SUNCOR ENERGY OFFSHORE EXPLORATION PARTNERSHIP TILT COVE EXPLORATION DRILLING PROJECT 2019-2028
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Drill Release Risk Assessment

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Suncor Energy Tilt Cove
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EXECUTIVE SUMMARY

The operational release of drill cuttings and fluids were modelled to support an Environmental Impact Statement (EIS) for Suncor, associated with the Tilt Cove Exploration Drilling Project 2019-2028. The Project Area is located approximately 325 km east southeast of St. John's, Newfoundland on the eastern edge of the Grand Banks and approximately 100 km west of the Flemish Pass. The water depth at the proposed drilling site selected for modelling is approximately 100 m. Operational discharges from the five planned drilling sections were modelled as either seafloor or sea surface releases. The release rate and location of the discharges in the water column depended on each drilling stage. The first two sections were simulated as seafloor releases of water based mud (WBM) and cuttings, while the remaining three sections were simulated as surface releases of cuttings with 6.9% by mass of the synthetic based mud (SBM) retained on the cuttings. Each of these simulations were performed for two different seasons (Summer and Fall) to evaluate how ocean current variability in the region may affect the patterns of cuttings and mud dispersion and deposition. This dispersion modelling targeted the most likely drilling windows for the Project, which were May-June and October-November, and referred to as Summer and Fall.

Discharge simulations were completed using the RPS MUDMAP modelling system. The MUDMAP model is used to predict the transport of drilling solids released in the marine environment and the resulting seabed deposition. The model inputs include information regarding the discharge characteristics (release location, rate of discharge, etc.), the properties of the sediment (particle sizes, density), as well as environmental characteristics (bathymetry and ocean currents), to predict the dispersion and transport of solids through the water column. The model output consists of the predicted three-dimensional movement and shape of the discharge plume, the concentrations of insoluble discharge components in the water column, and the accumulation of discharged solids on the seabed. The model predicts the transport of solid particles from the time of discharge or release to initial settling on the seabed. MUDMAP does not account for resuspension and transport of previously discharged solids; therefore, it provides a conservative estimate of the potential seafloor depositions.

Bathymetry was characterized using databases provided by NOAA National Geophysical Data Center and GEBCO. Currents for the North Atlantic region were acquired from the three-dimensional HYCOM (HYbrid Coordinate Ocean Model) circulation model. For this study, daily current data were obtained, and trends were analyzed for the period of January 2006 through December 2012 for the North Atlantic region. As with any hydrodynamic model, there is the potential that local currents may deviate from predictions based upon grid resolution and small-scale variability in ocean circulation dynamics. However, the data used is sufficient for this type of modelling.

In each modelled case, the deposition of muds and cuttings from operational discharges onto the seabed was controlled by the settling velocities of particles, the currents within the water column, and the depth of the water column. Modelled operational discharges from EL 1161 (~100 m) were predicted to produce a spatially confined depositional area of 7.28 mm thick. The difference in seasonality between both scenarios heavily influenced the seabed depositional patterns, because the current regimes for both modelled time periods were markedly different. Slow settling velocities associated with the fine silts/clays and coarse silts, which make up the largest fractions of the cuttings drilled with WBM and SBM, allowed for greater dispersion before settling out.

Summer simulations for the EL 1161 site were predicted to have weaker subsurface current regimes, with moderate directional variability, when compared to the fall simulations. This resulted in more even radial footprints predicted for summer simulations, when compared to the more elongated results predicted for the fall simulations. Depositional footprints during the summer simulations for thicknesses up to 0.5 mm typically did not extend as far as those for fall simulations. However, extents for thicknesses at or above 1 mm were greater during the summer simulations due to the weaker current regimes during this time period, which transported the discharged cuttings and muds a shorter distance from the wellhead and allowed for greater accumulation of the sediments near the wellhead. Therefore, the maximum depositional thickness was predicted to be greatest for simulations in the summer. Conversely, due to enhanced currents during the simulated fall period, depositional footprints above the

lowest threshold were predicted over a larger area and further from the wellhead. When comparing the riserless simulations to the cumulative simulations, the areal extents were nearly the same during the summer. Only at the 6.5 mm threshold were the areal extents predicted to be much greater for the cumulative simulations, when compared to the riserless simulations. This was due to the fraction of SBM that took less than a day to settle from the sea surface to the seabed, which made up approximately 35% of the SBM mass. The remaining roughly 65% was made up of finer SBM sediments and was predicted to be transported over 2.4 km from the wellhead and at thicknesses of 0.01 mm and lower. It should also be noted that approximately 78% of the total mass discharged at EL 1161 was discharged during the riserless stages, which explains why the depositional footprints were very similar between the riserless and cumulative simulations.

During the summer, depositional thicknesses at or above 0.1 mm were predicted to extend to the southeast up to 1.79 km and cover an area up to 1.45 km^2. Predicted depositional thicknesses at or above 1 mm extended to a maximum of 0.62 km and covered an area no greater than 0.27 km^2. Depositional thicknesses that reached 1.5 mm in thickness were predicted to extend less than 0.5 km from the wellhead and covered a maximum area of 0.18 km^2. The deposition at or above the predicted no effect concentrations (PNEC) threshold of 6.5 mm (Smit et al. 2008) was predicted to cover a maximum of 0.003 km^2 and extended up to 0.11 km from the wellhead. The maximum thickness during the summer simulations was predicted to be 7.28 mm, which is below the 10 mm thickness threshold that was also assessed.

