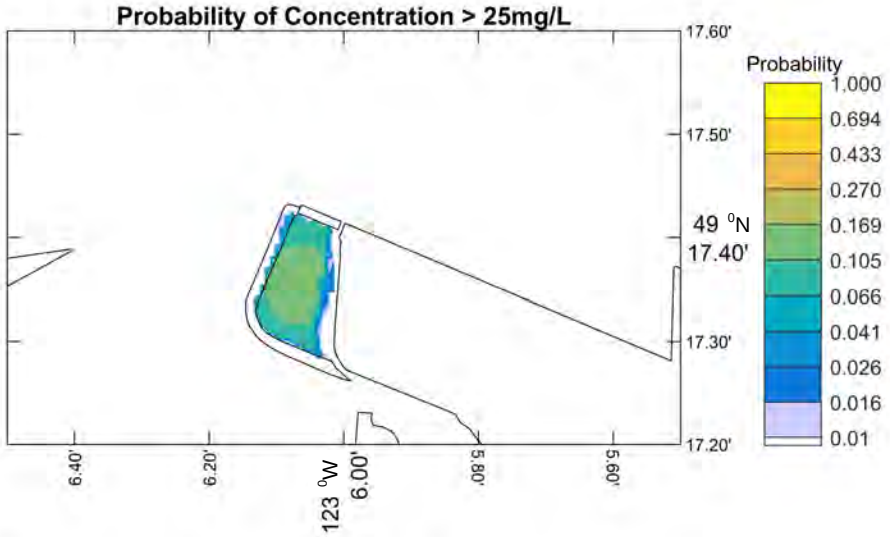
West Basin Infill Zone, Lift 1
TSS Source Attenuation at 100 m

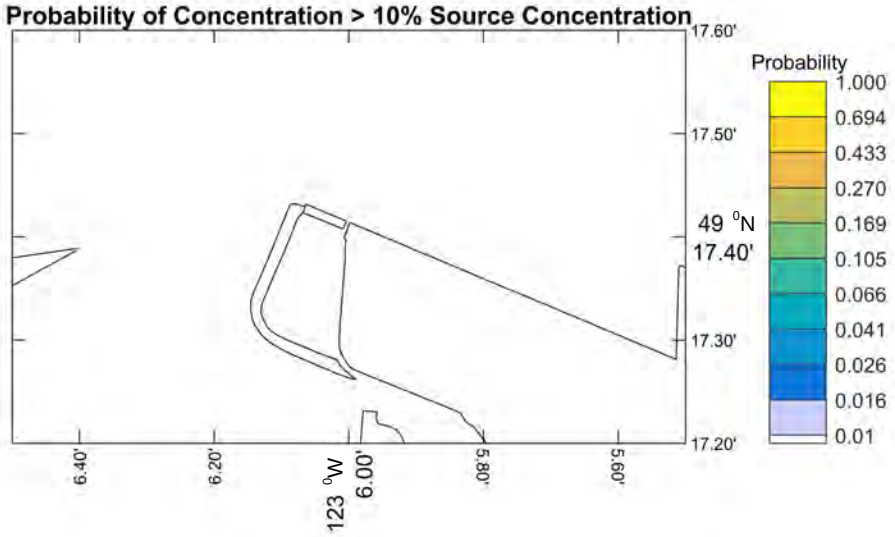
PROJECT NO.	DWN	CKD	APVD	REV
WTRM.03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech - VANC	March, 2017

Figure 4.3







NOTES

1) Probability is calculated over the full dredge period and is determined from 15 minute model data.
2) All concentrations are the maximum concentration over the water column (seabed to surface) at a given location.

STATUS
ISSUED FOR USE V:

CLIENT

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TETRA TECH

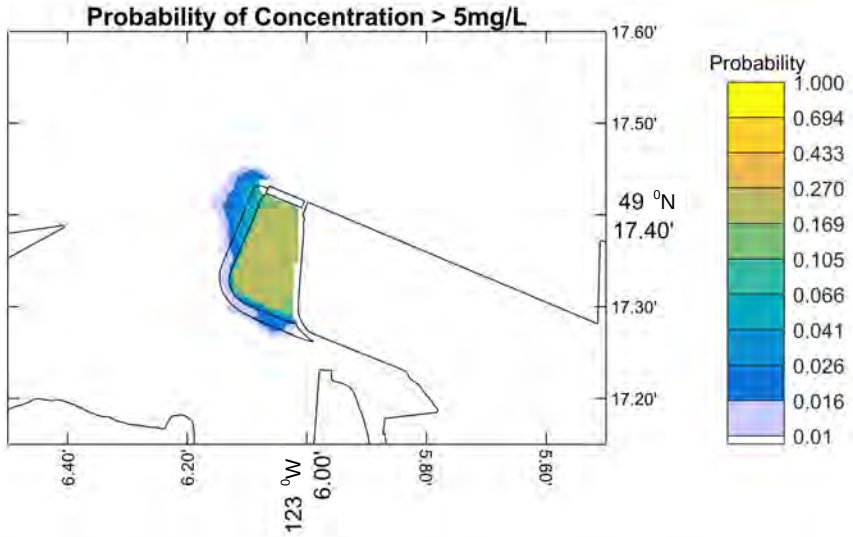
Dispersal Modelling of Infill Derived Fugitive Sediment

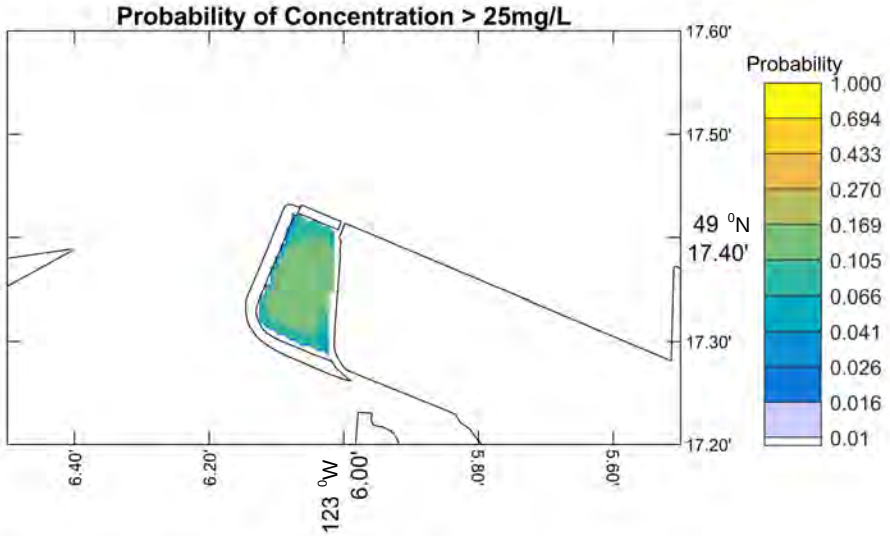
West Basin Infill Zone, Lift 2 Empty Maximum TSS Exceedance Probabilities

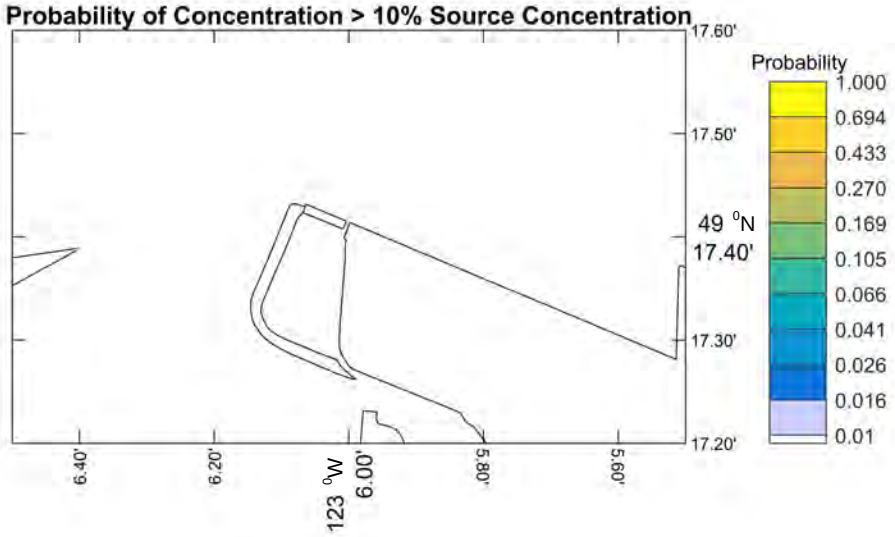
PROJECT NO.	DWN	CKD	APVD	REV
WTRM03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech - VANC	March, 2017

Figure 4.4







NOTES

1) Probability is calculated over the full dredge period and is determined from 15 minute model data.
2) All concentrations are the maximum concentration over the water column (seabed to surface) at a given location.

STATUS
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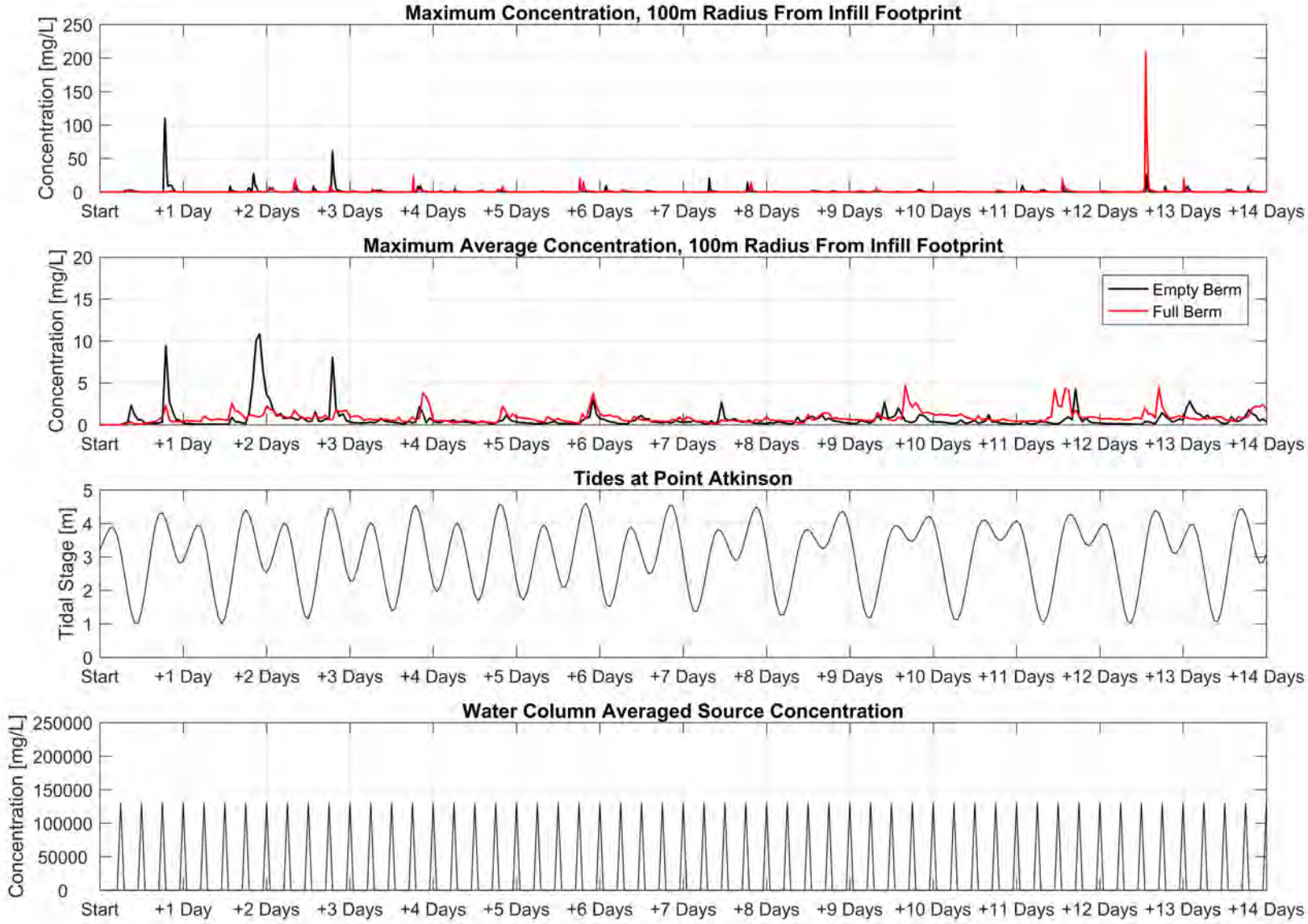
Dispersal Modelling of Infill Derived Fugitive Sediment

West Basin Infill Zone, Lift 2 Full Maximum TSS Exceedance Probabilities

PROJECT NO.	DWN	CKD	APVD	REV
WTRM03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech - VANC	March, 2017

Figure 4.5



NOTES

1) The concentration axis scale differs between plots.
2) Maximum concentration is the maximum of the maximum TSS over the water column (seabed to surface) along a boundary 100 m from the edge of the infill footprint.
3) Maximum Average concentration is the maximum of the average TSS over the water column (seabed to surface) along a boundary 100 m from the edge of the infill footprint.

