[CATEGORY]

AURORA LNG: MOF AND TERMINAL DREDGE MODELLING

Prepared for:

Stantec

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ASL File: PR 920
October 21 2016
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EXECUTIVE SUMMARY

ASL Environmental Sciences Inc. (ASL) have carried out a 3D numerical modelling study of potential sediment dispersal linked to the development of the Aurora LNG Terminal at Digby Island, near Prince Rupert, B.C. Canada, as requested by Stantec. This work supports the environmental approval process underway for Nexens' LNG Project.

The Aurora LNG project is located at Digby Island and the proposed dredge areas are within Casey Cove for the Materials Offloading Facility (MOF) and just off the southern end of the island for the Terminal Berths. Disposal of the dredgate is proposed to be at sea and is reported separately. The dredge modelling work quantifies the transport, dispersion and deposition of the sediment released due to both handling and resuspension during construction activities for the MOF and Berth areas at Digby Island. This is achieved using ASL's 3D hydrodynamic and sediment transport model, COCIRM-SED, which is well established for this purpose (Jiang et al., 2003; Fissel et al., 2006; Jiang and Fissel 2010).

The model simulations deal with Project sediments introduced by the dredge activity. All Total Suspended Sediment (TSS) and deposition values reported are for above background levels.

The modelled hydrodynamic data from the verification model runs were used to understand the predominant current flows and potential sediment transport. The sediment transport model was run in three depth steps for the MOF to ensure maximum suspension time for sediments and thus a conservative approach for TSS transport into Casey Cove.

Currents across the dredging zones are moderate, peaking at around 0.5 ms^{-1} in Casey Cove and 0.8 ms^{-1} at the Berths. Correspondingly, the modelled TSS distribution and deposition is very localised at both dredge sites. The sediment plumes extend northwards and southwards with the ebb and flood.

The maximum TSS plume extension is 2 km from the dredge source at Casey Cove and just over 1 km away from the source at the Berths. At both locations the main plume concentrations are very low, falling below 5 mg/L once outside the dredge areas. All high TSS concentrations are confined to the dredging points at all locations. They range from just over 200 mg/L above background at the MOF to around 70 mg/L at the Berths, which is consistent with the larger volumes dredged at the MOF.

Persistence of TSS above 5 mg/L above background for more than a few hours within the water columns is only seen at the MOF dredge site and even here it does not remain elevated for 24 hours.

At both the MOF and Berths areas, the predicted deposition of sediment is very local around the dredge points, which is consistent with the modelled TSS distribution. The maximum sediment volume removed is at the MOF and consequently the deposition here is highest at 0.12 m. However, outside the immediate dredge area this drops to 0.01 m or less.

At the Berths the maximum thickness of deposition predicted occurs at Berth 1 South, reaching 0.12 m, similar to at the MOF. However, this is extremely contained to within 50 m radius from the dredge source. Beyond this the deposition is 0.02 m or less. At Berth 1 North and Berth 2 the predicted deposition is 0.02 to 0.04 m within 200 m or less from the dredge source. Outside this area the values are predicted to drop to 0.01 m or less.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ADCP: Acoustic Doppler Current Profiler: measures current speed and direction

B1 N: Berth 1 North

B1 S: Berth 1 South

B2: Berth 2

CCME: Council of Canadian Ministers of the Environment

CD: Chart Datum

ECCC Environment and Climate Change Canada

HW: High Water

LAT: Lowest Astronomical Tide

LNG: Liquefied Natural Gas

LW: Low Water

MOF: Materials Offloading Facility

PSD Particle Size Distribution

TSS: Total Suspended Sediments (this is above background, measured in units of mg/L

1 INTRODUCTION

ASL Environmental Sciences Inc. (ASL) have carried out a 3D numerical modelling study of potential sediment dispersal linked to the development of the Aurora LNG Terminal at Digby Island, near Prince Rupert, B.C. Canada (Figure 1-1). This work was requested by Stantec in support of the environmental approval process underway for Nexens' LNG Project.

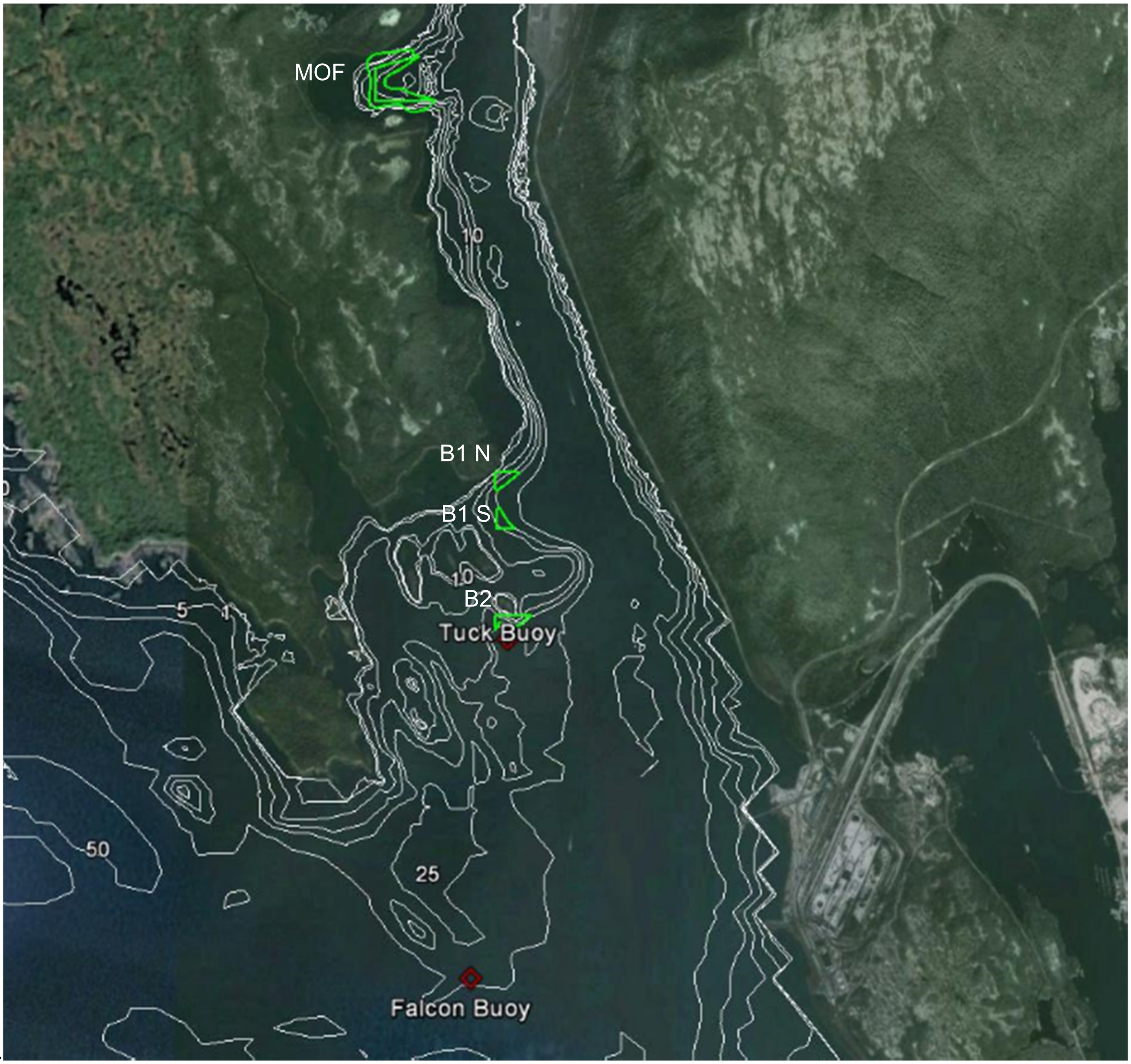


Figure 1-1. The map shows the MOF, Berth 1 North (B1 N) and South (B1 S) and Berth 2 (B2) proposed dredge areas (green outlines). Tuck and Falcon buoy are marked by red diamonds. Taken from Google Earth.

The proposed dredge areas required for construction of the facility are within Casey Cove for the Materials Offloading Facility (MOF) and just off the southern end of the island for the Terminal Berths. The Berths are defined as Berth 1 and Berth 2, as shown by Figure 1-1. Berth 1 has two separate north and south dredge areas and is referred to throughout the report as Berth 1 North (B1 N) and Berth 1 South (B1 S).

ASL's 3D hydrodynamic and sediment transport model was used for this study. COCIRM-SED is well established for this purpose (Jiang et al., 2003; Fissel et al., 2006; Jiang and Fissel 2010).

The model simulates the transport and deposition of the Project sediments introduced by dredge activity. All predictions of Total Suspended Sediment (TSS) and deposition values are for above background levels. To maintain a conservative approach no mitigation, such as silt curtains, were included in this modelling simulation.

Disposal of the dredgate is proposed to occur at sea and is reported separately.

1.1 Project Requirements

The modelling aims to quantify the transport, dispersion and deposition of sediment released due to both handling and resuspension during construction activities for the MOF and Terminal Berths areas at Digby Island.

To achieve this COCIRM-SED is set up as a large, coarse scale domain (blue box) to model the general oceanography of Chatham Sound, as shown in Figure 1-2. The large area model of Chatham Sound has a 210 by 210 m grid size, as set up for earlier studies (Jiang and Fissel, 2011; Lin et al. 2014); this project builds on the expertise gained from the previous modelling studies. For a detailed simulation of the sediment dispersal at the proposed MOF, B1 N, B1 S, and B2 sites, a high resolution, nested model domain has been set up, as shown by the red box in Figure 1-2.

Figure 1-3 shows the nested domain and the 30 m resolution bathymetry and hydrodynamics used for the model domain around Digby Island

The hydrodynamic current distribution results are extracted for the model domain and assessed for flow patterns that could potentially affect sediment transport results. This information is used to improve the sediment modelling approach. Results are described in Section 2.

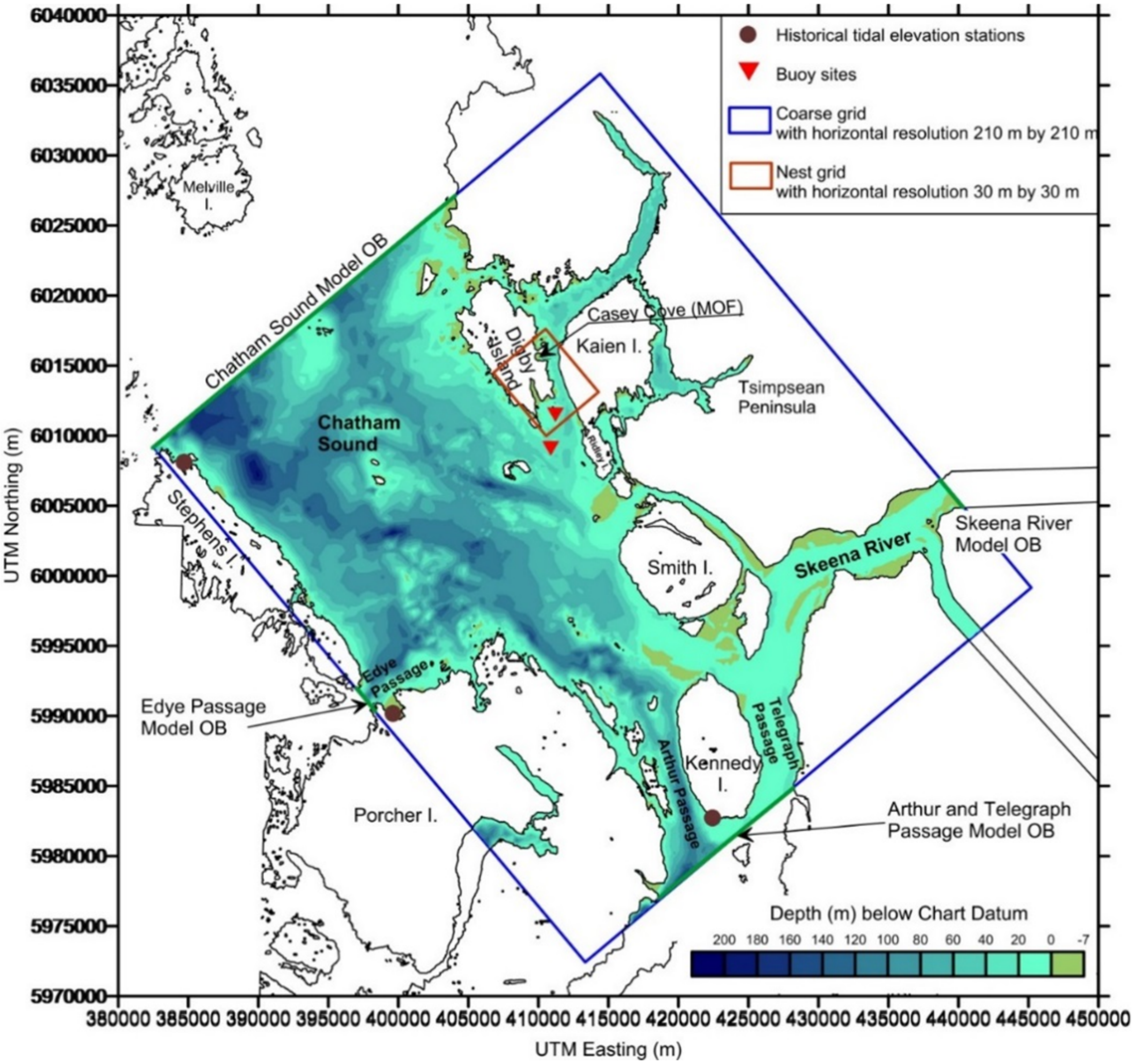


Figure 1-2: COCIRM large scale domain for Chatham Sound. The nested domain is shown as a red box and red triangles show the metocean buoy sites.

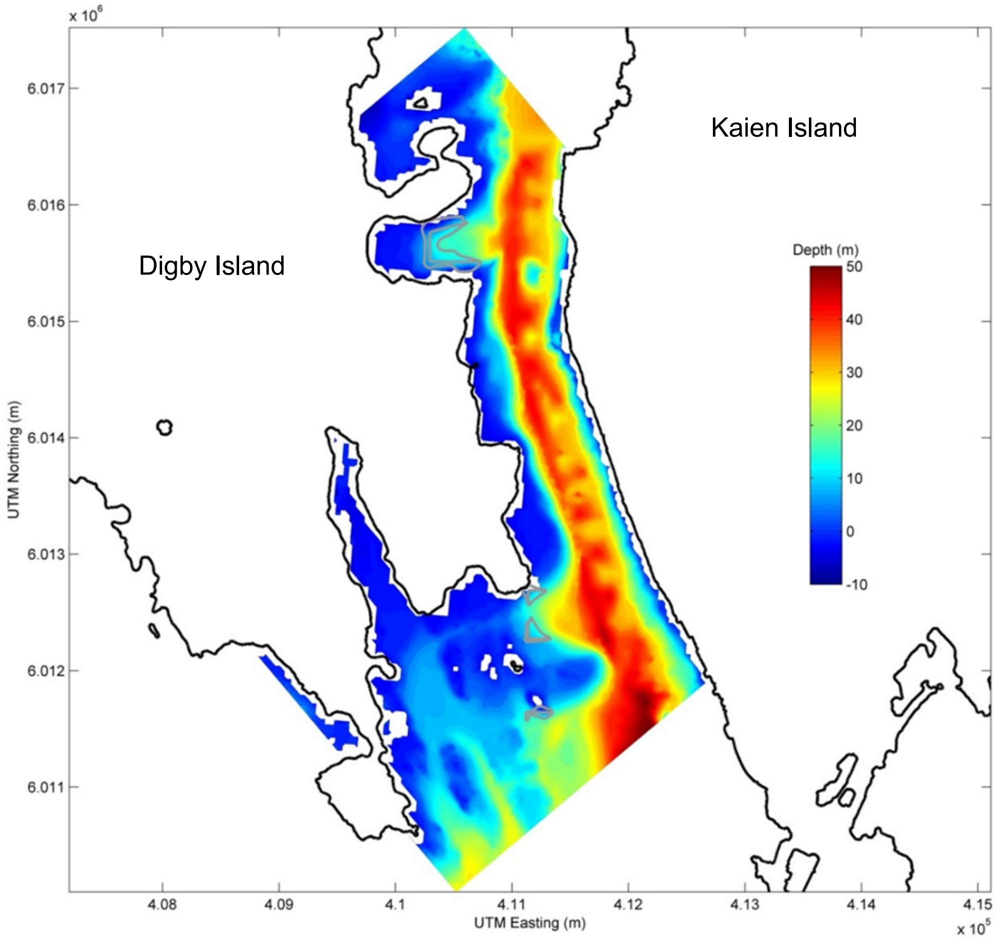


Figure 1-3: COCIRM nested high resolution model domain for Chatham Sound, covering the MOF at Casey Cove and the Terminal sites at the southern end of Digby Island. The bathymetry shows the main channel running north to south between Digby and Kaien Islands.

1.2 Organization of the Report

The report begins with a summary of the background oceanography in Section 2. After this, the work is dealt with in chronological fashion from model setup and validation (Sections 3 and 4), derivation of sediment particle size distribution (Section 5), inclusion of engineering and forcing data required to run the sediment transport model run (Section 6) through to a discussion of the results.

Prior to the results Section, a brief review of the processes affecting sediment transport is given in Section 7. Sections 8 to 11 present the results, which are discussed separately for the MOF and B1 N, B1 S and B 2. Section 12 presents the summary and conclusions.

2 BACKGROUND OCEANOGRAPHY

This Section shows the modelled hydrodynamic currents in the MOF and the Berths. These results were used to improve our knowledge of the current flows around the Project sites, and thus likely sediment transport pathways. This was used to inform the depth staged design of the sediment transport modelling for this area.

2.1 MODELLED CURRENTS

The current flow distribution was extracted from the hydrodynamic model for both Casey Cove and the area south of Digby Island for the Berths. The model domain marine boundaries are referred to as open and have to be provided with variables, such as water levels, to simulate flow in and out of the domain. To give context to the currents, the water levels at the open boundary are illustrated in Figure 2-1 for 6 December, 2015. The first Low Water (LW) is at 04:00, High Water (HW) is at 10:00 and the ebb LW is between 16:00 and 17:00. This date is also used to show modelled, depth averaged current vectors and reflects the time of year when dredging is expected to occur.

A sequence of current vector plots is presented showing the flood to ebb tidal sequence for both the MOF and Berths for 6 December 2015 (Figure 2-2 to Figure 2-5). The flood flow is predominantly northwards and the ebb is southwards.

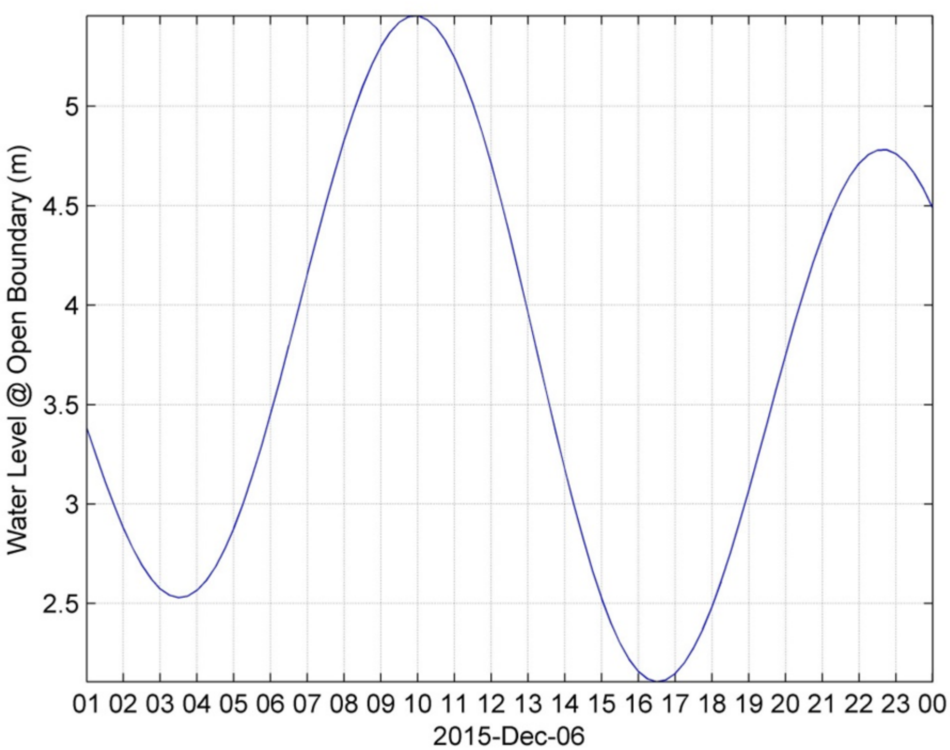


Figure 2-1: Tidal Phase for 6 December 2015.

2.1.1 Casey Cove, Digby Island

Figure 2-3 to Figure 2-3 show the depth averaged, current vector sequence for Casey Cove from LW through the flood and back to LW. The MOF dredge area is marked in grey.

The inner bay area of Casey Cove to the west of the MOF, reaches 5 m deep below Chart Datum (CD), but much of the area is above 0 m CD. The slope of the northern berth area also extends into the region above 0 m, although drying is only likely to occur intermittently at very low spring tides. Although this is an intertidal zone, the model shows weak to moderate currents flow right to the back of the cove throughout the flood to ebb cycle. Maximum currents are approximately 0.5 ms^{-1}.

The main flow of water is clockwise around the cove on the flood and anticlockwise on the ebb. However, as the flood and ebb flows establish in the main channel, counter currents can be seen to set up in Casey Cove and are maintained for several hours, as show in Figure 2-3 at 0700 and 1400. This counter current meets the opposing circulation and both currents virtually cancel out at the center of the bay. A very weak, eastwards flow is modelled leaving the middle of the cove.

The location where flows exit the cove varies depending on the strength of the counter current. This process is likely to bring material from the north and south side dredge zones of the MOF into Casey Cove on both tidal cycles, but will also help remove it via the centre of the bay. The currents within the bay appear strongest at low and high water, as the opposing flows weaken. In the main channel, the currents are strongest at mid ebb and flood.

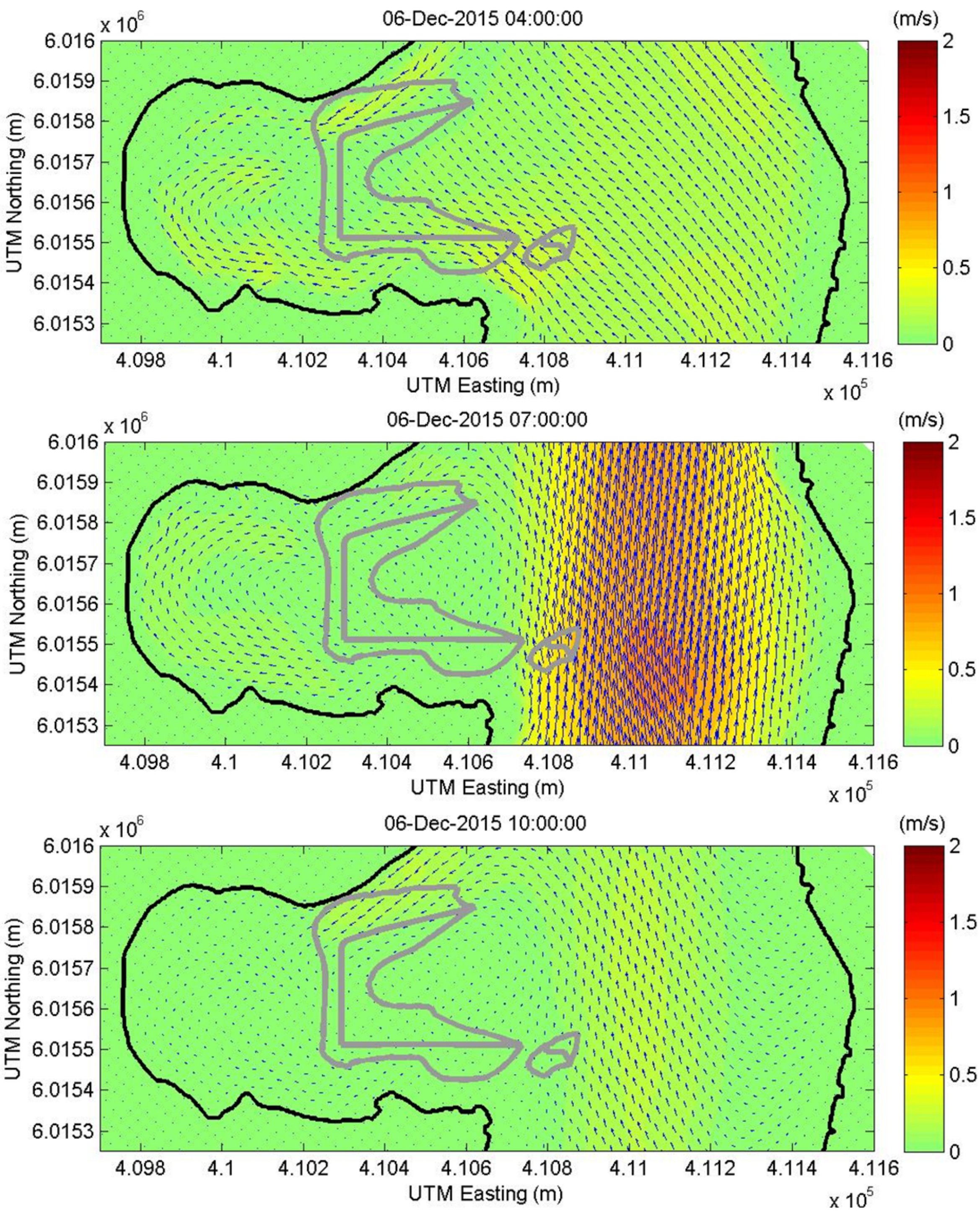


Figure 2-2. Modelled depth averaged currents (ms^{-1}) for Casey Cove at LW (top), mid-flood (middle) and HW (bottom). The proposed MOF dredge areas are shown in grey outline and the outer regions delineate the sloped areas.

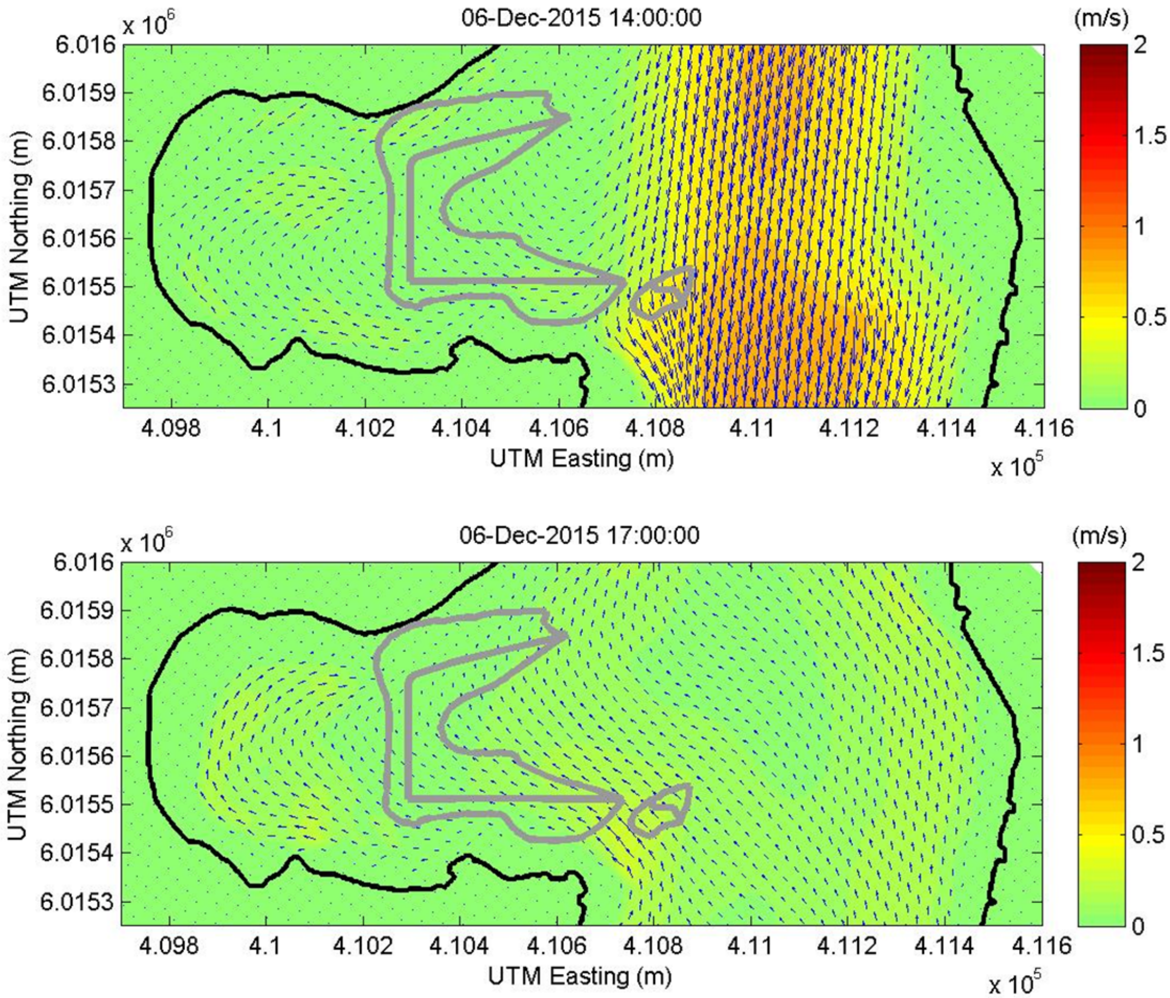


Figure 2-3: Casey Cove modelled depth averaged currents (ms^{-1}) for the mid-ebb (top) and for LW (bottom). The proposed MOF dredge areas are shown in grey outline and the outer regions delineate the sloped areas.