Fall simulations for the EL 1161 site were characterized by stronger subsurface current regimes, with greater variability, which led to slightly more elongated depositional footprints, when compared to summer scenarios. While the predominant current direction during the fall was southeasterly, the discharge of finer sediments in the WBM cuttings and muds were predicted to be transported by northerly and southwesterly currents that occurred temporarily during the first two drilling sections. This resulted in a broader depositional footprint that was predicted to extend to the north and southeast. This current variability resulted in a broader depositional footprint that extended to the north and southeast of the wellhead. During the fall simulations, thicknesses at or below 0.5 mm were predicted to extend further and had greater areal extents than the summer simulations. This was due to the stronger current regime that transported fine sediments with low settling velocities further from the wellhead. Because of this increased transport, the larger area of deposition had less accumulation of the sediments (i.e. thinner deposition). When comparing the cumulative and riserless simulations during the fall, the predicted areal extents for all depositional thicknesses were very similar. Depositional thicknesses at or above 0.1 mm were predicted to extend to the southeast up to 2.43 km and cover an area up to 2.14 km^2 during the fall. Predicted depositional thicknesses at or above 1 mm extended to a maximum of 0.76 km and covered an area no greater than 0.2 km^2. Depositional thicknesses that reached 1.5 mm in thickness were predicted to extend less than 0.6 km from the well head and cover a maximum area of 0.08 km^2. The maximum thickness predicted during the fall simulations was 2.64 mm, well below the thresholds of 6.5 and 10 mm, which were never reached.

The variations within predicted model results between the seasonal simulations were due to two main factors including: 1) settling velocity associated with different release substances and 2) current patterns (i.e. velocity, which is composed of speed and direction). The discharges modelled in this study may be considered representative of other potential discharges within the Project Area, as the depth of the sites (~100 m) are similar in depth to other locations within the Project Area. This dispersion modelling targeted the most likely drilling windows for the Project, which were May-June and October-November. Together, both drilling periods consist of representative current regimes for the area and the predicted results could be applicable to timeframes outside of the modelled temporal windows.

Document Summary

This report includes an introduction describing the region, a description of the modelling approach, and the results of the study. The model results are summarized in figures and tables in the main body of this document, describing the potential for WBM and SBM contamination within the water column and deposition on the seabed. This document is broken down into several sections. Section 1 includes an introduction to the modelling study and a description of project area. Section 2 includes the modelling approach using the MUDMAP model, scenarios, and a description of the model input data. Section 3 summarizes the seabed deposition and water column concentration model results. Section 4 provides conclusions and discussion points. Section 5 contains the references cited. Additional information may be found in supporting Appendix A, which provides a detailed description of the MUDMAP model, fates processes, and algorithms used.

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LIST OF ACRONYMS AND ABBREVIATIONS

Term	Definition
3D	Three-dimensional referring to x, y, and z directions (i.e. latitude, longitude, and depth)
EIS	Environmental Impact Statement
GEBCO	The General Bathymetric Chart of the Oceans operated by the International Hydrographic Organization (IHO) and Intergovernmental Oceanographic Commission (IOC) of UNESCO.
HYCOM	The U.S. Navy HYbrid Coordinate Ocean Model used for currents
MICOM	Miami Isopycnic-Coordinate Ocean Model
NCODA	U.S. Navy Coupled Ocean Data Assimilation
NOAA	National Oceanic and Atmospheric Administration
NRC	U.S. National Research Council
NRDA	The U.S. Natural Resource Damage Assessment
SBM	Synthetic based mud
SwRI	The Southwest Research Institute

1 INTRODUCTION

RPS conducted sediment dispersion modelling of operational releases of drill cuttings, water based mud (WBM), and synthetic based mud (SBM) in support of an Environmental Impact Statement (EIS) for the Suncor Energy Tilt Cove Exploration Drilling Project 2019-2028. The Project Area is located approximately 325 km east southeast of St. John's, Newfoundland on the eastern edge of the Grand Banks and approximately 100 km west of the Flemish Pass. The water depth at the proposed drilling site selected for modelling is approximately 100 m. Major currents, including the Labrador Current and the Gulf Stream, influence the circulation and biological productivity in this region.

Simulations of operational releases of WBM, SBM, and drill cuttings were completed using the RPS MUDMAP modelling system (Spaulding et al., 1994). MUDMAP predicts the transport of drilling solids released in the marine environment and the resulting seabed deposition. The model requires inputs describing: (i) the physical characteristics of the discharged effluent, (ii) the discharge timing and release location, and (iii) information describing the receiving waters (bathymetry, density structure, ocean currents). Model output includes estimates of environmental loadings to the seabed (deposition) from discharges associated with offshore drilling. A technical description of the MUDMAP model is included in Appendix A.

1.1 Project Area

Newfoundland is comprised of a series of islands off the east coast of Canada, and along with Labrador forms the easternmost Canadian province. The relatively shallow waters of the continental shelf extend eastward into the Northwest Atlantic Ocean, up to 500 km off the Newfoundland coast. The Tilt Cove Project Area is located within Exploration License (EL) 1161, approximately 325 km east southeast of St. John's, Newfoundland on the eastern edge of the Grand Banks immediately west of Suncor's Terra Nova oil field (Table 1-1 and Figure 1-1). This biologically productive region sits atop substantial petroleum resources, with the Hibernia and White Rose fields in close proximity. Bathymetry is consistently approximately 100 m within the area, as it is over much of the Grand Banks. Therefore, the water depth at the proposed drilling site selected for modelling was 100 m. The modelled release location is in the northeastern corner of EL 1161. However, regions within the broader model domain do exceed 4,500 m deep, in regions such as the Labrador Basin. The model domain extends from 42°N to 57°N and 40°W to 52°W, encompassing Canadian, U.S., and international waters.

Table 1-1. Hypothetical drilling location within the Tilt Cove Exploration Drilling Project Area.

Site Name	Latitude	Longitude	Water Depth (m)
Tilt Cove	46°32'46.5072" N	48°37'6.6282" W	100