STATUS
ISSUED FOR USE

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TETRA TECH

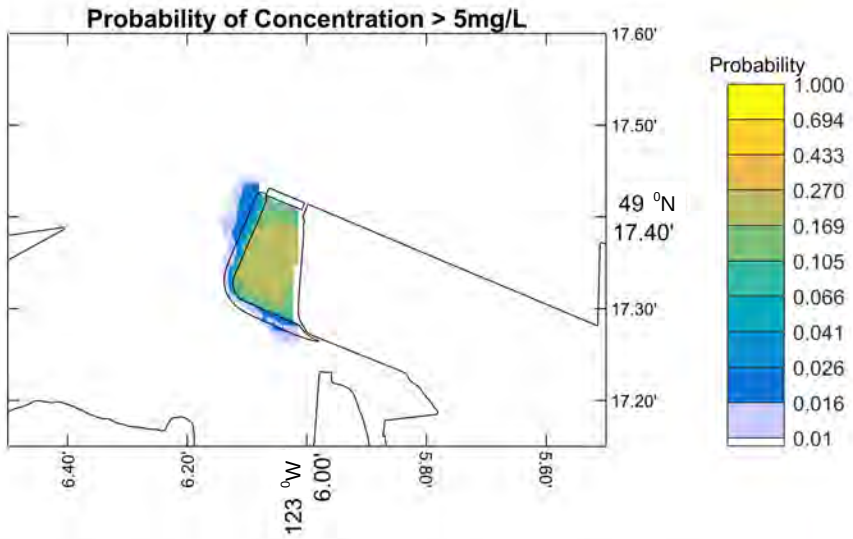
Dispersal Modelling of Infill Derived Fugitive Sediment

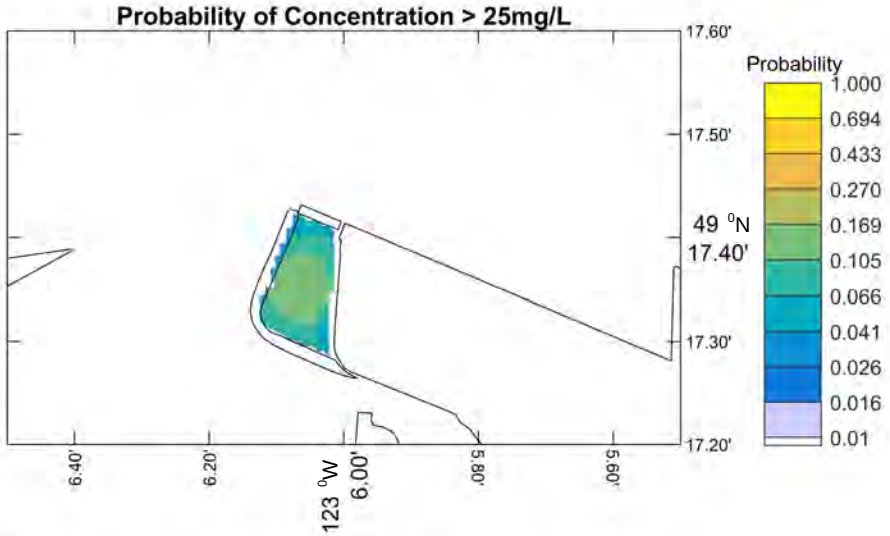
West Basin Infill Zone, Lift 2
TSS Source Attenuation at 100 m

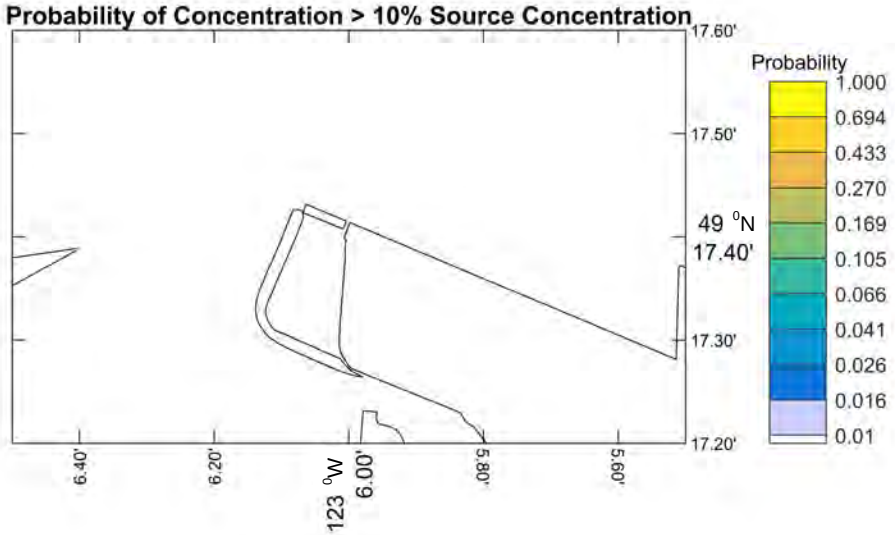
PROJECT NO.	DWN	CKD	APVD	REV
WTRM.03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech - VANC	March, 2017

Figure 4.6







NOTES

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2) All concentrations are the maximum concentration over the water column (seabed to surface) at a given location.

STATUS
ISSUED FOR USE

CLIENT

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TETRA TECH

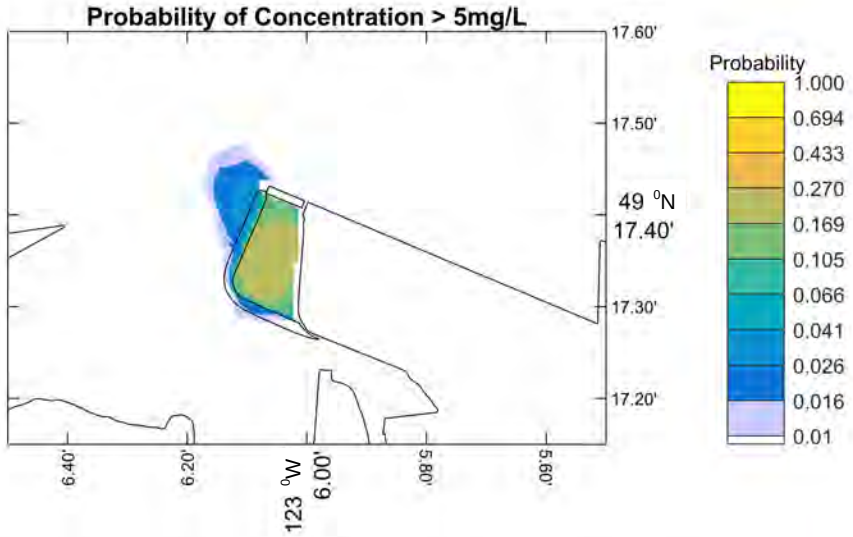
Dispersal Modelling of Infill Derived Fugitive Sediment

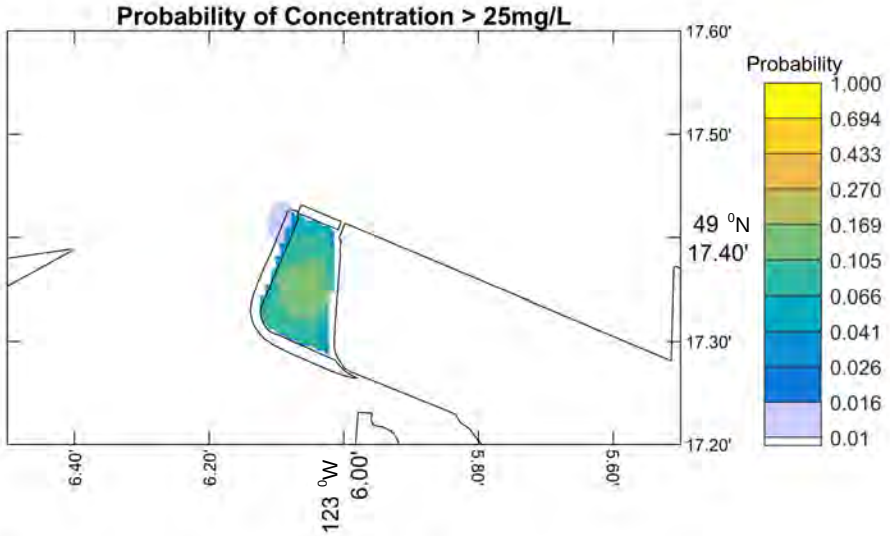
West Basin Infill Zone, Lift 3 Empty Maximum TSS Exceedance Probabilities

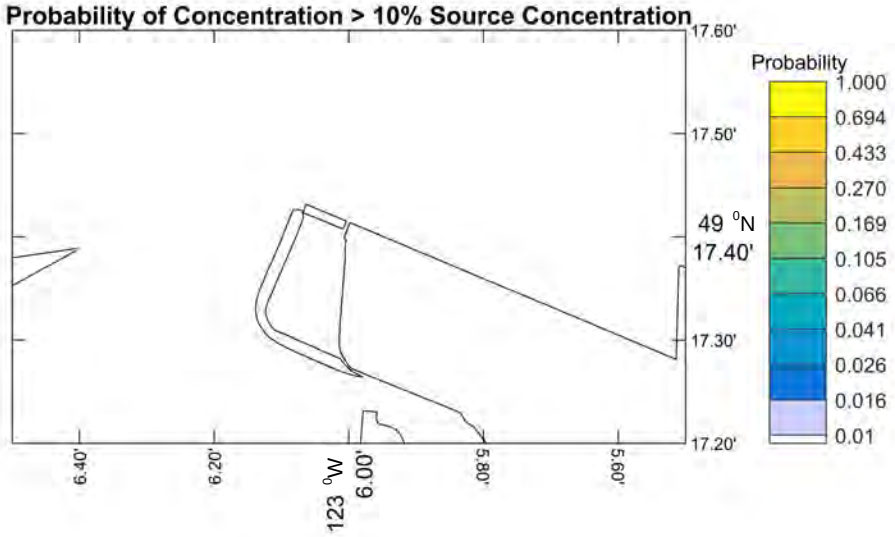
PROJECT NO.	DWN	CKD	APVD	REV
WTRM03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech - VANC	March, 2017

Figure 4.7







NOTES

1) Probability is calculated over the full dredge period and is determined from 15 minute model data.
2) All concentrations are the maximum concentration over the water column (seabed to surface) at a given location.

STATUS
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TETRA TECH

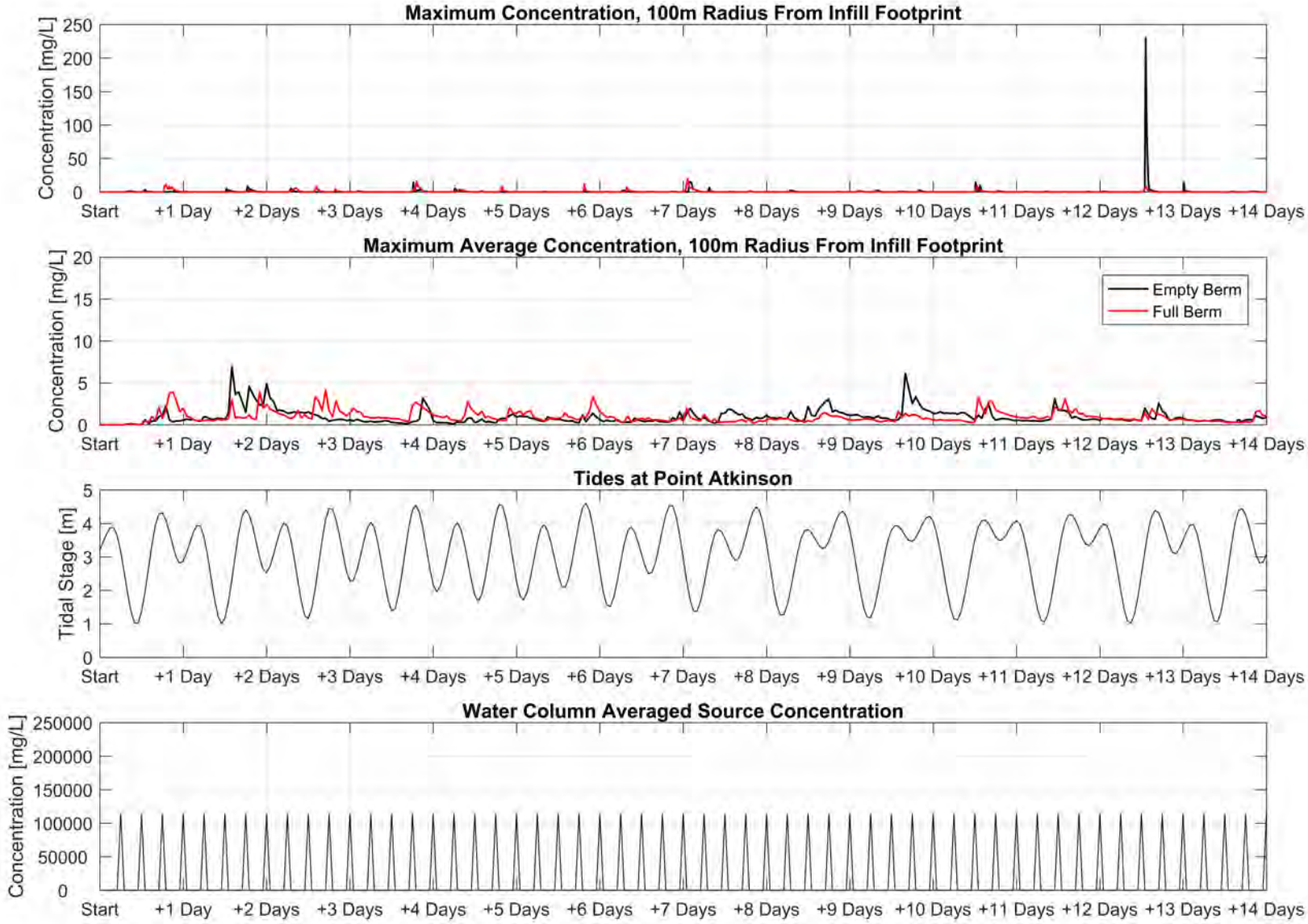
Dispersal Modelling of Infill Derived Fugitive Sediment

West Basin Infill Zone, Lift 3 Full Maximum TSS Exceedance Probabilities

PROJECT NO.	DWN	CKD	APVD	REV
WTRM03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech - VANC	March, 2017

Figure 4.8



NOTES

1) The concentration axis scale differs between plots.
2) Maximum concentration is the maximum of the maximum TSS over the water column (seabed to surface) along a boundary 100 m from the edge of the infill footprint.
3) Maximum Average concentration is the maximum of the average TSS over the water column (seabed to surface) along a boundary 100 m from the edge of the infill footprint.

STATUS
ISSUED FOR USE

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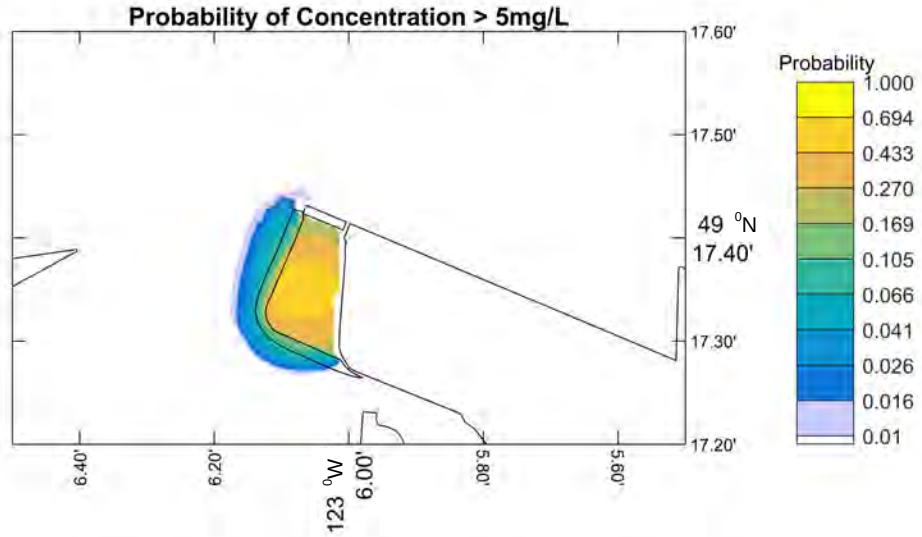
Dispersal Modelling of Infill Derived Fugitive Sediment