2.1.2 THE BERTHS

Figure 2-4 shows the modelled currents around the berth region from LW through to HW. Figure 2-5 shows the modelled currents during the ebb and following LW. The dredge areas are marked in grey. The currents around the dredge areas do not reach the peak values of 2 ms^{-1} seen in the main channel, but range from 0 to 0.5 ms^{-1}. Peak values of 0.7 ms^{-1} occur at mid flood about midway between B1 S and B2.

The flow across the region is predominantly northwards during the flood tide, beginning with a northwesterly trend and becoming northeasterly as the flow intensifies. During the southerly ebb tide, frictional effects combined with the Coriolis force,turn the current to the west across the berth region. This develops into a counter current early in the ebb and it remains strongly established until LW at

16:00. This current pattern suggests that the area will be well flushed during the flood tide but sediment could potentially re-enter the region on the ebb.

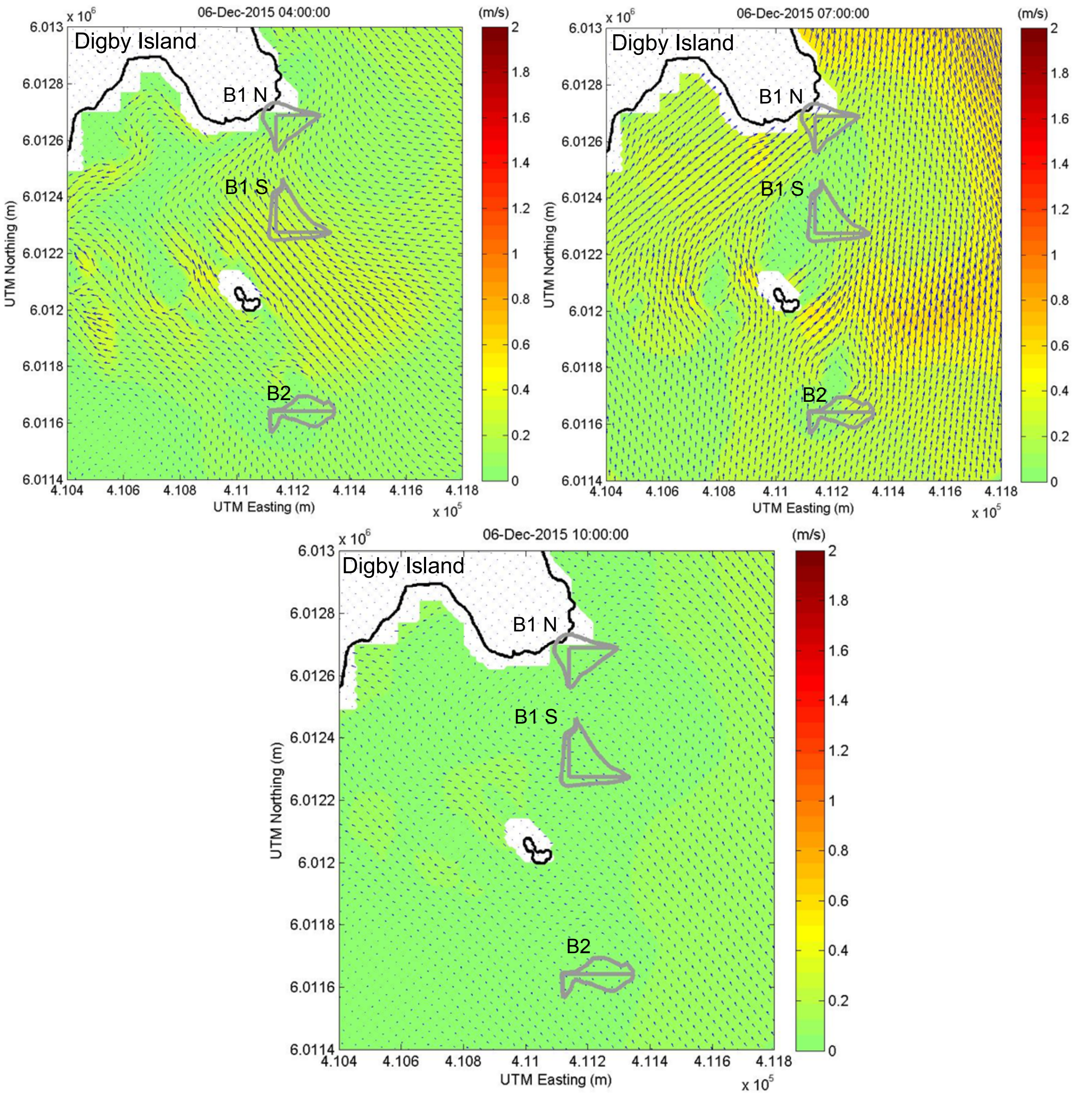


Figure 2-4. Modelled currents (ms^{-1}) around the berth region at LW (top left), flood (top right), and HW (bottom). The proposed Berth dredge areas are shown in grey outline, with the sloped areas delimited.

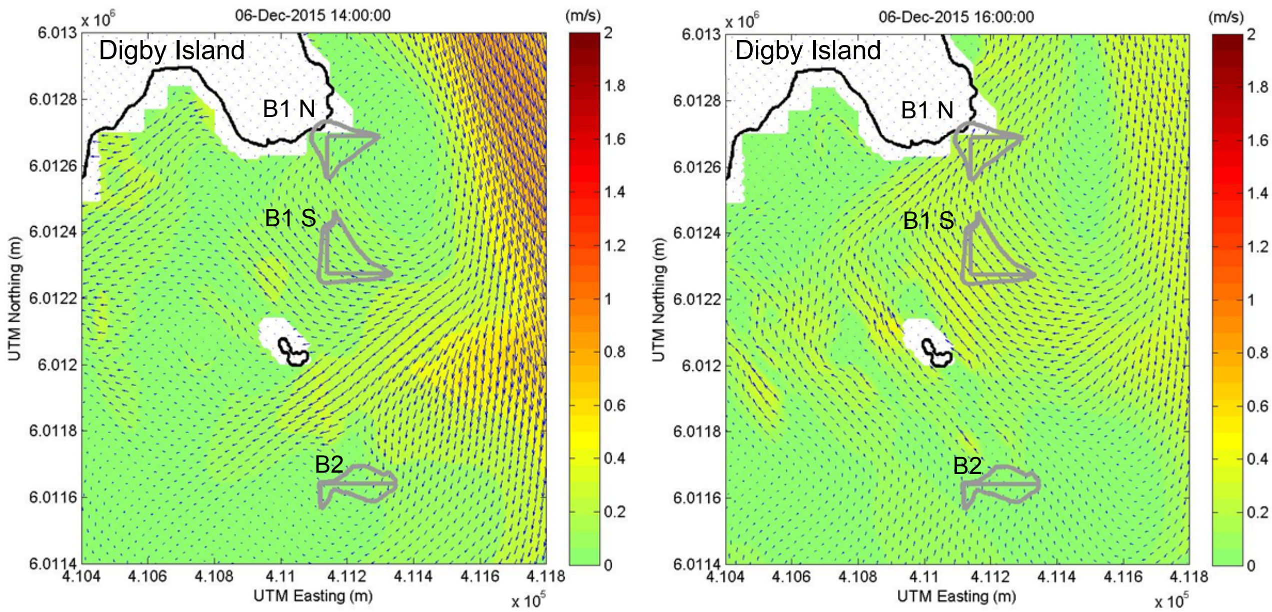


Figure 2-5: Modelled currents (ms^{-1}) around the berths during ebb (left) and LW (right).

2.2 OTHER MODELLING CONSIDERATIONS

A further consideration, that became apparent after discussion with the Client, was the presence of eelgrass in the vicinity of both the MOF and Berth proposed dredge locations. Given the entire area is highly dominated by tides, and to ensure the model captures any potential advection of sediment and deposition in these areas the model was set up to:

- Provide hourly time steps for data extraction
- Use the maximum water depth in three dredge stages at the MOF:
  - 0 to 5, 5 to 10 and 10 to 15 m
- Use the maximum depth for the Terminal, which is achieved in one stage

By extracting the data every hour, a picture of tidal flood and ebb activity can be acquired and the TSS distribution patterns better understood. This is likely to be particularly relevant in Casey Cove, where the tidal currents are shown to move around the bay and sediment can potentially be deposited within the cove.

The model for the MOF was revised to run in three depth stages. This is a more complex approach and involves combining the data extracted from each layer. However it ensures a conservative and near realistic approach to sediment transport within Casey Cove. The model is run in 5 m depth steps, adjusting the bathymetry to the deeper result after dredging and repeating until the desired dredge depth of 15 m below CD is reached, as shown in Figure 2-6.

By increasing the depth in stages the available water column is extended in a realistic fashion. This enables the modelled sediment to remain suspended longer and thus potentially be advected further. It is intended to capture any potential for advection, either into the head of the cove at the MOF or along the coast at the Berths, supporting the conservative but realistic approach for predicting effects of dredging.

The modelled current field around the Berths shows that the currents are similar to at the MOF. Given there is no embayment where high sediment concentrations might be entrapped, the model is run in standard fashion as one layer with no depth step adjustments.

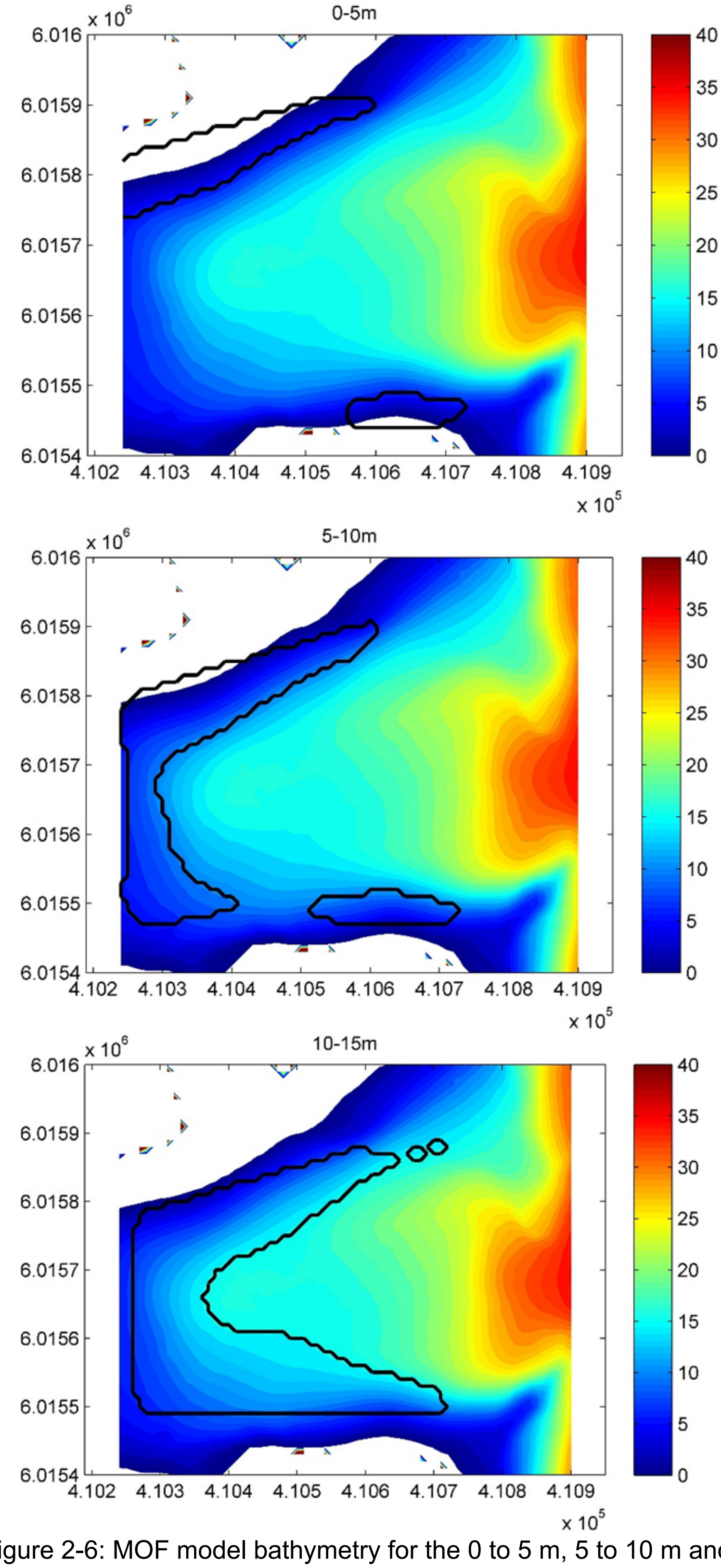


Figure 2-6: MOF model bathymetry for the 0 to 5 m, 5 to 10 m and 10 to 15 m depth steps. The MOF proposed dredge area is shown as a black outline.

3 COCIRM MODEL AND SET UP

This Section describes setting up the domain and running the hydrodynamic model. To accurately simulate the hydrodynamics of an area, the following are required to set the domain and provide open boundary conditions:

- Detailed bathymetry
- Freshwater input from the Skeena River
- Local temperature and salinity data to improve the stratification profile and thus the current flows within the layers.

To force the model for the proposed construction periods, local wind speeds and direction representative of strong wind events have been acquired. These are seasonally dependent and are based on data selected from a five year period to provide a conservative but realistic approach.

The model was verified against current data acquired from Tuck and Falcon buoys, just south of the proposed Berths location. COCIRM-SED was then set up with the relevant engineering data and run to produce TSS and deposition distribution maps.

3.1 COCIRM-SED DESCRIPTION

The 3D numerical model COCIRM-SED used in this study represents a computational fluid dynamics, sediment transport and water quality modeling approach for river, estuarine and coastal applications (Jiang et al., 2003; Jiang et al., 2008; Jiang and Fissel, 2010). COCIRM-SED is a highly-integrated model, consisting of six sub-modules, including circulation, wave, multi-size sediment transport (including particle tracking), morphodynamics, and water quality (Figure 3-1). The model can be operated on either an integrated or an individual module basis. To run the model for sediment transport, inputs are required for the ocean currents, sediment grain size and percentage fraction for each sediment category.

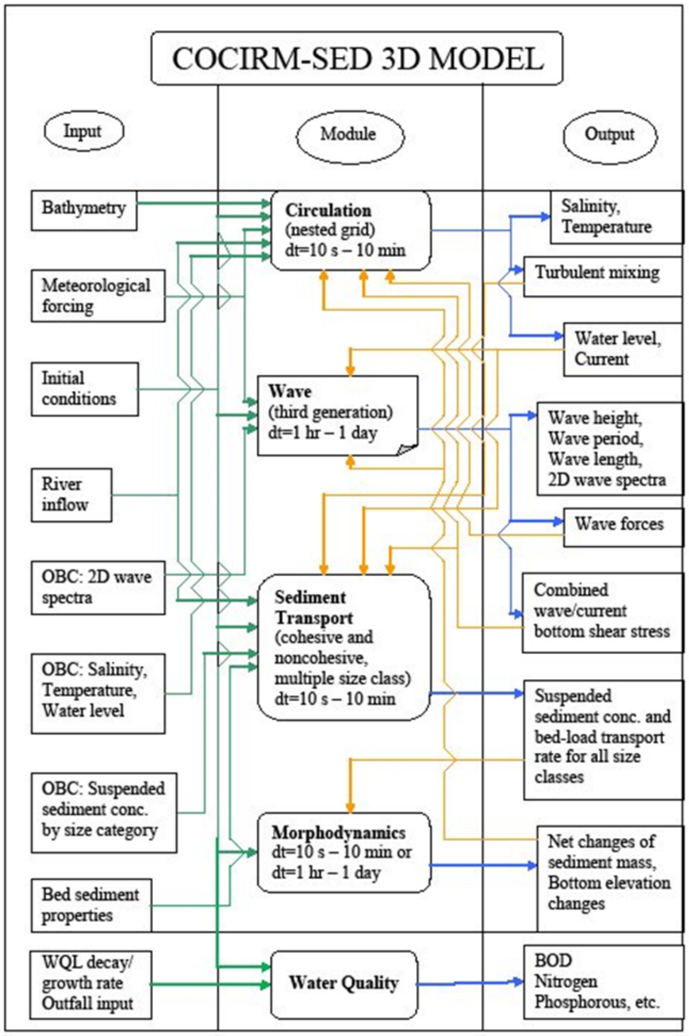


Figure 3-1. Schematic diagram of the COCIRM-SED numerical model.

3.2 MODEL DOMAIN SETUP

The COCIRM-SED model for the sediment dredge modelling around Digby Island operates on two spatial scales:

- Full scale, covering the entire Chatham Sound, including Brown Passage
- Near-field, providing a high resolution model of the MOF and Terminal dredge locations

The full scale domain models the oceanography within Chatham Sound, covering an area of 42 km by 48.3 km. It includes the southern portion of Chatham Sound, Arthur Passage, Telegraph Passage, Edye Passage, Skeena River, and the narrow channel network surrounding Digby Island and Prince Rupert Harbour (Figure 1-2). This full scale model is required to capture the length and time scales of the basic forcing mechanisms of tides, winds and the large inflow from the Skeena River. It has a horizontal grid size of 210 m by 210 m.

To resolve the detailed current action and sediment dispersion within the MOF and Terminal dredge sites, a near field, high resolution, nested grid was set up. This provides a horizontal grid size of 30 m that allows the tidal flows to be resolved around the dredge areas (

Figure 1-3).

In the vertical, both full and near-field scale models used 13 z-layers, with a higher resolution in the surface 20 m to account for salinity and temperature stratification effects. The 210 m and 30 m model grids are coupled at their interfaces and solved together for every time step. This is achieved in a single modelling procedure using the two-way, dynamic nested grid scheme in COCIRM-SED.

ASL used vector digital charts from the Canadian Hydrographic Service (CHS), combined with survey bathymetric data provided by Stantec. The survey data were in the format of UTM Easting, UTM Northing and seabed elevation relative to CD. These data were gridded to provide a good representation of the water depths in the outer model domain. Very high resolution chart data from Nexen were supplied and used for the inner model domain, including the Casey Cove MOF. This was in absence of detailed survey data for Casey Cove. Optimising the bathymetric domain resolution notably improves the model performance.

The next step was to set up the model forcing for the hydrodynamic modelling of currents. This uses:

- Three tidal height elevations spanning three open boundaries
- The Skeena River discharge
- Water temperature and salinity characteristics
- Representative surface winds

The three model open boundaries are Chatham Sound to the north, Edye Passage to the west and Arthur and Telegraph Passages to the south (Figure 1-2). Tidal elevations at these boundaries were derived from seven major tidal height constituents (O1, P1, K1, N2, M2, S2, K2) using the Fisheries and Oceans Canada (DFO) standard tidal prediction program. The Skeena River discharge data were obtained from the Canadian Hydrological Database, archived by Environment and Climate Change Canada (ECCC).

Wind data were obtained from the Holland Rock weather station, operated by ECCC.

The initial water properties (temperatures, salinities and densities) within the model domain and at the boundaries were derived using historical CTD data from DFO's online archive. To provide an improved representation of the stratification of the region, these data were supplemented using data from the Prince Rupert Port Authority (PRPA) quarterly Marine Environmental Water Quality (MEWQ) program. This gave the best representation of the density flow surfaces in the proposed dredge areas, and thus optimum current predictions.

4 Model Verification

The COCIRM-SED full scale, hydrodynamic model has been calibrated and verified in previous studies by comparison with historical current meter data collected within the model domain. Overall good agreement was found between the circulation model results and the ocean current observations from the locations listed in Table 4-1 (Jiang and Fissel, 2011; Lin et al., 2014; Lin et al., 2015).

Table 4-1: Full scale model calibration results.

Observational dataset	Period	Depth (m)	Used for
Kinahan Island	1982 Jun	111	Calibration
RUP2	1993 Jul	17, 31	Verification
AWAC	2013 Jan	17	Verification
Porpoise Channel	2013 Dec	every 2 m from 2.5 m above seabed	Verification

4.1 Nested Hydrodynamic Model Verification

Further verification of the modelled currents was conducted for this present study for the nested model domain. The nested region uses refined model inputs, including higher resolution bathymetry data and improved temperature and salinity data in the vicinity of the dredge area. ADCP current moorings were deployed by Ausenco on behalf of Nexen for the Aurora LNG project. The observations are used for comparison with the modelled results. These were located at Tuck and Falcon buoys in the vicinity of the Berths (Figure 1-1).

The current verification run was carried out for the period 2 to 20 December, 2014. This is a time of strong winds that are representative of the winter construction period for the MOF and Terminal Berths. Model results were saved hourly and compared with the ADCP current data at Tuck Buoy. The results are displayed in Figure 4-1 to Figure 4-3, with observations at Tuck Buoy in red and modelled predicted currents in blue. The model results were compared with the measured values at surface, mid depth and near bottom, 2.7 m, 7.7 m, and 16.7 m respectively. The total water depth is 17.5 m and the data at the 16.7 m bin are considered representative of near bottom currents.

Overall the comparison shows very good agreement of the model currents to observations. There are a few very large speed values in the observed data, which are attributed to buoy motion. A moored buoy is often susceptible to spikes in the current data due to pitch and roll of the sensor by wave action and these are considered noise. Readings at Tuck Buoy gave a maximum current speed of up to 40.2 cms^{-1} at 16.7 m depth, which is unrealistic for near the seabed values. The company that collected and supplied the ADCP data (Ausenco) confirmed there were some discrepancies in data quality and the uncertainties are larger than desired for the purpose of comparison to model output. However, the data indicate that the model is performing well in this region, following the trends in the observed data. There are many instances at each depth where the model slightly over-predicts the currents, as shown in Figure 4-1 to Figure 4-3.

An assessment comparing the mean and percentile fit between the observed and the modelled current speeds is given in Table 4-2. The observed results are slightly biased due to the data spikes; however, the mean results show that at all depths the model is slightly over-predicting the current speed 75 % of the time. This is a conservative result for the model, which is preferred for sediment transport modelling. At the 95th percentile level the model slightly under predicts at 7.7 m and 16.7 m depths, but given the maximum spikes in the buoy data, this is considered to be a good fit. As shown by Figure 4-1 and Figure 4-2, the field data are noisier in the upper part of the water column, which is consistent with orbital wave motion affecting the ADCP sensor.

Table 4-2: Maximum and mean speeds for model results and observations for model results.

Percentile	Max		Mean		95%		75%	
Depth (m)	**OBS** (cm/s)	**MODELLED** (cm/s)	**OBS** (cm/s)	**MODELLED** (cm/s)	**OBS** (cm/s)	**MODELLED** (cm/s)	**OBS** (cm/s)	**MODELLED** (cm/s)
2.7	**41.1**	**31.1**	**14.0**	**12.9**	26.5	26.5	17.5	18.5
7.7	**37.7**	**27.0**	**13.0**	**11.7**	26.5	23.5	16.5	17.5
16.7	**40.2**	**19.9**	**9.1**	**9.7**	19.5	17.5	11.5	13.5

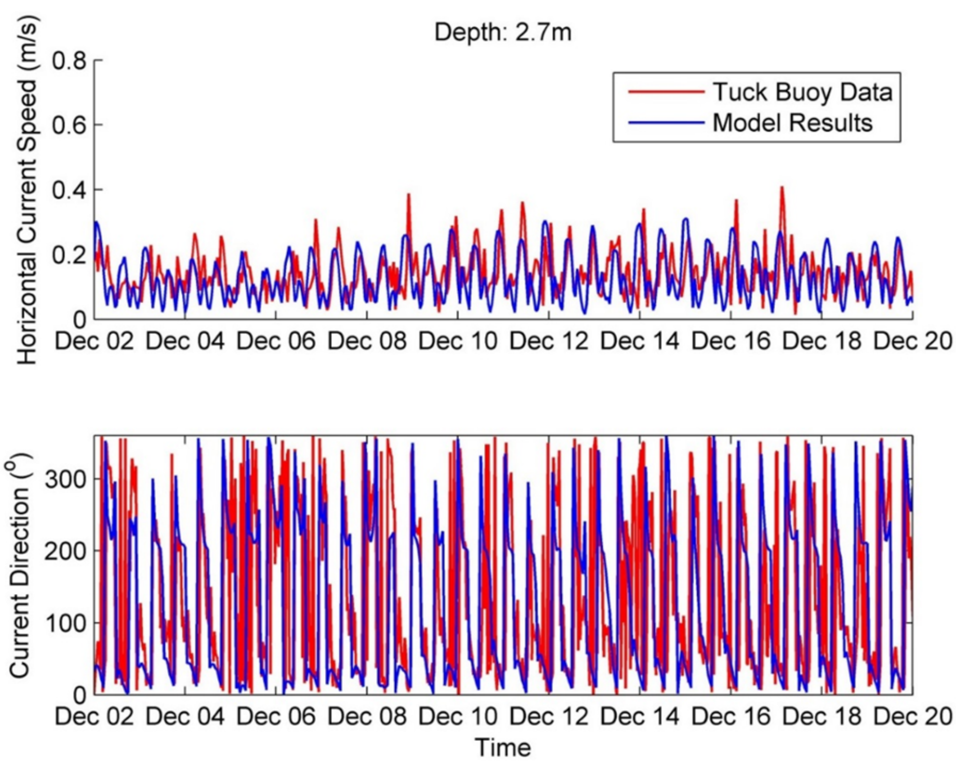


Figure 4-1: Modelled and measured ocean currents at 2.7 m depth at Tuck Buoy ADCP mooring.

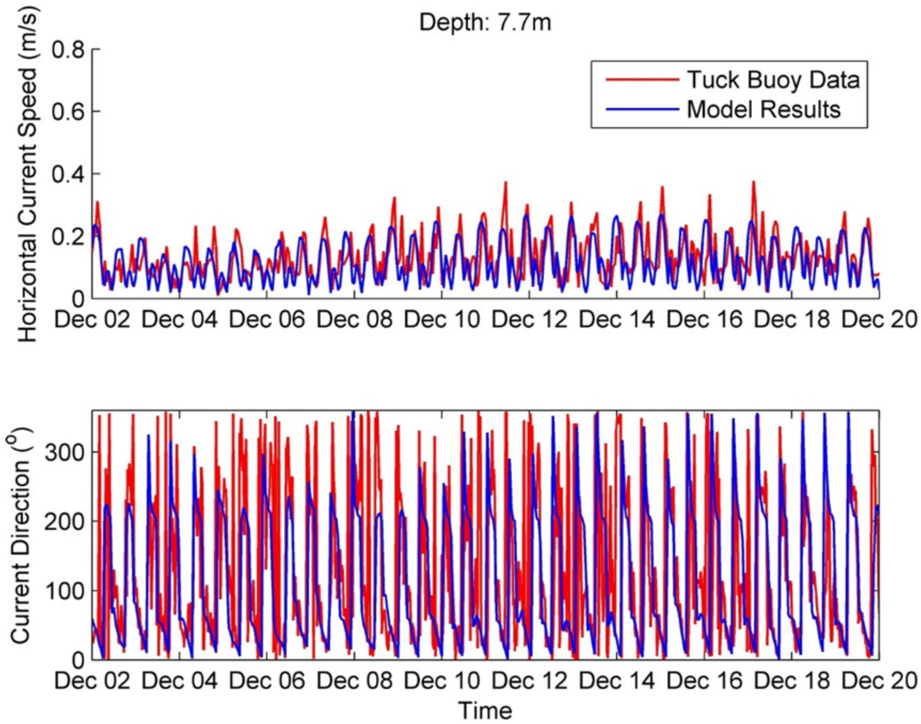


Figure 4-2: Modelled and measured ocean currents at 7.7 m depth at Tuck Buoy ADCP mooring.

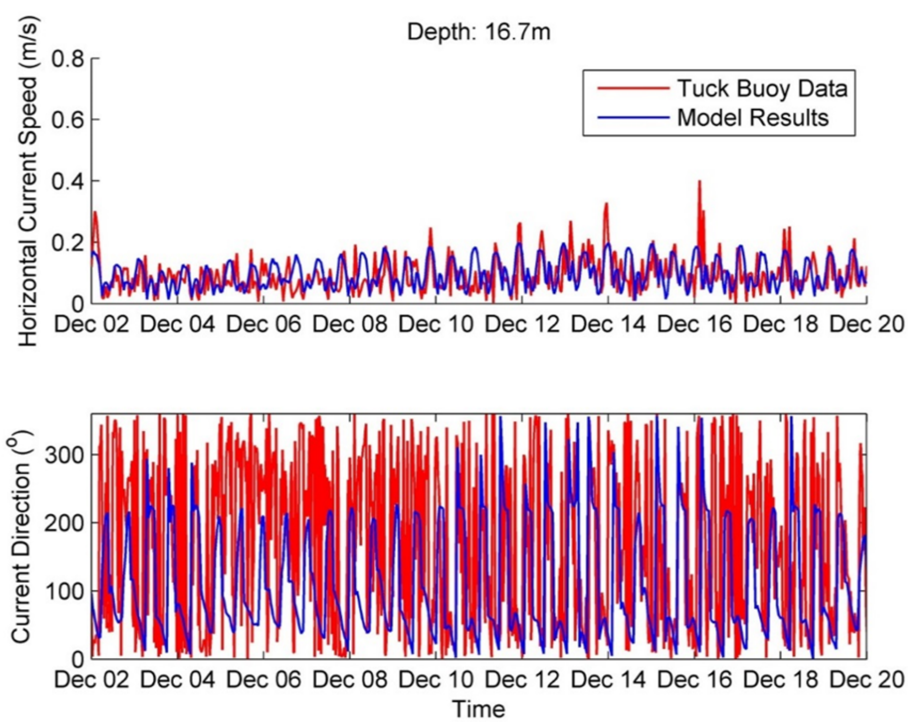


Figure 4-3: Modelled and measured ocean currents at 16.7 m depth at Tuck Buoy ADCP mooring.