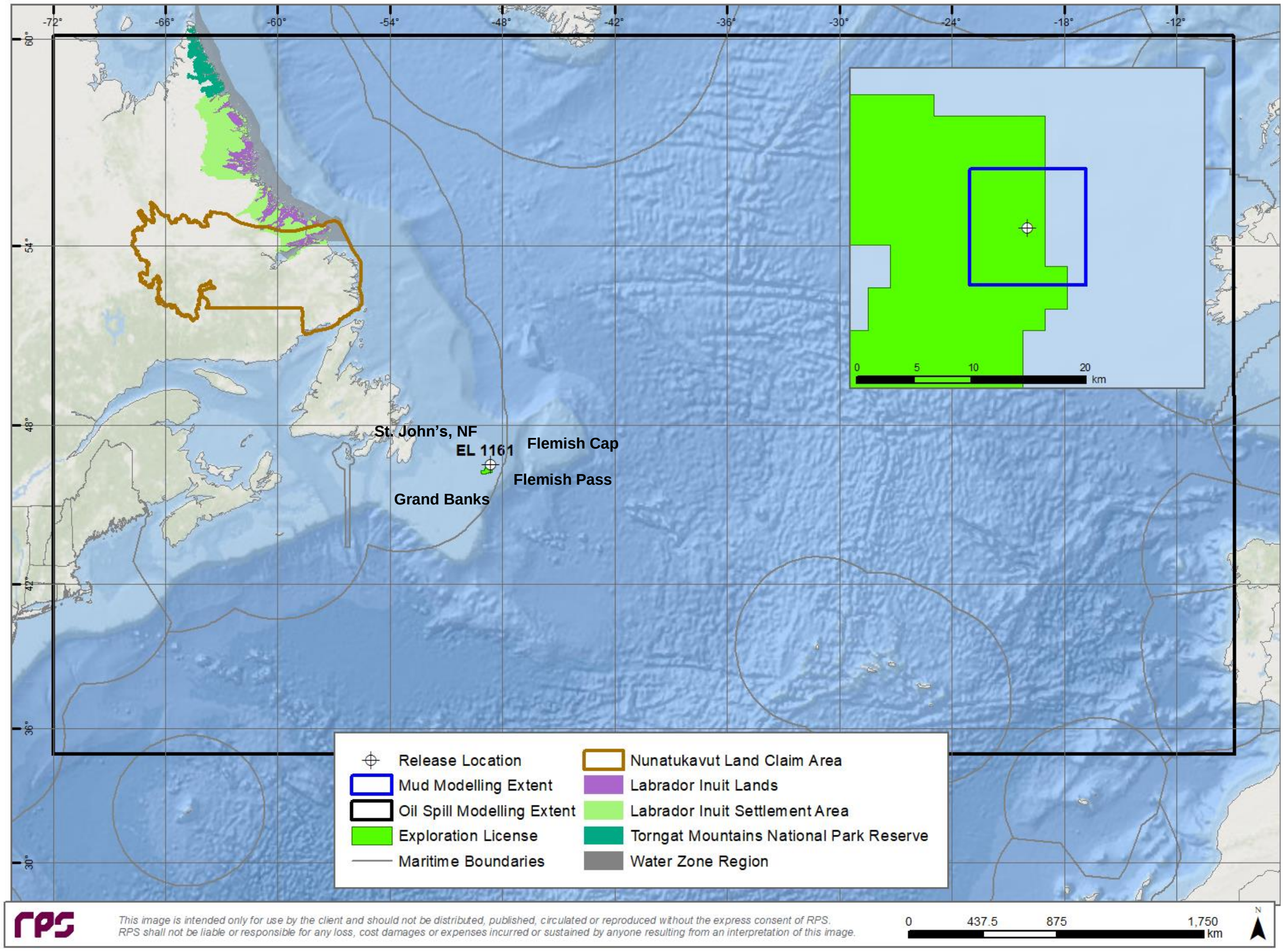


Figure 1-1. Project Area, including the hypothetical release location for EL 1161.

1.2 Circulation and Currents

The Labrador Current dominates the large-scale ocean circulation in the Newfoundland region. Originating in the Arctic Ocean, the Labrador Current flows south along the coasts of Labrador and then Newfoundland (Figure 1-2). This southerly current intensifies as waters funnel through the offshore branch, which follows the Flemish Pass between the Grand Banks and Flemish Cap. To a lesser extent, a portion of the Labrador Current flows through an inshore branch, which follows the Avalon Channel between Newfoundland and the Grand Banks. Over parts of the Grand Banks, currents are generally weak and flow southward (Fuller and Myers, 2014). Maximum current speeds in the upper 200 m of the water column range from 0.3 to 2.0 m/s (C-NLOPB, 2014). The strong southerly current dominates the yearly average flow and winds may only account for approximately 10% of current variability in this region (Petrie and Isenor, 1985). South of the Flemish Pass, the Labrador Current mixes with the North Atlantic Current. The boundary where these two currents converge produces extremely energetic and variable frontal systems and eddies on smaller scales, on the order of kilometers (Volkov, 2005). Due to these eddies, local transport may advect parcels of water in nearly any direction. Satellite and drifter studies of current dynamics demonstrate this complexity; however, drifting parcels generally move to the south and east (Han and Tang, 1999; Petrie and Anderson, 1983; Richardson, 1983) where they intersect with the North Atlantic Current.