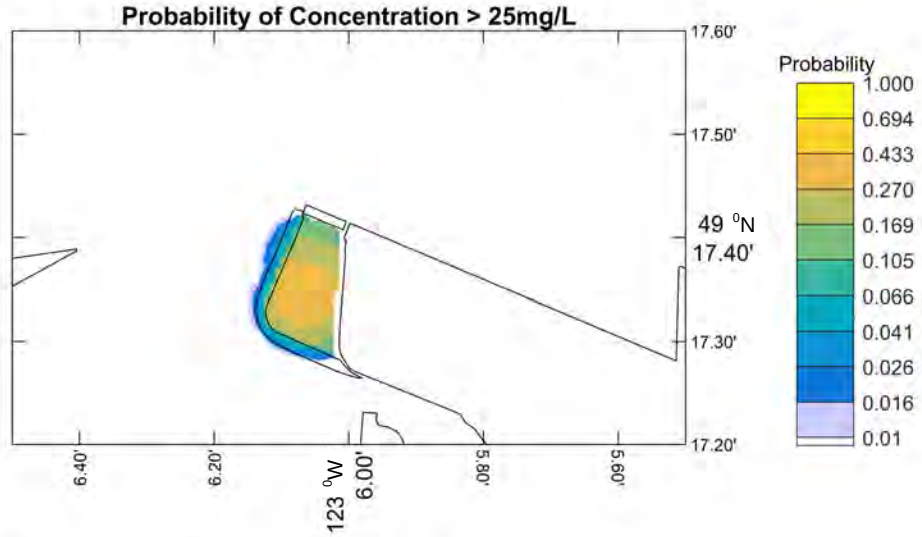
West Basin Infill Zone, Lift 3
TSS Source Attenuation at 100 m

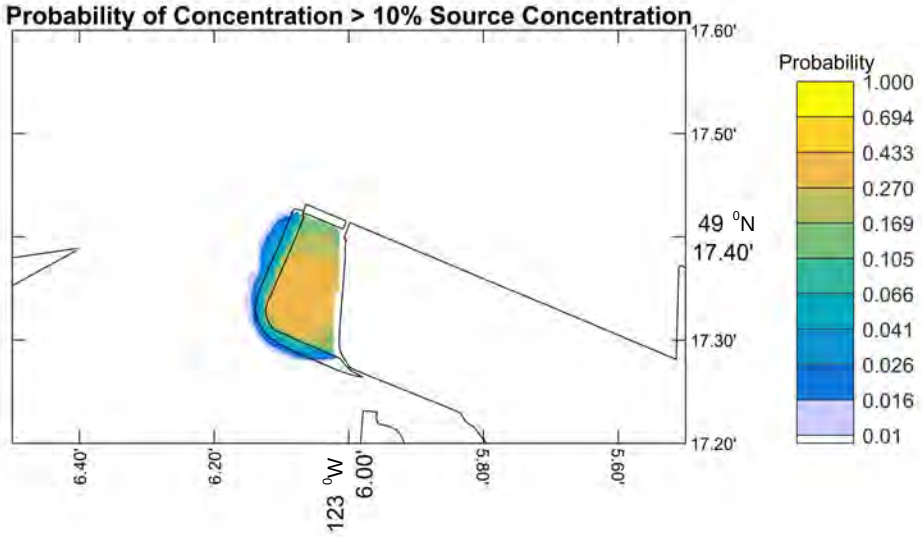
PROJECT NO.	DWN	CKD	APVD	REV
WTRM.03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech - VANC	March, 2017

Figure 4.09







NOTES

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2) All concentrations are the maximum concentration over the water column (seabed to surface) at a given location.

STATUS
ISSUED FOR USE

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TETRA TECH

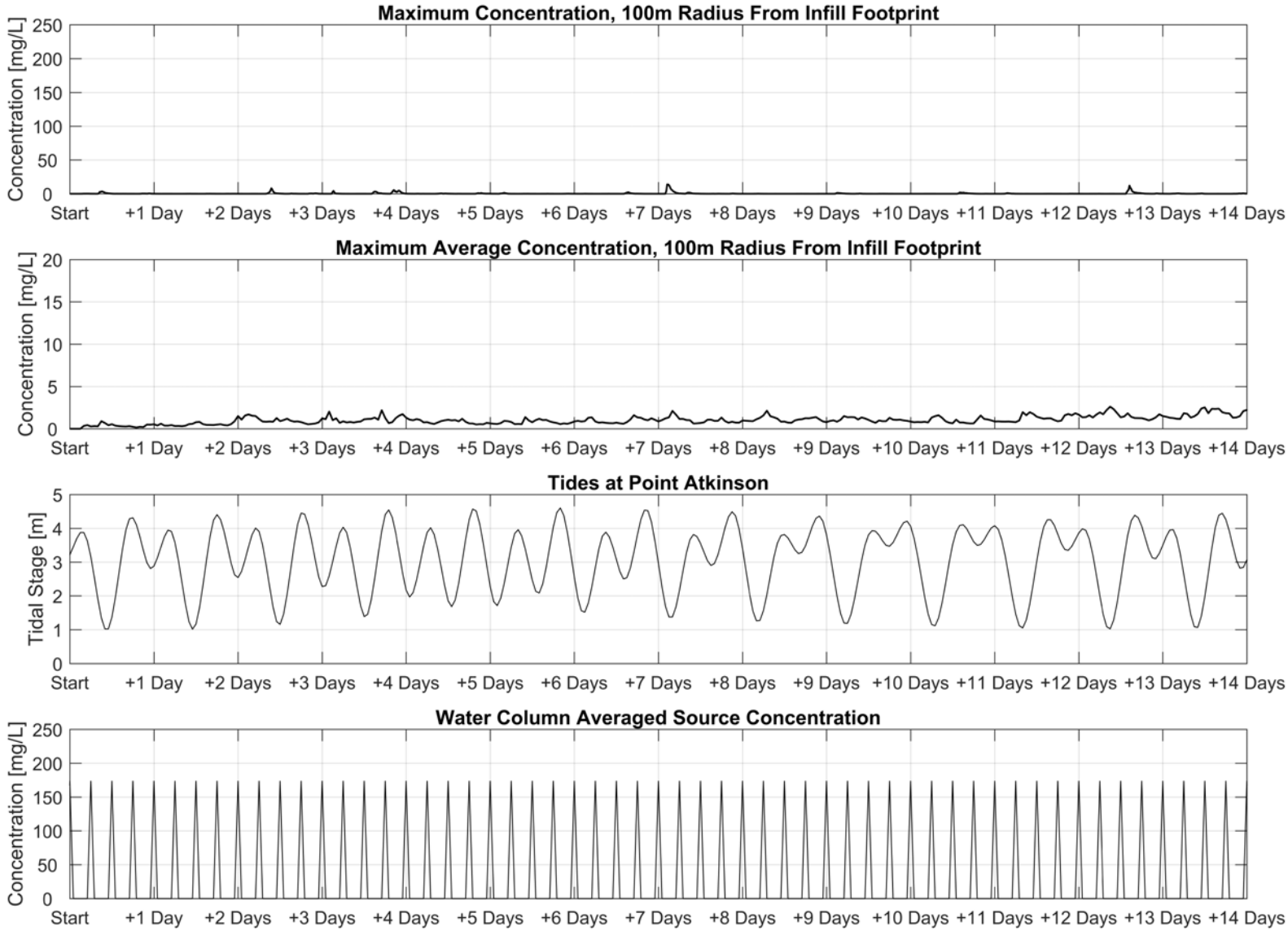
Dispersal Modelling of Infill Derived Fugitive Sediment

West Basin Infill Zone, Lift 4 Empty Maximum TSS Exceedance Probabilities

PROJECT NO.	DWN	CKD	APVD	REV
WTRM03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech EBA - VANC	March, 2017

Figure 4.10



NOTES

1) The concentration axis scale differs between plots.
2) Maximum concentration is the maximum of the maximum TSS over the water column (seabed to surface) along a boundary 100 m from the edge of the infill footprint.
3) Maximum Average concentration is the maximum of the average TSS over the water column (seabed to surface) along a boundary 100 m from the edge of the infill footprint.

STATUS
ISSUED FOR USE

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TETRA TECH

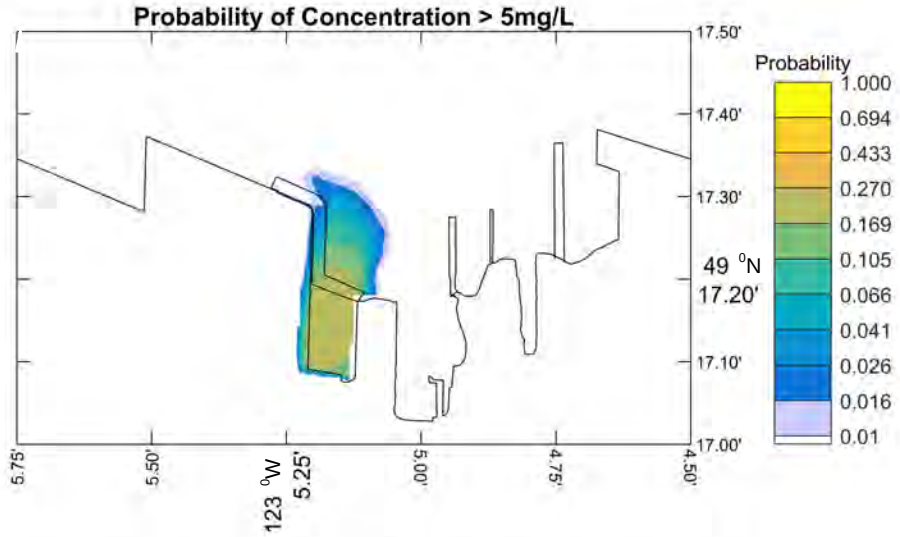
Dispersal Modelling of Infill Derived Fugitive Sediment

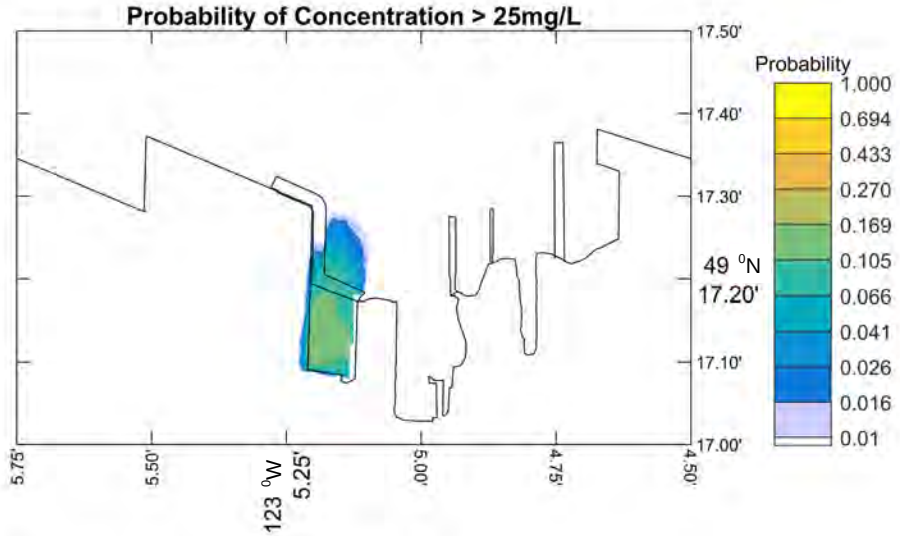
West Basin Infill Zone, Lift 4
TSS Source Attenuation at 100 m

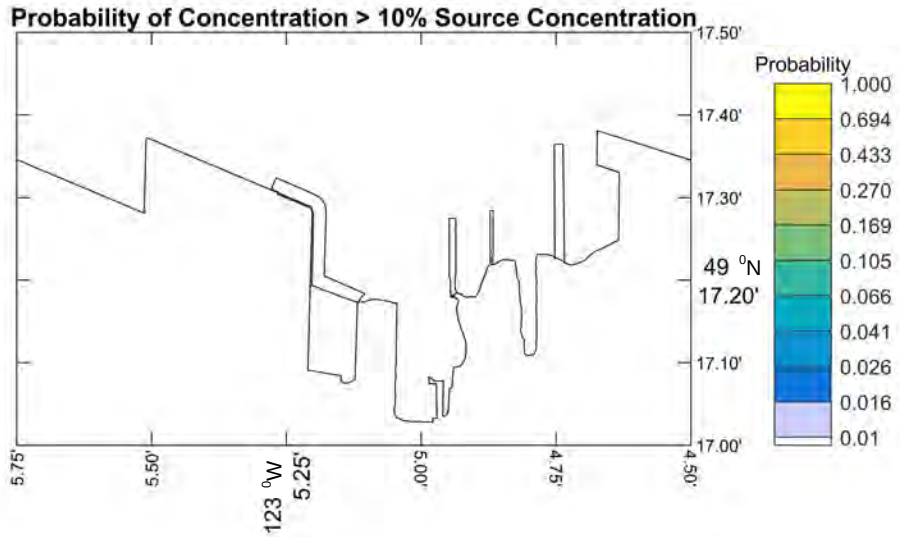
PROJECT NO.	DWN	CKD	APVD	REV
WTRM.03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech - VANC	March, 2017

Figure 4.11







NOTES

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2) All concentrations are the maximum concentration over the water column (seabed to surface) at a given location.

STATUS
ISSUED FOR USE

CLIENT

AECOM

TETRA TECH

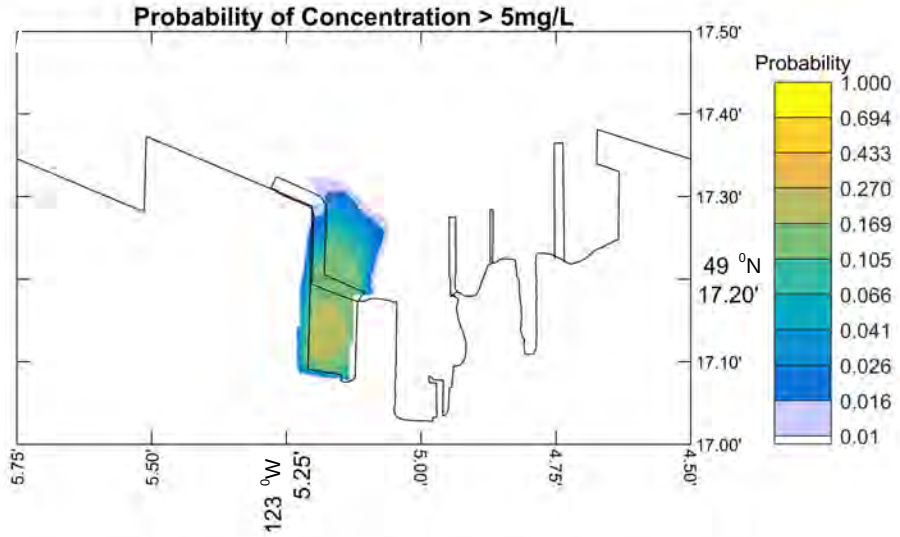
Dispersal Modelling of Infill Derived Fugitive Sediment