5 Sediment Particle Size Distribution Rationale

Defining the sediment Particle Size Distribution (PSD) is an essential step prior to modelling the transport pathways in COCIRM-SED. The sediment type must be defined accurately at each site in both the horizontal and the vertical dimensions down to the required dredge depths. Finer sediment will remain in suspension longer and thus travel further and coarser grained material will settle out quicker and nearer to the dredge area.

Particle size data were obtained from Stantec's environmental field sampling program for the proposed dredge areas (Stantec, 2016). Samples were collected from the top 2 m of sediment, but in many cases were restricted to the top 1 m due to very rocky bottom conditions at most sites.

ASL undertook a background study to extrapolate these data down to the proposed 15 m dredge depth. This used information from previous studies and other historical data to characterise the sediment distribution in the Chatham Sound region. The field data were then assessed in context with the supporting spatial and temporal information. The results were used to define the vertical dredge profile sediment PSD used to model sediment dispersion. The following sections describe the results in detail.

5.1 Physical Processes Affecting Sediment Distributions

The differences in PSD between the MOF, Berths 1 and 2 dredge areas of the Aurora project are consistent with our understanding of the local and regional influences of sediments in the coastal areas of southern Chatham Sound. The sediment regime of open areas of sea are highly influenced by river sediment transport and resuspension generating near bottom transport. In contrast, close to land erosion plays an important role, transporting sands and soil-based sediment into the coastal zone.

The Skeena River discharge carries large quantities of silts and clays to the outer part of the Skeena delta. The magnitude of the Skeena River relative to Chatham Sound is shown by Conway et al. (1996) (Figure 5-1). The sands transported by the Skeena River only extend to the area around the southern and western side of Smith Island, Luternauer (1976), (Figure 5-2). The finer silts and clays remain in suspension longer and become the dominant bottom sediment type in open areas off Lelu, Ridley and Digby Islands. These results are shown in Figure 5-1 and are derived from the earlier research of Luternauer (1976) and McLaren (2016).

Figure 5-2 and Figure 5-3 show the progression towards smaller particle sizes with increasing distance from the Skeena River, up to Digby Island. In open water areas, to the south of Digby Island and west of Ridley Island, the dominant sediment type is medium silt. The gradient in particle sizes is consistent with the slower vertical settling rates of the finer sediments. The lack of coarser sediments demonstrates the cessation of bedload sediment transport beyond Smith Island (Conway, 1996).

In local areas adjacent to the coastlines of both Digby and Ridley Islands, the sediments tend to be somewhat coarser, with more sand and less mud being evident. This is attributed to land-based sediments entering the water due to the erosion and washouts caused by heavy rainfall events. This is similar to the distributions of coarse silt and fine sand further to the south off Smith Island.

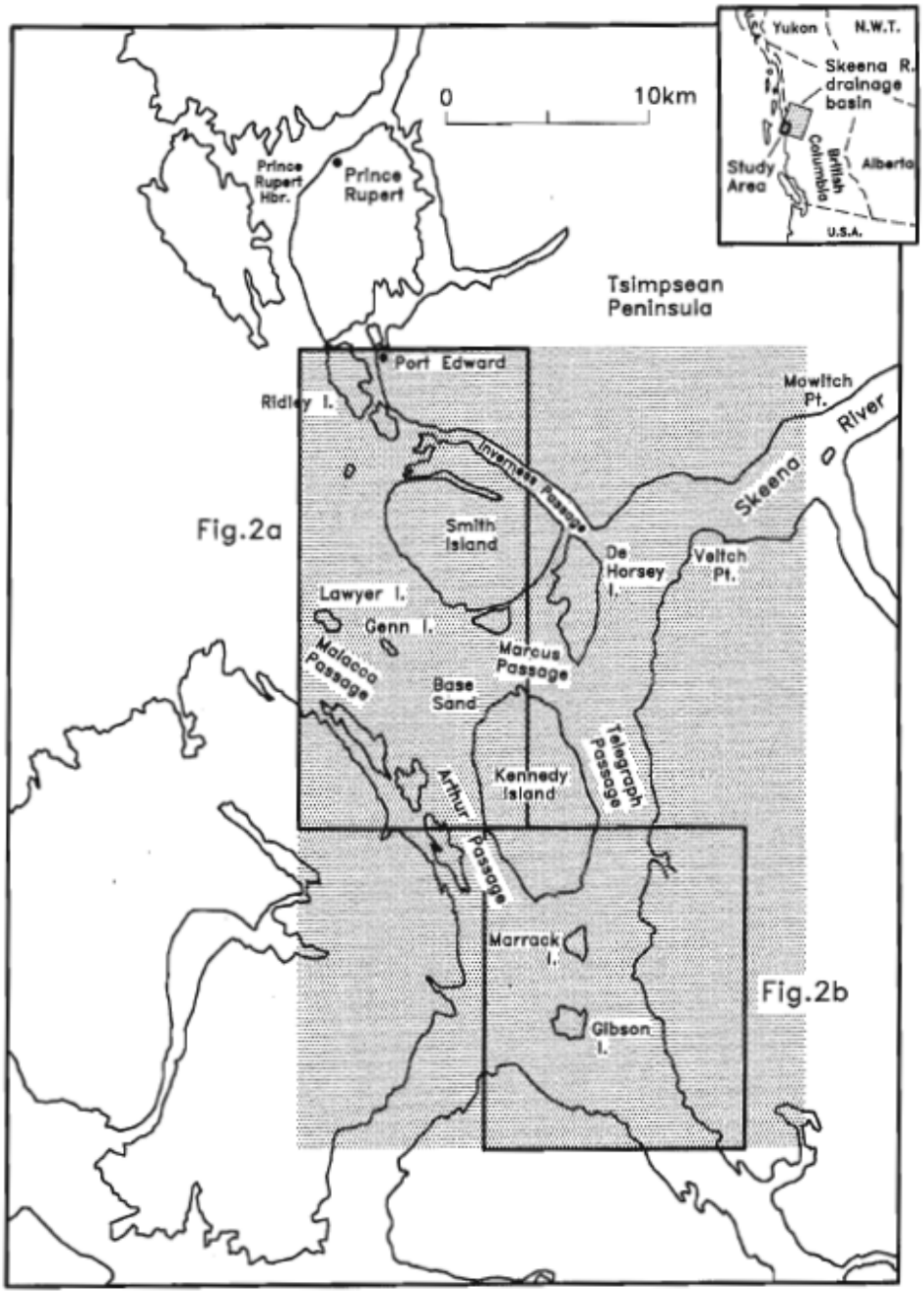


Figure 5-1: Location of the Skeena River delta study area. Drainage area of the Skeena is shown on the inset map (Conway et al., 1996).

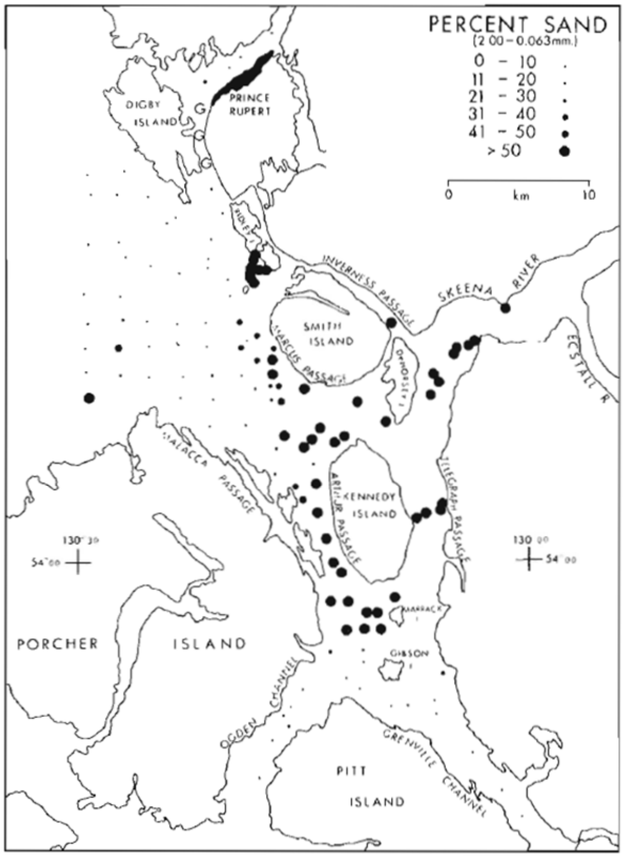


Figure 49. 4. Per cent sand distribution. Shelly gravels were collected at 40 m depth south of Prince Rupert at sites denoted "G".

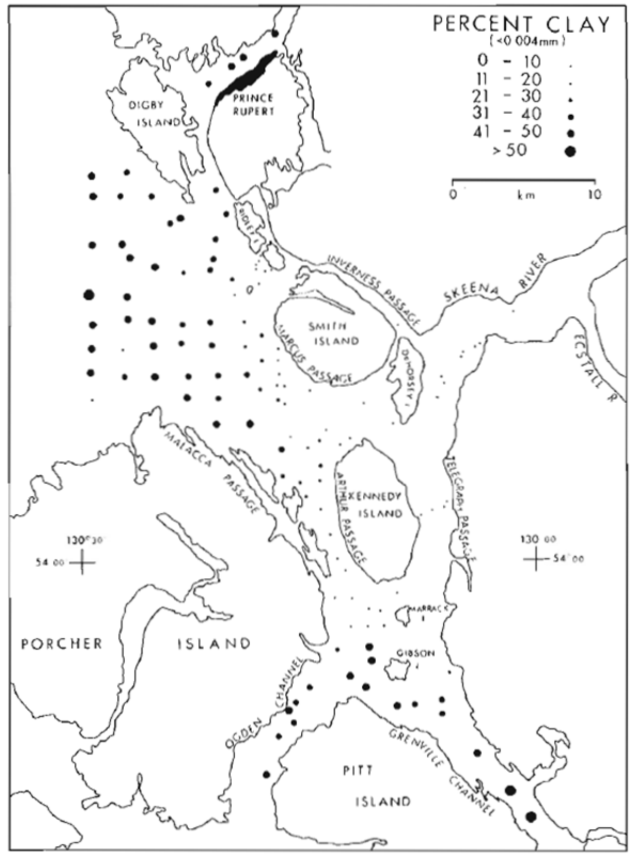


Figure 49. 5. Per cent clay distribution. Sites of greatest accumulation may well be dominant sinks for pollutant material absorbed on or associated with the finer component of the sediment.

Figure 5-2: Horizontal percentage distribution of sand (left panel) and clay (right panel) at the Skeena Delta. from Luternauer (1976).

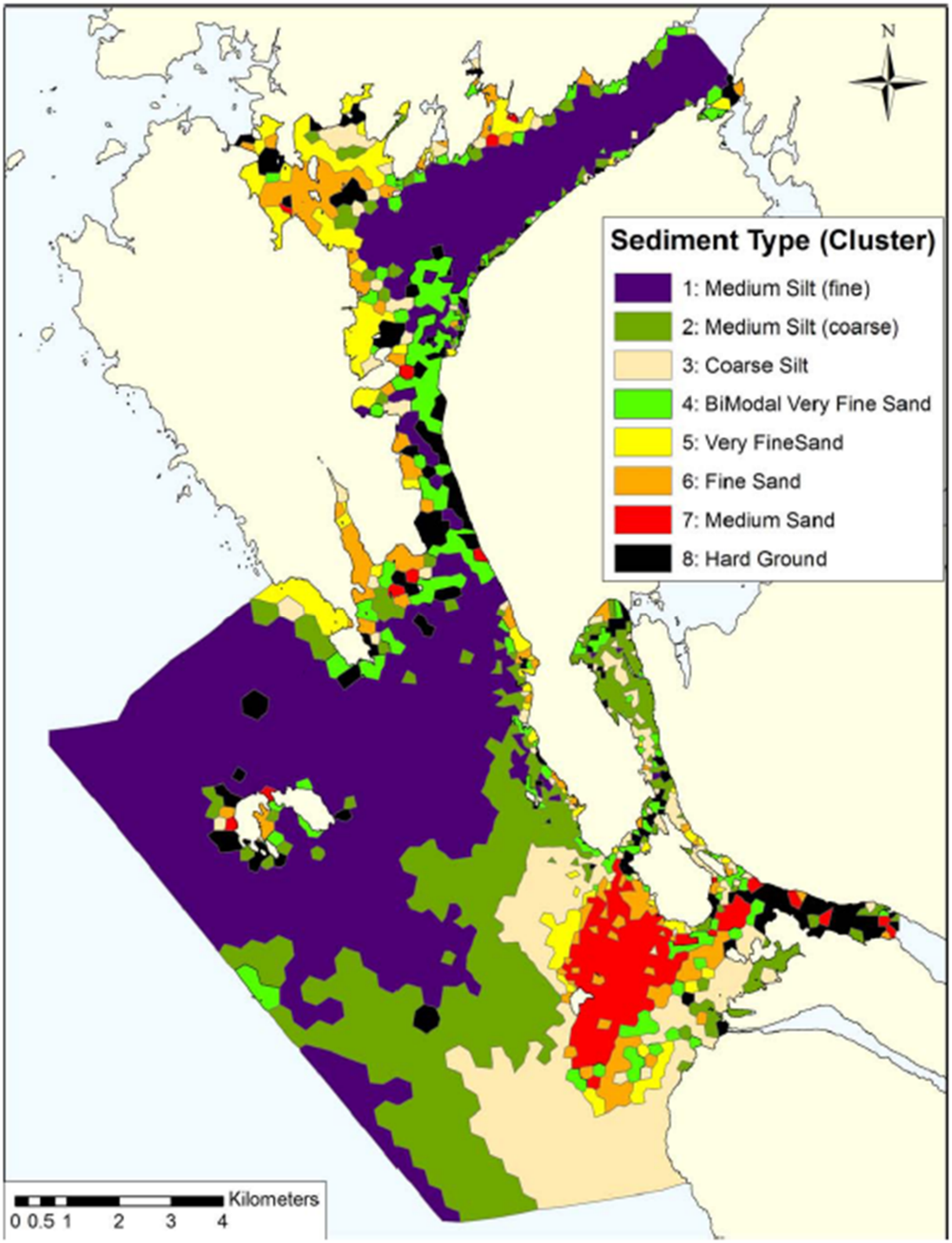


Figure 5-3: Surficial sediment types as determined by cluster analysis of 2636 sediment samples collected in 2014. The clusters are ordered by increasing grain size as detailed in McLaren (2016).

5.2 General Trends from the Field Data

The field sampling results were used to compile Table 5-1, which summarises the percentage clay and silts detected at the MOF and Berth locations for the depths sampled. The data are binned into 0 to 1 m, 0 to 0.5 m and 0.5 to 1 m depth categories. The values were computed using the 75th percentile weighting toward clays and silts, the 50th percentile for fine sands and the 25th percentile for gravel. The higher weightings to the fine sediments, compared to lower ones for the coarser sands, represents a conservative approach which maintains the presence of the finer sediments. These remain in suspension longer and increase the resulting TSS values and the areal extent of deposition. The total particle size percentages listed in Table 5-1 did not add up to 100% because gravel content was not listed. The mud category is defined as clay plus silt.

For each location, fine sediments (muds) are more abundant in the near surface layer (0 to 0.5 m) and coarser sediments (sand) are more abundant in the 0.5 to 1 m layer. Whilst the sampling was sparse below 1 m, the evidence shows the proportion of coarser sediments increases further in the 1.0 – 2.5 m depth measurements.

Table 5-1: Results from the sediment sampling field programs for Aurora LNG project (Stantec, January 2016).

Area	**Clay** (75th Percentile)	**Silt** (75th Percentile)	**Sand (50th Percentile**	**Approx. Mud‡ Total percentile**
Aurora MOF Total (0-1m)	**14.8**	**30.0**	**41.3**	**44.8**
Aurora MOF Total (0-0.5m)	15.8	32.7	37.7	48.5
Aurora MOF Total (0.5-1 m)	12.4	26.4	47.6	38.8
Aurora B1 N (0-1m)	**18.4**	**34.3**	**33.1**	**52.7**
Aurora B1 N (0-0.5m)	19.1	36.6	31.2	55.7
Aurora B1 N (0.5-1m)	9.4	17.0	36.6	26.4
Aurora B1 S (0-1m)	**21.3**	**41.9**	**31.9**	**63.2**
Aurora B1 S (0-0.5m)	24.4	47.9	23.9	72.3
Aurora B1 S (0.5-1m)	16.4	33.5	41.7	49.9
Aurora B2 (0-1m)	**27.4**	**51.8**	**7.0**	**79.2**
Aurora B2 (0-0.5 m)	28.9	53.9	13.5	82.8
Aurora B2 (0.5-1m)	22.6	50.9	9.4	73.5

‡ Muds are defined as clay plus silt.

The amount of mud in the 0 to 1 m depth interval increased from north to south: 44.8% at the MOF, 52.7% at B1 N, 63.2% at B1 S and 79.2% at B2. There is a corresponding decrease in sand content from north to south.

This is consistent with the background understanding of the region's regime, the higher sand and gravel levels at Casey Cove and B1 N being attributed to land inputs due to erosion. Whereas, B1 S and B2 are increasingly exposed to the open waters to the south which bring in the Skeena River silt and clay particle sizes.

5.3 Comparisons to Regional Particle Size Distributions

Table 5-2 shows a comparison of regional sediment PSD data across the area with protected areas represented by Porpoise Channel data and more open waters by Canpotex data, off Ridley Island. The effect of local coastal erosion, increasing the coarse sediment content, is clearly evident in Porpoise Channel. This is the location of the proposed MOF for the Pacific NorthWest LNG project and sampling shows the surface sediments have 57% mud, 31% sand and the deeper sediments also have relatively high sand content. This is consistent with the relationship identified for the Casey Cove MOF area in Table 5-1.

Table 5-2: Sediment Particle Size Distributions for other sites in the region.

Area	Sediment Depth	Percent Composition (Median)			
		Clay	Silt	Sand	Approx. Mud ǂ Total
West coast of Ridley Island (Canpotex)	surface	28.5	65.0	6	93.5
	5 m	31.5	58.5	9	90.0
Porpoise Channel (PNW data sources)	subtidal surface	14.6	42.8	31.2	57.4
	1.5-5.5 m	14.3	27.3	37.6	41.6
	5.5-12.5 m	20.4	31.9	35.2	51.7

ǂ Muds are defined as clay plus silt.

The more open water areas, represented by the Canpotex dredging area off Ridley Island, are predominantly mud (93.5% at the surface and 90% at 5 m), with little sand (6% and 9%, respectively). The Canpotex sediment PSD's are comparable to those for the most southerly Aurora B2 site (79% muds and 7% fine sands). The slightly lower value for muds at the B2 berth site are thought to be due to its location at the entrance to an embayment, compared to the more open water setting of the Canpotex area.

5.4 Estimation of Sediment Particle Size Distributions at Depths of 0 to 15 m

The review of Chatham Sound sediment transport processes is used with the regional measurements of sediment PSD and the field data supplied by Stantec to extrapolate the sediment PSD. The sediment horizon has measured data (0 to 2 m depth), but this approach enables the deeper horizons of the proposed dredge areas (up to 15 m below CD) to be represented.

A trend of coarser sediment with increasing sediment depth is seen in both the Aurora site and regional analysis. This enables a conservative approach using the 0 to 1 m sediment PSD values to represent the 0 to 5 m deep sediments.

Below this depth, the analysis suggests that the sediment composition will become increasingly coarse at 5 to 15 m, similar to the measurements for Porpoise Channel MOF. However, the uncertainties resulting from extrapolating between the two locations requires a conservative approach. For modelling purposes, the same PSD values are used for Casey Cove at 0 to 5 m and at 5 to 15 m depths. For the more exposed Aurora LNG B1 and B2 sites a conservative approach was maintained, using the PSD distribution obtained for the 0 to 1 m horizon for all depths of the dredge profile. This is consistent with the relatively small increase in coarse sediment with depth noted for the Canpotex PSD, obtained from a more exposed area.between the surface and 5 m.

This approach applies data derived from the analysed field data PSD values for the 0 to 1 m measurement depth to the full 15 m proposed dredge depth. A uniform distribution is applied, which may result in greater predicted mobility of the sediments below 1 m when released during dredging. This is a conservative approach for estimating the impacts of the MOF and Terminal dredging releases on the local environment.

6 COCIRM-SED: SEDIMENT TRANSPORT MODEL SETUP

This section describes setting up the model to include the engineering data and running the sediment transport module. This is described in detail here, outlining the engineering model requirements, followed by sections on the detailed requirements and values used.

6.1 MODEL REQUIREMENTS

The model simulations run using CORCIRM-SED are based on specific engineering data supplied by the Client that specify the following parameters:

- Sediment particle size distribution
- Schedule
- Dredge areas and depths
- Volume of dredgate (rock is not included in the model)
- Dredger type and number on site
- Productivity
- Operating hours and downtime (no dredge activity)

These data are used to identify the specific times for the model tide and wind forcing data and to describe the dredge plan. Derivation of the sediment particle size distribution is described in the previous section and the results derived are presented in the input table (Table 6-1).

6.2 ENGINEERING DATA

The Client has specified that a clamshell dredger will be used and there will only be one on any individual site at any time. There is a period of overlap at the end of the MOF dreging and during the Berth 1 dredging. The dredge activity is scheduled during the DFO least-risk work window (November 30 to February 15) to reduce overlap with sensitive fish species and life stages.

The following assumptions are based on the draft engineering document supplied by the Client (Moffat and Nichol, 2016). Further updates were receieved from the Client throughout the project, such as revised productivity and schedule via email. The final model intputs are captured in the input table (Section 6.4) for each of the following:

- Sediment particle size distribution as defined in Section 5
- The dredging is simulated over a 2 year period to ensure it remains within the DFO least-risk window. B2 dredging occurs in the second period. If productivity is decreased then dredging will be scheduled over a longer timeframe to ensure compliance.
- The operating hours are:
    - MOF: 20 hours/day with 4 hours downtime.
    - Berths: 10 hours/day with 14 hours downtime.
- Dredge areas include the slopes at the MOF and Berths.

- Volumes of dredgate are specified in the input table for each area.
- Losses: From a clamshell dredger are 3%, based on United States Army Corp of Engineers (USACE, 1984) maximum loss value
- Vertical Distribution: (Clamshell: 40% of all losses are spread equally whilst moving up through the water column; the other 60% are on the surface (when the bucket comes out of water).
- Productivity for this dredger has been given as 375 m^3hr^{-1}.
- Modelling for the MOF will be in three steps: 0 to 5 m, 5 to 10 m and 10 to 15 m, with a 5 m increase in the depth between steps, as described in Section 2.2 and Figure 2-6.

6.3 Model Run Forcing

For the sediment transport modelling, tidal elevations at open boundaries in 2016 to 2018 were predicted based on the known seven tidal height constituents (see section 3). Surface winds and Skeena River discharges are not predictable and representative years are picked using conservative principles from the previous ten years of data. The 2011 wind data were selected as representative of a year with strong wind forcing, looking specifically at winter and spring conditions. The corresponding Skeena River discharges for 2011 winter were also used to drive the model freshwater input. Conservative choices are essential for these parameters as they have significant effects on the model hydrodynamics.

The wind forcing data used represents a period of strong winds taken from a five year data set for the construction months. They are representative of the season and not just the year stated. The year is included purely for calculations of time.

6.4 Final Input Tables used for Modelling

Table 6-1 summarises the input table used to run the sediment transport part of the modelling work. The full input table is in Appendix A: Input Tables. The input table details the scheduled start and stop construction times, the sediment volume dredged and the depth stages simulated.

For the MOF, there is only one dredge unit working at any one time and the model simulates the depths being worked down in 5 m steps. The sediment release points are selected at the representative location of subvolumes calculated based on the depth changes in each step. A second dredger starts at Berth 1 before the MOF is finished to maintain the schedule within the DFO least risk work window. There is only one dredger working at any one site.

Table 6-2 and Table 6-3 are a summary of the particle size distribution for the MOF and Berths 1 and 2.

Table 6-1: Engineering data input table for the MOF and Berth dredge areas.

Dredge Area	Model Run	From Depth (m)	To Depth (m)	Model Depth* (m)	Dredge Volume (m3)		Start (yr required for calculation)	End (yr required for calculation)	Duration (day)
					Total	By model run			
MOF	MOF1	0	5	0	365,000	63,178	30/11/2016	08/12/2016	8.2
	MOF2	5	10	5		98,111	08/12/2016	21/12/2016	13.0
	MOF3	10	15	10		203,711	21/12/2016	17/01/2017	27.1
B1 N	B1 N	0	15	0	161,400	51,680	29/12/2016	11/01/2017	13.3
B1 S	B1 S	0	15	0		66,790	12/01/2017	29/01/2017	17.3
B2	B2	0	15	0		42,930	30/11/2017	11/12/2017	11.2

* Depth during the model run.

Table 6-2: Sediment Particle Size Distribution for the MOF (uniform across the depth range at this location)

Model Run	From Depth (m)	To Depth (m)	PSD (%)			
			Clay (<0.004mm)	Silt (<0.063mm to >=0.004mm)	Fine Sand (<0.25mm to >=0.063mm)	Gravel and coarse sand (>=0.25mm)
MOF1	0	5	14.8	30.0	41.3	13.9
MOF2	5	10				
MOF3	10	15				

Table 6-3: Sediment Particle Size Distribution for the Terminals: Berth 1 and 2

Model Run	From Depth (m)	To Depth (m)	PSD (%)			
			Clay (<0.004mm)	Silt (<0.063mm to >=0.004mm)	Fine Sand (<0.25mm to >=0.063mm)	Gravel and coarse sand (>=0.25mm)
B1 N	0	15	18.4	34.3	33.1	14.2
B1 S	0	15	21.3	41.9	31.9	4.9
B2	0	15	27.4	51.8	7.0	13.8

7 Sediment Transport Processes

This Section outlines the processes affecting sediment transport and distribution in the marine environment. The following processes are briefly described:

- Settling out times
- Resuspension
- Tidal cycles and variations in current strength

All predicted TSS concentrations and deposition values are provided as above background. The modelling only deals with Project related sediments predicted to be released by the dredge activity.

7.1 Settling Out

In shallow water, settling out rates result in rapid deposition of sediments from the water column, particularly for the larger particles of sand and silt, as shown by the settling velocity values listed in Table 7-1. At 1 m water depth, the fine clay sediments will settle out in approximately 30 minutes, the silt in about 5 minutes and the fine sand in about 2.5 minutes (USACE, 1984). Hence, depending on water depth, the TSS may not be available for transport for very long.

Modelling of sediment dispersion at the MOF used the settlement times for the various particle sizes, in relation to changes in water depth associated with the three steps of dredging (0 to 5 m, 5 to 10 m, 10 to 15 m). This provides a near realistic simulation of the effects of the proposed dredging on the sediment plume and distribution.

Table 7-1: Table of settling out velocities (USACE, 1984).

Solids Fraction	Specific Gravity	Volumetric Fraction	Fall Velocity (Ft/Sec)	Deposition Void Ratio	Critical Shear Stress Lbs/Ft^2	Cohesive? Y or N
Clumps	1.6	-	3.0	0.4	99	N
Gravel	2.7	-	1.0	0.5	99	N
Coarse_Sand	2.7	-	0.5	0.55	0.02-0.03	N
Medium_Sand	2.7	-	0.1	0.6	0.01-0.03	N
Fine_Sand	2.7	-	0.02	0.7	0.01-0.02	N
Silt	2.65	-	0.01	3-6	0.007-0.01	Y
Clay	2.65	-	0.002	5-10	0.0006-0.007	Y

7.2 Resuspension

Resuspension of the bottom sediments often occurs in shallow water environments where strong currents persist. Once the near bottom current shear exceeds the seabed critical shear stress value, the sediments are released back into the water column. The ranges for critical shear stress values used for each sediment category are presented in Table 7-1. The resuspension process will be occurring naturally in the shallow water zones, releasing sediment back into the water column.

7.3 TIDES

The tidal ranges (m) during the dredge period in years one and two are shown in Figure 7-1 and Figure 7-2 respectively. The variations in tidal height correspond to the fortnightly spring and neap cycle. The larger spring tides have a peak height of 3 m or more above and below mean sea level. The neap tides are nearer 2 m height at HW and 2.5 m below mean sea level at LW. These variations in tidal range also correspond to stronger currents during spring tides and weaker ones during neaps and hence correspond closely to peaks and troughs in TSS extent, distribution and the presence of resuspension events.

During Year (Winter) One, the dredge activities a the MOF and Berth 1 continue for 60.5 days, during which 3 fortnightly, spring to neap cycles occur. The conditions are initially neap tides, but include two spring events around December 13 and Jauary 12. During Year(Winter) Two the dredge period is 11 days, with one spring to neap cycle occurring. This starts with spring tide conditions which peak on 5th December 2016.