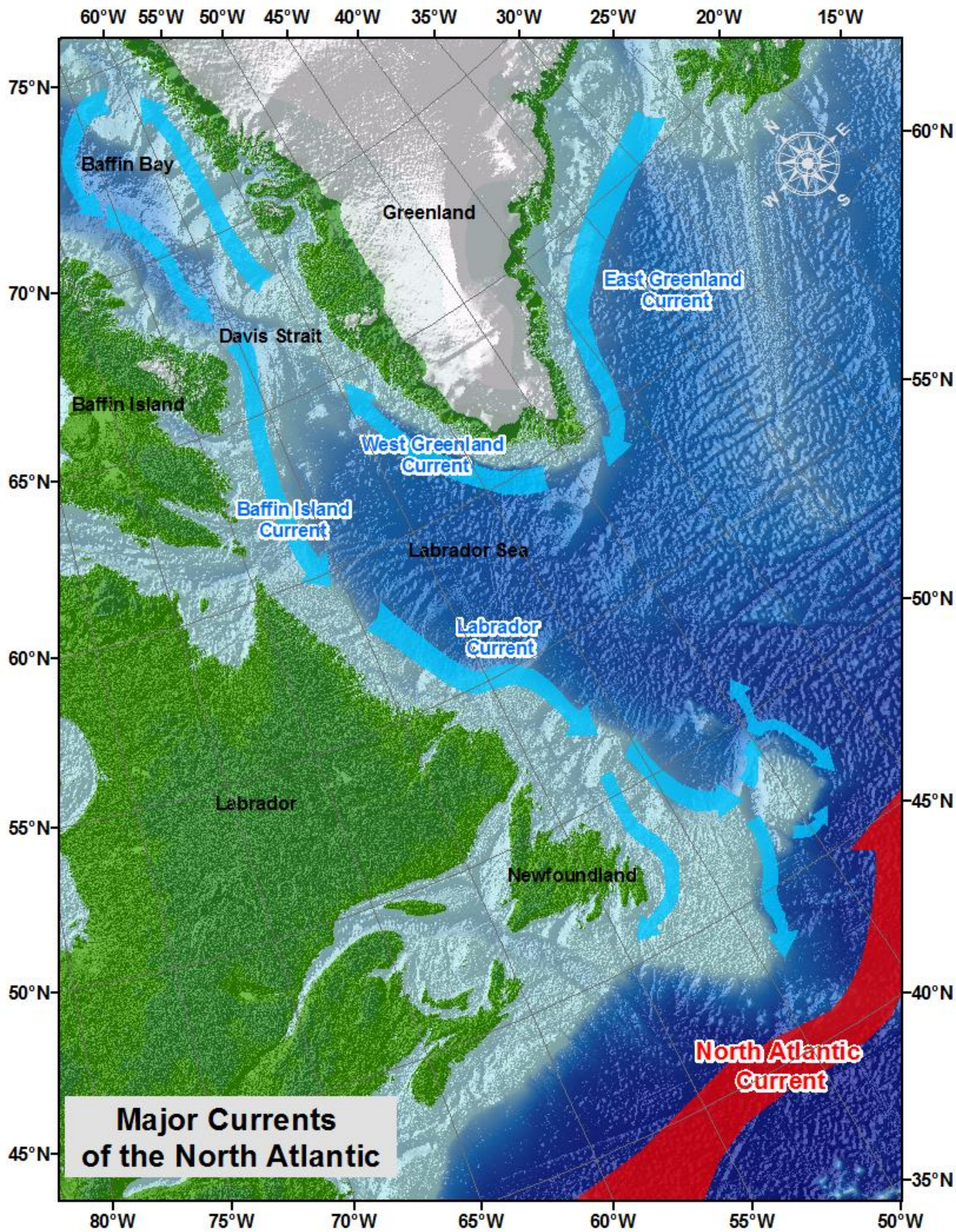


Figure 1-2. Large scale ocean currents in the Newfoundland region (USCG, 2009).

Currents for the North Atlantic region were acquired from the HYCOM (HYbrid Coordinate Ocean Model) circulation model. HYCOM is a primitive-equation ocean general circulation model that evolved from the Miami Isopycnic-Coordinate Ocean Model (MICOM) (Halliwell, 2002; Halliwell et al., 1998, 2000; Bleck, 2002). The HYCOM global ocean system is a 3D dynamic model that uses Mercator projections between 78° S and 47° N and a bipolar patch for regions north of 47° N to avoid computational problems associated with the convergence of the meridians at the pole. The 1/12° equatorial resolution provides gridded ocean data with an average spacing of ~7-8 km between each point. Data is assimilated through the Navy Coupled Ocean Data Assimilation (NCODA) system (Cummings, 2005). The NCODA system employs a Multi-Variate Optimal Interpolation scheme, which uses model forecasts as an initial guess. The system refines the initial estimates with available satellite and in-situ temperature and salinity data that are applied through the water column using a downward projection of surface information (Fox et al., 2002). Bathymetry is derived from the General Bathymetric Chart of the Oceans (GEBCO; Jones et al., 1994). Forcing for the model comes from the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR, Saha et al., 2010).

The HYCOM surface current pattern for the area of interest from 2006-2012 (Figure 1-3) illustrates that the site is close to the inshore branch of the Labrador Current near the Flemish Cap. The monthly current roses of HYCOM at EL 1161 illustrate that the predominant current direction to the southeast during the October-February period, while for the rest of the year is likely to have highest probability of currents to the east, but with a greater degree of variability (Figure 1-4). Monthly surface current speeds (cm/s) derived from the HYCOM model are moderate, with monthly average current speeds between 15 and 24 cm/s and 95th percentile current speeds between about 30 and 50 cm/s (Figure 1-5). The vertical current profile and current roses presented in Figure 1-6 compare the distribution of horizontal flow at various depths, interpolated from the HYCOM closest grid nodes to the drilling site. In addition, timeseries of horizontal current vectors (in cm/s) at five different depths are presented to portray variability in current speed and direction at different water levels (Figure 1-6 and Figure 1-7). Both the vertical profiles and the current vectors illustrate that the current speed decreases as the depth increases. The current direction varies throughout the water column but predominantly flows towards the southeast to east on the surface and transitions to a split northward and southward flow along the bottom layer.

All figures display current data in the oceanographic convention, indicating the direction in which currents are flowing towards.