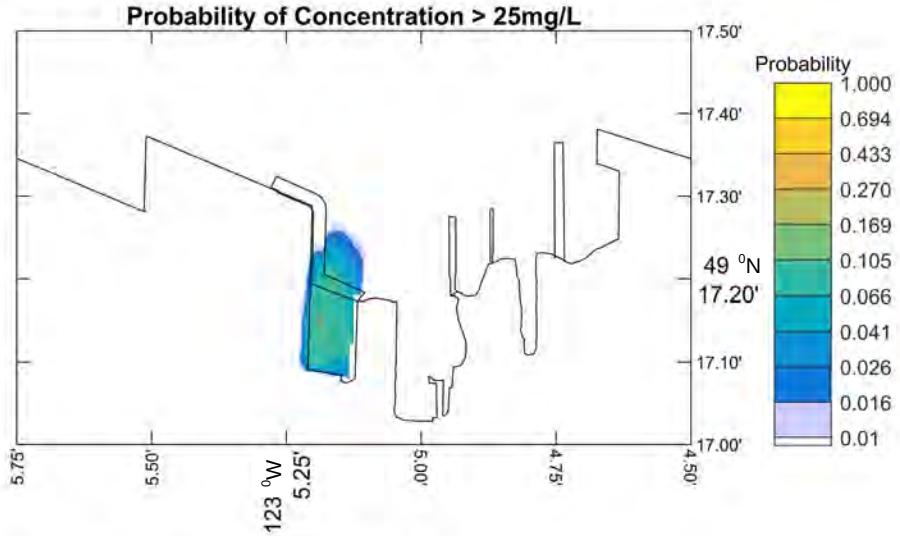
East Basin Infill Zone, Lift 1 Empty Maximum TSS Exceedance Probabilities

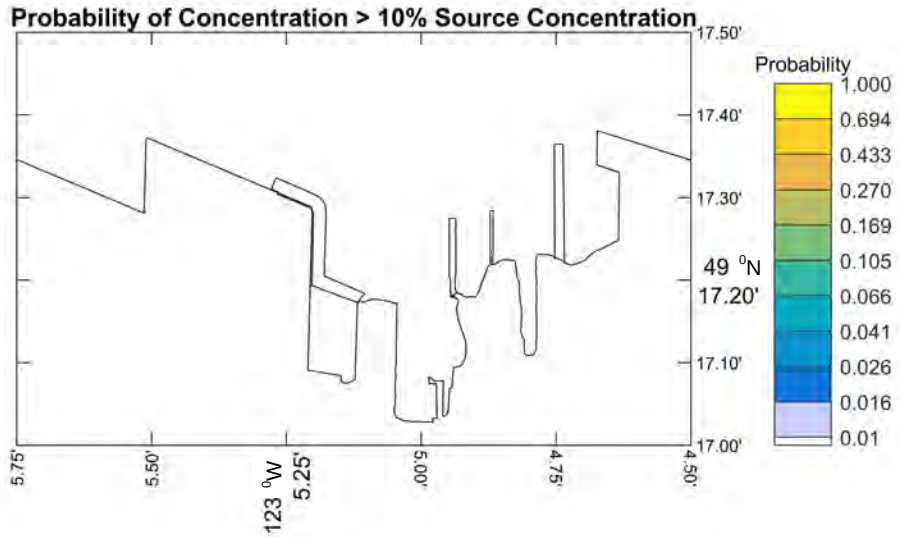
PROJECT NO.	DWN	CKD	APVD	REV
WTRM03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech - VANC	March, 2017

Figure 4.12







NOTES

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2) All concentrations are the maximum concentration over the water column (seabed to surface) at a given location.

STATUS
ISSUED FOR USE

CLIENT

AECOM

TETRA TECH

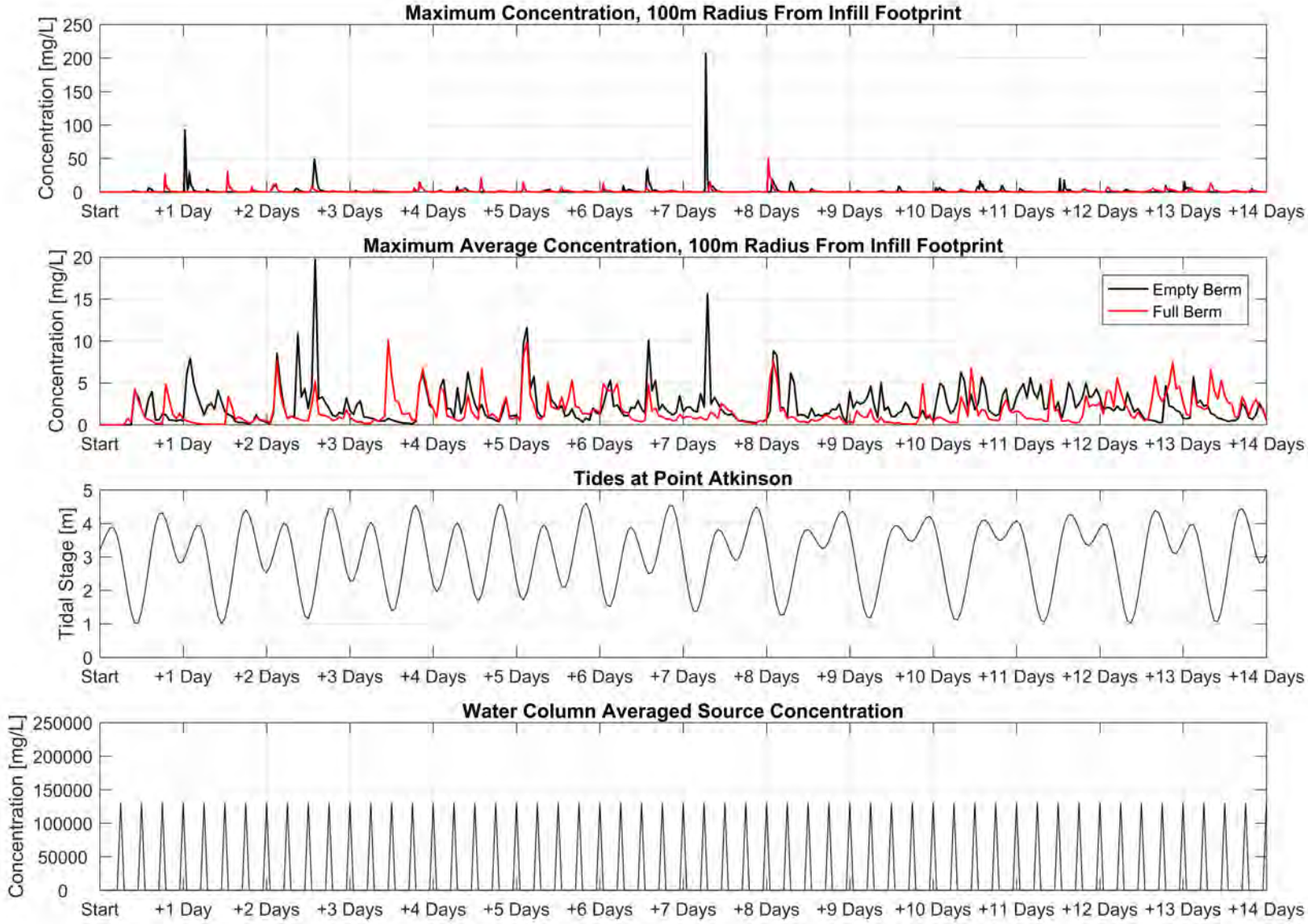
Dispersal Modelling of Infill Derived Fugitive Sediment

East Basin Infill Zone, Lift 1 Full Maximum TSS Exceedance Probabilities

PROJECT NO.	DWN	CKD	APVD	REV
WTRM03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech - VANC	March, 2017

Figure 4.13



NOTES

1) The concentration axis scale differs between plots.
2) Maximum concentration is the maximum of the maximum TSS over the water column (seabed to surface) along a boundary 100 m from the edge of the infill footprint.
3) Maximum Average concentration is the maximum of the average TSS over the water column (seabed to surface) along a boundary 100 m from the edge of the infill footprint.

STATUS
ISSUED FOR USE

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TETRA TECH

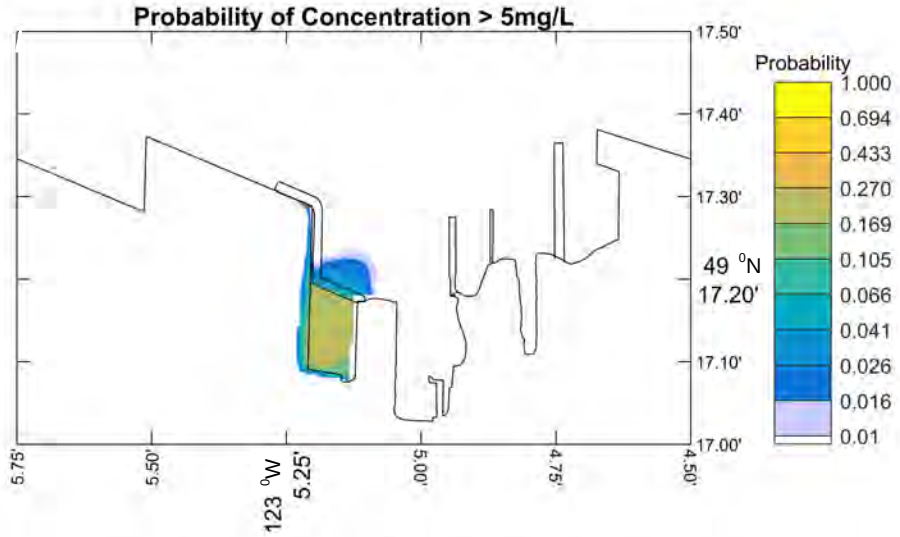
Dispersal Modelling of Infill Derived Fugitive Sediment

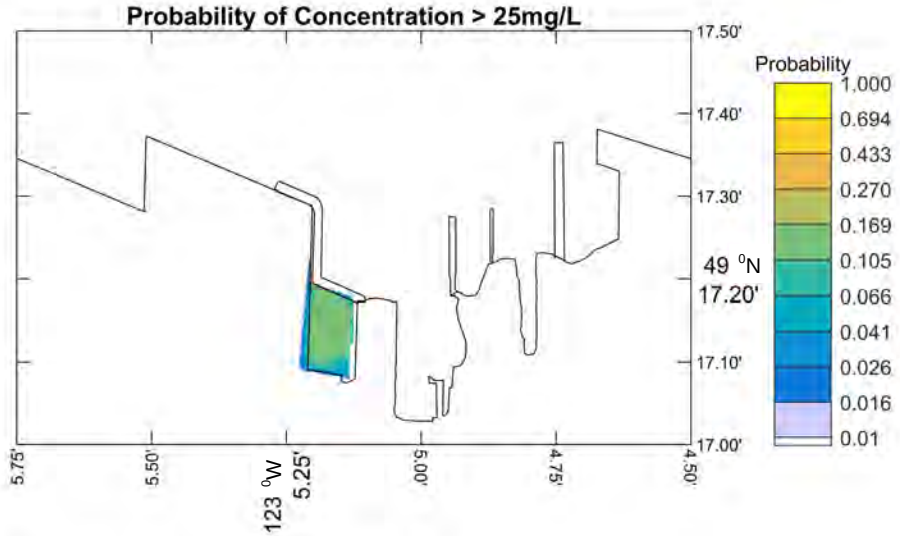
East Basin Infill Zone, Lift 1
TSS Source Attenuation at 100 m

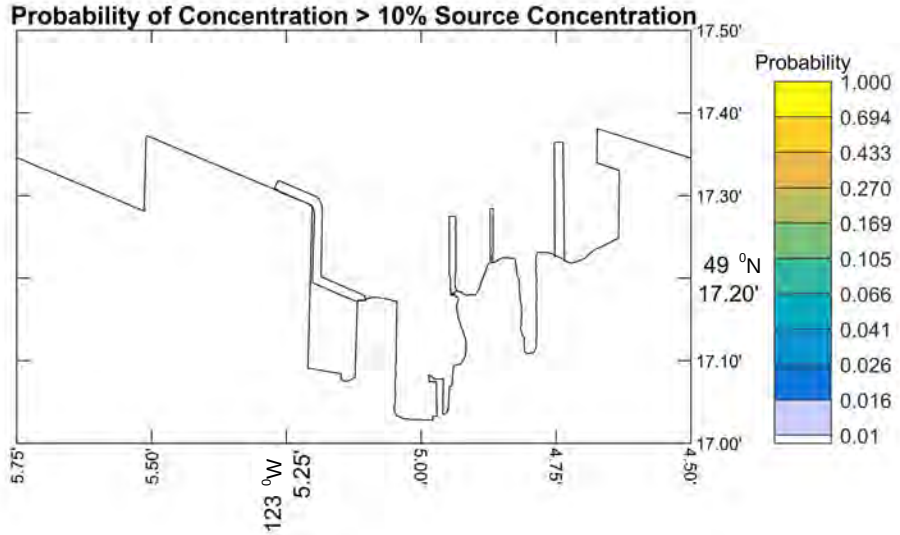
PROJECT NO.	DWN	CKD	APVD	REV
WTRM.03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech - VANC	March, 2017

Figure 4.14







NOTES

1) Probability is calculated over the full dredge period and is determined from 15 minute model data.
2) All concentrations are the maximum concentration over the water column (seabed to surface) at a given location.

STATUS
ISSUED FOR USE

CLIENT

AECOM

TETRA TECH

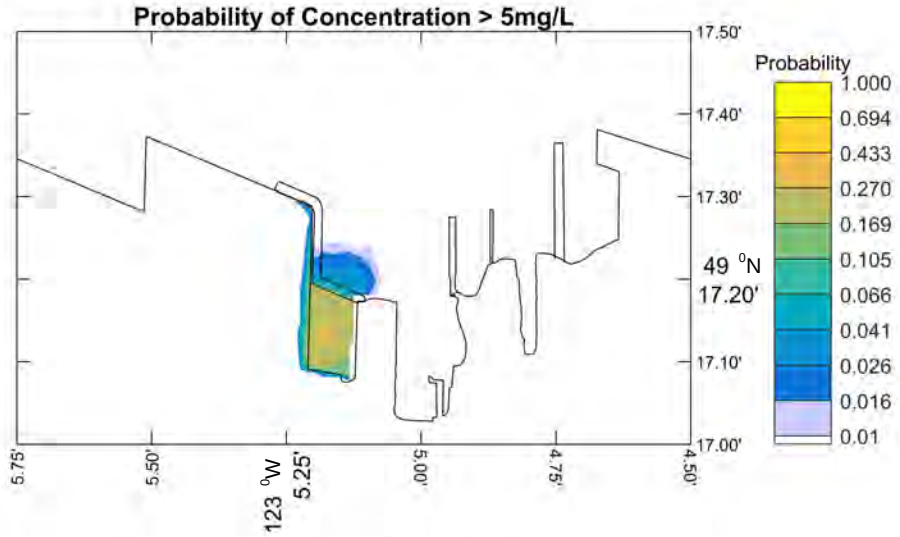
Dispersal Modelling of Infill Derived Fugitive Sediment