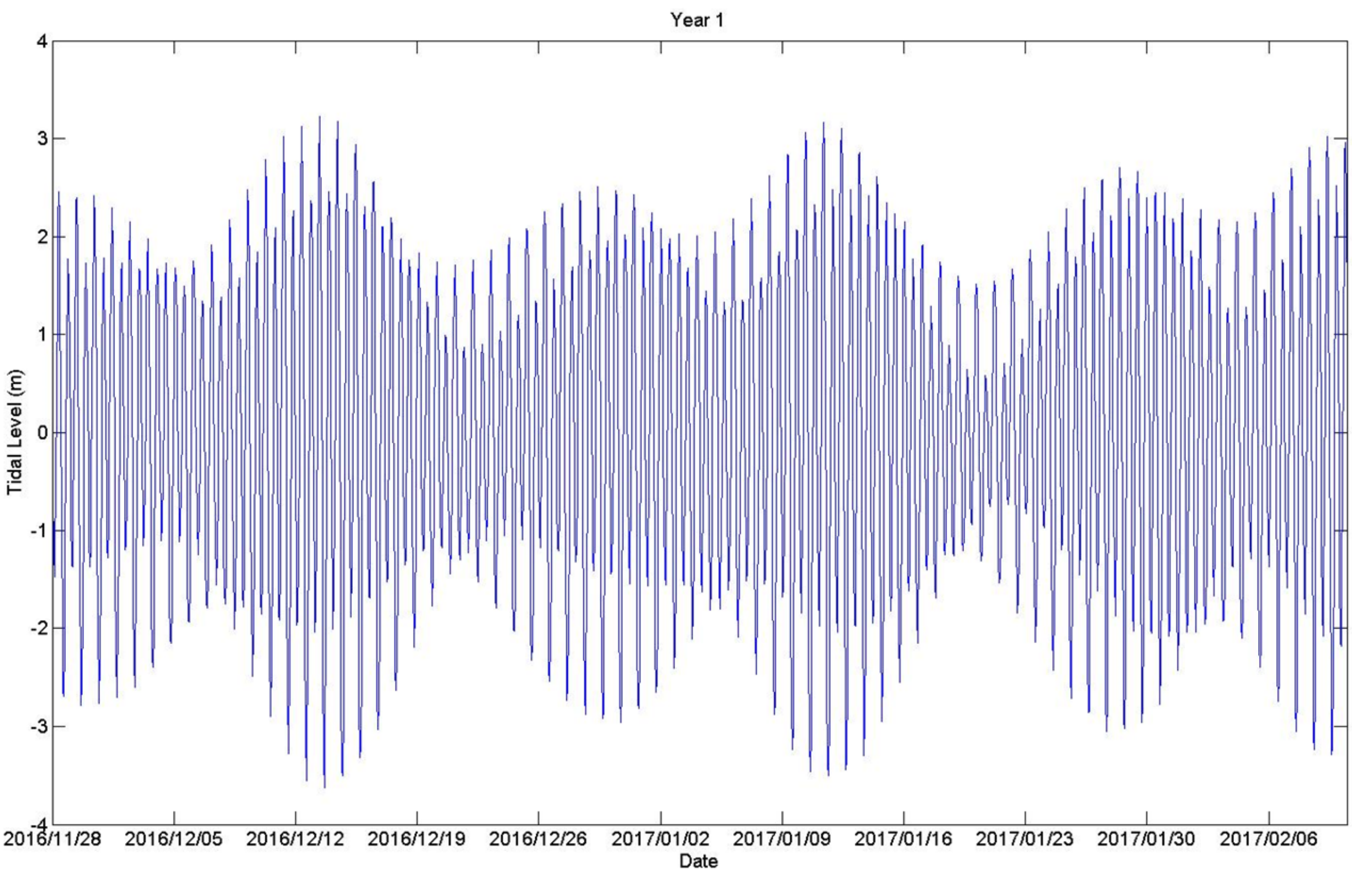


Figure 7-1: Tidal sequence for the 60.5 day dredge period in Year One showing the spring to neap cycles.

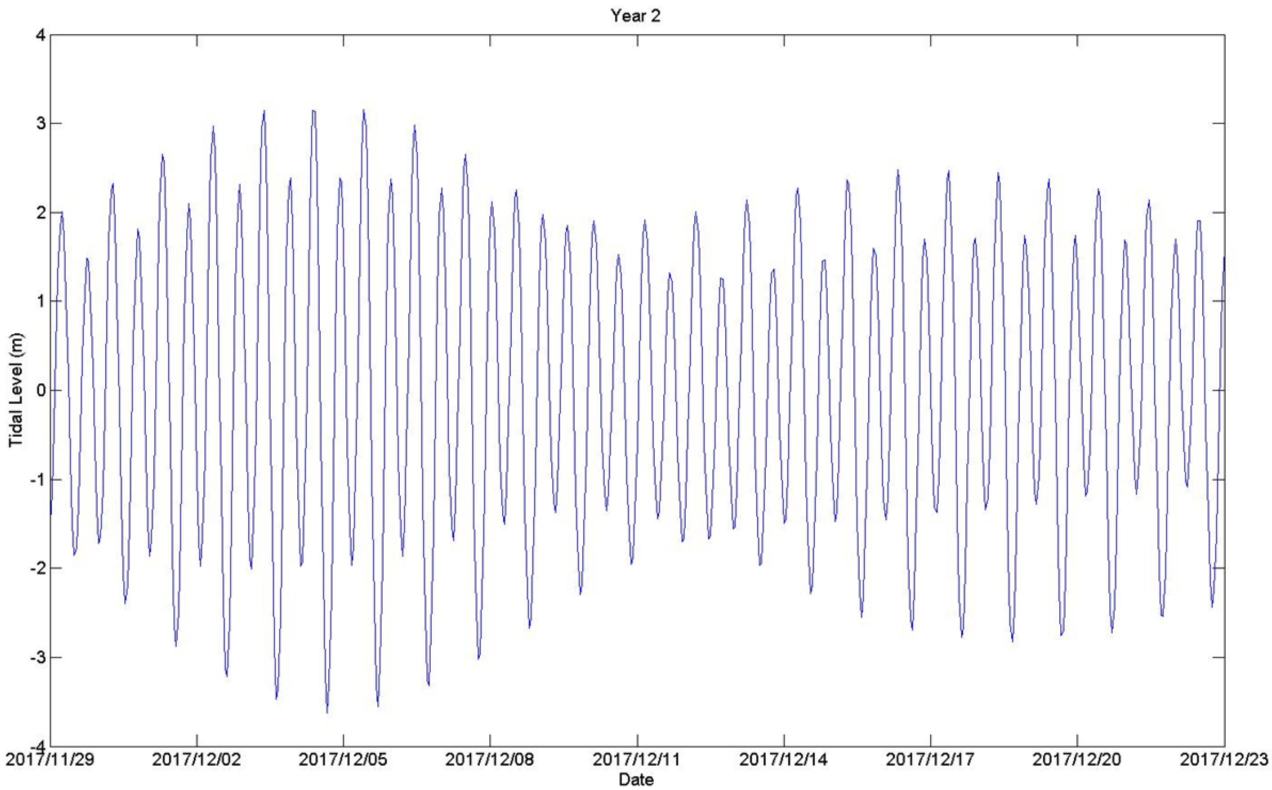


Figure 7-2: Tidal sequence for the 11 day dredge period in Year Two showing the spring to neap cycle.

8 TSS Maximum Peaks and Extents

The maximum, cummulative extent of the TSS plume is shown in Figure 8-1, which displays the combined, maximum TSS for the entire MOF and B1 N and B1 S dredge areas in Year One. Figure 8-2 shows the combined, maximum TSS for the B2 dredge areas, which will occur in Year Two. The figures show the spatial envelopes of areas with TSS higher than 0.5 mg/L above background. The TSS values are depth averaged.

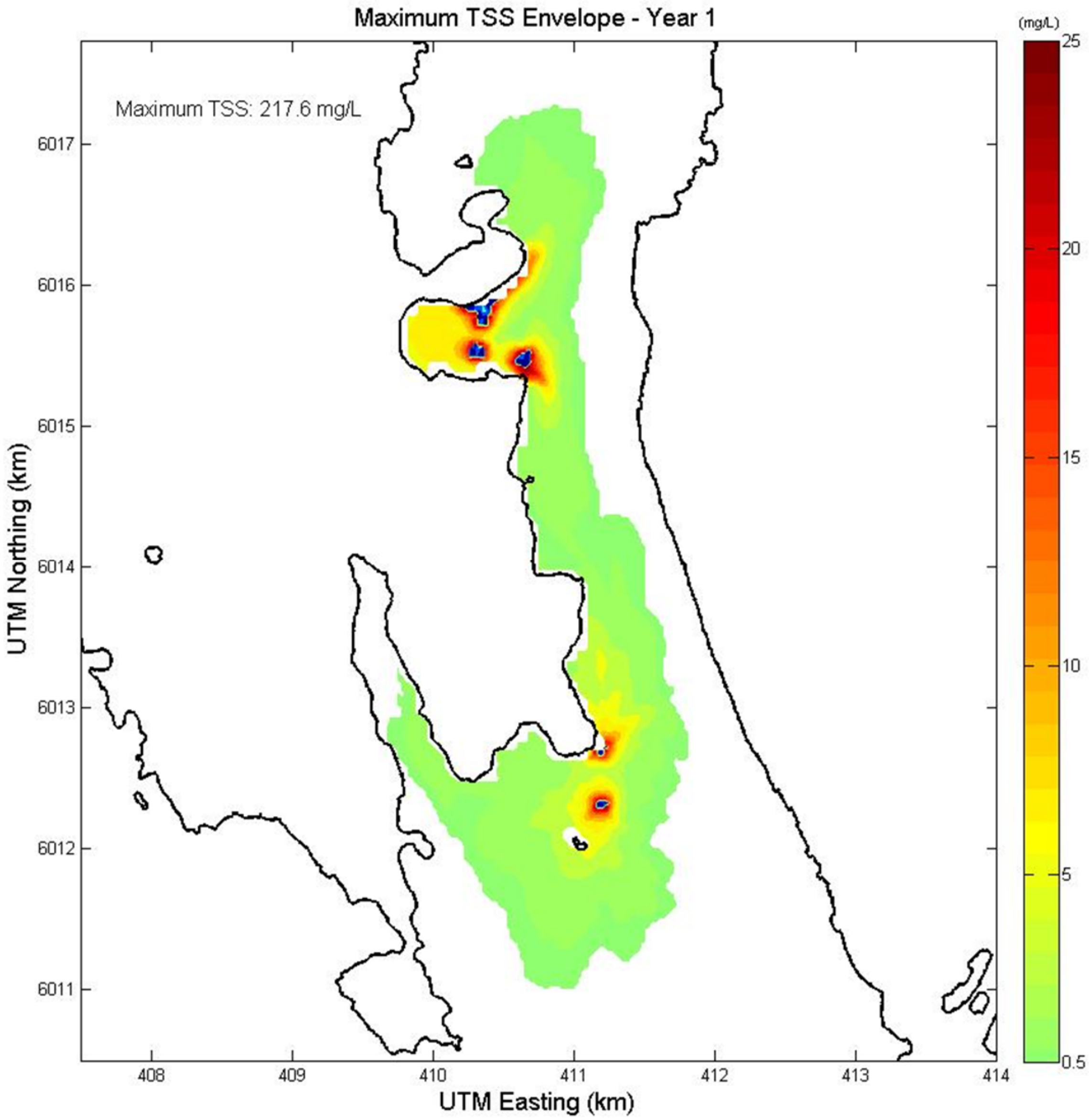


Figure 8-1: Maximum cumulative TSS for Year One for the MOF and B1 N and B1 S. The maximum TSS of 218 mg/L above background occurs at the MOF. At Berths 1 North and South the maximum TSS levels are 66.71 mg/L and 73.82 mg/L above background respectively.

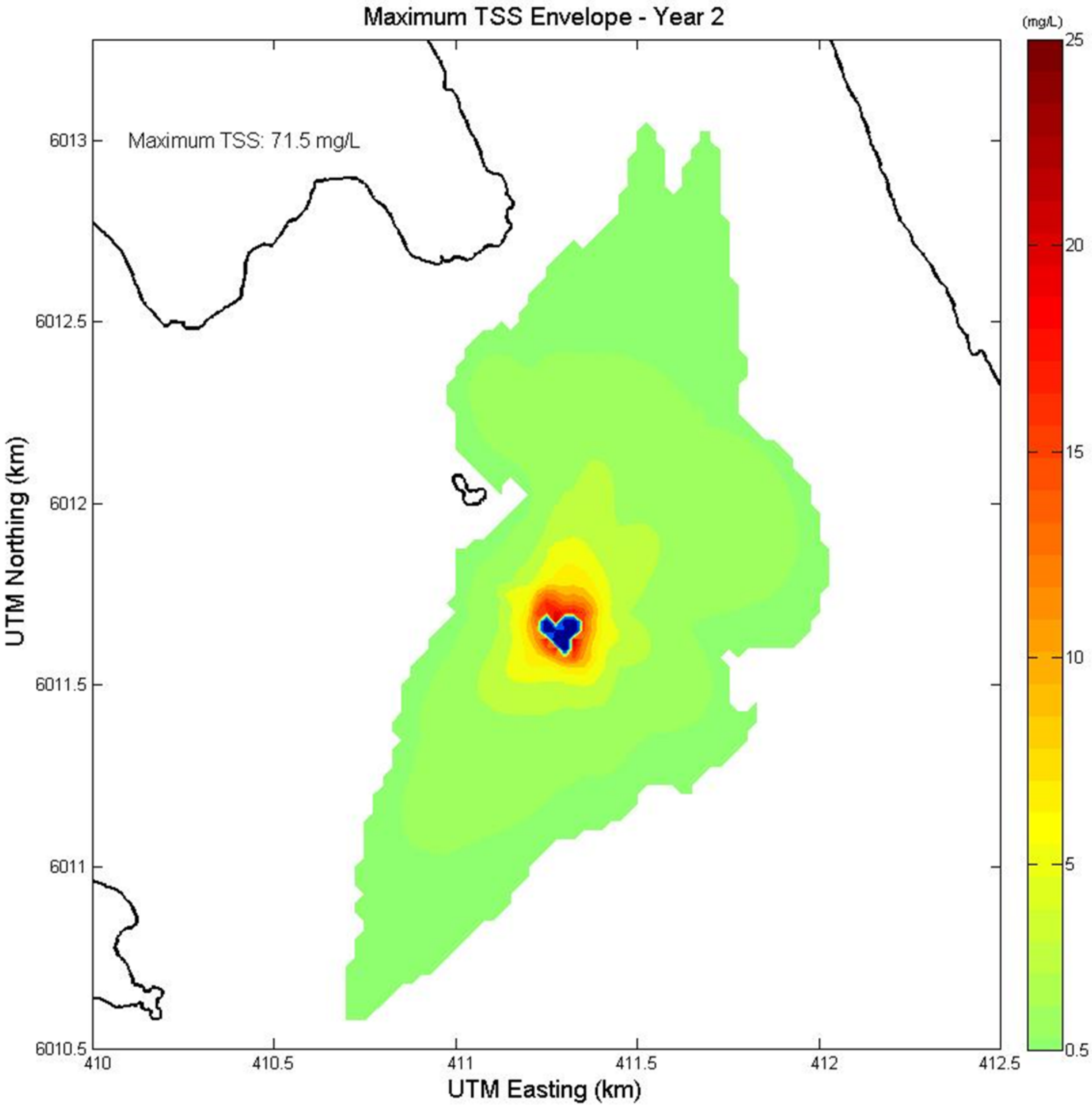


Figure 8-2: Maximum TSS for the entire dredge period in Year Two shows the TSS extents from B2 dredging. The maximum TSS level is 71.5 mg/L above background.

This cumulative TSS distribution will never occur at any one time, but the figure does show the maximum values reached across the region and the maximum northern and southern extents of the plumes. In reality, the combined ebb and flow extents from the MOF and B1 N and B1 S areas will not overlap. At any one point in time the plumes are either travelling north with the flood tide, or south on the ebb tide.

8.1 MOF TSS Maximum Extent and Duration

The proposed dredge activity for the MOF lasts 49 days in the first year. The maximum TSS predicted is 218 mg/L above background and occurs during the inital 0 to 5 m dredge. Detailed reporting on the extent and persistence of TSS plumes over a 24 hour period, is discussed in Section 9.1.

The maximum extent of the TSS plume at the MOF to either the north or south, during all the dredging around the bay, is less than 2 km from the dredge area. Levels observed outside of Casey Cove are at most 4 mg/L above background. This is below the 5 mg/L Canadian and British Columbia water quality guideline for protection of aquatic life (Canadian Council of Ministers of Environment [CCME], 2016, and British Columbia Ministry of Environment [MOE], 2016) that applies to continuous activities.

At the head of Casey Cove there is an area of eelgrass. The maximum values predicted here are around 7 mg/L, and are discussed in detail in Section 9.2.

8.2 Berth 1 North and South TSS Maximum Extent and Duration

The proposed dredge activity at B1 N and B1 S is for 13 and 17 days respectively in Year One.

Similarly to the MOF, the berth dredge areas show the highest predicted concentrations close to the actual dredge points. At Berths 1 North and South, the maximum TSS levels are 66.7 mg/L and 73.8 mg/L above background, respectively. These events are discussed in Section 10.

At B1 N and B1 S, shown in Figure 8-1, the values exceeding the 5 mg/L above background water quality guideline extend up to 0.5 km north and south of the dredge point. The TSS plume boundaries here have a slight elliptical shape, following the ebb and flood tidal excursions.

During the 30 day dredge period there are two neap and one spring tidal periods where the tidal currents will vary from weak to strong. The model predicts that transport of the TSS remains limited during these periods.

8.3 Berth 2 TSS Maximum Extent and Duration

The proposed dredge activity for B2 is for 11 days. The B2 dredgate is also confined to the immediate dredge area and the model predicts a maximum of 71.5 mg/L above background at the centre of the dredge footprint. As for B1 N and B1 S, the tidal excursions will spread the plume north and south in an elliptical distribution. Values greater than 5 mg/L above background are confined to within 250 m of the dredge boundary. During the 11 day dredge period a spring tide and most of a neap tide are modelled, covering the maximum current effects.

9 MOF TSS and Deposition Results

This Section discusses examples of the MOF results for the TSS distribution and the resultant deposition. All predicted TSS concentrations are provided as above background. The model run for the MOF is for 48 days. Results are discussed in terms of :

- Maximum TSS extent and duration outside the immediate dredge area
- Maximum individual TSS locations
- Maximum TSS occurrence in Casey Cove
- TSS persistence beyond the end of dredging
- Total deposition

9.1 Peak TSS Levels

The maximum predicted TSS at the MOF is 218 mg/L and occurs on 30.11.16, during the first nine days of the model run (Figure 9-1). The initial dredge phase is on the northern side of Casey Cove, removing the only area where there is a 0 to 5 m sediment layer. This is the only prediction of a peak in TSS of this magnitude. The model predicts other peaks in TSS above 25 mg/L at the MOF southeastern and southern dredge points, shown in Figure 8-1, but of a magnitude lower, at 73 and 91 mg/L respectively. These are shown in detail in Figure 9-2 and Figure 9-3. Whilst dredging activity is occurring the dredge area remains above 25 mg/L.

The maximum TSS event was investigated using a 24 hour sequence to characterise its extent and duration, as summarised in Table 9-1 for the hourly TSS levels and tidal states. Snapshots in Figure 9-1 capture the point source and extent during the full tidal cycle, beginning at HW at 09:00 on November 30 and continuing through to mid-flood at 08:00 on December 1.

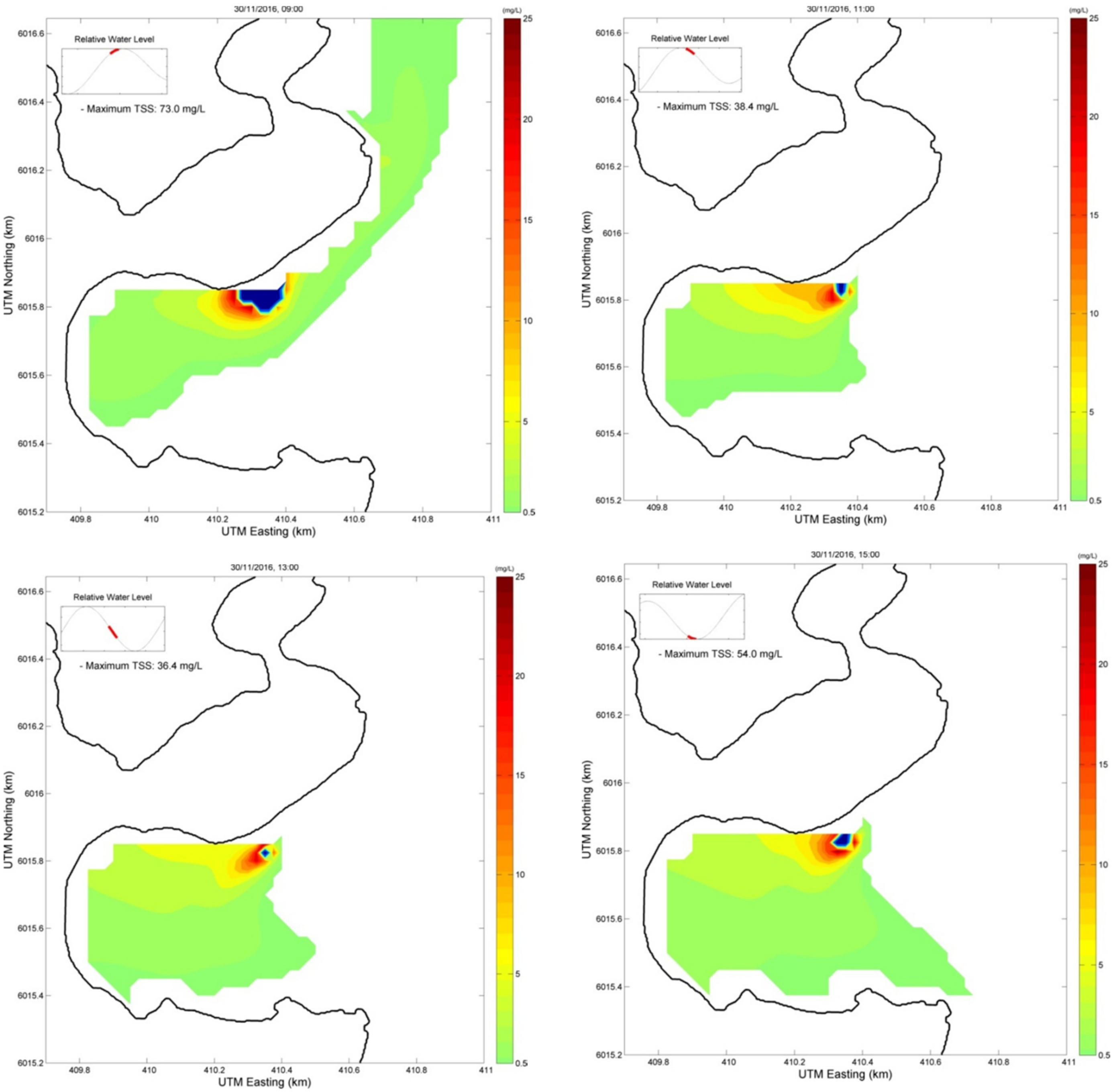
The 0 to 5 m dredge horizon is partially within the intertidal zone, as shown in Figure 2-6, and parts are extremely shallow. Hence the TSS load can become very concentrated in the water column. Dredging activity is mainly in neap tide conditions, finishing after eight days in the early part of the spring cycle, during which the currents are very weak. The currents are not transporting the sediment far, leading to a concentration of material in this confined, shallow region.

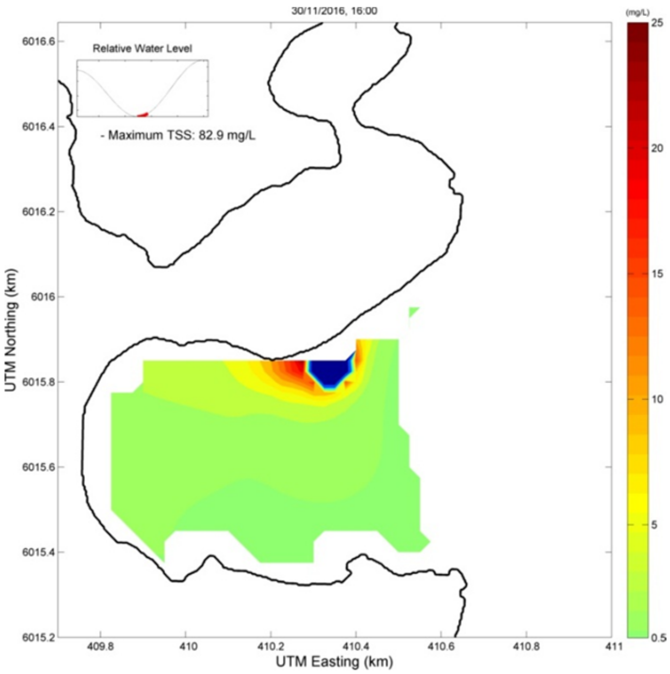
Figure 9-1 shows values exceeding 25 mg/L as cyan (25 to 50 mg/L), light blue (50 to 100 mg/L) and dark blue (> 100 mg/L). Although the peak values are above 25 mg/L for virtually the entire 24 hour period (blue region), they are extremely confined. They only occur in the immediate dredge area and range in width from around 20 to 200 m in diameter. The small increases in diameter are linked to the tidal direction, occurring between LW and HW on the flood tide, with the maximum width occurring at mid flood tide, a time of maximum currents.

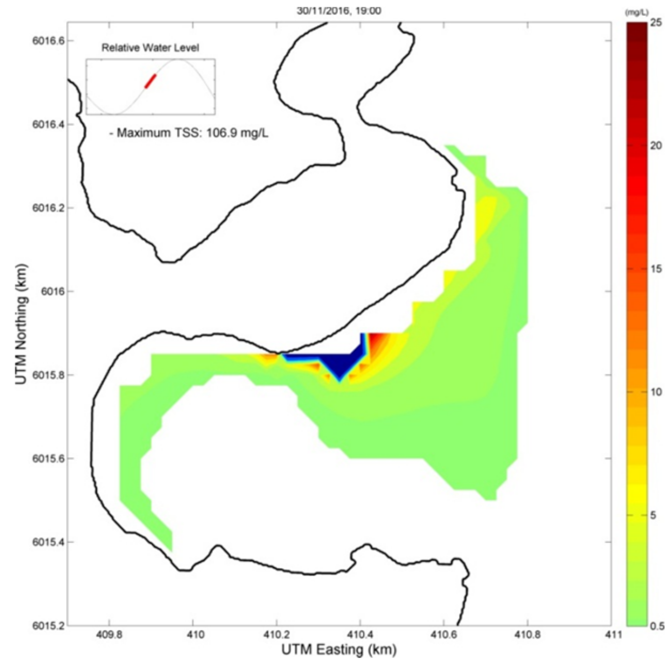
Peak events for the 5 to 10 and 10 to 15 m dredge horizons at the MOF southeastern and southern dredge points (sediment release points) within Casey Cove are indicated in Figure 8-1 and are shown in detail in Figure 9-2 and Figure 9-3. The peak TSS levels at these locations are considerably lower, at 72.9 and 90.8 mg/L, respectively compared to 218 mg/L at the northern release point. Both maxima occur near HW when currents will be weaker, and thus the suspended sediment remains more concentrated in one location. This is consistent with the tidal state at the times peak values are simulated for the first 0 to 5 m dredge phase on the northern side. Once dredging moves onto the deeper horizons, dilution of the suspended sediments maintains lower TSS concentrations in the water column. This is despite the higher volumes removed at these stages. During this period spring and neap tides occur but the distribution does not exceed the footprint shown in Figure 8-1.

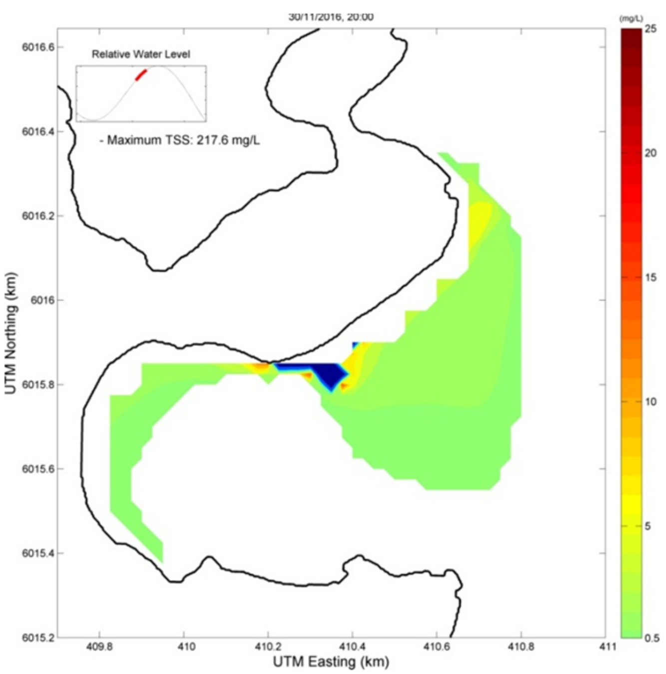
Table 9-1: Summary of the Maximum TSS values and tidal states for the 0 to 5 m dredge for the entire 24 hour sequence: 08:00 on November 30 until 08:00 on December 1. Examples of the snapshots shown in Figure 9-1 are highlighted in blue.