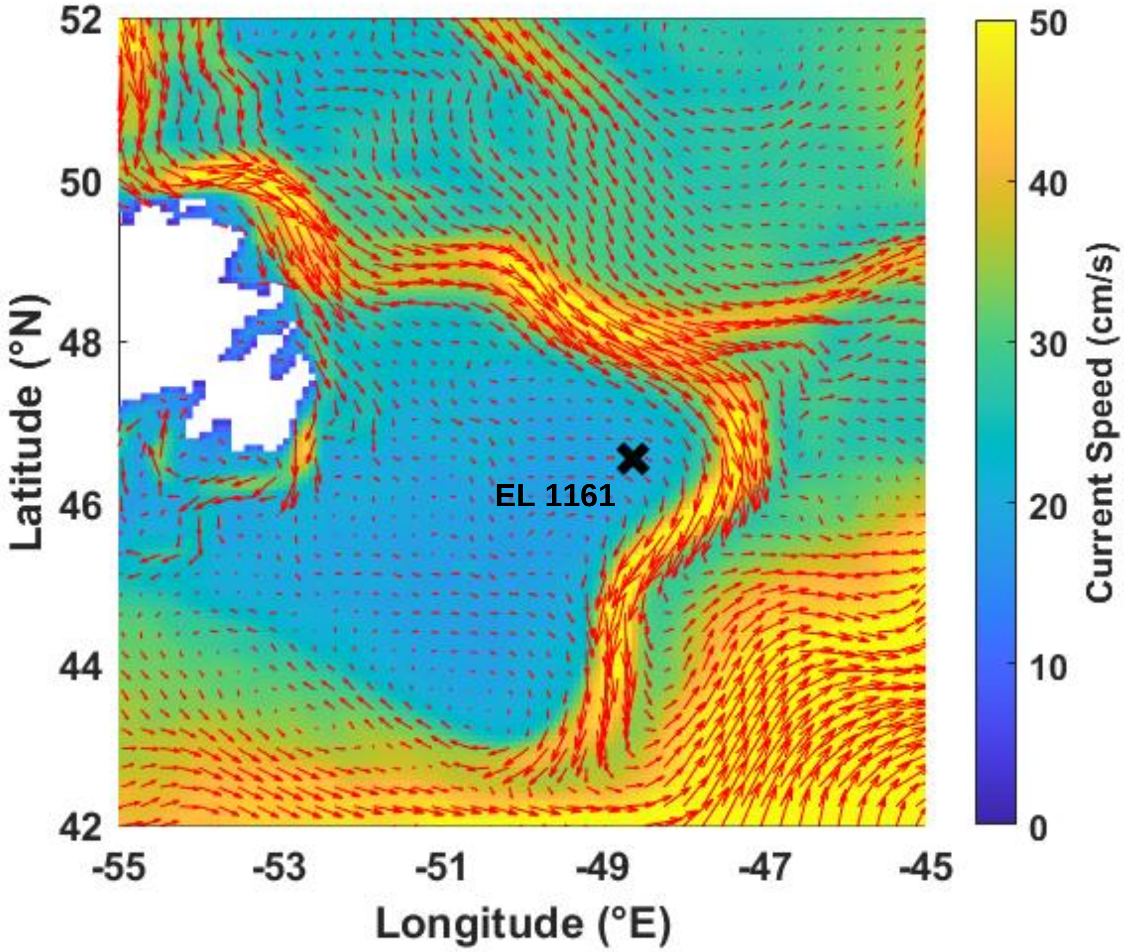


Figure 1-3. Average surface current speed (cm/s) in color, and speed and direction presented by red vectors offshore Newfoundland from HYCOM (2006 – 2012). The black X represents the EL 1161 drilling site.

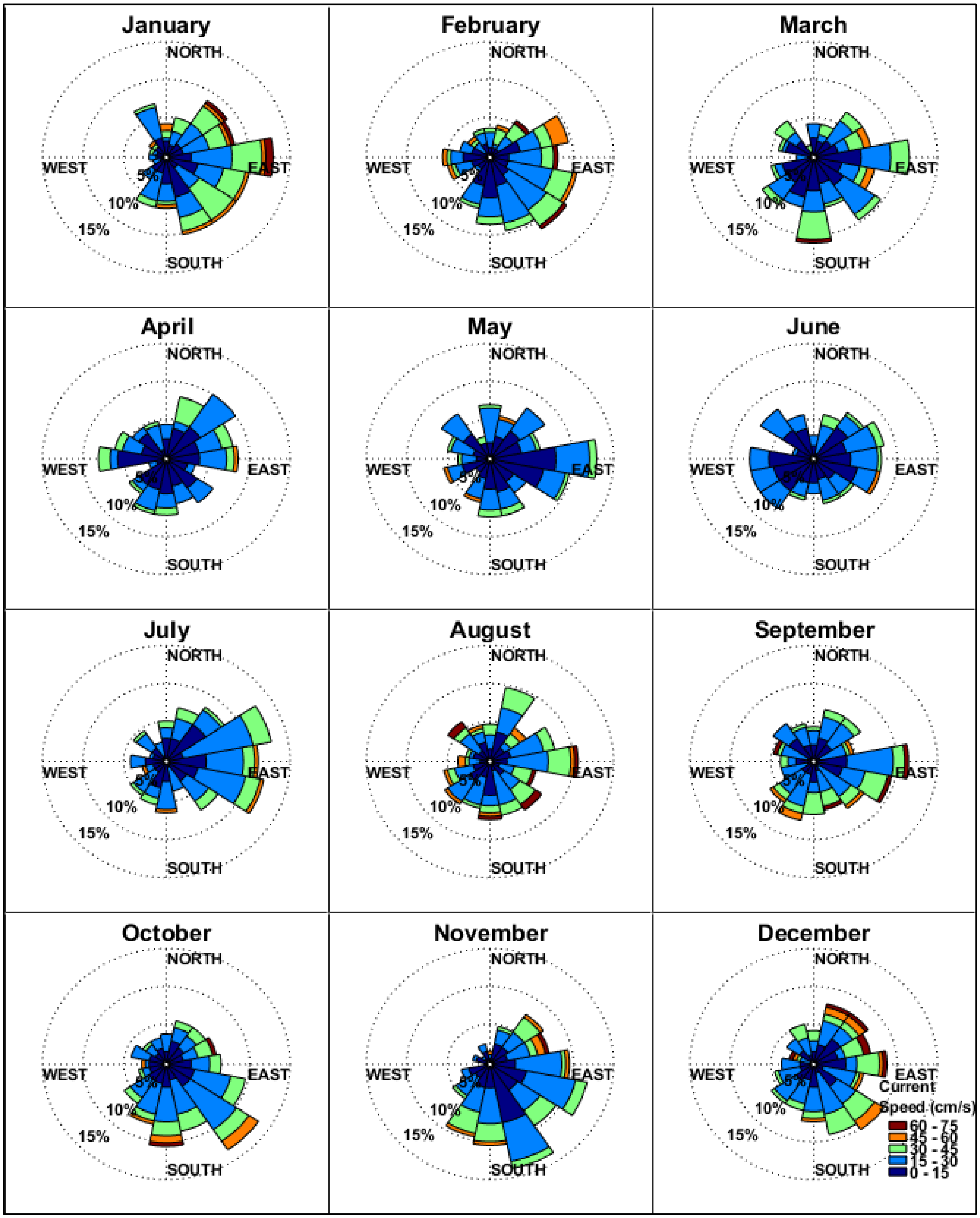


Figure 1-4. Current roses illustrating the distribution of HYCOM surface currents (speed and direction) by month at EL 1161 (model period from 2006-2012); using oceanographic convention (i.e. direction currents are flowing toward).