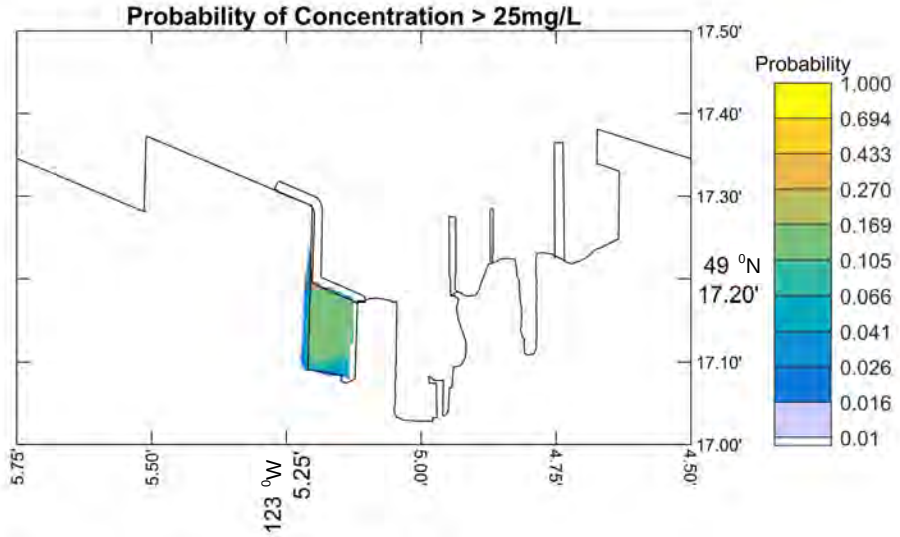
East Basin Infill Zone, Lift 2 Empty Maximum TSS Exceedance Probabilities

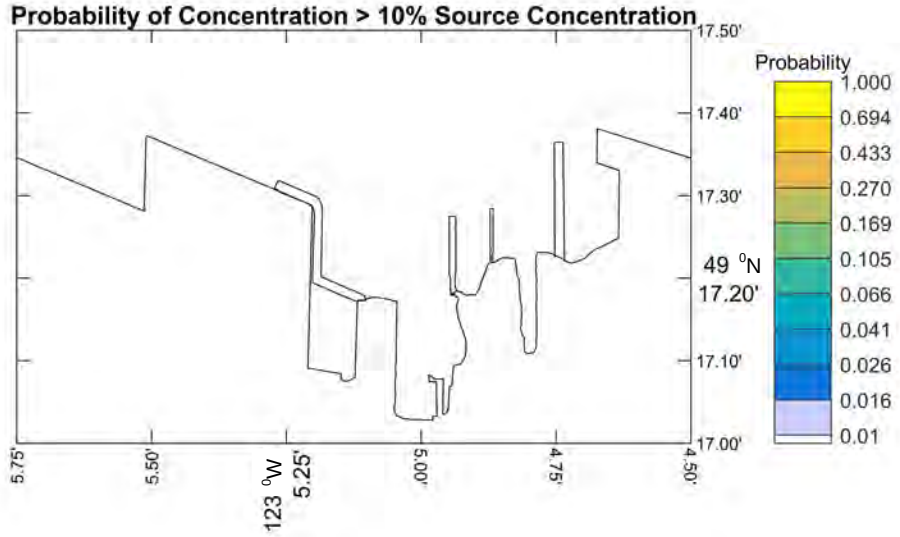
PROJECT NO.	DWN	CKD	APVD	REV
WTRM03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech - VANC	March, 2017

Figure 4.15







NOTES

1) Probability is calculated over the full dredge period and is determined from 15 minute model data.
2) All concentrations are the maximum concentration over the water column (seabed to surface) at a given location.

STATUS
ISSUED FOR USE

CLIENT

AECOM

TETRA TECH

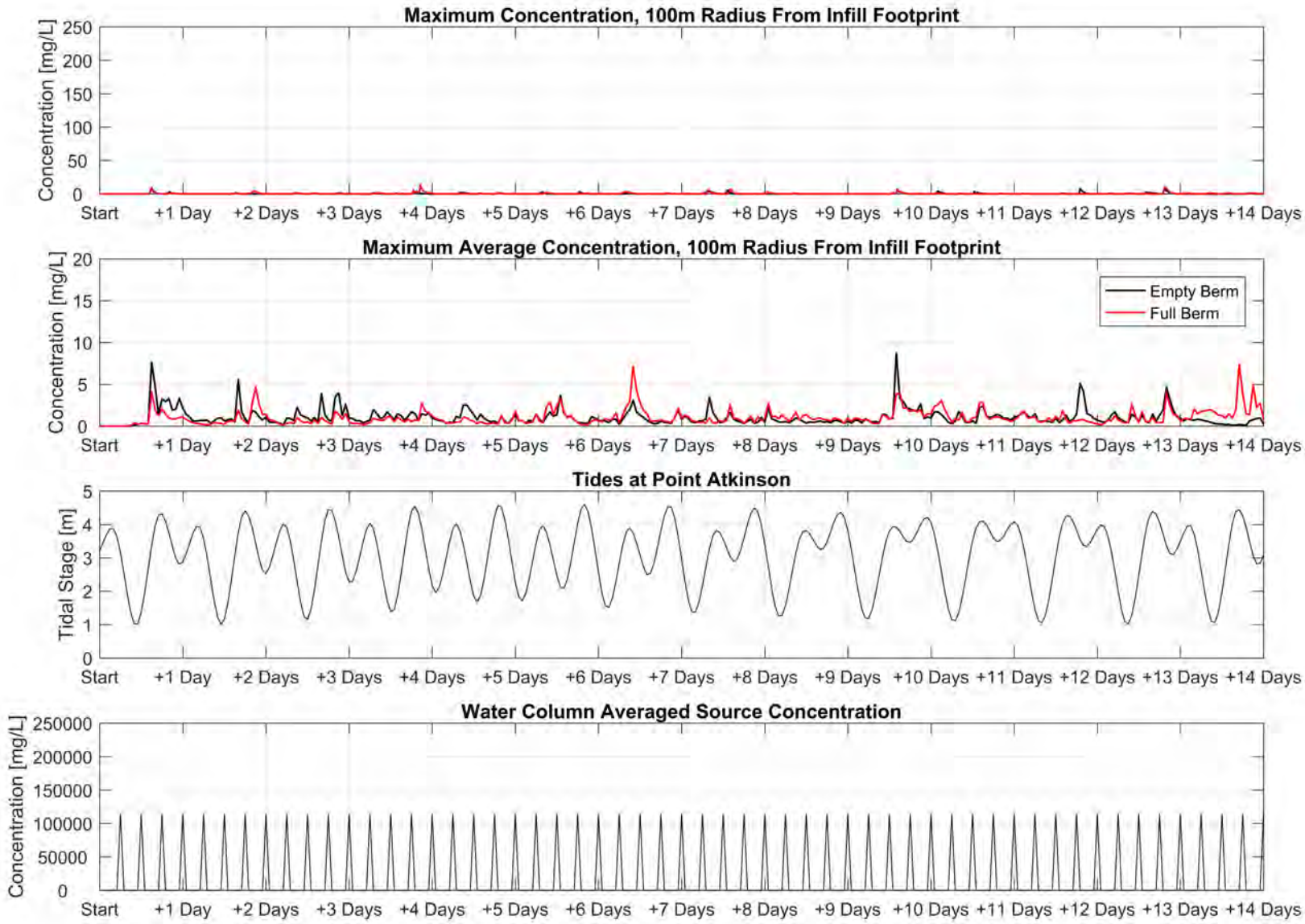
Dispersal Modelling of Infill Derived Fugitive Sediment

East Basin Infill Zone, Lift 2 Full Maximum TSS Exceedance Probabilities

PROJECT NO.	DWN	CKD	APVD	REV
WTRM03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech - VANC	March, 2017

Figure 4.16



NOTES

1) The concentration axis scale differs between plots.
2) Maximum concentration is the maximum of the maximum TSS over the water column (seabed to surface) along a boundary 100 m from the edge of the infill footprint.
3) Maximum Average concentration is the maximum of the average TSS over the water column (seabed to surface) along a boundary 100 m from the edge of the infill footprint.

STATUS
ISSUED FOR USE

CLIENT

AECOM

TETRA TECH

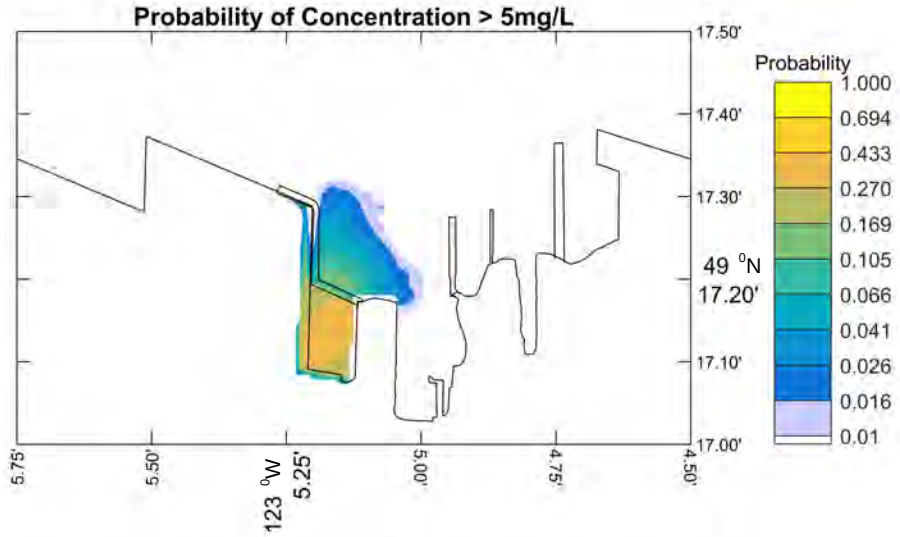
Dispersal Modelling of Infill Derived Fugitive Sediment

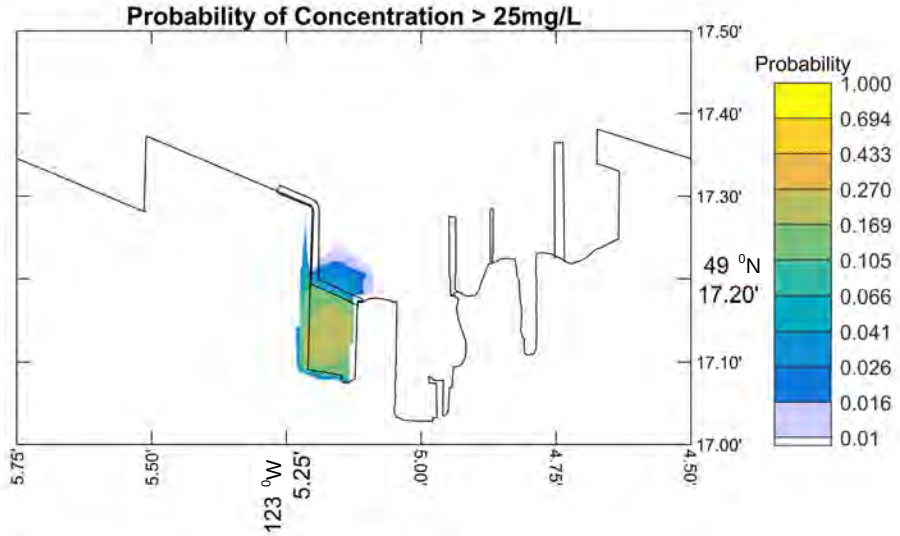
East Basin Infill Zone, Lift 2
TSS Source Attenuation at 100 m

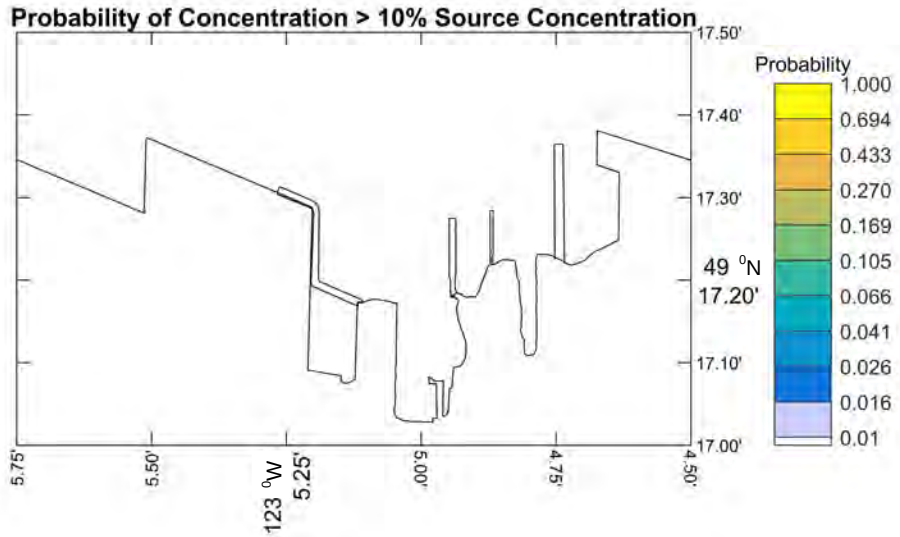
PROJECT NO.	DWN	CKD	APVD	REV
WTRM.03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech - VANC	March, 2017

Figure 4.17







NOTES

1) Probability is calculated over the full dredge period and is determined from 15 minute model data.
2) All concentrations are the maximum concentration over the water column (seabed to surface) at a given location.

STATUS
ISSUED FOR USE

CLIENT

AECOM

TETRA TECH

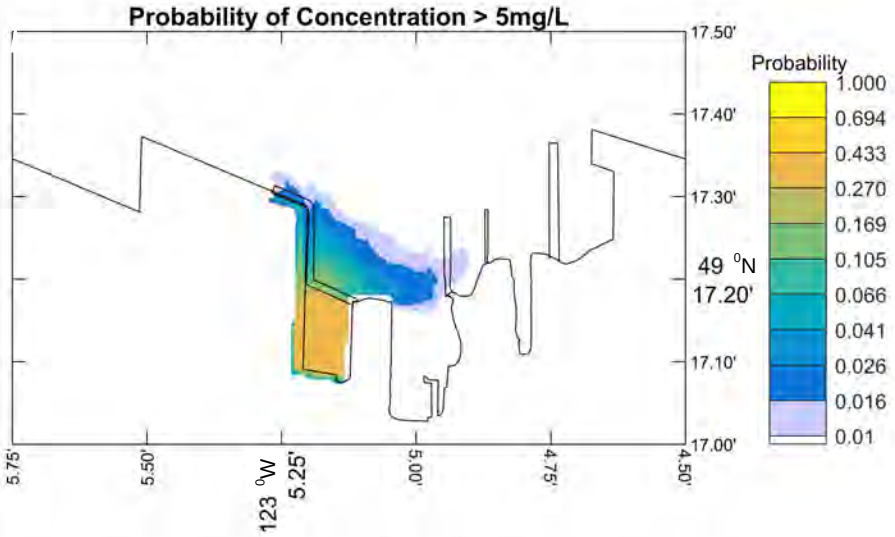
Dispersal Modelling of Infill Derived Fugitive Sediment