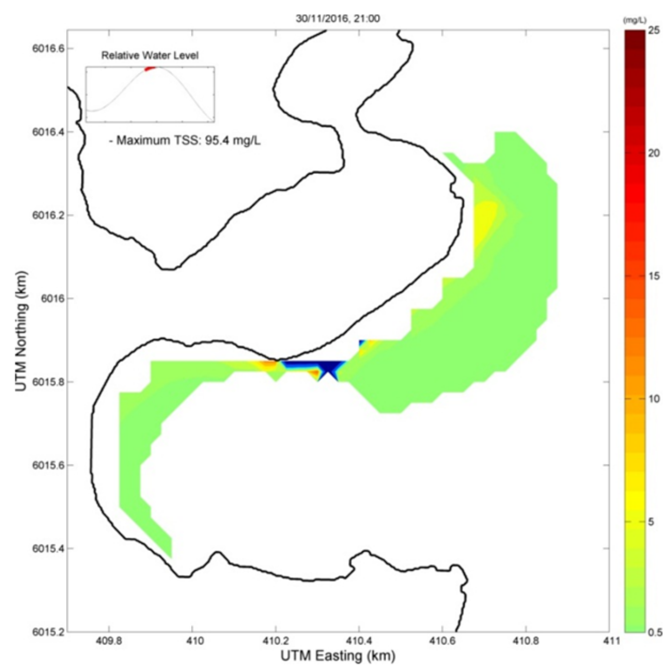
Day (dd/mm/yy)	Time (hh)	Max TSS (mg/L)	Tidal Level (m in ref. to mean)	Tidal State	Approx Width (m) of max zone > 25 mg/L (blue)
30/11/16	08	98.8	0.86	Late Flood	100
30/11/16	09	73.0	1.56	Near HW	150
30/11/16	10	53.7	1.77	HW	50
30/11/16	11	38.4	1.47	Early Ebb	30
30/11/16	12	34.1	0.79	Mid Ebb	20
30/11/16	13	36.4	-0.08	Mid Ebb	20
30/11/16	14	40.1	-0.87	Late Ebb	30
30/11/16	15	54.0	-1.35	Near LW	50
30/11/16	16	82.9	-1.37	LW	100
30/11/16	17	90.4	-0.90	Early Flood	190
30/11/16	18	102.5	-0.06	Mid Flood	180
30/11/16	19	106.9	0.94	Mid Flood	180
30/11/16	20	217.6	1.83	Late Flood	150
30/11/16	21	95.4	2.37	Near HW	150
30/11/16	22	95.2	2.40	HW	120
30/11/16	23	52.4	1.86	Early Ebb	100
01/12/16	00	14.5	0.88	Mid Ebb	0
01/12/16	01	31.6	-0.35	Mid Ebb	20
01/12/16	02	33.5	-1.54	Late Ebb	20
01/12/16	03	47.1	-2.42	Near LW	30
01/12/16	04	47.3	-2.79	LW	90
01/12/16	05	34.1	-2.57	Near LW	90
01/12/16	06	35.7	-1.85	Early Flood	90
01/12/16	07	27.1	-0.80	Mid Flood	60
01/12/16	08	39.6	0.32	Mid Flood	130


30/11/2016, 09:00
Relative Water Level
- Maximum TSS: 73.0 mg/L
30/11/2016, 11:00
Relative Water Level
- Maximum TSS: 38.4 mg/L
30/11/2016, 13:00
Relative Water Level
- Maximum TSS: 36.4 mg/L
30/11/2016, 15:00
Relative Water Level
- Maximum TSS: 54.0 mg/L
(mg/L)
UTM Northing (km)
UTM Easting (km)


30/11/2016, 16:00
Relative Water Level
- Maximum TSS: 82.9 mg/L
UTM Northing (km)
UTM Easting (km)
(mg/L)


30/11/2016, 19:00
Relative Water Level
- Maximum TSS: 106.9 mg/L
UTM Northing (km)
UTM Easting (km)
(mg/L)


30/11/2016, 20:00
Relative Water Level
- Maximum TSS: 217.6 mg/L
UTM Northing (km)
UTM Easting (km)
(mg/L)


30/11/2016, 21:00
Relative Water Level
- Maximum TSS: 95.4 mg/L
UTM Northing (km)
UTM Easting (km)
(mg/L)

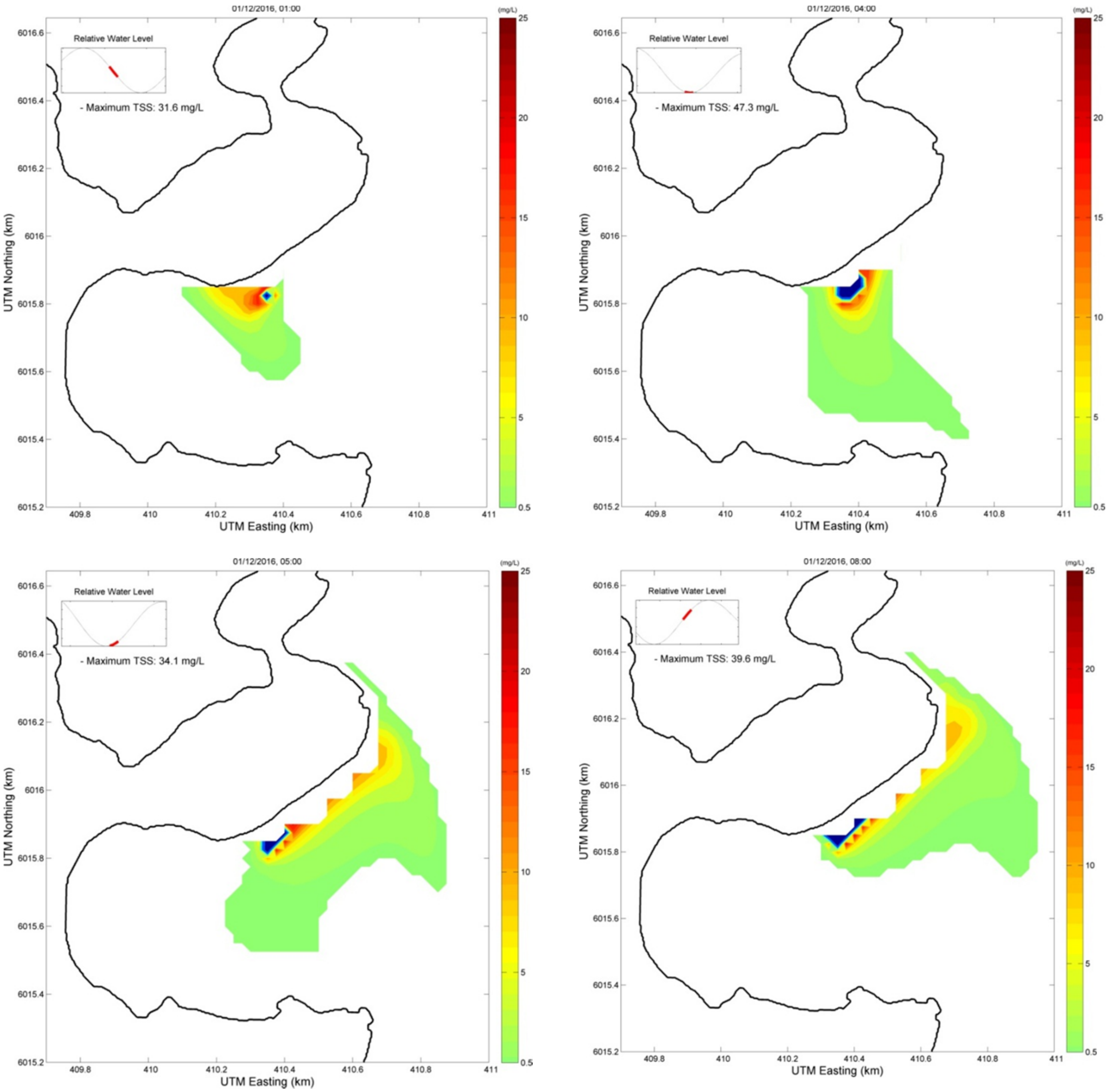


Figure 9-1: MOF TSS Maximum Extent over a Tidal Cycle occurring on November 30 at 20:00. The plots show the TSS distribution from 09:00 (LW) on November 30 to 08:00 (mid flood) on December 1. The cyan, light blue and dark blue show TSS values 25-50, 50-100 and >100 mg/L respectively. The inset shows the tidal state.

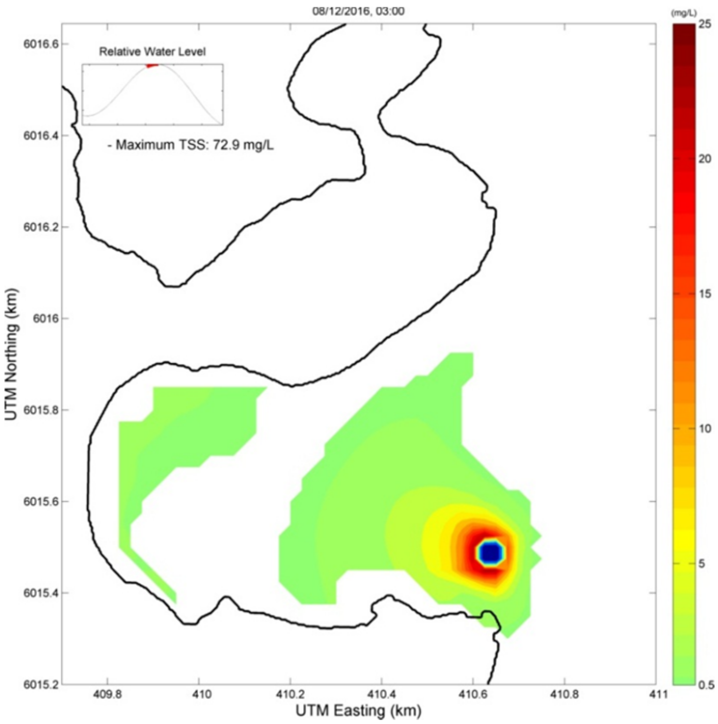


Figure 9-2: Peak TSS at the MOF release point at the southeastern extent of the bay on December 8 at 03:00, HW.

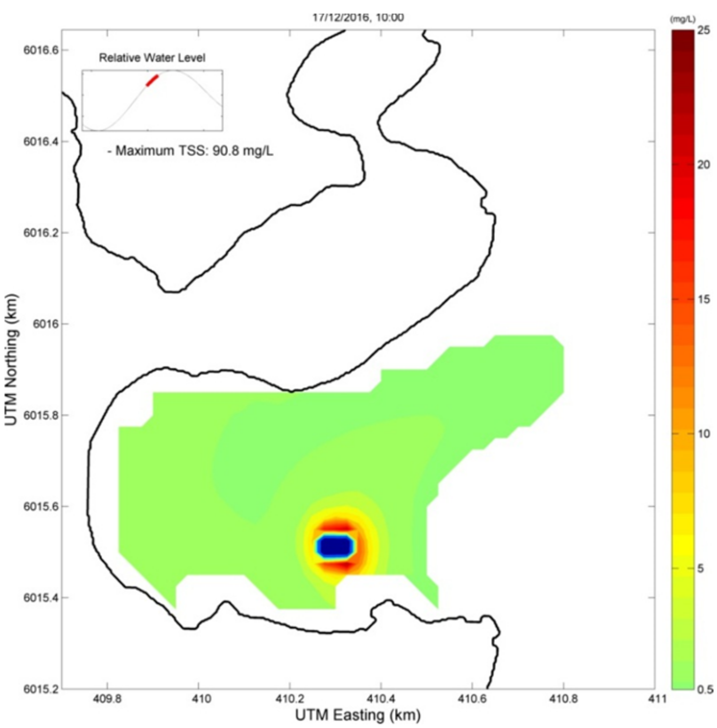


Figure 9-3: Peak TSS at the MOF release point to the south of the bay on December 17 at 10:00, near HW.

9.2 TSS in Casey Cove

During the MOF dredge activity the TSS levels at the back of Casey Cove were noted to persist at 5 to 9 mg/L for a 24 hour period during 19 December. This was investigated further.

A time series of the maximum TSS concentrations within Casey Cove throughout the MOF dredge phase is given in Figure 9-4. The graph shows the maximum occurring anywhere within the cove, so the elevated TSS figures don't necessary persist at just one point. The graph is useful to show the maximum fluctuations and rapid return to 3 mg/L or less once the source is removed during downtime. It is necessary to review the snapshots to assess persistence over time for each area.

Within the cove the 5 mg/L guideline value was exceeded several times, particularly during the MOF 0 to 5 m (8 days) and 5 to 10 m (13 days) horizon dredge phases. However, these periods do not persist once the source is removed. Post dredging activity, the TSS values immediately return to zero very early in the settling out period. This suggests that either:

- The currents are ceasing to bring material into the cove
- The currents are flushing the material out of the cove
- The sediment is being rapidly deposited.

It is likely that currents are ceasing to bring material into the Casey Cove, as the deposition values for the cove are uniform and below 2 cm. This is shown in the discussion on deposition (Section 9.4 and Figure 9-10). The snapshot sequences for the peak TSS distribution in Casey Cove, during the three MOF dredge phases (Figure 9-5, Figure 9-6 and Figure 9-7), support this interpretation. The scale is enhanced to 0 to 5 mg/L to show the Casey Cove TSS distribution exceeding this level. The maximum value for the area is recorded.

Maximum distribution occurs between HW and mid ebb, when currents peak. The values of 5 mg/L spreads over up to half the region during the 5 to 10 m dredge phase (Figure 9-6), but are more confined during the other dredge phases (Figure 9-5 and 9-7). These peak distributions are not maintained beyond a few hours, reinforcing the suggestion that material is only entering the cove at peak tidal flow.

Figure 9-8 provides a detailed, hourly sequence of the conditions on December 19 for another peak in TSS distribution in Casey Cove occurring during the 5 to 10 m horizon dredge period. Tides at this time were weak, at the end of the spring cycle, and it appears material is not being flushed out of the cove as quickly as the rest of the time. The single peak of almost 9 mg/L occurs at around HW when the currents are near slack.

During the final dredge stage of the MOF, from the 10 to 15 m horizon, the amount of material removed is double that of the previous dredge stages. However TSS levels within Casey Cove and in the MOF area are lowest during this phase.

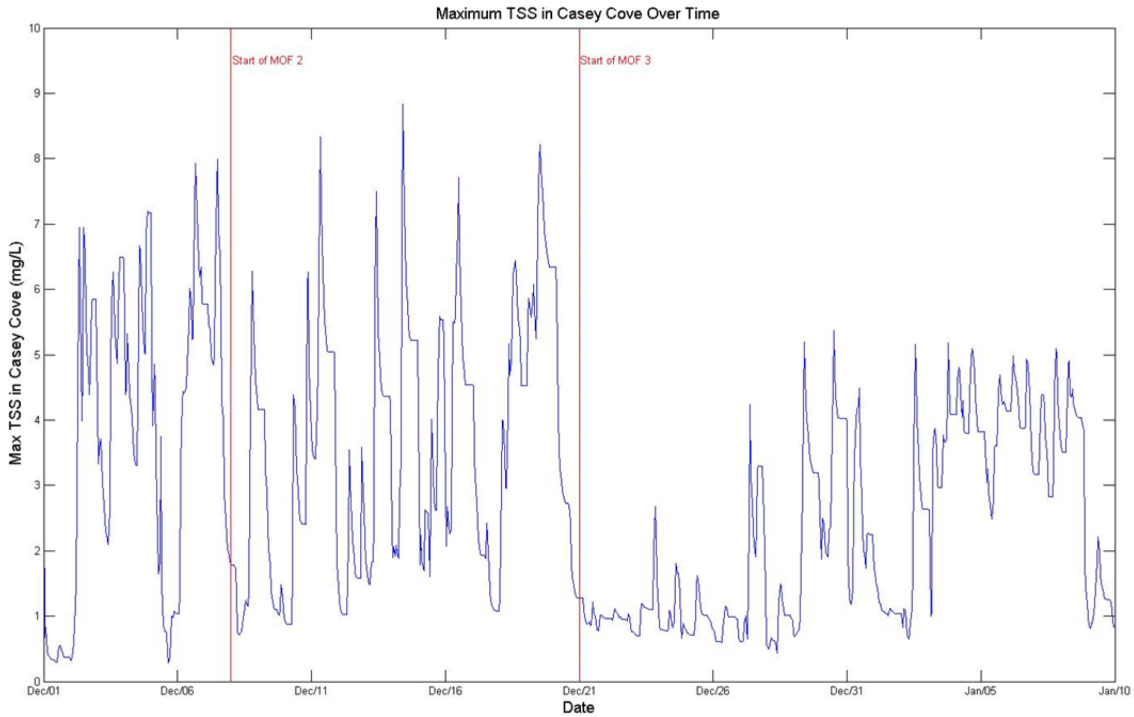


Figure 9-4: Maximum TSS timeseries for Casey Cove: MOF 2 and 3 refer to the 5-10 m and 10-15 m dredge horizons respectively.

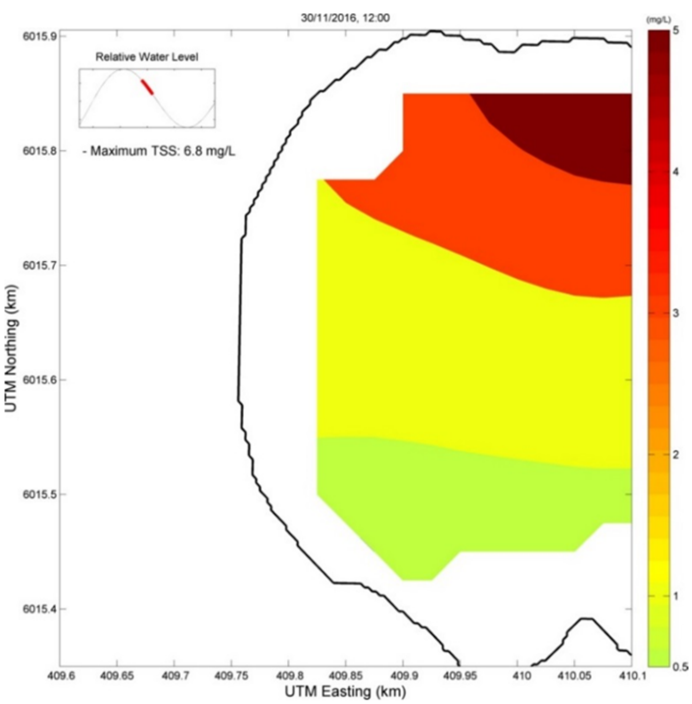


Figure 9-5: TSS snapshot December 30 at 12:00 for inner area of Casey Cove showing the maximum extents during the MOF 0 to 5 m dredge phase. Maximum value was 6.8 mg/L.

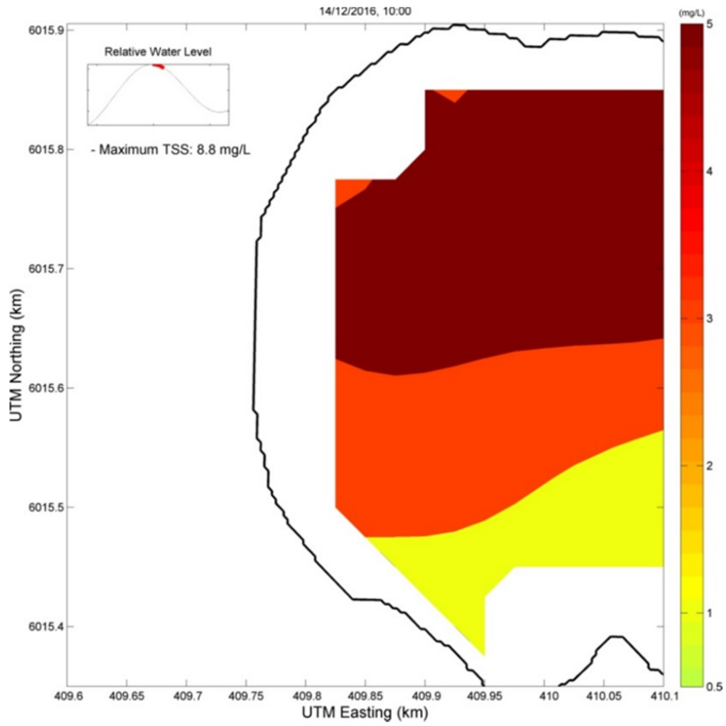


Figure 9-6: TSS snapshot December 14 at 10:00 for the inner area of Casey Cove showing the maximum extents during the MOF 5 to 10 m dredge phase. Maximum value was 8.8 mg/L.

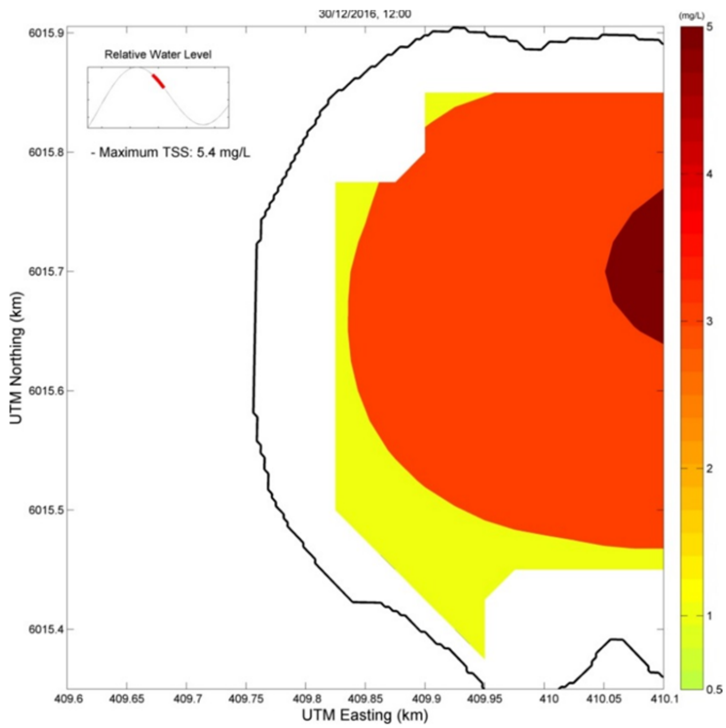
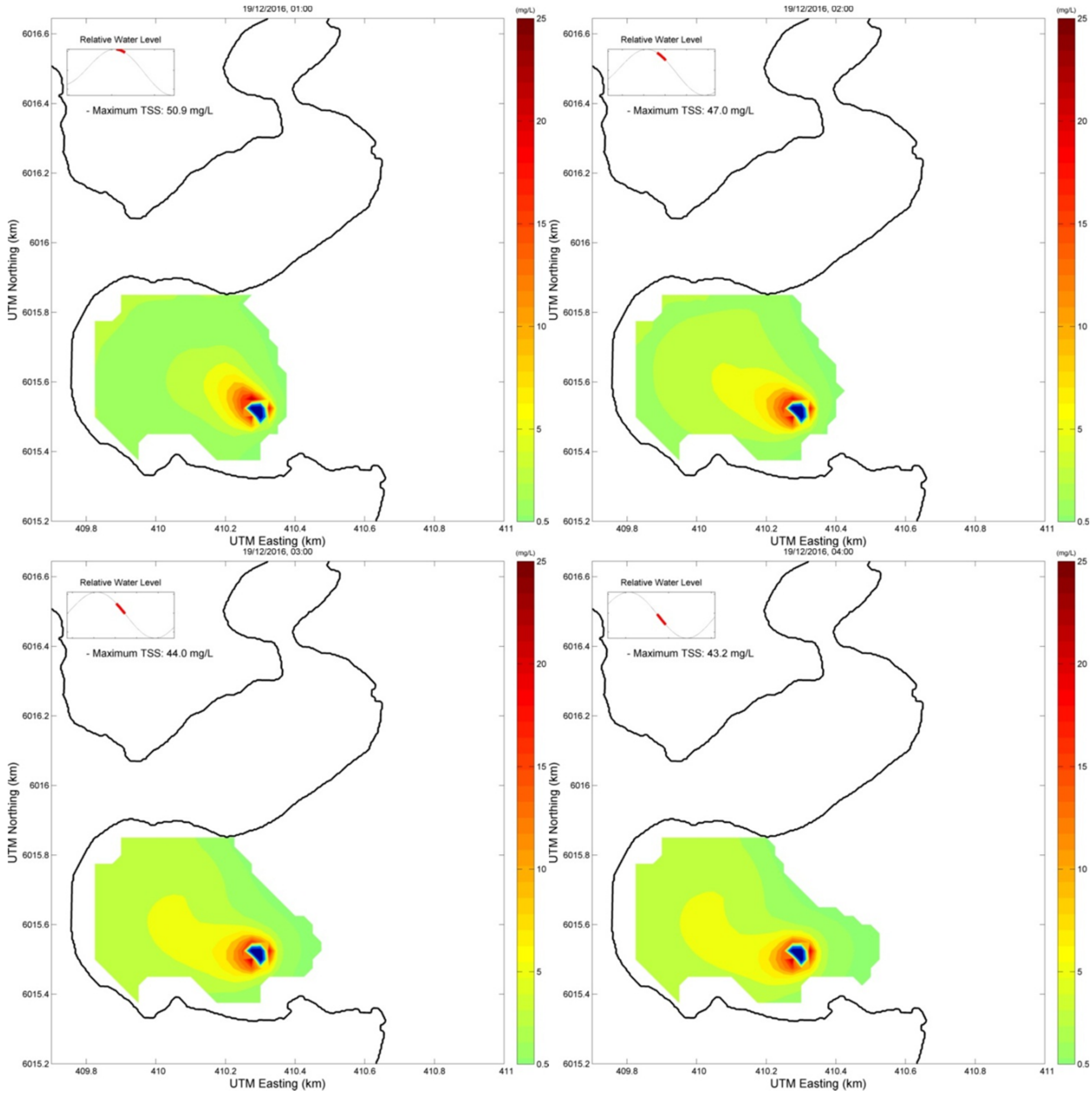
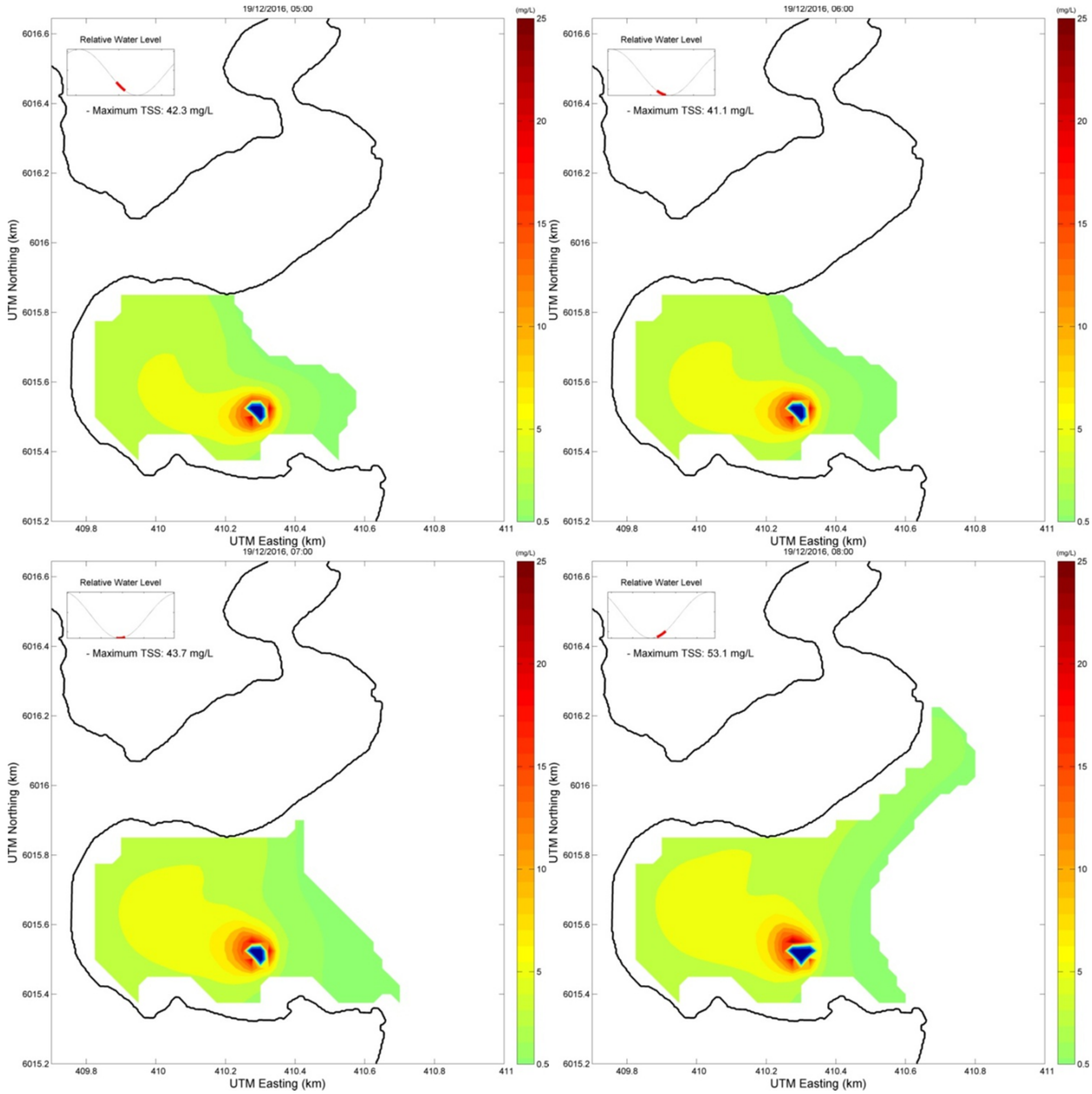


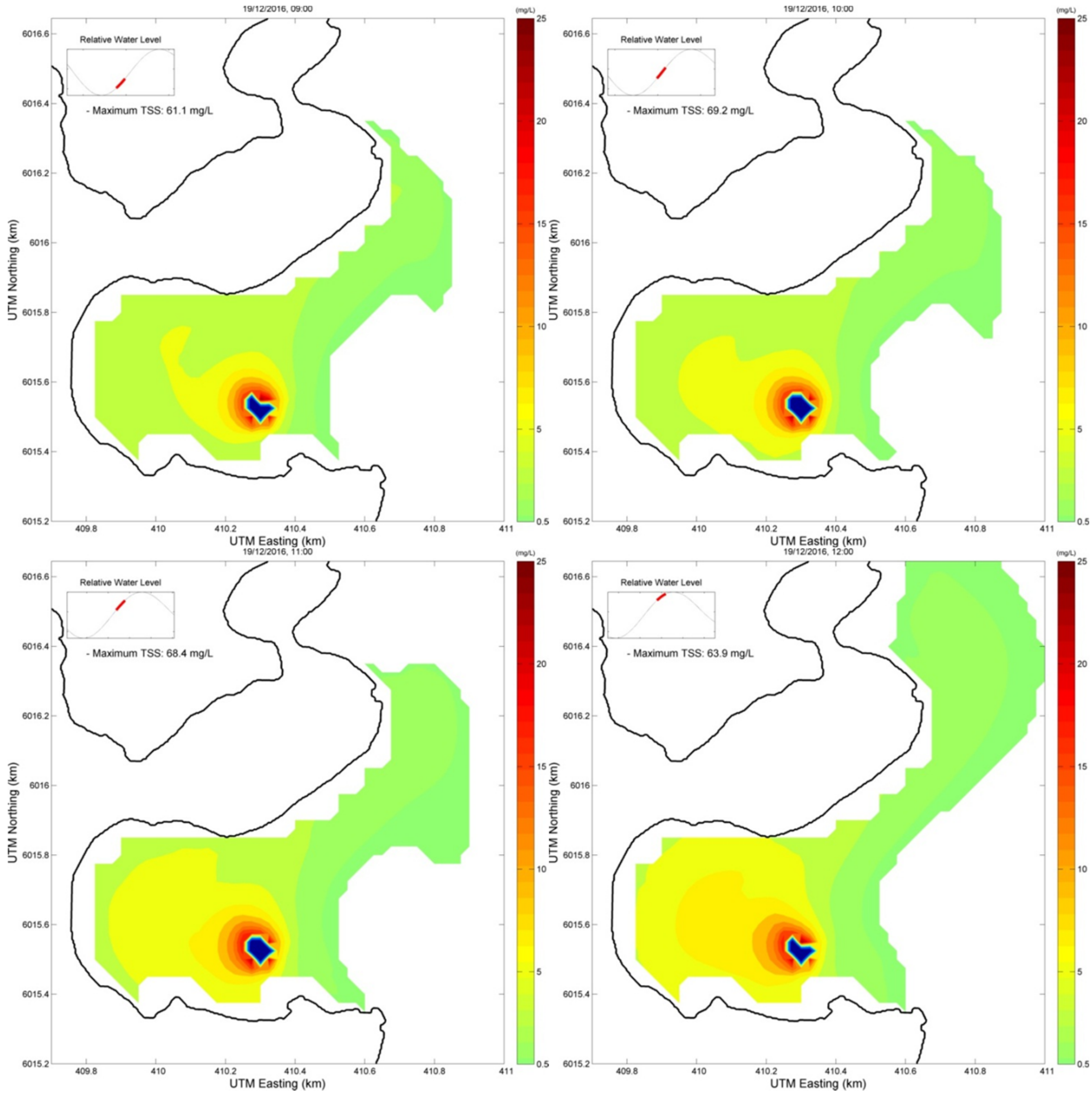
Figure 9-7: TSS snapshot December 30 at 12:00 for the inner area of Casey Cove showing the maximum extents during the MOF 10 to 15 m dredge phase. Maximum value was 5.4 mg/L.