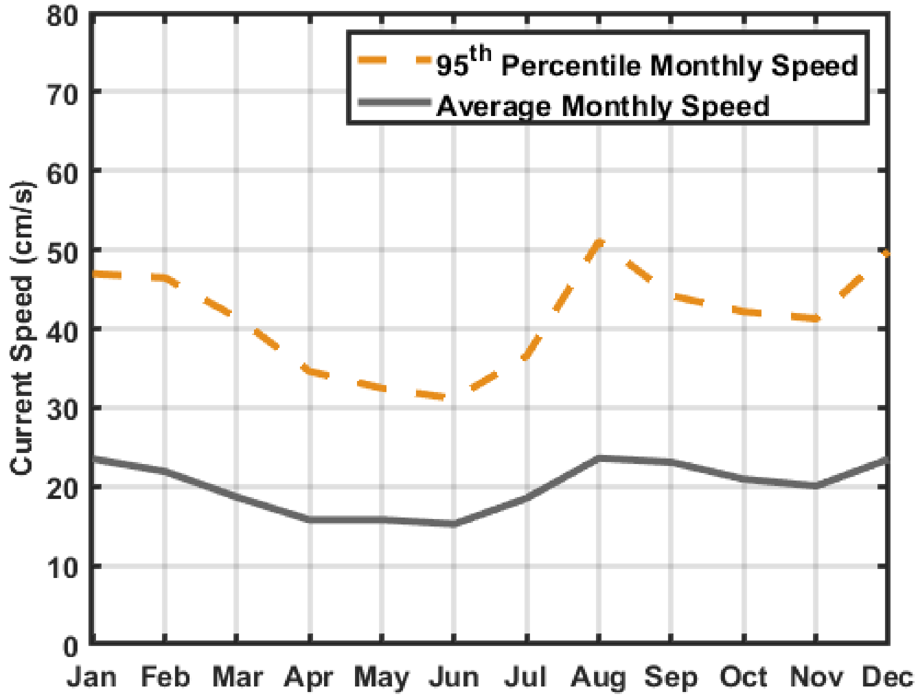


Figure 1-5. Monthly average (grey solid) and 95th percentile (orange dashed) HYCOM surface current speed (cm/s) statistics at EL 1161.

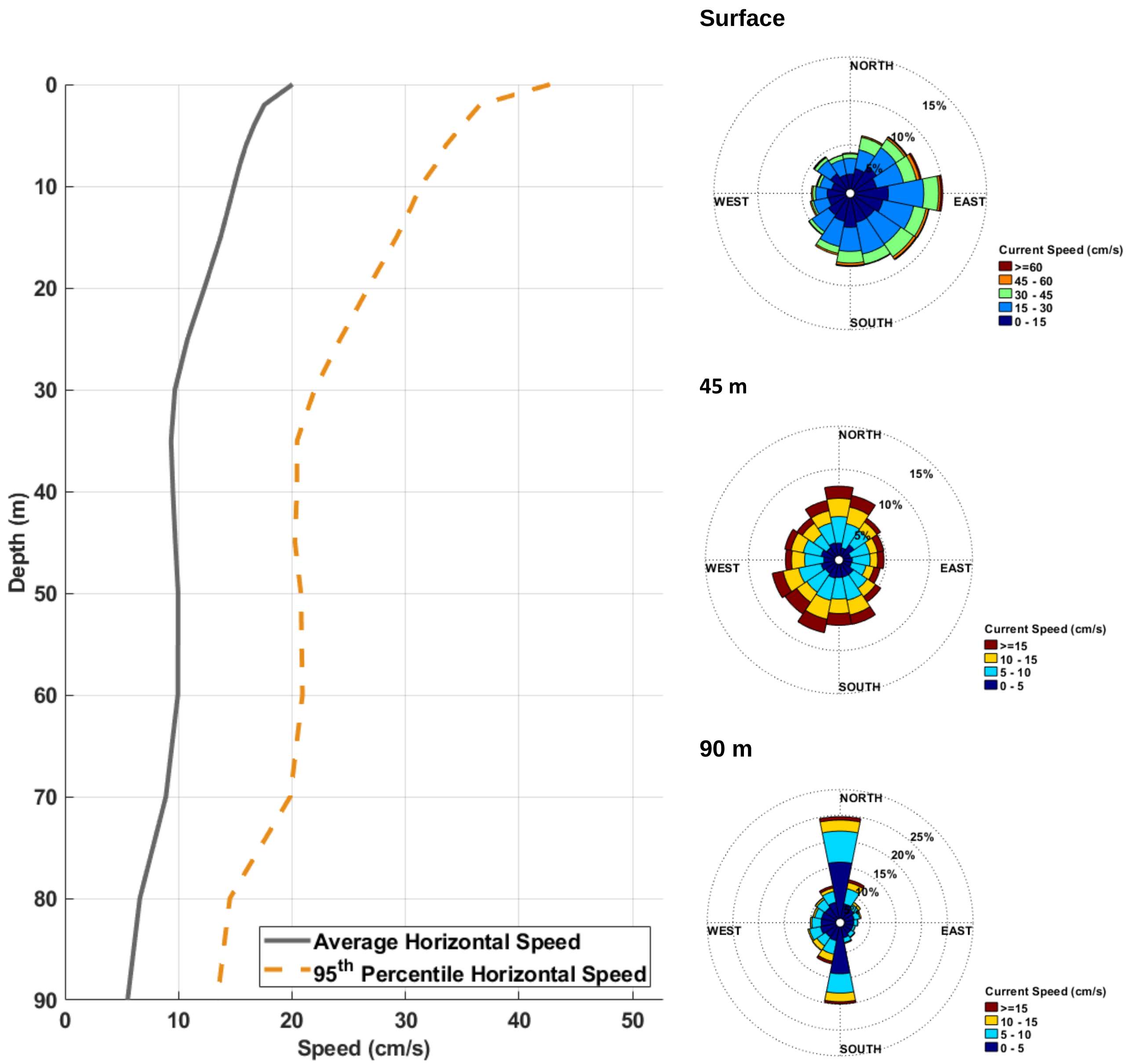


Figure 1-6. Vertical profile of average and 95th percentile horizontal current speed (cm/s) by depth (m) (left) and current roses at multiple depths presented in oceanographic convention (direction currents are flowing toward) (right) at EL 1161; derived from HYCOM model currents between 2006 and 2012.