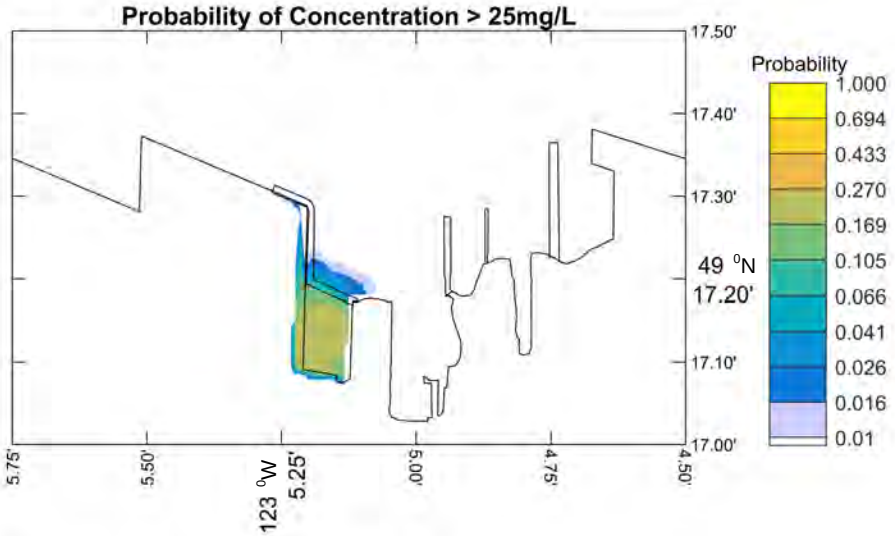
East Basin Infill Zone, Lift 3 Empty Maximum TSS Exceedance Probabilities

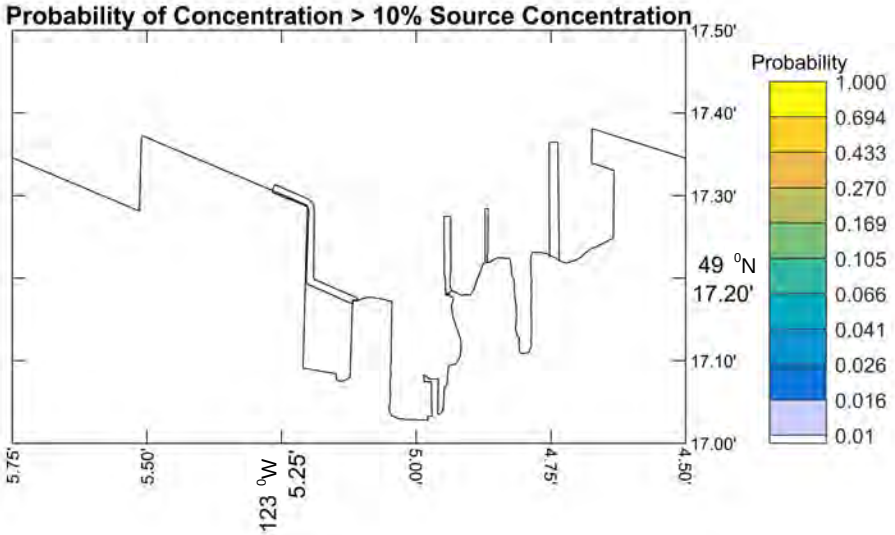
PROJECT NO.	DWN	CKD	APVD	REV
WTRM03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech - VANC	March, 2017

Figure 4.18







NOTES

1) Probability is calculated over the full dredge period and is determined from 15 minute model data.
2) All concentrations are the maximum concentration over the water column (seabed to surface) at a given location.

STATUS
ISSUED FOR USE

CLIENT

AECOM

TETRA TECH

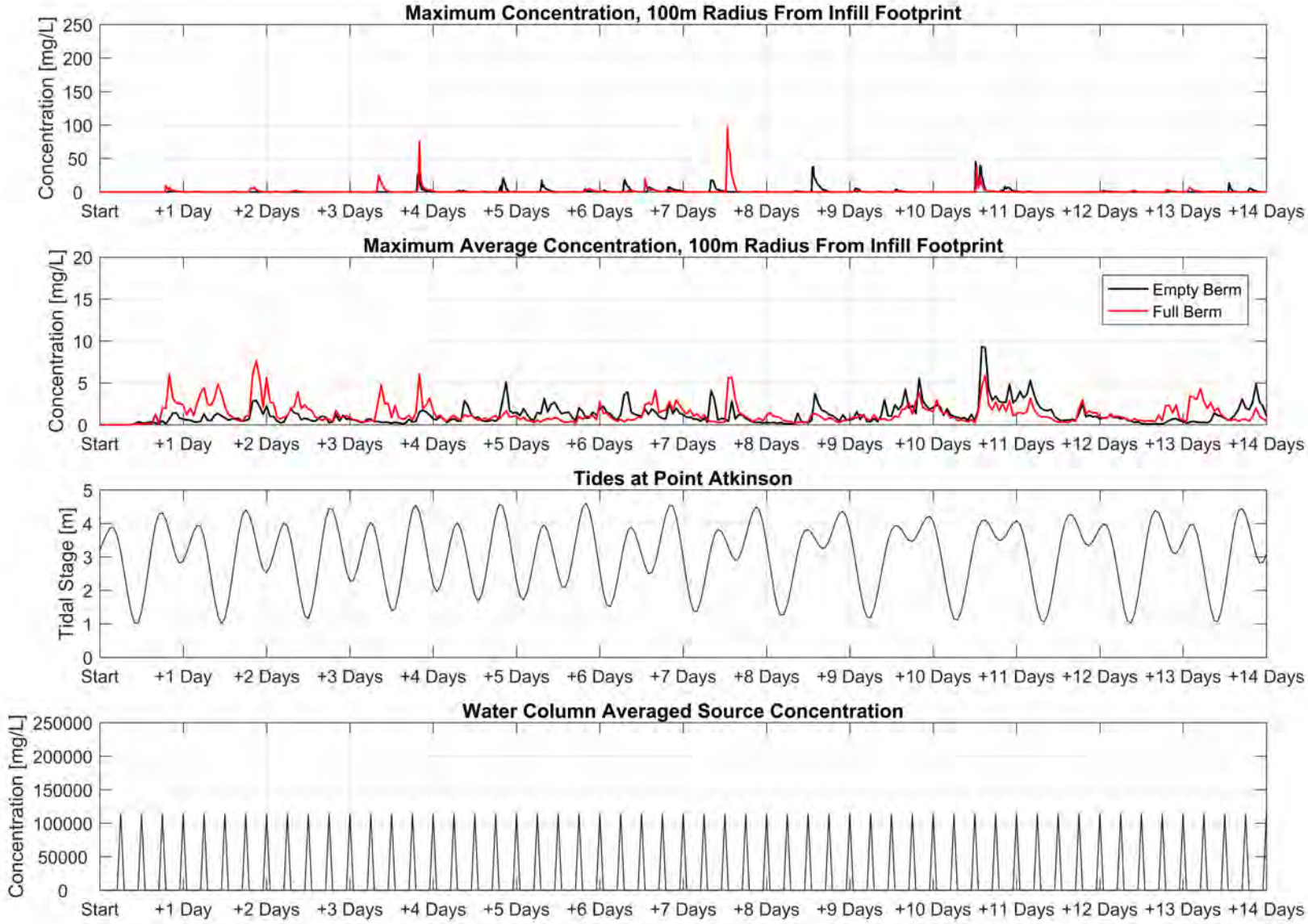
Dispersal Modelling of Infill Derived Fugitive Sediment

East Basin Infill Zone, Lift 3 Full Maximum TSS Exceedance Probabilities

PROJECT NO.	DWN	CKD	APVD	REV
WTRM03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech - VANC	March, 2017

Figure 4.19



NOTES

1) The concentration axis scale differs between plots.
2) Maximum concentration is the maximum of the maximum TSS over the water column (seabed to surface) along a boundary 100 m from the edge of the infill footprint.
3) Maximum Average concentration is the maximum of the average TSS over the water column (seabed to surface) along a boundary 100 m from the edge of the infill footprint.

STATUS
ISSUED FOR USE

CLIENT

AECOM

TETRA TECH

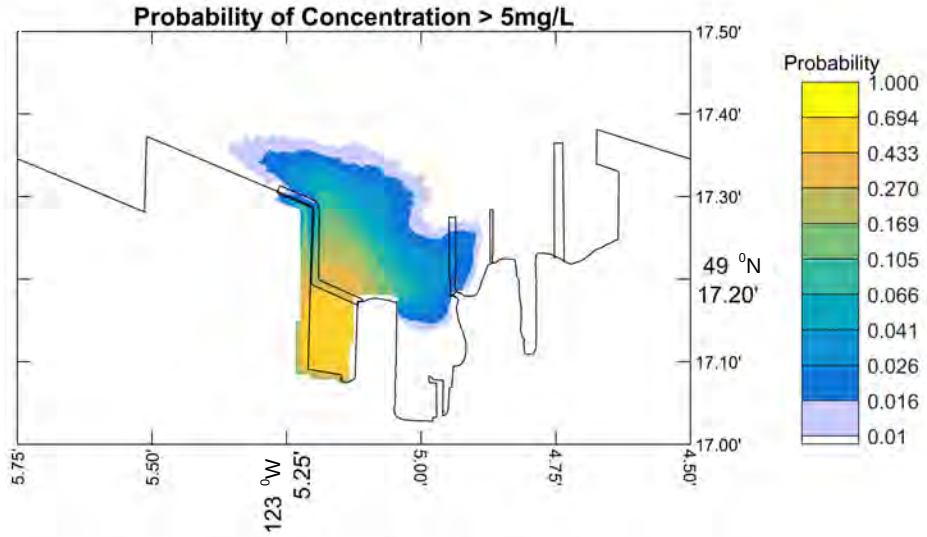
Dispersal Modelling of Infill Derived Fugitive Sediment

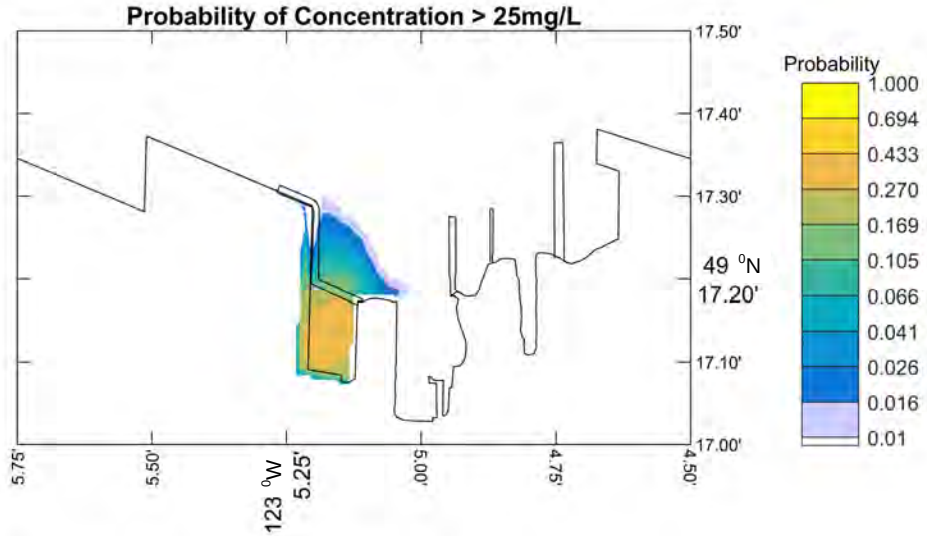
East Basin Infill Zone, Lift 3
TSS Source Attenuation at 100 m

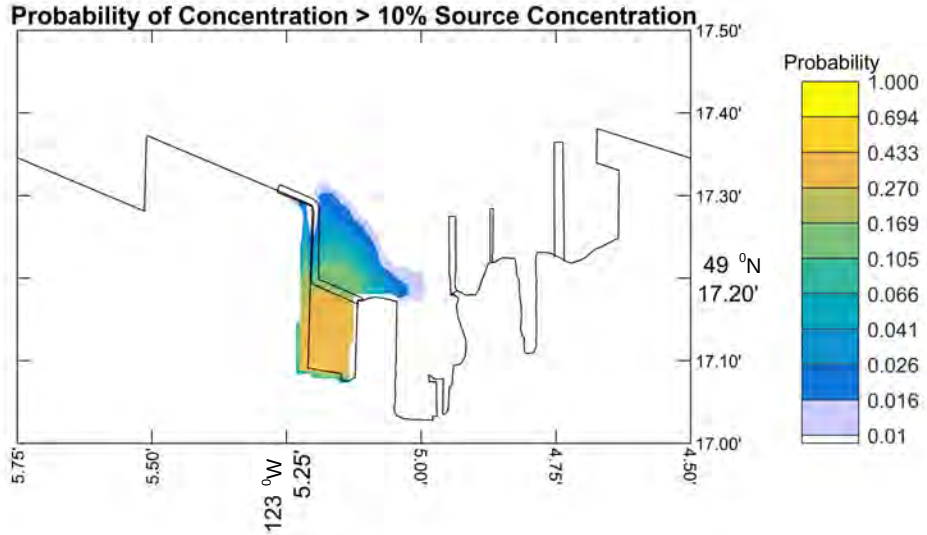
PROJECT NO.	DWN	CKD	APVD	REV
WTRM.03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech - VANC	March, 2017

Figure 4.20







NOTES

1) Probability is calculated over the full dredge period and is determined from 15 minute model data.
2) All concentrations are the maximum concentration over the water column (seabed to surface) at a given location.

STATUS
ISSUED FOR USE

CLIENT

AECOM

TETRA TECH

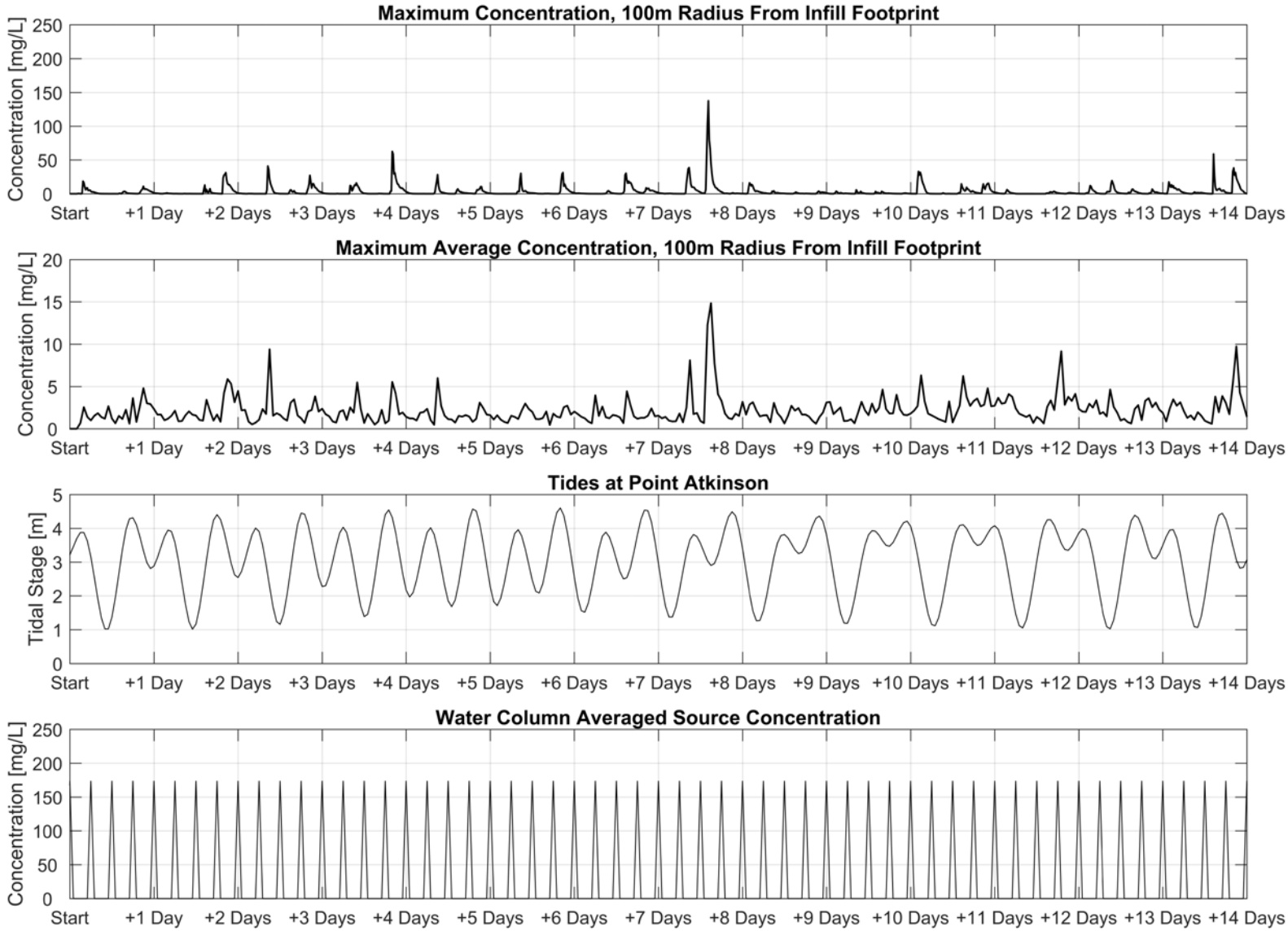
Dispersal Modelling of Infill Derived Fugitive Sediment

East Basin Infill Zone, Lift 4 Maximum TSS Exceedance Probabilities

PROJECT NO.	DWN	CKD	APVD	REV
WTRM03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech - VANC	March, 2017

Figure 4.21



NOTES

1) The concentration axis scale differs between plots.
2) Maximum concentration is the maximum of the maximum TSS over the water column (seabed to surface) along a boundary 100 m from the edge of the infill footprint.
3) Maximum Average concentration is the maximum of the average TSS over the water column (seabed to surface) along a boundary 100 m from the edge of the infill footprint.