ASL

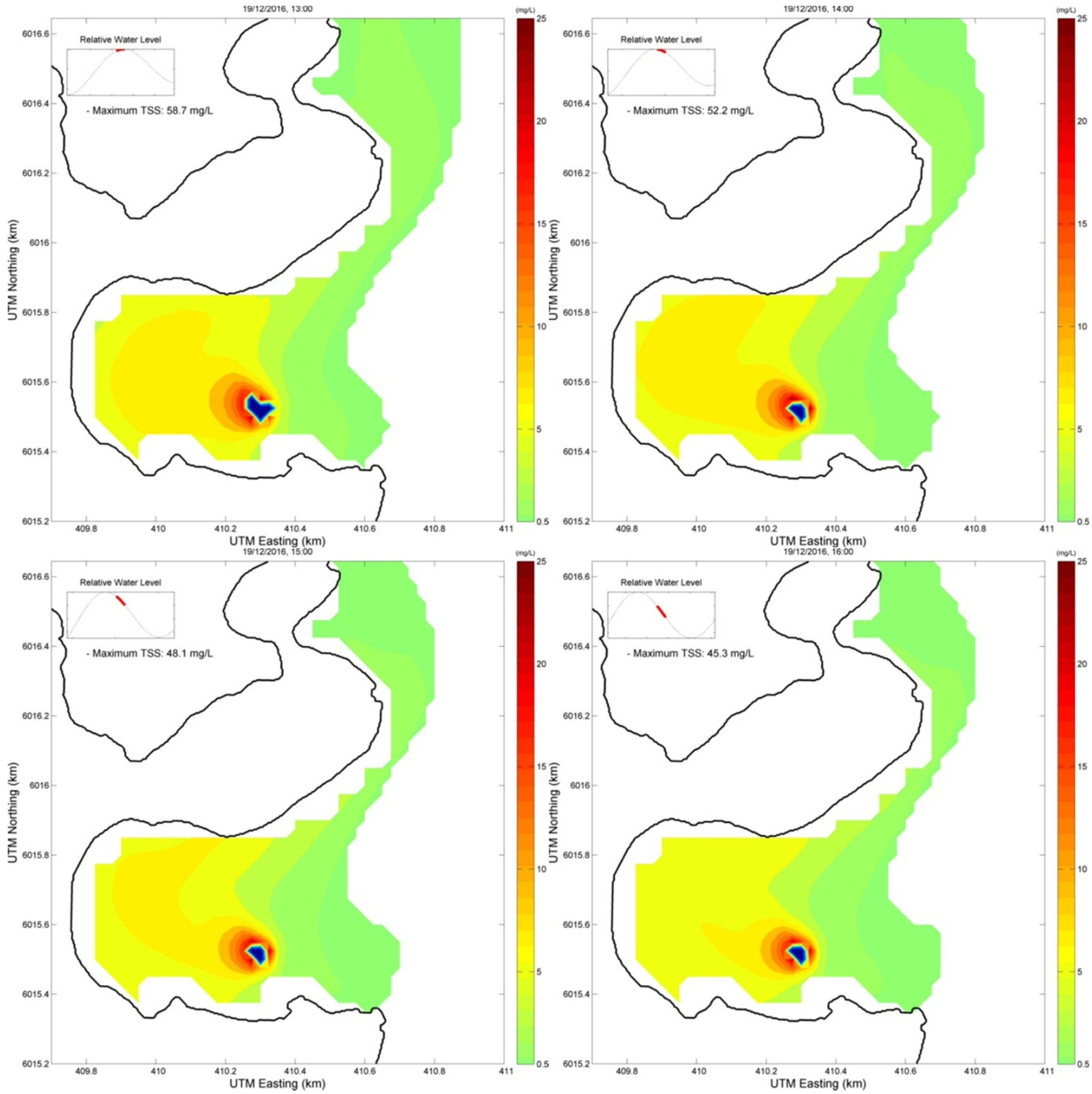


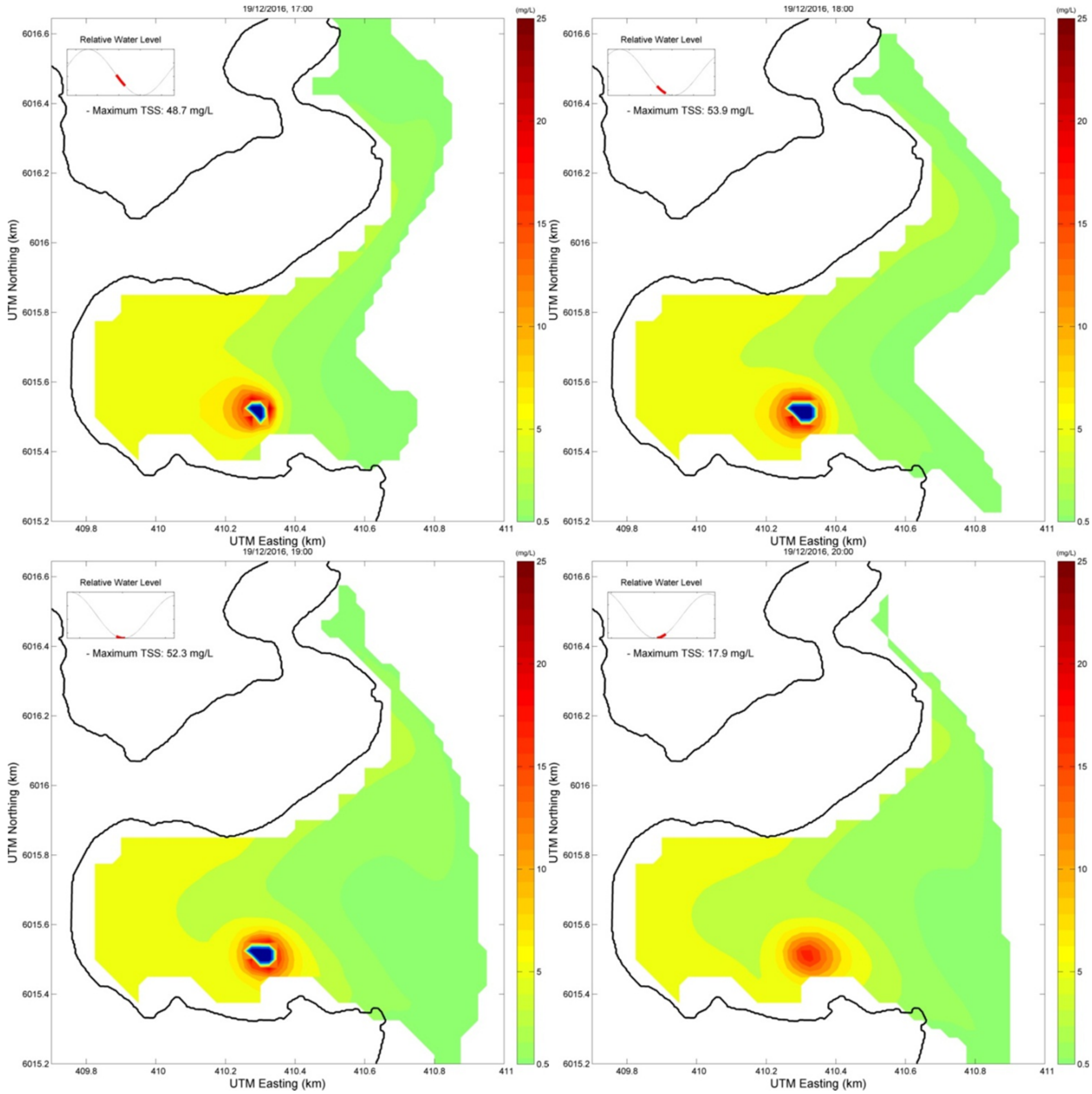
19/12/2016, 01:00
Relative Water Level
- Maximum TSS: 50.9 mg/L
19/12/2016, 02:00
Relative Water Level
- Maximum TSS: 47.0 mg/L
19/12/2016, 03:00
Relative Water Level
- Maximum TSS: 44.0 mg/L
19/12/2016, 04:00
Relative Water Level
- Maximum TSS: 43.2 mg/L
(mg/L)
UTM Northing (km)
UTM Easting (km)


19/12/2016, 05:00
Relative Water Level
- Maximum TSS: 42.3 mg/L
19/12/2016, 06:00
Relative Water Level
- Maximum TSS: 41.1 mg/L
19/12/2016, 07:00
Relative Water Level
- Maximum TSS: 43.7 mg/L
19/12/2016, 08:00
Relative Water Level
- Maximum TSS: 53.1 mg/L
UTM Northing (km)
UTM Easting (km)
(mg/L)



19/12/2016, 09:00
Relative Water Level
- Maximum TSS: 61.1 mg/L
19/12/2016, 10:00
Relative Water Level
- Maximum TSS: 69.2 mg/L
19/12/2016, 11:00
Relative Water Level
- Maximum TSS: 68.4 mg/L
19/12/2016, 12:00
Relative Water Level
- Maximum TSS: 63.9 mg/L
UTM Northing (km)
UTM Easting (km)
(mg/L)


19/12/2016, 13:00
Relative Water Level
- Maximum TSS: 58.7 mg/L
19/12/2016, 14:00
Relative Water Level
- Maximum TSS: 52.2 mg/L
19/12/2016, 15:00
Relative Water Level
- Maximum TSS: 48.1 mg/L
19/12/2016, 16:00
Relative Water Level
- Maximum TSS: 45.3 mg/L
UTM Northing (km)
UTM Easting (km)
(mg/L)


19/12/2016, 17:00
Relative Water Level
- Maximum TSS: 48.7 mg/L
19/12/2016, 18:00
Relative Water Level
- Maximum TSS: 53.9 mg/L
19/12/2016, 19:00
Relative Water Level
- Maximum TSS: 52.3 mg/L
19/12/2016, 20:00
Relative Water Level
- Maximum TSS: 17.9 mg/L
UTM Northing (km)
UTM Easting (km)
(mg/L)

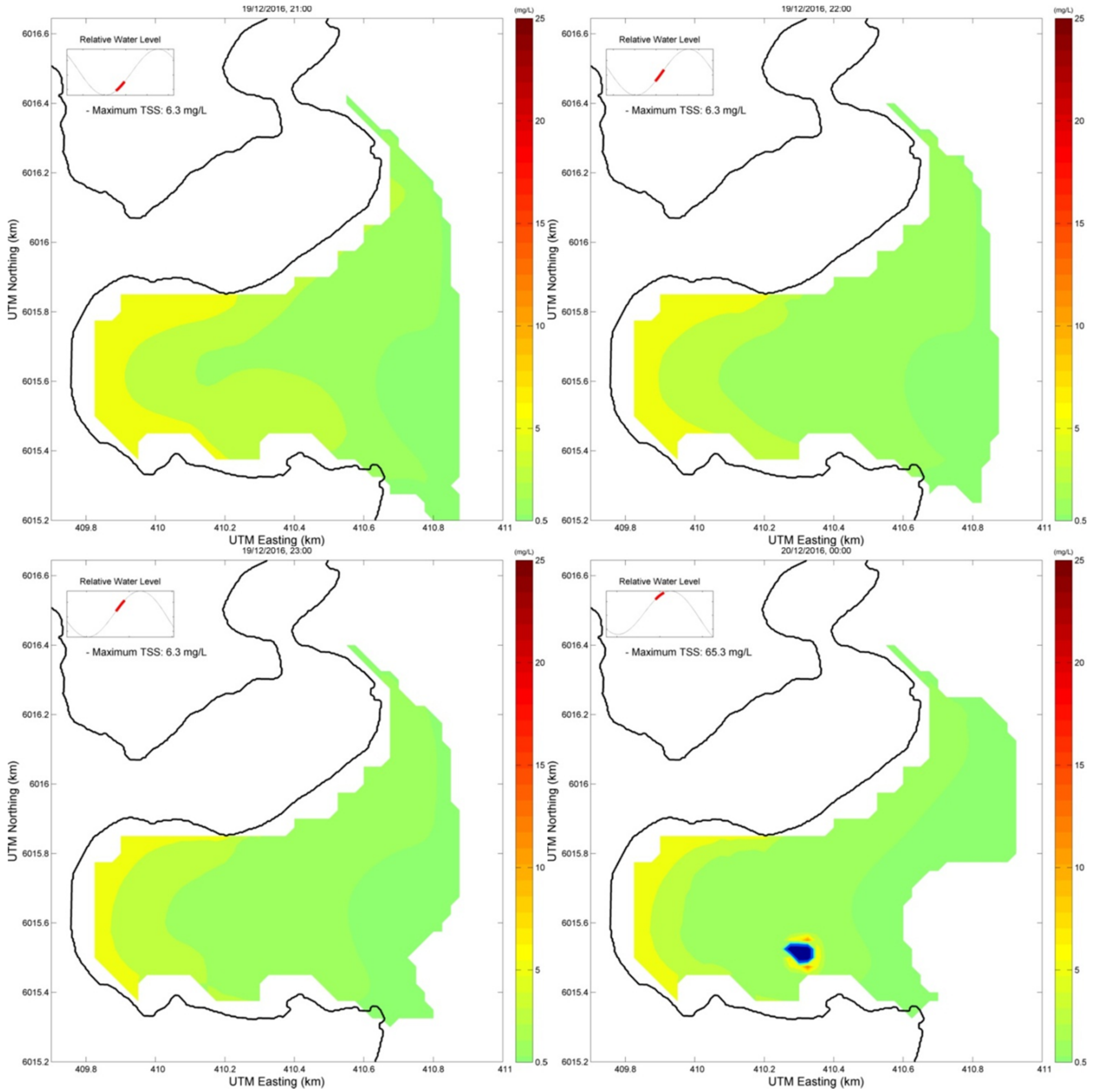


Figure 9-8: MOF TSS Maximum Extent over a Tidal Cycle occurring within Casey Cove from December 19 at 01:00 (HW) to December 20 at 00:00 (near HW). The cyan, light blue and dark blue show TSS values 25-50, 50-100 and >100 mg/L respectively. The inset shows the tidal state.

9.3 TSS Peak Persistence

During the entire 49 days of dredge activity in the MOF, the predicted TSS levels are persistently elevated at around 60 mg/L (Figure 9-9). The snapshots have shown that these high levels are closely confined to the dredge location. Any plumes extending outside of Casey Cove are below 5 mg/L and only persist for short periods of time. There are a few brief periods when peak TSS levels exceed 120 mg/L, but these are extremely short lived. Once the dredge activity ceases, the TSS values rapidly fall back to near zero and there is no obvious resuspension in the ten day post dredge period.

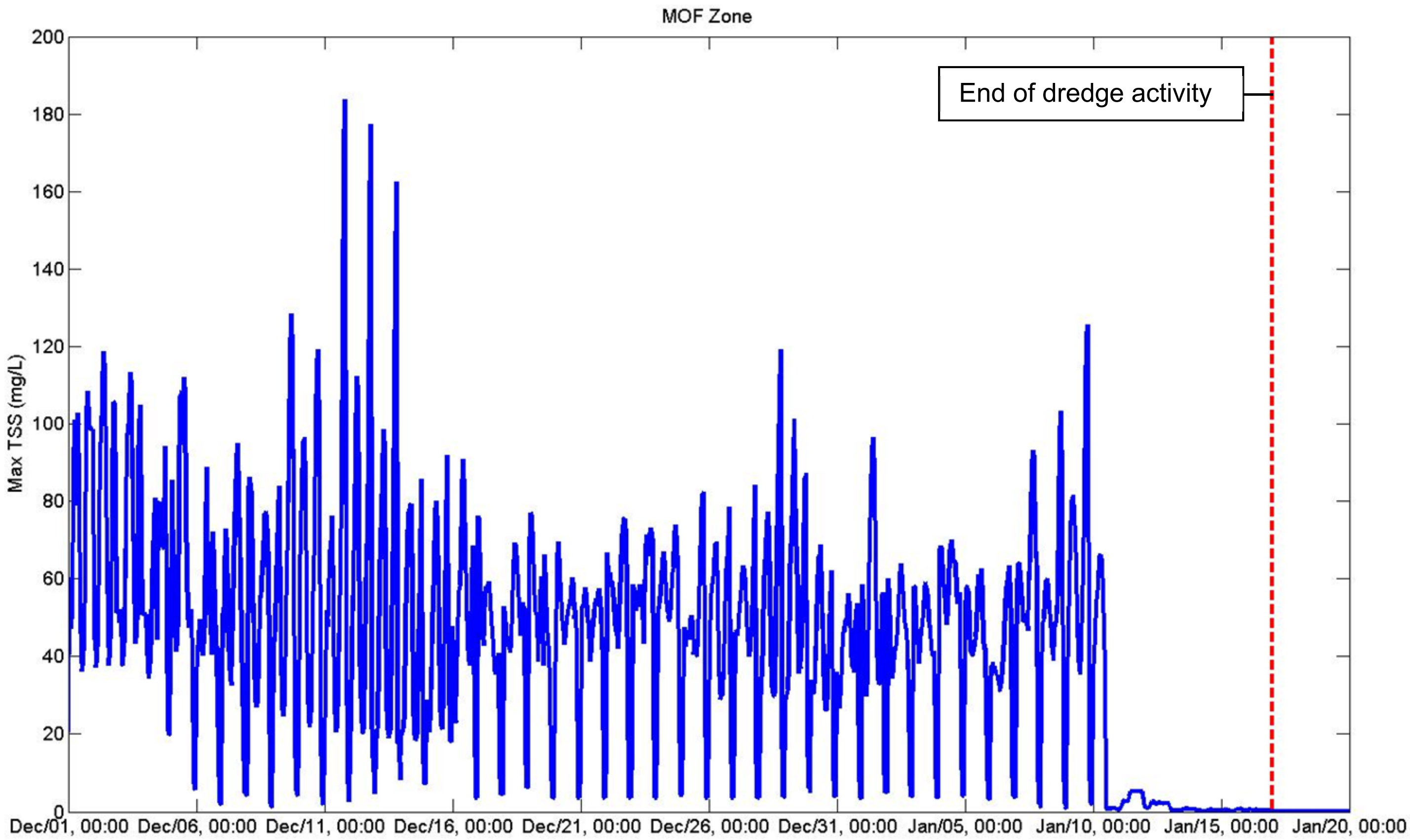


Figure 9-9: TSS levels at the MOF from January 5 to 20. Dredge activity ceases on January 17.

9.4 MOF Deposition

Figure 9-10 shows the deposition at the end of the 49 day dredge period for the MOF. The majority of material is closely confined to the area under construction, with very little spread either into the cove or to the outer area. Outside the immediate dredge zones, both inside Casey Cove and just offshore, the deposition is 1 cm or less. Within the dredge zone the maximum deposition is 12 cm.

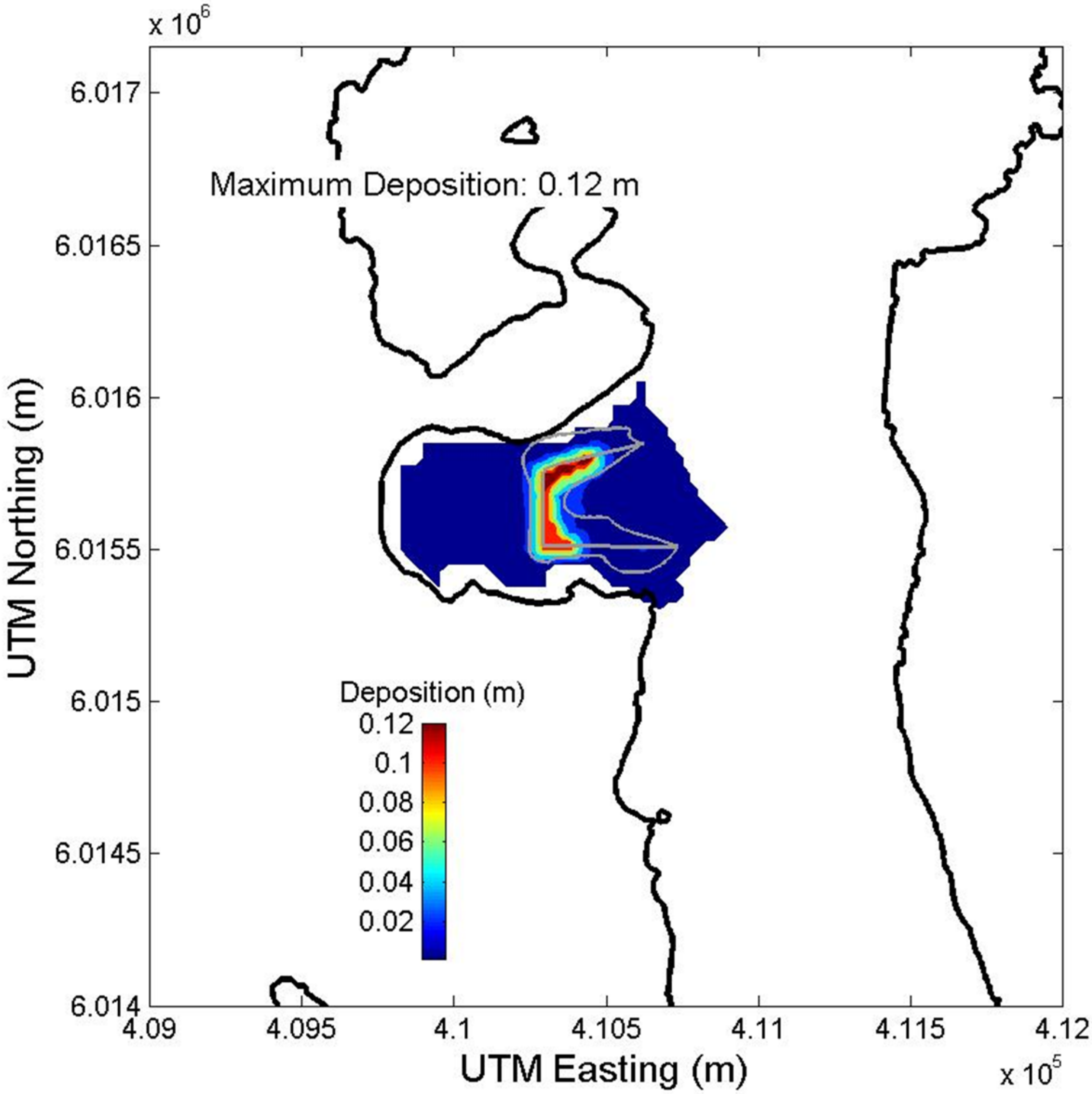


Figure 9-10: Deposition in the MOF at the end of the entire 49 days of dredging.

10 Terminal Berths TSS and Deposition Results

This Section shows examples of the B1 N, B1 S, and B2 results for the TSS distribution. At the Berths, the dredging is modelled as occurring in one stage from 0 to 15 m depth (below CD). The total volumes are small, similar to the Step One removal of the 0 to 5 m layer at the MOF (Table 6-1). The dredge activity at the berths is limited to 10 hours per 24 hour cycle and it is notable that the sediments settle out within a short time period at all the berths once dredge activity ceases.

The tidal influence differs as the spring to neap cycle varies for each area and dredge time. B1 S is notably subject to weaker tides than B2, which experiences a complete spring tide cycle during the dredge. These differences are notable in the figures showing the maximum TSS distributions (Figure 8-1 and Figure 8-2). The predicted TSS levels are reported as mg/L above background.

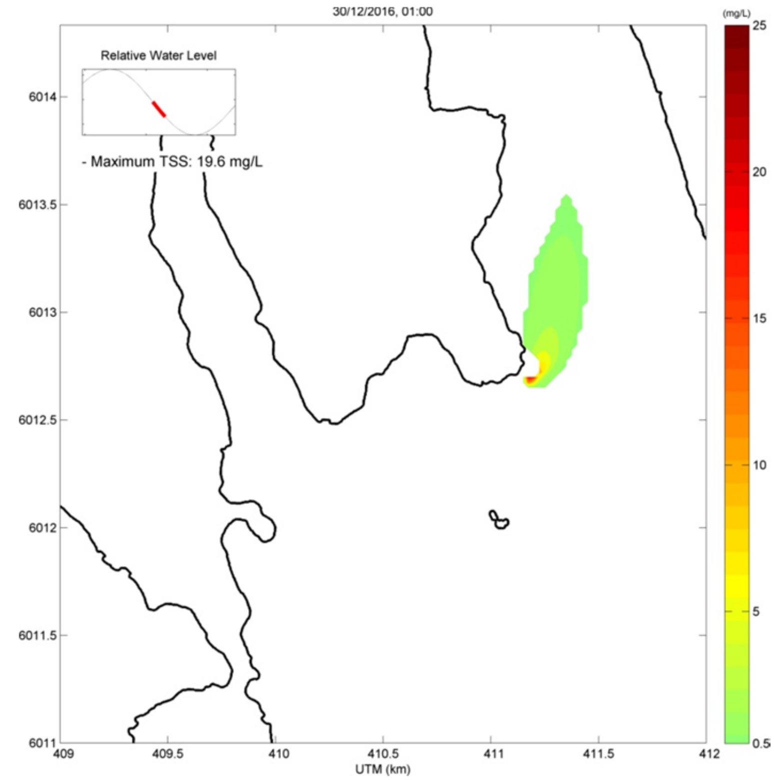
Results are discussed in terms of:

- Maximum TSS extent for each berth
- TSS duration and persistence outside the immediate dredge area
- Maximum Deposition for each berth

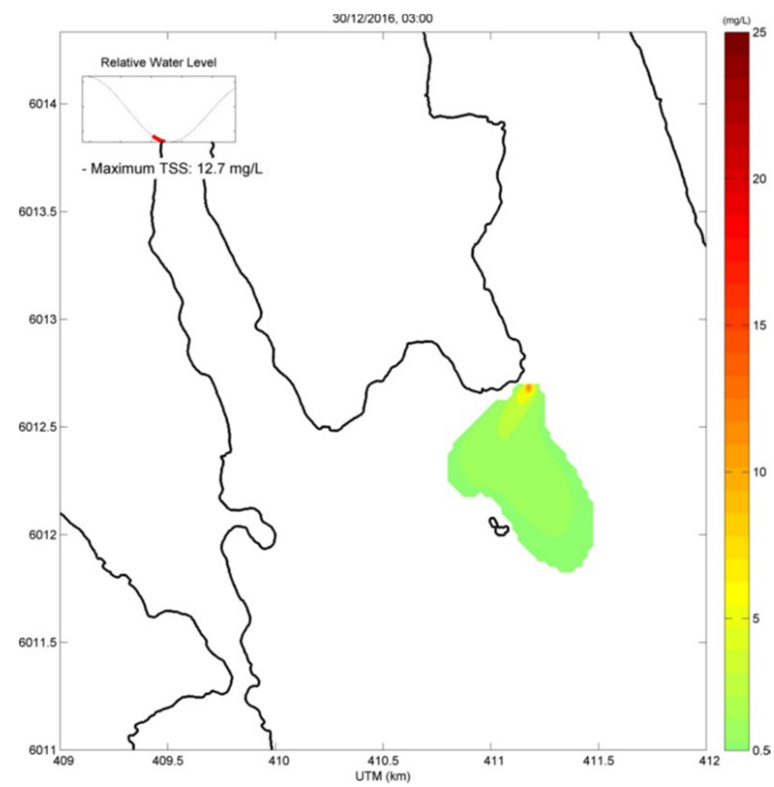
10.1 Berth 1 North TSS Extents and Persistence

Similarly to the MOF, the berth dredge areas show the highest concentrations closely confined to the actual dredge points (Figure 10-1). The maximum predicted TSS at B1 N is 66.7 mg/L, which is much lower than the MOF values of just over 200 mg/L. The distribution is again tidally dominated, with the plumes extending northwards and southwards with the ebb and flood tides, although a more complex back eddy system exists here than at Casey Cove.