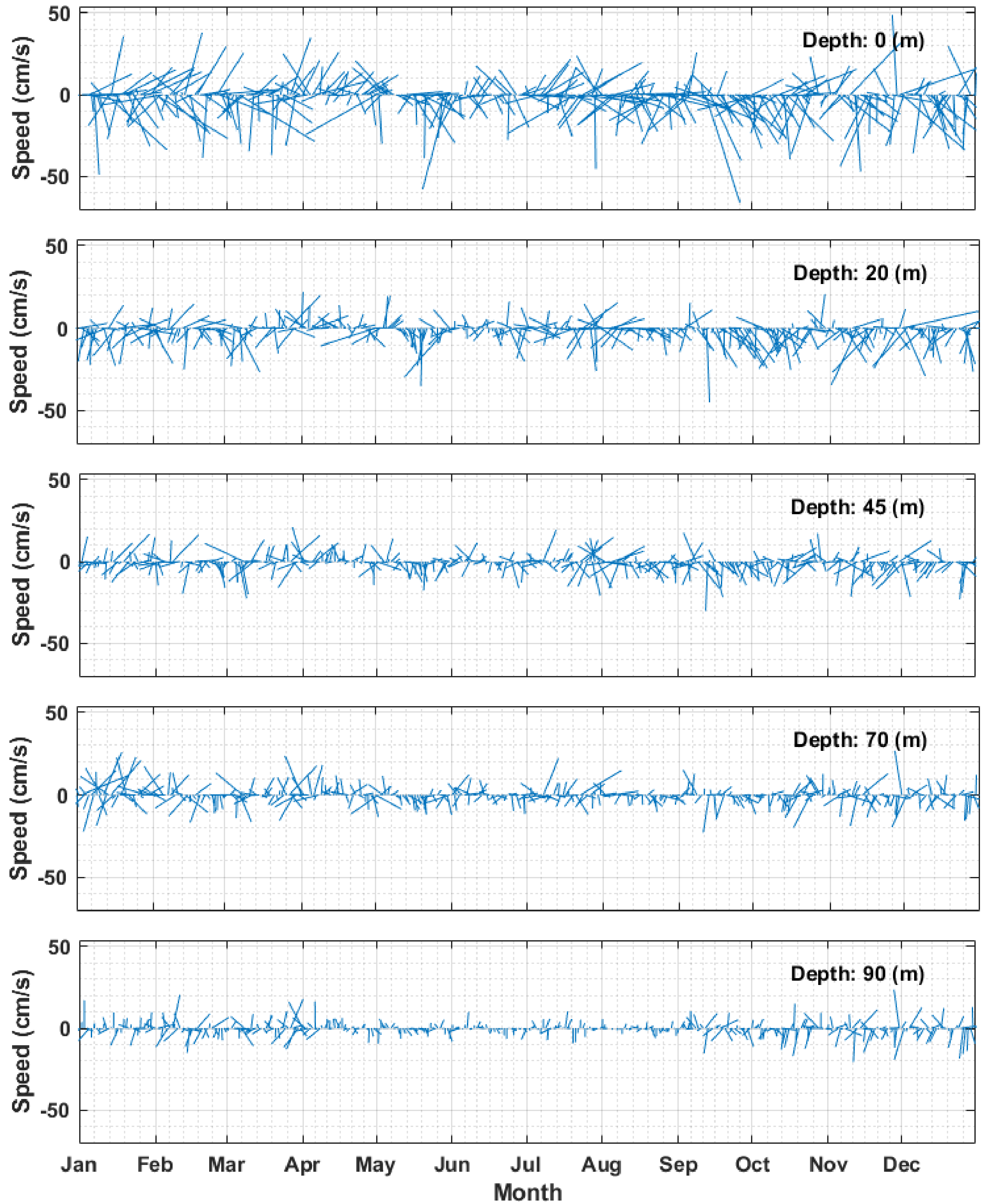


Figure 1-7. Timeseries of HYCOM current speeds (cm/s) in 2012 at five water levels at EL 1161.

2 MODELLING APPROACH

2.1 Modelling Tool – MUDMAP Dispersion Model

Drilling discharge simulations were completed using the RPS MUDMAP modelling system (Spaulding et al., 1994). MUDMAP is a numerical model developed by RPS to predict the near- and far-field transport, dispersion, and bottom deposition of drilling mud and cuttings. In MUDMAP, the equations governing conservation of mass, momentum, buoyancy, and solid particle flux are formulated using integral plume theory, and then solved using a Runge-Kutta numerical integration technique. The model includes three stages: convective descent/ascent, dynamic collapse, and far field dispersion. It allows the transport and dispersion of the release to be modelled through all stages of its movement. The initial dilution and vertical spreading of the release is predicted in the convective descent/ascent process. The far field process predicts the transport and dispersion of the release caused by the ambient current and turbulence fields. In the dynamic collapse process, the release impacts the surface or bottom, or becomes trapped by vertical density gradients in the water column.

MUDMAP is widely used to simulate settling and dispersion of drilling mud and cuttings for offshore environmental impact assessments and follows the same theoretical framework as several other common cuttings models (IOGP, 2016). The equations and solutions in MUDMAP are based on thirty years of research and the model is regularly updated as new scientific research is presented. The system has been applied for discharge operations in both coastal and offshore environments, with excellent agreement among results compared with other industry accepted models, such as the Offshore Operators Committee Mud and Produced Water Discharge Model (Spaulding et al., 1994). Examples of the model validation are provided in Burns et al. (1999), King and McAllister (1997, 1998), and Tetra Tech (2002). Limitations of the MUDMAP model are similar to those that exist for most other cuttings dispersion models (IOGP, 2016), including that it does not account for certain complex process such as aggregation (or degradation) of cuttings as they settle, flocculation, or post-depositional consolidation of cuttings over time. MUDMAP does not account for the resuspension and transport of previously discharged solids; therefore, it provides a conservative estimate of the potential seafloor depositions.