STATUS
ISSUED FOR USE

CLIENT

AECOM

TETRA TECH

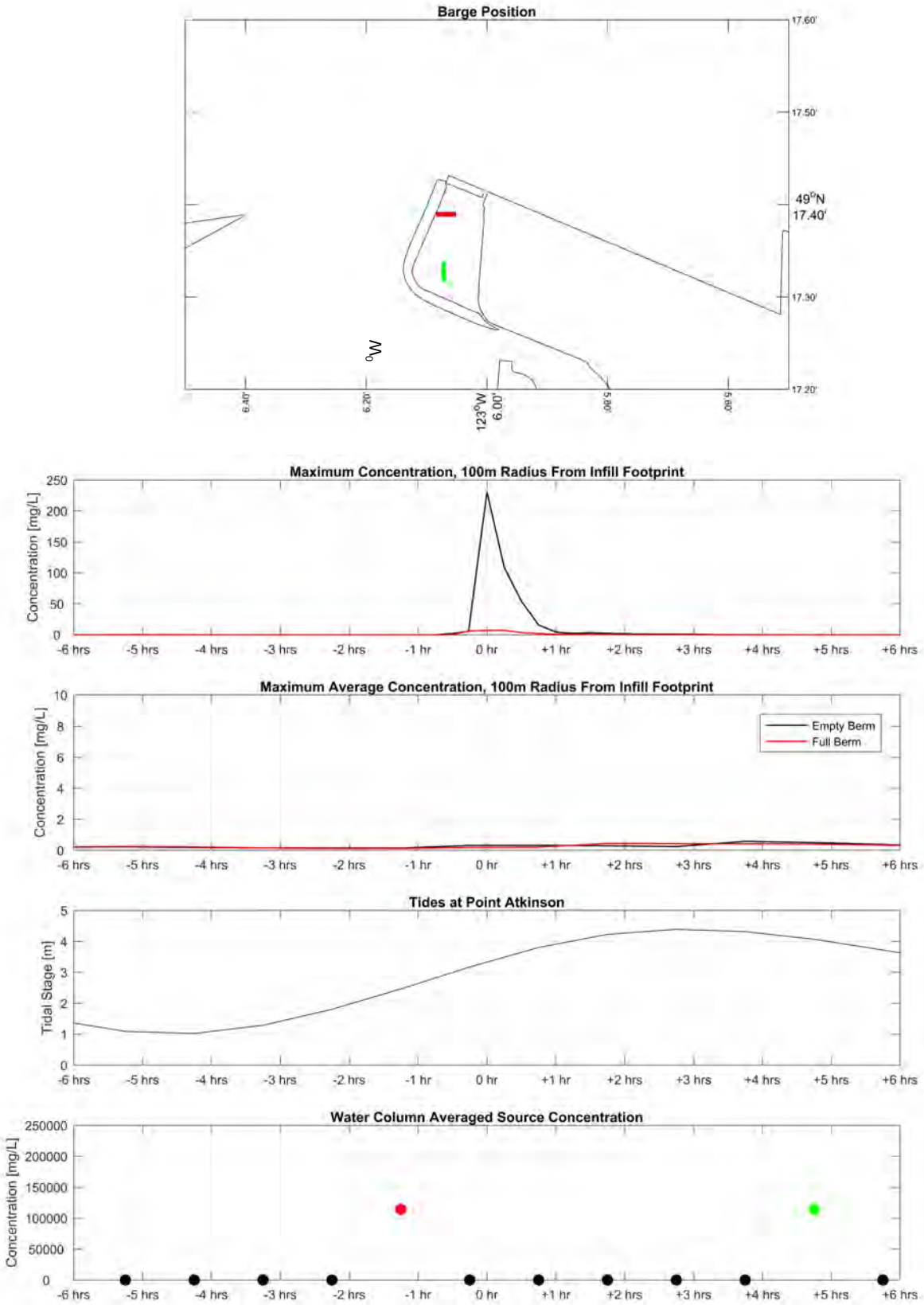
Dispersal Modelling of Infill Derived Fugitive Sediment

East Basin Infill Zone, Lift 4
TSS Source Attenuation at 100 m

PROJECT NO.	DWN	CKD	APVD	REV
WTRM.03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech - VANC	March, 2017

Figure 4.22



NOTES

1) Barge position is indicated in the upper panel by either a red or green box, corresponding to a red or green point in the bottom panel indicated the hopper dump time.

STATUS
ISSUED FOR USE

CLIENT

AECOM

TETRA TECH

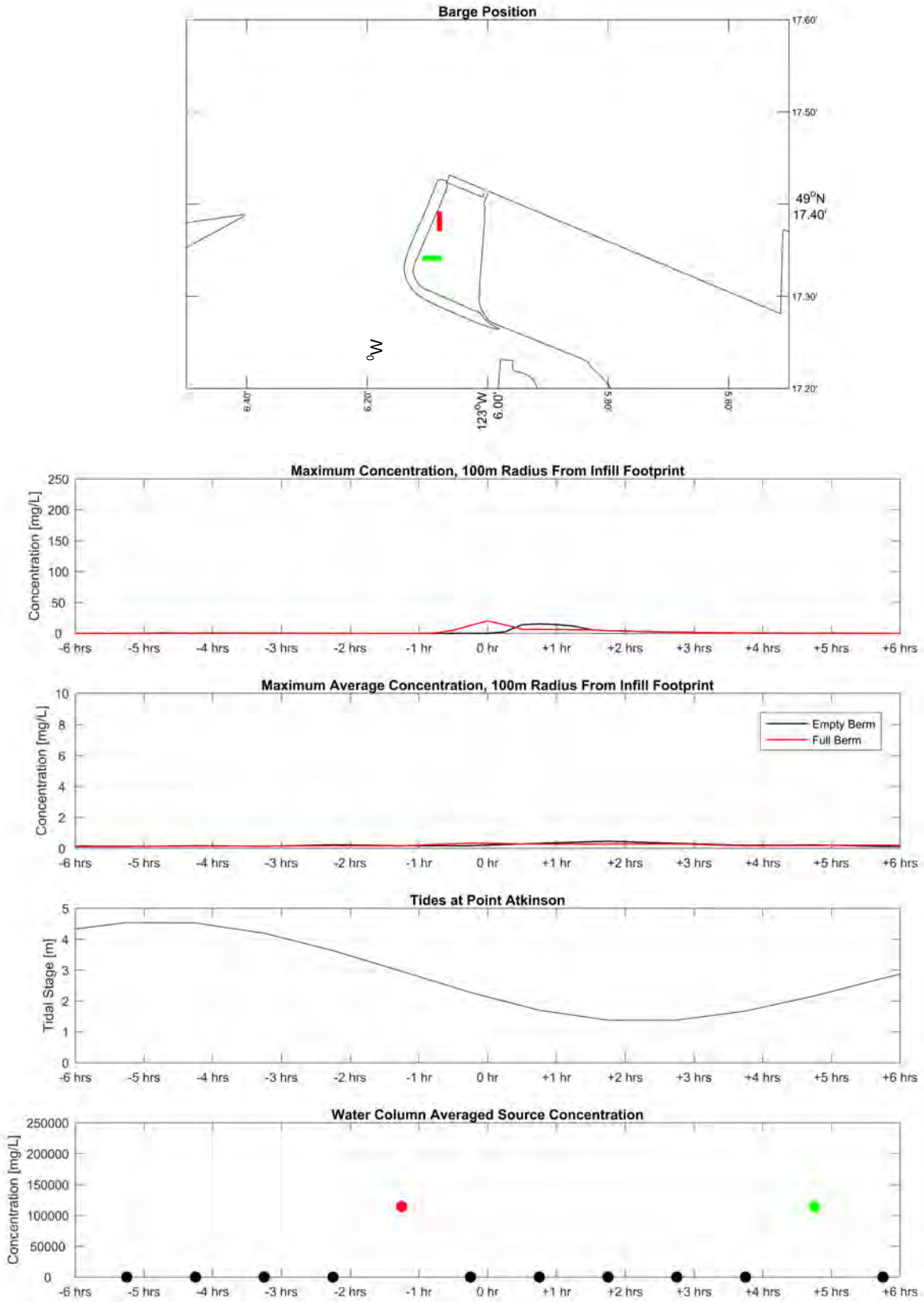
Dispersal Modelling of Infill Derived Fugitive Sediment

West Basin Infill Zone, Lift 3 Empty TSS Concentration Peak, Flood Tide

PROJECT NO.	DWN	CKD	APVD	REV
WTRM03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech - VANC	March, 2017

Figure 4.23



NOTES

1) Barge position is indicated in the upper panel by either a red or green box, corresponding to a red or green point in the bottom panel indicated the hopper dump time.

STATUS
ISSUED FOR USE

CLIENT

AECOM

TETRA TECH

Dispersal Modelling of Infill Derived Fugitive Sediment

West Basin Infill Zone, Lift 3 Empty TSS Concentration Peak, Ebb Tide

PROJECT NO.	DWN	CKD	APVD	REV
WTRM03017	JM	JM	JAS	0

OFFICE	DATE
Tetra Tech - VANC	March, 2017

Figure 4.24

APPENDIX A

TETRA TECH'S GENERAL CONDITIONS

GENERAL CONDITIONS

HYDROTECHNICAL

This report incorporates and is subject to these “General Conditions”.

1.1 USE OF REPORT AND OWNERSHIP

This report pertains to a specific site, a specific development, and a specific scope of work. The report may include plans, drawings, profiles and other supporting documents that collectively constitute the report (the “Report”).

The Report is intended for the sole use of TETRA TECH’s Client (the “Client”) as specifically identified in the TETRA TECH Services Agreement or other Contract entered into with the Client (either of which is termed the “Services Agreement” herein). TETRA TECH does not accept any responsibility for the accuracy of any of the data, analyses, recommendations or other contents of the Report when it is used or relied upon by any party other than the Client, unless authorized in writing by TETRA TECH.

Any unauthorized use of the Report is at the sole risk of the user. TETRA TECH accepts no responsibility whatsoever for any loss or damage where such loss or damage is alleged to be or, is in fact, caused by the unauthorized use of the Report.

Where TETRA TECH has expressly authorized the use of the Report by a third party (an “Authorized Party”), consideration for such authorization is the Authorized Party’s acceptance of these General Conditions as well as any limitations on liability contained in the Services Agreement with the Client (all of which is collectively termed the “Limitations on Liability”). The Authorized Party should carefully review both these General Conditions and the Services Agreement prior to making any use of the Report. Any use made of the Report by an Authorized Party constitutes the Authorized Party’s express acceptance of, and agreement to, the Limitations on Liability.

The Report and any other form or type of data or documents generated by TETRA TECH during the performance of the work are TETRA TECH’s professional work product and shall remain the copyright property of TETRA TECH.

The Report is subject to copyright and shall not be reproduced either wholly or in part without the prior, written permission of TETRA TECH. Additional copies of the Report, if required, may be obtained upon request.

1.2 ALTERNATIVE REPORT FORMAT

Where TETRA TECH submits both electronic file and hard copy versions of the Report or any drawings or other project-related documents and deliverables (collectively termed TETRA TECH’s “Instruments of Professional Service”), only the signed and/or sealed versions shall be considered final. The original signed and/or sealed version archived by TETRA TECH shall be deemed to be the original. TETRA TECH will archive the original signed and/or sealed version for a maximum period of 10 years.

Both electronic file and hard copy versions of TETRA TECH’s Instruments of Professional Service shall not, under any circumstances, be altered by any party except TETRA TECH.

TETRA TECH’s Instruments of Professional Service will be used only and exactly as submitted by TETRA TECH.

Electronic files submitted by TETRA TECH have been prepared and submitted using specific software and hardware systems. TETRA TECH makes no representation about the compatibility of these files with the Client’s current or future software and hardware systems.

1.3 STANDARD OF CARE

Services performed by TETRA TECH for the Report have been conducted in accordance with the Services Agreement, in a manner consistent with the level of skill ordinarily exercised by members of the profession currently practicing under similar conditions in the jurisdiction in which the services are provided. Professional judgment has been applied in developing the conclusions and/or recommendations provided in this Report. No warranty or guarantee, express or implied, is made concerning the test results, comments, recommendations, or any other portion of the Report.

If any error or omission is detected by the Client or an Authorized Party, the error or omission must be immediately brought to the attention of TETRA TECH.

1.4 ENVIRONMENTAL AND REGULATORY ISSUES

Unless expressly agreed to in the Services Agreement, TETRA TECH was not retained to investigate, address or consider, and has not investigated, addressed or considered any environmental or regulatory issues associated with the project.

1.5 DISCLOSURE OF INFORMATION BY CLIENT

The Client acknowledges that it has fully cooperated with TETRA TECH with respect to the provision of all available information on the past, present, and proposed conditions on the site, including historical information respecting the use of the site. The Client further acknowledges that in order for TETRA TECH to properly provide the services contracted for in the Services Agreement, TETRA TECH has relied upon the Client with respect to both the full disclosure and accuracy of any such information.