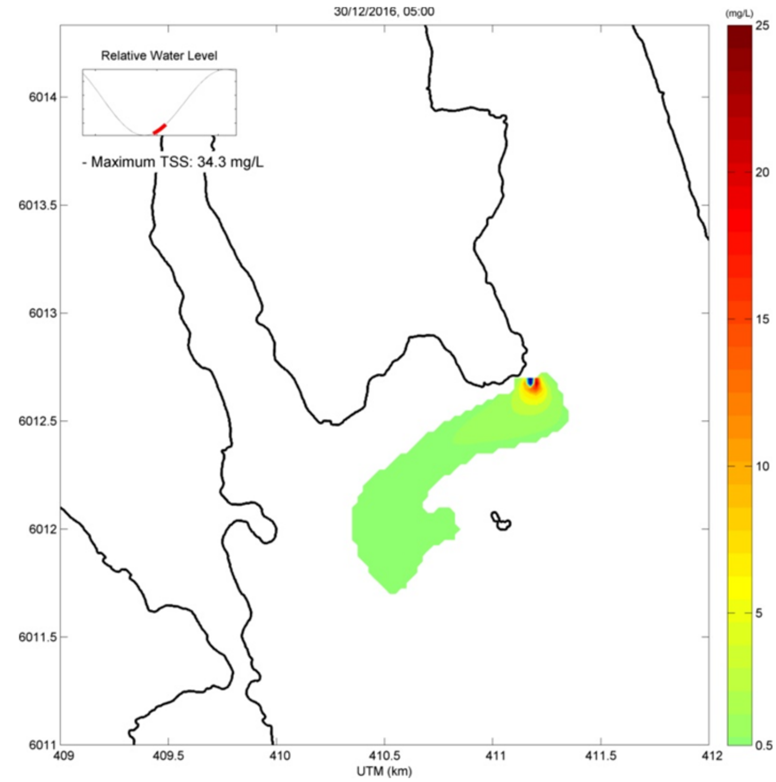
During the 14 hours per day of dredge downtime, there is no evidence of any TSS signature, with the sediment settling out within two hours of dredge cessation. The maximum northerly plume extent observed occurs at 09:00 on December 30 and reaches just over 1 km. Values within the plume are mainly 4 mg/L or less. Similarly a southerly plume occurs on the same day just after low water at 05:00, but here the values are below 3 mg/L.

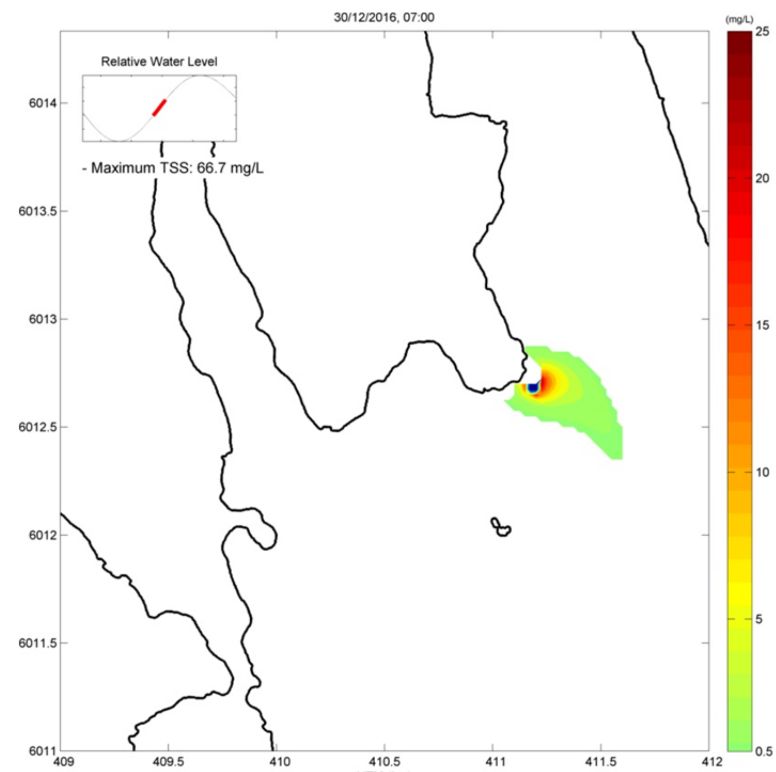


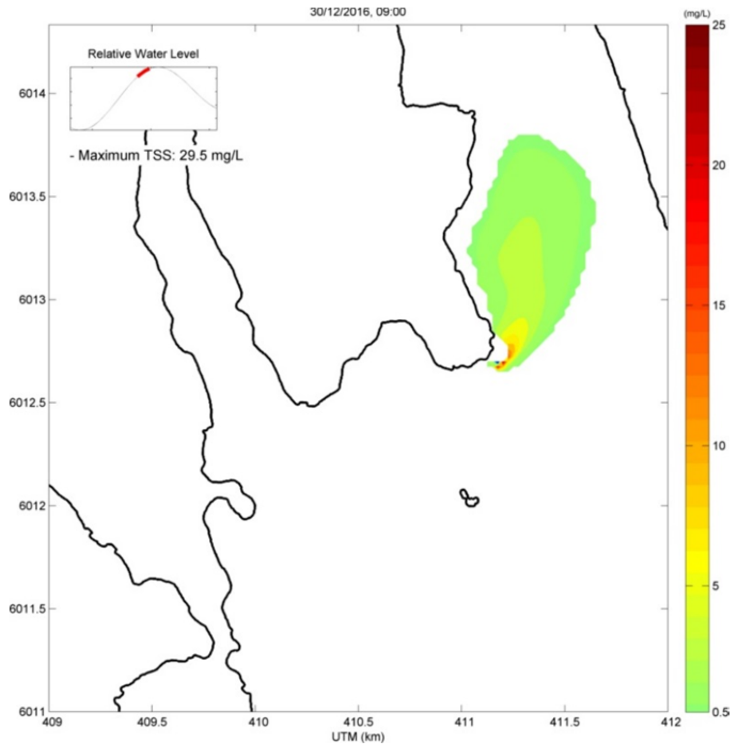
30/12/2016, 01:00
Relative Water Level
- Maximum TSS: 19.6 mg/L
UTM (km)
(mg/L)



30/12/2016, 03:00
Relative Water Level
- Maximum TSS: 12.7 mg/L
UTM (km)
(mg/L)


30/12/2016, 05:00
Relative Water Level
- Maximum TSS: 34.3 mg/L
(mg/L)
UTM (km)


30/12/2016, 07:00
Relative Water Level
- Maximum TSS: 66.7 mg/L
(mg/L)
UTM (km)



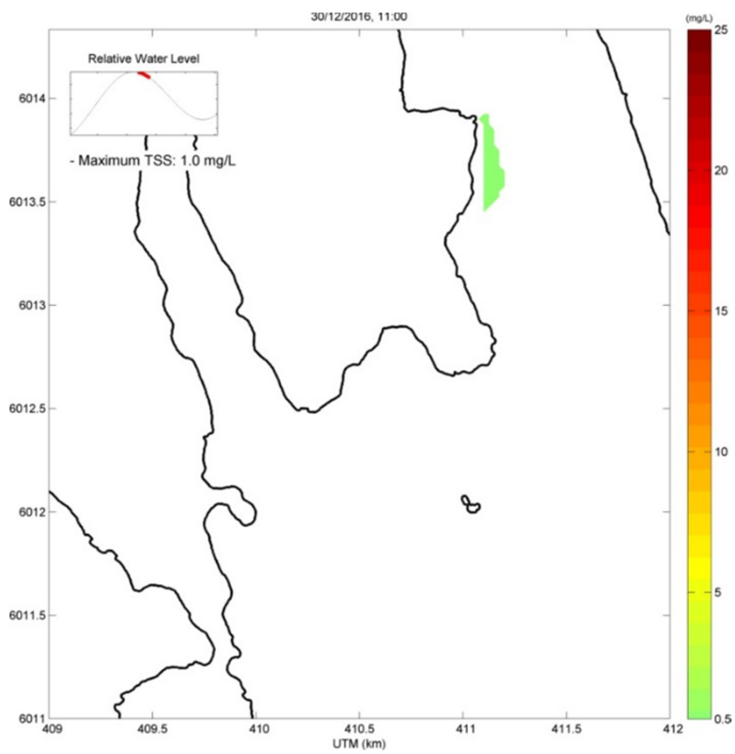


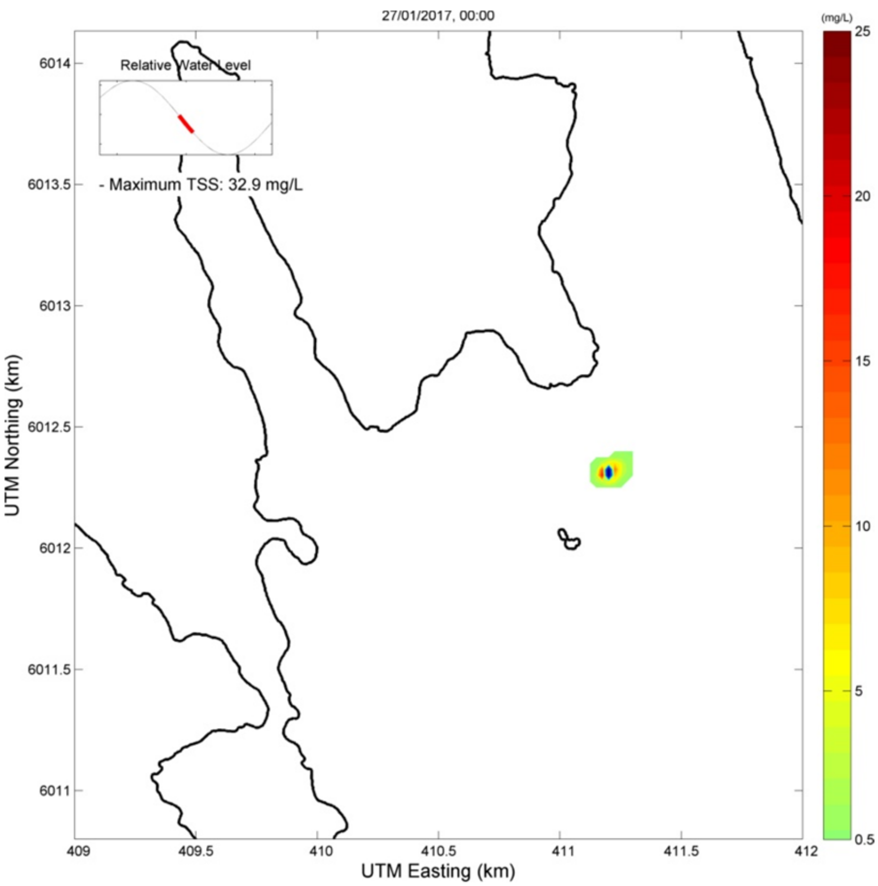
Figure 10-1: B1 N time series for the 10 hour period around the maximum TSS event on December 30 from 01:00 to 11:00. The cyan, light blue and dark blue show TSS values 25-50, 50-100 and >100 mg/L respectively.

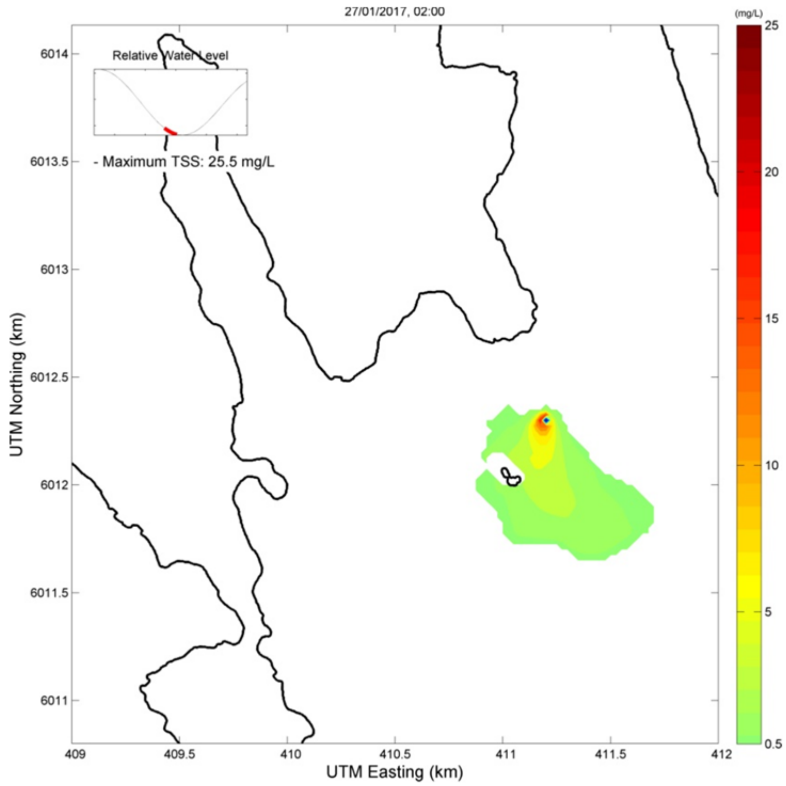
10.2 Berth 1 South TSS Extents and Persistence

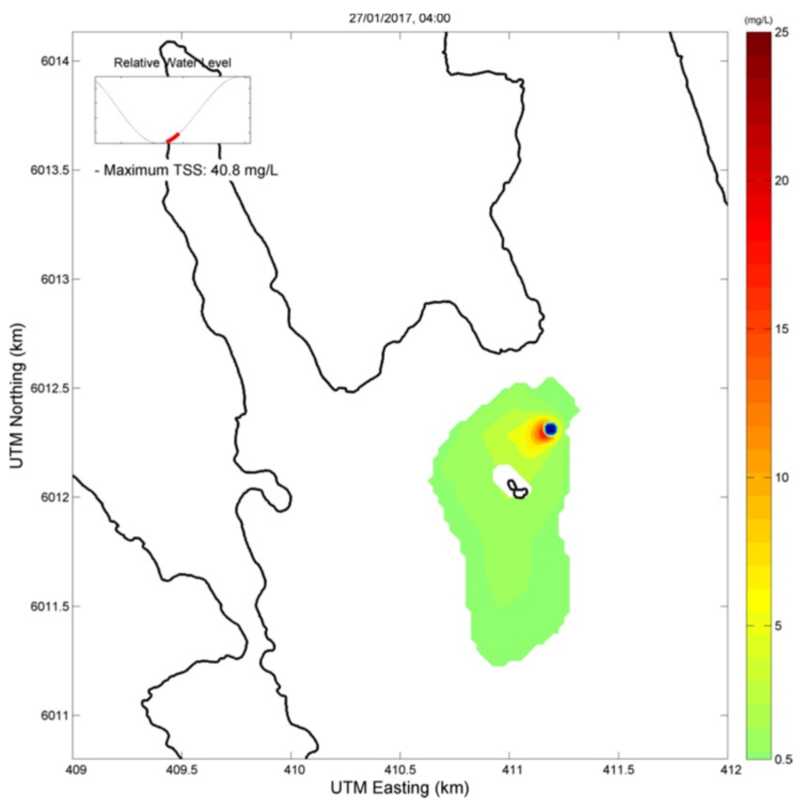
Dredge activity here is modelled as starting at 00:00 on January 27, at mid ebb on a neap tide. At this time the initial plume is confined to less than 250 m maximum width on its major axis and peaks at 32.9 mg/L (Figure 10-2).

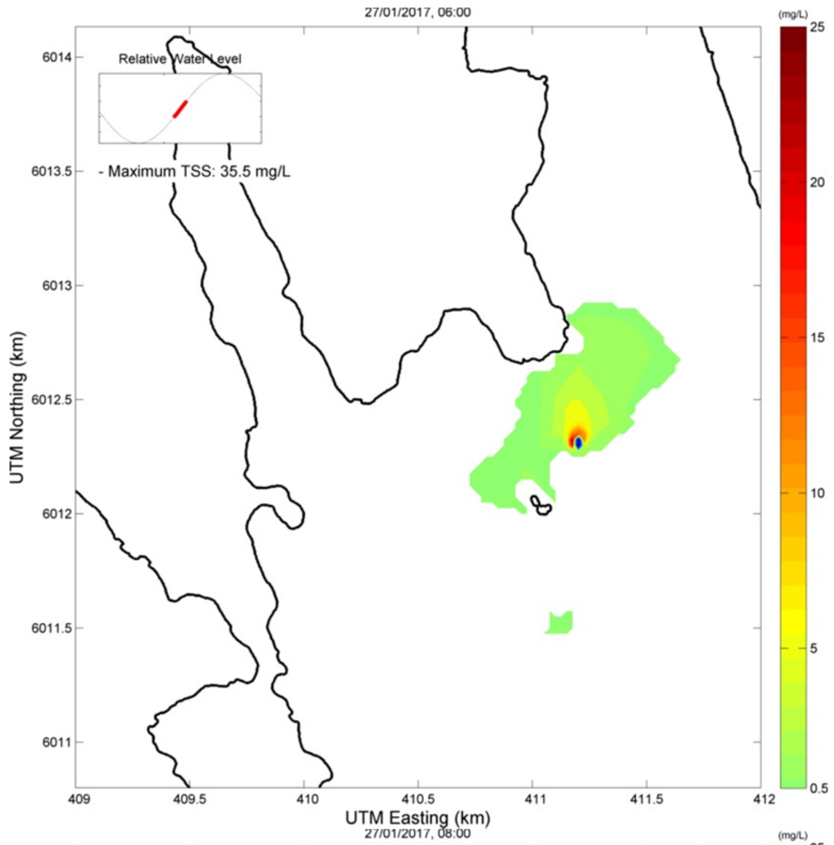
At 02:00 the tide is near LW and concentrations decrease as the plume spreads out to the southeast. Two hours later the plume reaches 1 km to the south, its maximum southern extent. At maximum tidal currents, mid flood, the plume is transported northwards by around 600 m and continues in this trend throughout the flood tide, stretching out in a narrow ribbon. The predicted peak value of 73.8 mg/L occurs at near HW as the currents decrease and the sediments become concentrated in the dredge zone. At 10:00 dredging has ceased and the central TSS drops to 8.2 mg/L within the hour.

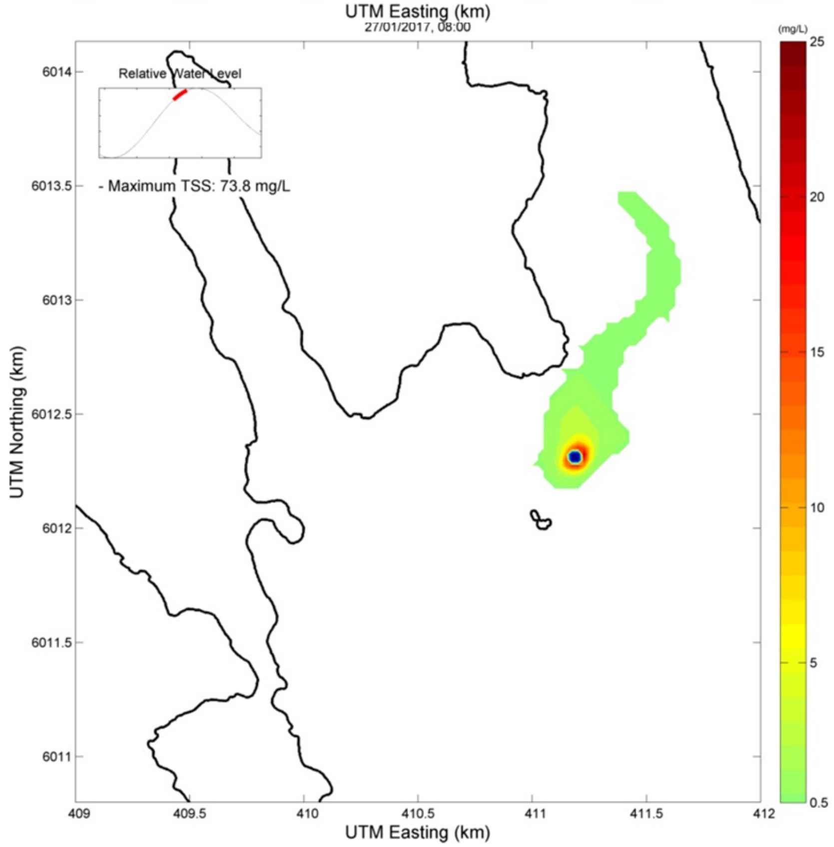
Throughout this cycle, the maximum width of the TSS zone exceeding 5 mg/L is less than 250 m. Again these TSS distributions reflect concentration of suspended sediments at times of low current activity.




27/01/2017, 02:00
Relative Water Level
- Maximum TSS: 25.5 mg/L
UTM Northing (km)
UTM Easting (km)
(mg/L)
6014
6013.5
6013
6012.5
6012
6011.5
6011
409
409.5
410
410.5
411
411.5
412
25
20
15
10
5
0.5


27/01/2017, 04:00
Relative Water Level
- Maximum TSS: 40.8 mg/L
UTM Northing (km)
UTM Easting (km)
(mg/L)
6014
6013.5
6013
6012.5
6012
6011.5
6011
409
409.5
410
410.5
411
411.5
412
25
20
15
10
5
0.5


27/01/2017, 06:00
Relative Water Level
- Maximum TSS: 35.5 mg/L
UTM Northing (km)
UTM Easting (km)
(mg/L)
6014
6013.5
6013
6012.5
6012
6011.5
6011
409
409.5
410
410.5
411
411.5
412
25
20
15
10
5
0.5


27/01/2017, 08:00
Relative Water Level
- Maximum TSS: 73.8 mg/L
UTM Northing (km)
UTM Easting (km)
(mg/L)
6014
6013.5
6013
6012.5
6012
6011.5
6011
409
409.5
410
410.5
411
411.5
412
25
20
15
10
5
0.5

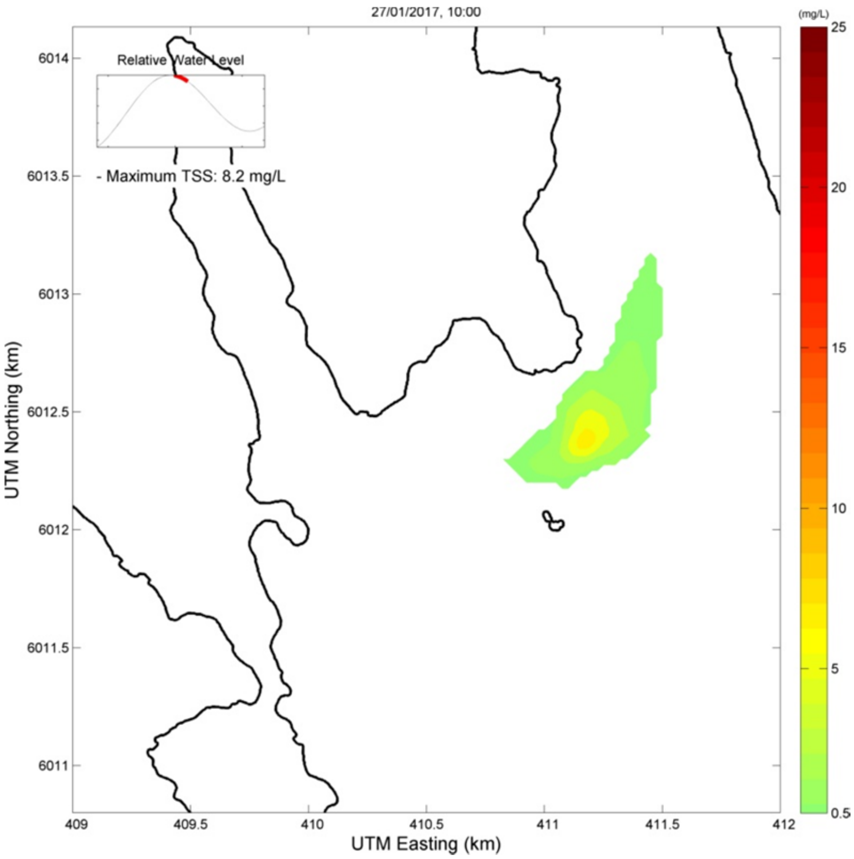
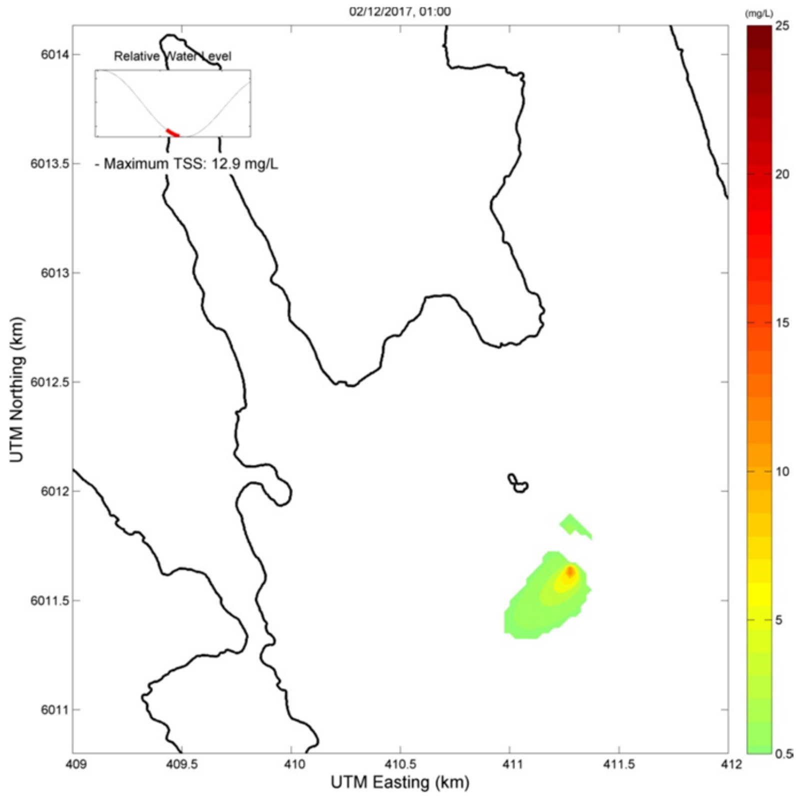


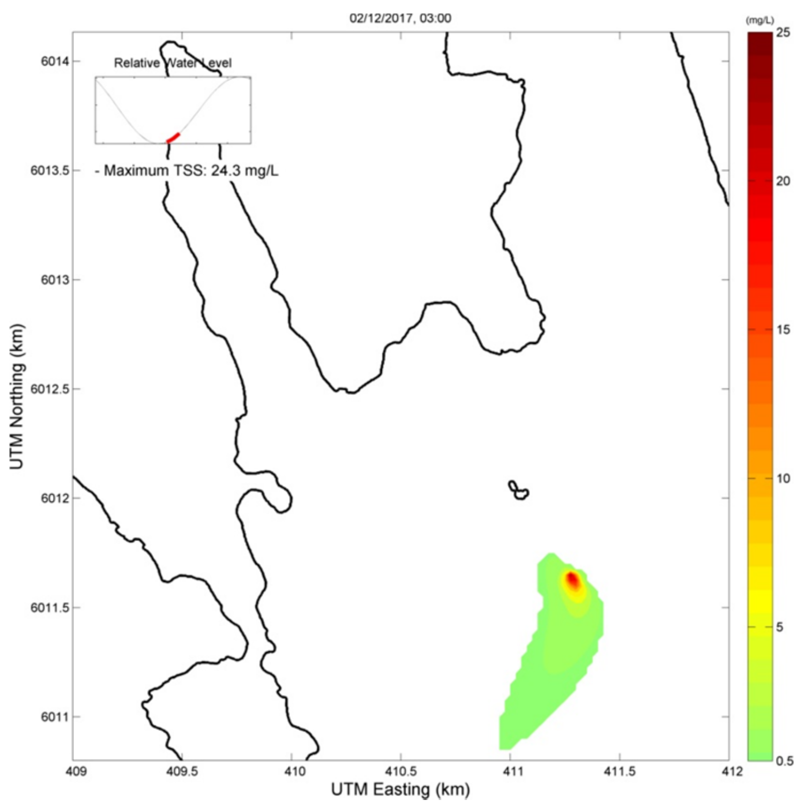
Figure 10-2: B1 S time series for the 10 hour period around the maximum TSS event on January 27. The cyan, light blue and dark blue show TSS values 25-50, 50-100 and >100 mg/L respectively. The inset shows the tidal state.

10.3 Berth 2 TSS Extents and Persistence

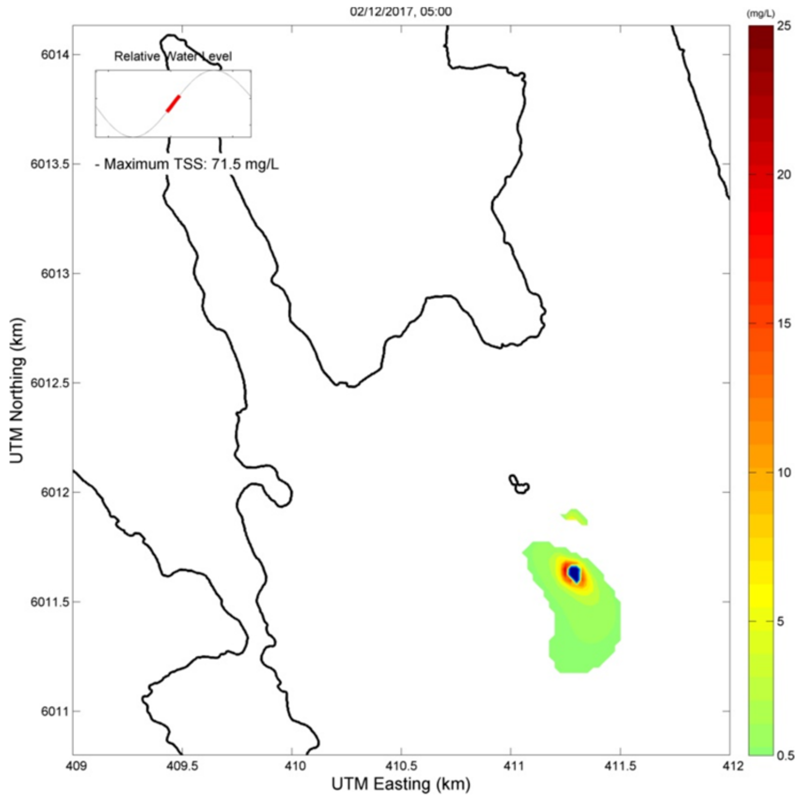
The maximum predicted TSS event at Berth 2 is 71.5 mg/L and occurs on December 2 at 05:00 near LW when currents are weaker (Figure 10-3). The snapshots for December 2 show the plume developing and moving over the tidal cycle, following the ebb and flood tide excursions. The maximum southerly extent occurs at 03:00 just after LW and is within 1 km of B2 dredge area. The maximum northerly extent is similar but has an east to west spread, occurring at near HW (07:00). This is a maximum single event.

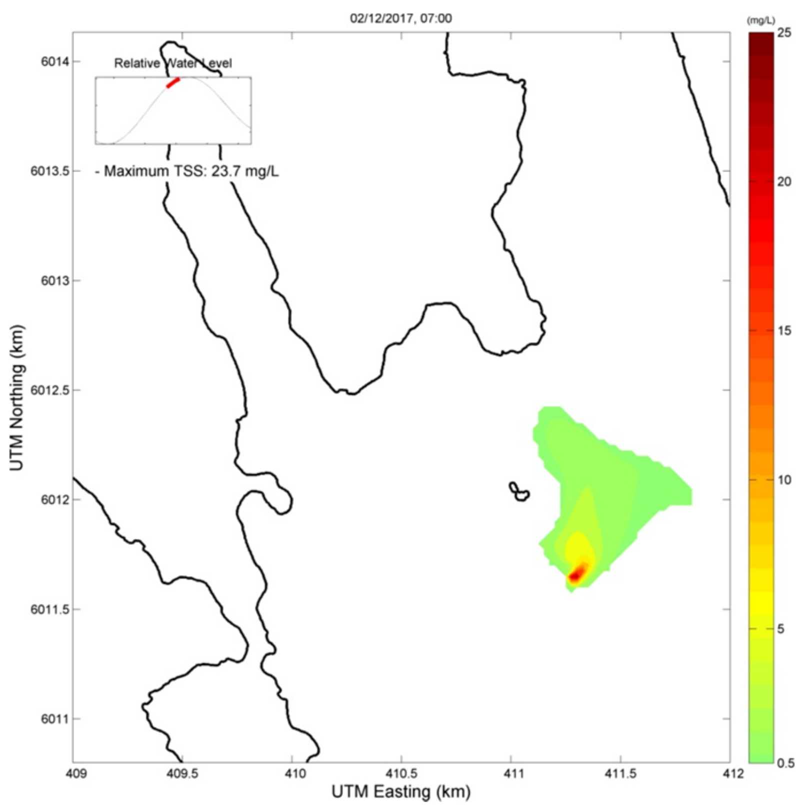


02/12/2017, 01:00
Relative Water Level
- Maximum TSS: 12.9 mg/L
UTM Northing (km)
UTM Easting (km)
(mg/L)



02/12/2017, 03:00
Relative Water Level
- Maximum TSS: 24.3 mg/L
UTM Northing (km)
UTM Easting (km)
(mg/L)


02/12/2017, 05:00
Relative Water Level
- Maximum TSS: 71.5 mg/L
UTM Northing (km)
UTM Easting (km)
(mg/L)


02/12/2017, 07:00
Relative Water Level
- Maximum TSS: 23.7 mg/L
UTM Northing (km)
UTM Easting (km)
(mg/L)

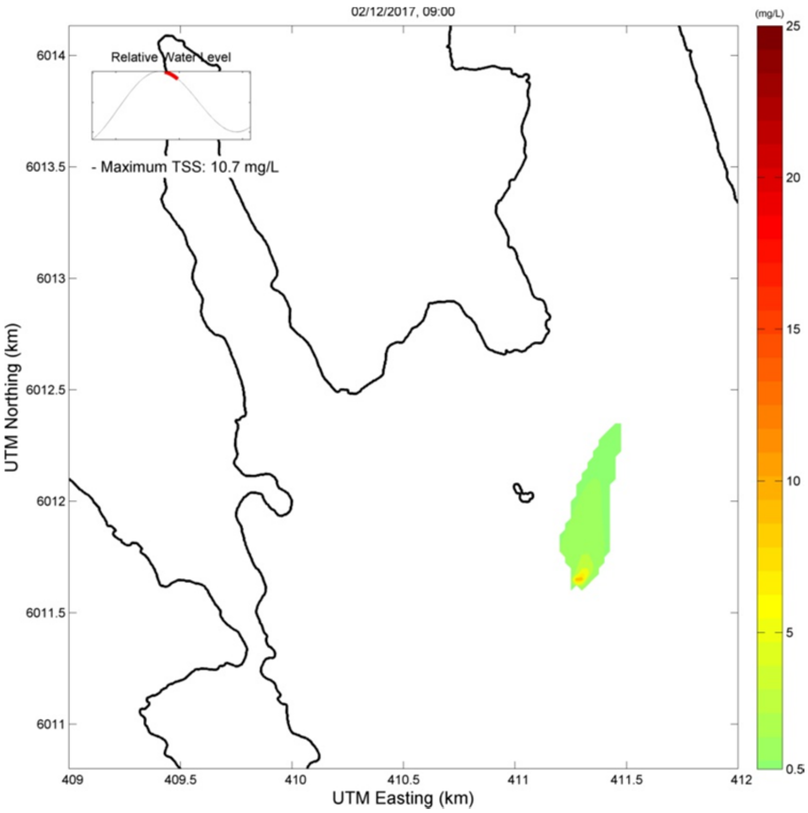


Figure 10-3: B2 sequence showing the maximum TSS event on December 2 at 05:00. The cyan, light blue and dark blue show TSS values 25-50, 50-100 and >100 mg/L respectively. The inset shows the tidal state.

10.4 Berth 1 North and South Deposition

At B1 N and B1 S the volumes dredged are small in comparison to the total dredge volume at the MOF. At B1 N the maximum predicted deposition is 0.04 m and occurs within and just outside the northern boundary (Figure 10-4). This indicates the TSS transport is weakly dominated by the flood tide. This deposition is less than 0.01 m thick and extends just over 500 m north of the dredge boundary. Values of up to 0.02 m deposition extend 200 m from the dredge boundary, again with a slight northward bias due to the flood tide.

At B1 S the maximum predicted deposition is 0.12 m (Figure 10-5), which is comparable to that at the MOF for much higher dredge volumes (Figure 9-10). The volume removed at B1 S is only slightly larger than that for B1 N, but peak deposition is much more confined, falling within the center of the dredge area. This results in a relatively thick, localised deposition layer of less than 100 m diameter. During the B1 S construction period the tides are at their weakest. They extend over the end of a spring cycle and up to mid neap tides (Figure 7-1), which is consistent with the resultant TSS distribution. Deposition outside the dredge area is predominantly around 0.01 m thickness and extends less than 500 m from the dredge area. As predicted for B1 N, the bias is with the flood tide, but here the axis of deposition is northeast to southwest.

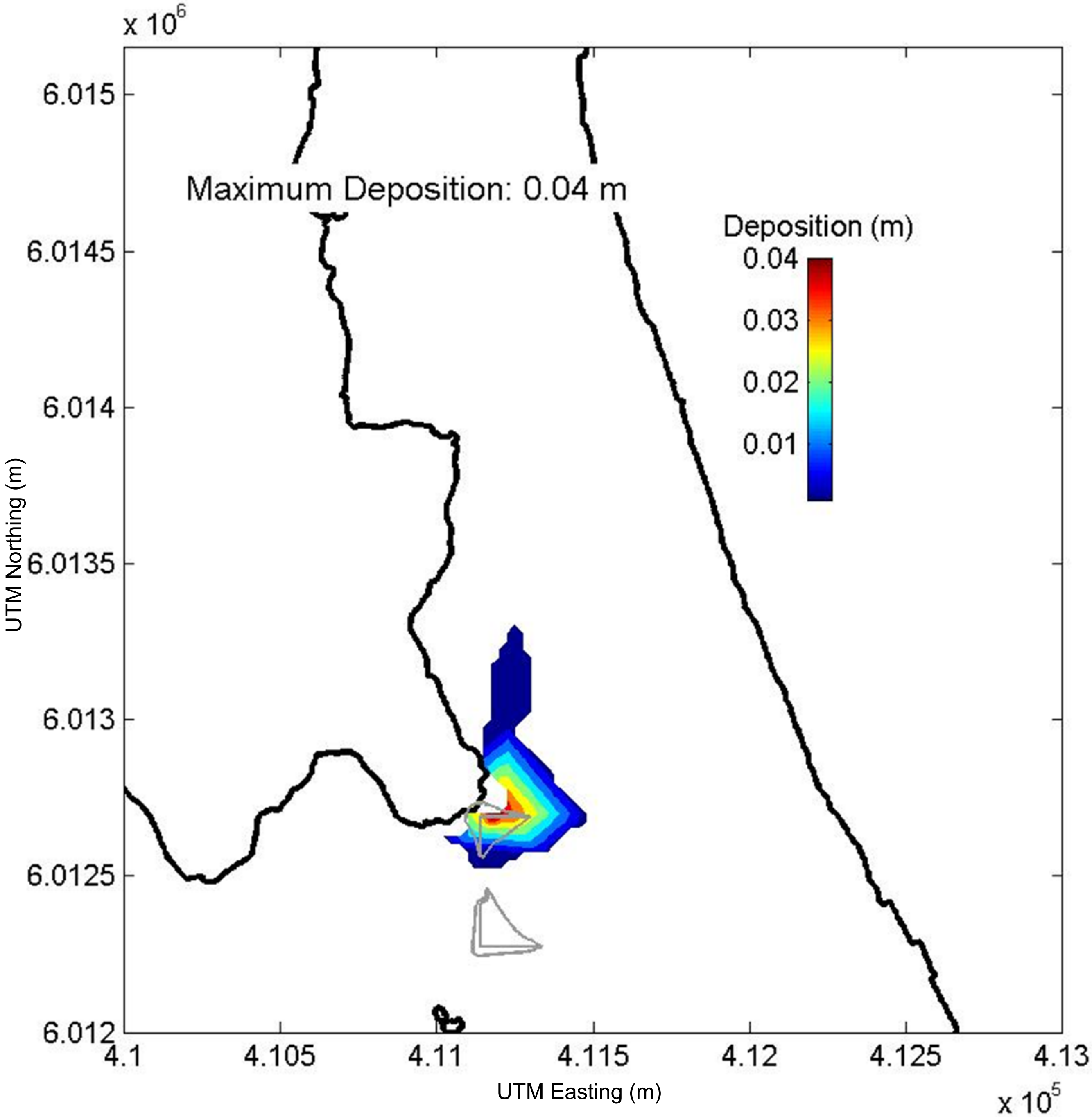


Figure 10-4: Deposition at B1 N at the end of the entire 13.3 days of dredging.

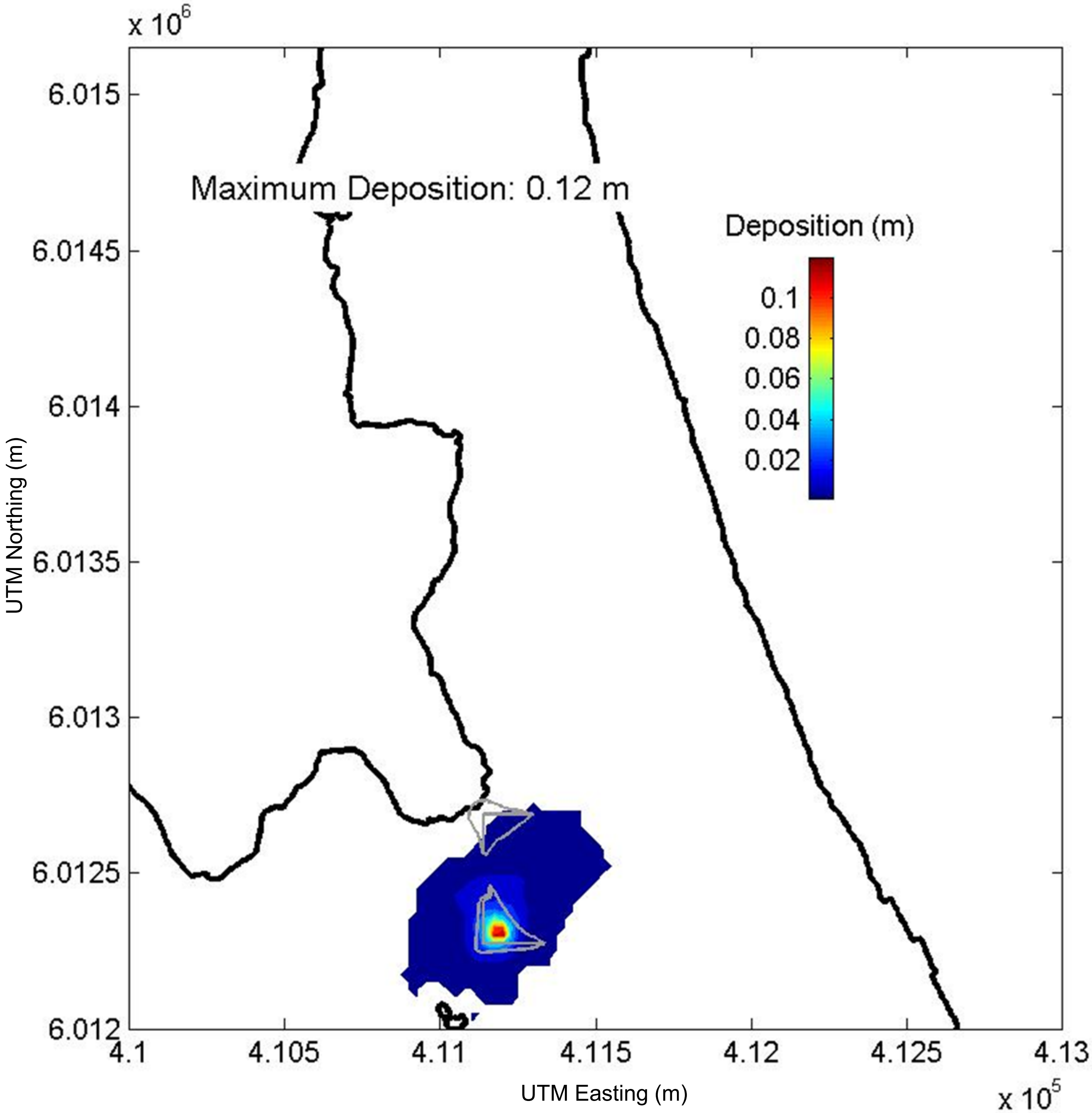


Figure 10-5: Deposition at B1 S at the end of the entire 17.3 days of dredging.

10.5 Berth 2 Deposition

At B2 the deposition is confined to the immediate vicinity around the dredge area, similar to B1 N. The smaller volume of sediment removed is reflected in the thin layer of deposition, reaching 2 cm at the centre and quickly becoming 0.5 cm or less within 200 m. The directional bias here is to the southwest, suggesting the ebb currents are slightly dominant. The maximum plume length is less than 300 m from the dredge centre and very discrete.

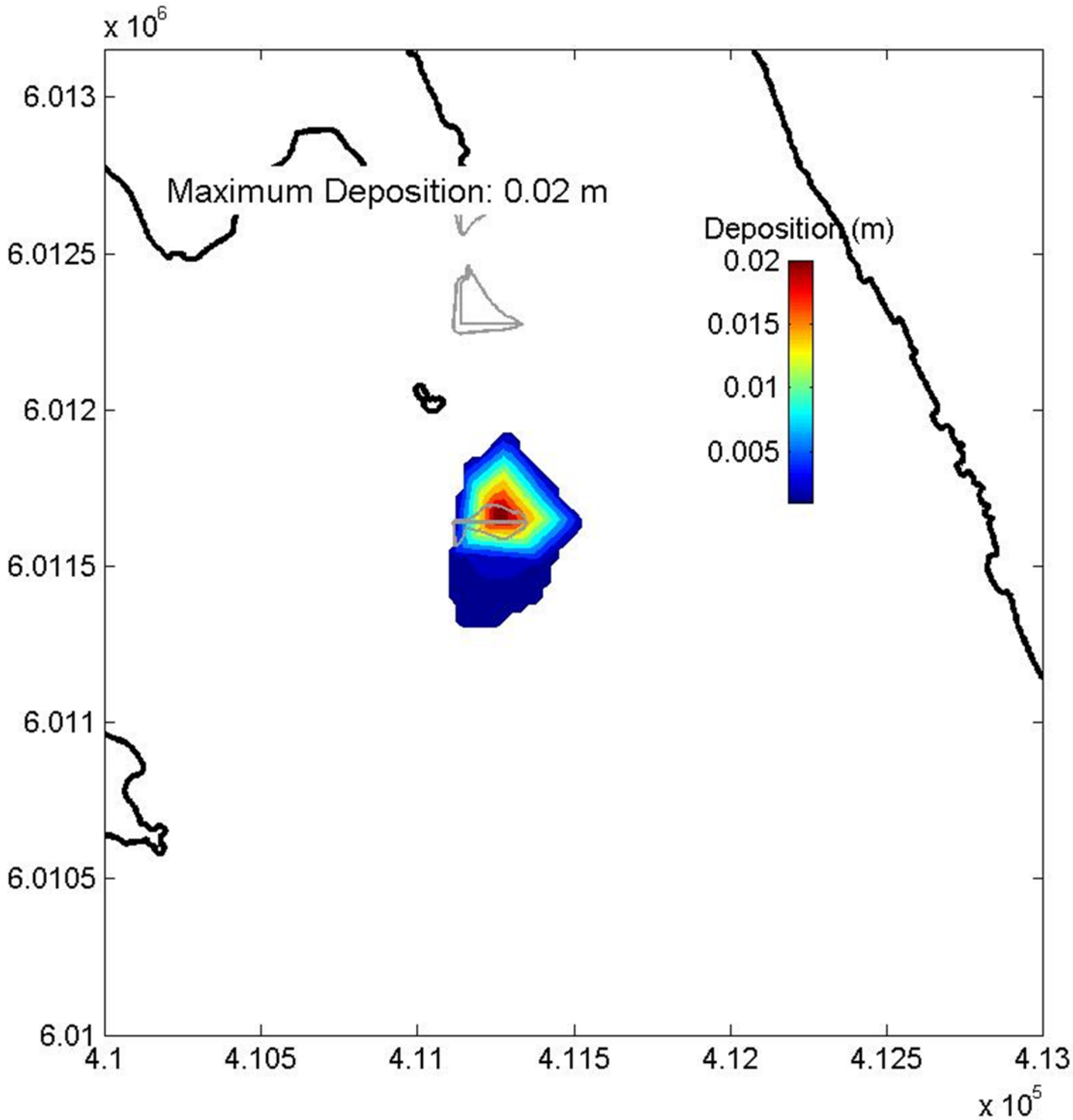


Figure 10-6: Deposition at B2 at the end of the entire 11.2 days of dredging.

11 Total Resuspension for the Construction Periods

Figure 11-1 shows the total resuspension occurring over the two year construction period at the MOF, B1 N, B1 S, and B2. It is notable that as soon as dredge activity stops the TSS reverts to background levels within a few hours. In Year Two there is a very small resuspension event on December 12, but this is very short lived, reverting to background TSS within a few hours.

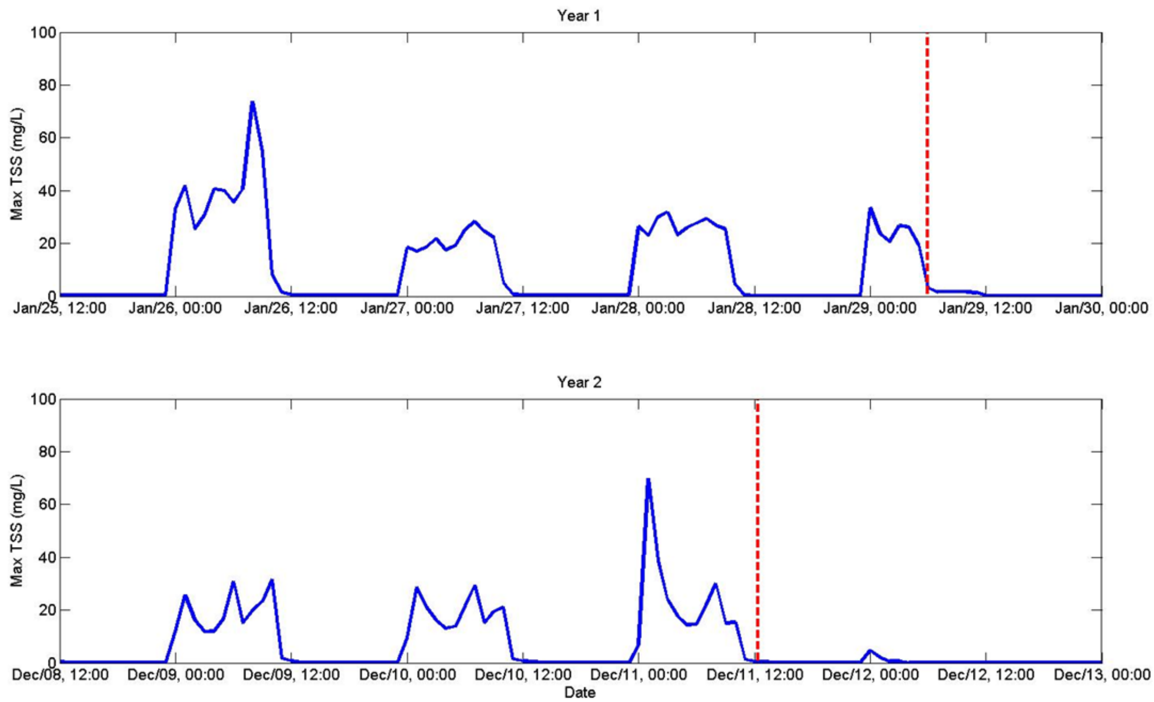


Figure 11-1: TSS maximum time series for Year 1 and 2, including resuspension occurrences in the 10 days following dredge cessation (red line).

12 Summary and Conclusions

12.1 TSS

The results presented are for the maximum TSS predicted over the entire dredge period. This provides the worst case scenario for a conservative evaluation. Current speeds across the dredging zones are moderate, peaking at around 0.5 ms^{-1} in Casey Cove and 0.8 ms^{-1} at the Berths. The TSS maximums are considered to be well contained to the area of construction activity

For the MOF immediate dredge areas the TSS values are always above 25 mg/L. At the MOF the maximum dispersion of the dredgate occurs at the northern dredge point during the 0 to 5 m dredge step. Values exceeding 25 mg/L extend mainly in the east to west axis due to the tidal effects and the maximum width predicted is 200 m. Values exceeding 5 mg/L can extend beyond this, most noticeably as a narrow plume to the north along the coastline. The predictions show the maximum extent of the plume to be around 500 m to the north and 200 m in width. The maximum extent of the TSS plume, greater than 1 mg/L above background, is approximately 2 km from the dredge boundary at Casey Cove.

For the Berth immediate dredge areas the TSS values can range from 12 to 74 mg/L, but the predicted horizontal axis of this region is 100 m or less. Values exceeding 5 mg/L can extend as a narrow plume northwards to a maximum distance of 700 m, with widths remaining within 300 m.

Persistence of TSS above 5 mg/L for more than a few hours within the water columns is predicted only at the MOF dredge site. Even here it remains for less than 24 hours.

12.2 Deposition

In all the proposed dredge areas, the deposition of sediment is localised around the modelled dredge centres, which is consistent with the modelled TSS distribution. The maximum sediment proposed to be removed is at the MOF and consequently the deposition associated with dredging is highest here, predicted to be 0.12 m. However, outside the dredge zones this immediately drops to 0.01 m or less.

At the Berths the maximum thickness of deposition is predicted to be at the berth B1 S. It reaches 0.12 m, similar to that at the MOF, here it is contained within the dredge area. Beyond 50 m from the dredge release point depostion is predicted to be 0.02 m or less. At berth areas B1 N and B2, the deposition is predicted to be 0.02 to 0.04 m at the dredge area. These maximum areas are confined horizontally to a 200 m radius or less. Again values are predicted to be 0.01 m or below outside this area.

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14 Appendix A: Input Tables

14.1 MOF Input Table: Winter 1

MOF Model Run: Year 1

Dredge Area	Material	Methods	Model Run #	From Depth (m)	To Depth (m)	Adjusted Model Depth throughout each run (m)	Dredge Volume (m^3)	Sub volume (m^3)	Year 1: Start (year is not relevant), inc. for calculation)	Year 1: End (year is not relevant)	Duration: Duration (day)	Duration: Operation times calculated from total volume/productivity/ hrs per day	Number of units operating at any time	Operation per day (hour)	Stoppage per day (hour)	Productivity (m^3/hour)	Dry density (10^3 kg/m^3)	Sediment releasing: Loss rate	Sediment releasing: kg/s	Sediment releasing: Vertical Distribution	PSD (%): Clay (<0.004mm)	PSD (%): Silt (<0.063mm to >=0.004mm)	PSD (%): Fine Sand (<0.25mm to >=0.063mm)	PSD (%): Gravel and coarse sand (>=0.25mm)
			MOF1	0	5	0		63,178	30/11/2016	08/12/2016	8.2	8.4	1											
MOF	Sediment	Clamshell	MOF2	5	10	5	365,000	98,111	08/12/2016	21/12/2016	13.0	13.1	1	20.00	4.00	375	1.088	3.0%	4.54	BHD/clamshell: 40% of all losses is spread equally whilst moving up through water column, the other 60% on the surface (when bucket comes out of water)	14.8	30.0	41.3	13.9
			MOF3	10	15	10		203711	21/12/2016	17/01/2017	27.1	27.2	1											

14.2 Berths Input Table: Winter 1 and 2

Berth Model Run

Dredge Area	Material	Methods	Model Run #	From Depth (m)	To Depth (m)	Adjusted Model Depth throughout each run (m)	Dredge Volume (soft) (m^3)	Sub volume (soft) (m^3)	Start (year is not relevant), inc. for calculation)	End (year is not relevant)	Duration		Number of units operating at any time	Operation per day (hour)	Stoppage per day (hour)	Productivity (m^3/hour)	Dry density (10^3 kg/m^3)	Sediment releasing			PSD (%)			
											Duration (day)	Operation times calculated from total volume/productivity/ hrs per day						Loss rate	kg/s	Vertical Distribution	Clay (<0.004mm)	Silt (<0.063mm to >=0.004mm)	Fine Sand (<0.25mm to >=0.063mm)	Gravel and coarse sand (>=0.25mm)
Berth 1N	Sediment +Rock	Clamshell	Berth1N	0	15	0	118,470	51,680	29/12/2016	11/01/2017	13.3	13.8	1				0.996		4.15		18.4	34.3	33.1	14.2
Berth 1S	Sediment +Rock	Clamshell	Berth1S	0	15	0		66,790	12/01/2017	29/01/2017	17.3	17.8	1	10.00	14.00	375	0.860	3.0%	3.58	BHD/clamshell: 40% of all losses is spread equally whilst moving up through water column, the other 60% on the surface (when bucket comes out of water)	21.3	41.9	31.9	4.9
Berth 2	Sediment +Rock	Clamshell	Berth2	0	15	0	42,930	42,930	30/11/2017	11/12/2017	11.2	11.4	1				0.687		2.86		27.4	51.8	7.0	13.8

14.3 Assumptions

Assumptions

- Productivity has been revised to 375m3/hr as per the revised dredge plan (15.4.16)
- Dredge areas include the slopes at the MOF and the Berths
- Sediment Release in the vertical: BHD/clamshell: 40% of all losses is spread equally whilst moving up through water column, the other 60% on the surface (when bucket comes out of water)
- Total sediment Release rate: 3%
- No gap between different sub-areas (conservative)
- MOF is being run at 3 levels with a bathymetry adjustment to 5 and then 10 m after the first and second model runs. This is to capture any TSS transport into Casey Cove
- Berths will be run with the initial bathymetry (0) as this is in an open region.
- Data will be extracted at hourly intervals to ensure tidal effects are captured
- The time of year (ie month) is important but the year is not relevant
- For the berths the start date allows for the time specified for overburden dredging first. The removal of the rock is then continuous after this providing a conservative approach
- Dates and productivity revised based on new dredge information supplied by Molly Brewis 15th April 2016