1.6 INFORMATION PROVIDED TO TETRA TECH BY OTHERS

During the performance of the work and the preparation of this Report, TETRA TECH may have relied on information provided by persons other than the Client.

While TETRA TECH endeavours to verify the accuracy of such information, TETRA TECH accepts no responsibility for the accuracy or the reliability of such information even where inaccurate or unreliable information impacts any recommendations, design or other deliverables and causes the Client or an Authorized Party loss or damage.

1.7 GENERAL LIMITATIONS OF REPORT

This Report is based solely on the conditions present and the data available to TETRA TECH at the time the Report was prepared.

The Client, and any Authorized Party, acknowledges that the Report is based on limited data and that the conclusions, opinions, and recommendations contained in the Report are the result of the application of professional judgment to such limited data.

The Report is not applicable to any other sites, nor should it be relied upon for types of development other than those to which it refers. Any variation from the site conditions present at or the development proposed as of the date of the Report requires a supplementary investigation and assessment.

It is incumbent upon the Client and any Authorized Party, to be knowledgeable of the level of risk that has been incorporated into the project design, in consideration of the level of the hydrotechnical information that was reasonably acquired to facilitate completion of the design.

The Client acknowledges that TETRA TECH is neither qualified to, nor is it making, any recommendations with respect to the purchase, sale, investment or development of the property, the decisions on which are the sole responsibility of the Client.

1.8 JOB SITE SAFETY

TETRA TECH is only responsible for the activities of its employees on the job site and was not and will not be responsible for the supervision of any other persons whatsoever. The presence of TETRA TECH personnel on site shall not be construed in any way to relieve the Client or any other persons on site from their responsibility for job site safety.

Appendix E Centerm Site Specific TSS-Turbidity Relationship

Site Specific TSS-Turbidity Relationship

1. Background

For it to be a useful parameter for assessing water quality, total suspended solids (TSS), measured as milligrams per litre (mg/L), must be converted into turbidity, measured as Nephelometric Turbidity Units (NTUs). Whereas TSS cannot be directly measured in real time in the field, turbidity can be measured in the field, and there is usually a good correlation between turbidity and TSS, if a site-specific relationship can be developed. Using linear regression, the relationship between TSS and turbidity can be generated, enabling measured turbidity to be used as a surrogate for TSS. This document explains how the linear regression line is derived from the data.

2. Methodology

AECOM collected core samples of sediment from the proposed eastern and western dredge areas of the Centerm Expansion Project (CEP). These samples were provided to Maxxam Analytics as part of the investigations for a disposal at sea permit. Maxxam used a portion of the sediment samples from both the western and eastern dredge area to create samples of sediment in water of increasing concentrations of suspended sediment. Each sample was measured for turbidity using a meter similar to the YSI ProDSS Multiparameter Sampling Instrument. The samples were then analyzed for TSS. The methodology is provided below.

2.1 Procedure

Nine steps were required in creating a series of samples with varying TSS concentrations that were then measured for turbidity:

- Step 1: Two composite samples were created: Set #1, from the western basin, and Set #2, from the eastern basin, following standard compositing procedures. Each composite comprised equal parts of a number of samples taken from the western and eastern basins, respectively.
- Step 2: A hand-held turbidity meter having a range of 10 NTUs to 200 NTUs was calibrated.
- Step 3: A 1 L plastic bottle, labelled “Set #1 – 1”, was filled with 900 mL of deionized water.
- Step 4: A small quantity of homogenized sediment from the Set #1 composite was added to the bottle. The bottle was then capped and shaken for 60 seconds to fully suspend the sediments.
- Step 5: The turbidity of the sample was measured with a handheld meter.
- Step 6: Steps 4 and 5 were repeated until the turbidity read 25 ±5 NTUs.
- Step 7: Samples were capped and set aside.
- Step 8: Steps 3 through 7 were repeated for each composite (adjusting the label accordingly); increasing the target NTU each time to produce 10 samples for each composite with the following approximate NTU values: 25, 35, 50, 65, 80, 95, 110, 125, 140, and 160 (each ±5 NTUs).
- Step 9: Samples were submitted to Maxxam Analytics for measurement and reporting of TSS.

3. Results

3.1 Western Dredge Area

Table 1 presents the TSS and corresponding turbidity values for the western dredge area using the data supplied by Maxxam. Figure 1 shows the scatter plot of points and the linear regression line generated using MS Excel.

Table 1. Western Dredge Area Laboratory Generated TSS/Turbidity Data

Physical Properties	Units	SET #1-1	SET #1-2	SET #1-3	SET #1-4	SET #1-5	SET #1-6	SET #1-7	SET #1-8	SET #1-9	SET #1-10
Total Suspended Solids	mg/L	39.3	71.0	70.0	87.3	106.0	147.0	185.0	190.0	207.0	294.0
Turbidity	NTU	26.1	46.2	39.6	62.9	89.3	96.8	118.0	124.0	157.0	227.0

Accuracy measured to ±5 NTUs

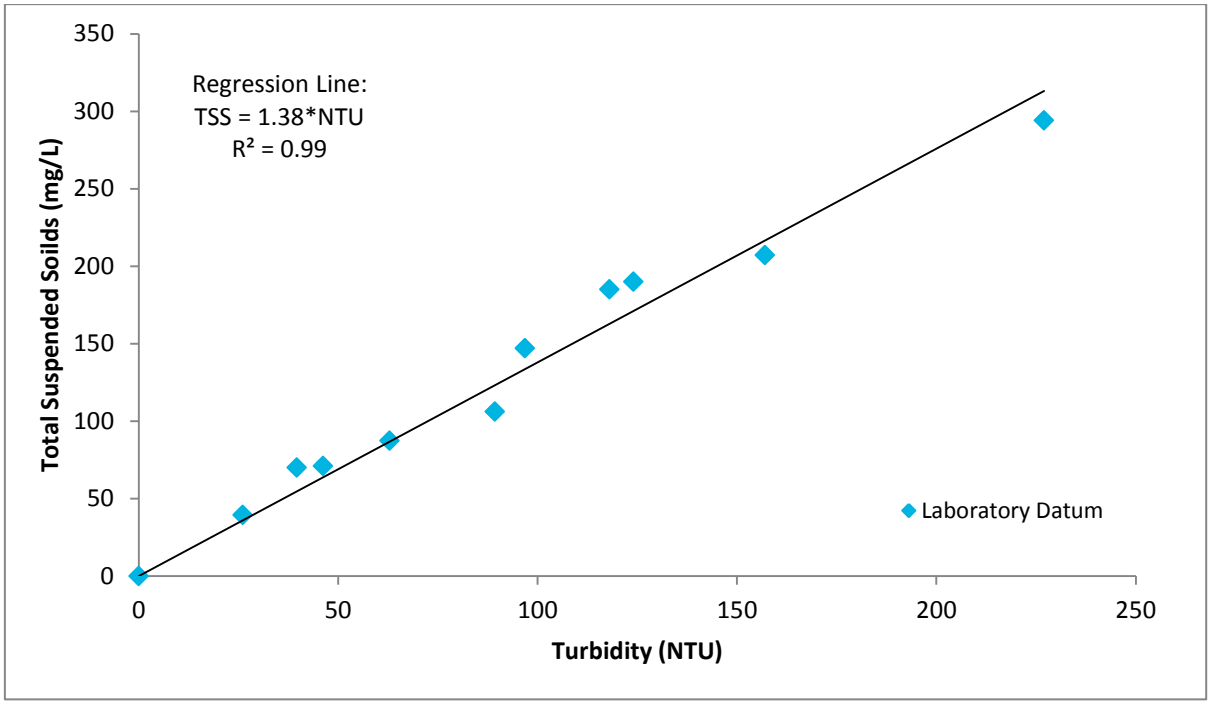


Figure 1. Regression Line for Total Suspended Solids versus Turbidity, Western Dredge Area

3.2 Eastern Dredge Area

Table 2 presents the TSS and corresponding turbidity values for the eastern dredge area based on the analysis described in Step 9 of the methodology above. Figure 2 depicts the regression line of this relationship.

Table 2. Eastern Dredge Area Laboratory Generated TSS/Turbidity Data

Physical Properties	Units	SET #2-1	SET #2-2	SET #2-3	SET #2-4	SET #2-5	SET #2-6	SET #2-7	SET #2-8	SET #2-9	SET #2-10
Total Suspended Solids	mg/L	39.5	60.3	64.5	80.5	147.0	77.7	252.0	192.0	252.0	310.0
Turbidity	NTU	23.0	39.3	57.3	65.4	86.9	104.0	121.0	126.0	135.0	174.0

Accuracy measured to ±5 NTUs

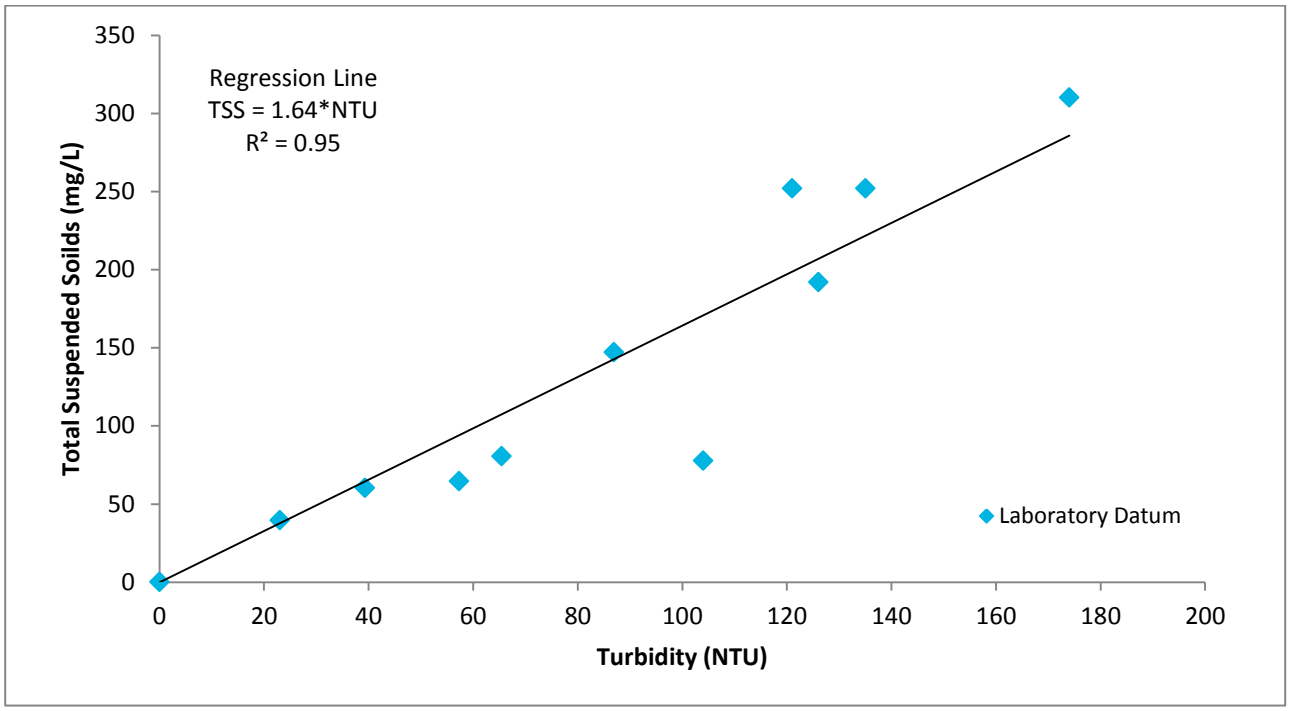


Figure 2. Regression Line for Total Suspended Solids versus Turbidity, Eastern Dredge Area

4. Summary

Based on the laboratory results provided by Maxxam and the analysis carried out by AECOM, the correlation between TSS and turbidity for the sediment from the east and west dredge areas was high. However, the regression analysis indicated that the relationship differed between the two areas, and therefore two different equations were used to convert the TSS values to turbidity in NTUs for monitoring purposes. Based on the regression equations provided in Section 3, Table 3 and Table 4, the NTU equivalents for the TSS values generated by the numeric modelling used to assess sediment dispersion during dredging. The regression line for samples from the western dredge area has an equation of y=1.38x, with a correlation coefficient, R^2, of 0.9719. The formula y=1.3791x can be used to determine the value of TSS that corresponds with a known turbidity level. The application of this process can be seen in Table 3, which presents a summary of depth-averaged TSS concentrations at each Compliance Point (CP) for the CEP western area.

Table 3. Expected TSS and NTU Concentrations at Western Monitoring Locations

Percentile	WCP-1		WCP-2		WCP-3		WCP-4		WCP-5	
	TSS	NTU	TSS	NTU	TSS	NTU	TSS	NTU	TSS	NTU
Maximum	34.5	25.0	28.6	20.7	8.2	5.9	10.2	7.4	19.1	13.8
95th	8.6	6.2	8.6	6.2	3.7	2.7	5.4	3.9	9.7	7.0
75th	4.4	3.2	4.4	3.2	1.9	1.4	2.7	2.0	4.8	3.5
Median	3.0	2.2	3.0	2.2	1.0	0.7	1.6	1.2	2.5	1.8
25th	2.1	1.5	2.1	1.5	0.5	0.4	0.9	0.7	1.3	0.9
Minimum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5 mg/L Percentile:	82nd		82nd		99th		94th		76th	

Note: 1. From regressions, NTU value is equal to the TSS/1.3791

2. Based on Canadian Council of Ministers of the Environment Canadian Water Quality Guidelines for the Protection of Aquatic Life (CCME 2002); Based on BC MOE British Columbia Approved Water Quality Guidelines: Aquatic Life, Wildlife & Agriculture (BC MOE, 2017).

By contrast, the regression line for samples from the eastern dredge area has an equation of y=1.6421x with a correlation coefficient, R^2, of 0.8591. The formula y=1.6421x can be used to determine the value of TSS that corresponds with a known turbidity level. The application of this process can be seen in Table 4, which presents a summary of depth-averaged TSS concentrations at each CP for the CEP eastern area.

Table 4. Expected TSS and NTU Concentrations at Eastern Monitoring Locations

Percentile	ECP-1		ECP-2		ECP-3		ECP-4	
	TSS	NTU	TSS	NTU	TSS	NTU	TSS	NTU
Maximum	20.9	12.7	7.3	4.4	17.3	10.5	29.1	17.7
95th	8.5	5.2	3.5	2.1	8.3	5.1	11.5	7.0
75th	4.1	2.5	1.7	1.0	5.3	3.2	5.6	3.4
Median	1.9	1.2	1.0	0.6	3.6	2.2	3.3	2.0
25th	0.9	0.5	0.5	0.3	2.4	1.5	2.1	1.3
Minimum	0.0	0.0	0.0	0.0	0.0	0.0		0.0
5 mg/L Percentile:	83rd		99th		71st		71st	

Note: 1. NTU value is equal to the TSS/1.6421

2. Based on Canadian Council of Ministers of the Environment Canadian Water Quality Guidelines for the Protection of Aquatic Life (CCME 2002); Based on BC MOE British Columbia Approved Water Quality Guidelines: Aquatic Life, Wildlife & Agriculture (BC MOE, 2017).

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