The MUDMAP model output consists of three-dimensional predictions of the movement and shape of the discharge plume, the concentrations of insoluble (i.e., cuttings and mud) discharge components in the water column, and the accumulation of discharged solids on the seabed. The model predicts the transport of solid particles from the time of discharge or release to initial settling on the seabed. The near- and far-field transport of sediments is estimated using a large model domain that tracks the mass of particles as they are transported throughout the water column. During post-processing, a finer grid with a resolution of 5 m is used to estimate environmental loadings to the seabed (deposition) from discharges associated with offshore drilling. With simplifying assumptions, concentrations of hydrocarbons or other pollutants adhered to cuttings can be derived from the seabed loading (Nedwed et al., 2004). The algorithms for the far field and passive diffusion stage are based on a particle based random walk model. More details about MUDMAP are included in Appendix A.

2.2 Mixing Parameters

For discharges near the sea surface, a horizontal dispersion (i.e., mixing) coefficient of 2.0 m^2/s was used to account for the turbulence of the sediment as it was transported from the release site. A vertical dispersion coefficient of 0.001 m^2/s was used to account for the influence of turbulence within the water column. These values were selected, based upon professional judgment and previous experience, to represent typical conditions of the deep marine environment.

2.3 Discharge Schedule

Representative drilling schedules were provided to RPS by Suncor to characterize discharges from five planned drilling sections at EL 1161 (Table 2-1). The first two sections will be drilled using WBM. The remainder of the drilling sections will require the use of SBM. The provided discharge schedule consists of a release of 480 m^3 of drill cuttings and 9,831 m^3 of drilling fluids at the modelled site over the duration of the anticipated drilling campaign. Expected drilling seasons were also provided to RPS by Suncor and modelled over a period designed to best represent the timing of discharges from five planned drilling sections at Tilt Cove. This schedule captures approximately 1 month of work at the simulated drilling location and season, with 16.5 days of active discharge occurring.

Table 2-1. Proposed drilling program for Tilt Cove (provided by Suncor). Each row defines drilling sections beginning with the sediment-water-interface (1) down to the reservoir (5).

Section	Diameter (mm)	Drilling Period		Drilling Duration (days)	Discharge Duration (days)	Cuttings Discharge			Drilling Fluid (Mud) Discharge[1]			Mud Type	Release Depth[2]
		Scenario 1	Scenario 2			Vol. (m^3)	Solid Mass (tonnes)**	Rate (m^3/d)	Vol. (m^3)	Solid Mass (tonnes)**	Rate (m^3/d)		
1	1067	Summer	Fall	1	0.5	55	143	110	3271	799	6541	WBM	Seabed
2	660	Summer	Fall	2	1	150	390	150	6541	1,599	6541	WBM	Seabed
3	445	Summer	Fall	7	4	140	385	35	9.7	27	2.4	SBM	Sea Surface
4	311	Summer	Fall	10	7	115	316	16.4	7.9	22	1.1	SBM	Sea Surface
5	216	Summer	Fall	7	4	20	55	5	1.4	4	0.3	SBM	Sea Surface
Total				**27**	**16.5**	**480**	**1,289**		**9,831**	**2,451**			

Notes: 1. Cuttings from sections drilled with SBM were modelled with an additional 6.9% by weight to account for base fluid that was assumed to be adhered to cuttings
2. Releases were simulated at 5 m above seabed or 5 m below the sea surface
**Values used for the drilling simulations; Mass is calculated using volumes of muds and cuttings (Table 2-1), as well as bulk densities of the materials and percent solid by weight (Table 2-2)

During the initial phases of drilling (first 2 sections in Table 2-1), all cuttings and the WBM were expected to be released directly to the seabed (approximately 5 m above the wellhead on the seafloor). Subsequent sections would be drilled using SBM and cuttings would be returned to the platform and cleaned prior to discharge. The direct release of bulk SBM was not expected to occur as part of operational drilling, although for modelling, it was presumed that a fraction of the drilling fluid (approximately 6.9% by mass of the SBM cuttings) would remain adhered to cuttings drilled with SBM. The release of these combined surface returns (cuttings and adhered SBM) was simulated from a depth of 5 meters below the sea surface at a continuous discharge rate.

The schedule provided by Suncor indicated an expected spud date within May or October. Because the drilling schedule is variable, a modelling strategy was developed to compare the potential differences in seabed deposits during different offshore conditions for both proposed drilling dates. Two (2) representative deterministic scenarios were performed at the theoretical well location using the MUDMAP dispersion model, each covering a period of approximately two months (spanning all active drilling stages and time necessary to allow for settling of fine particles):

- Scenario 1 – Summer (May – June)
- Scenario 2 – Fall (October – November)

As described in Section 1.2, currents in the area are predominately to the east and southeast, with some variability. RPS performed a qualitative review of the HYCOM dataset between 2006-2012, comparing current statistics (speeds and directions) from each year at multiple depths for each modelled season. Current trends for the two model periods during 2012 were in agreement with the overall 7-year trend and were thus deemed suitable as a representative modelling period.

2.4 Discharge Solids Characteristics

To assess the fate of drilling discharges in the marine environment, it is crucial to characterize the components of the released materials. The composition of the drilling mud applied will depend on the characteristics of the formation being drilled. This composition is variable and determines the density and weight of the discharged fluid, its toxicity, and the settling velocities of the material released into the water column.

A description of the specific components of the drilling fluids to be used, including the percent solid material and concentration and type of weighting materials, was provided by RPS based on prior drilling discharge studies. The discharge solids characteristics of the drilling by-products varies between drilling sections (Table 2-2).

Table 2-2. Bulk density of drilling discharges used for modelling.

Discharged material	Bulk density (ppg)	Bulk density (kg/m^3)	Percent solid by weight	Average SG of solid fraction
WBM cuttings	21.7	2,600	100	2.6
WBM fluids	10.2	1,222	20	3.8
SBM cuttings	23.0	2,750	100	2.75

Particle size data, along with material density, are used to estimate settling velocities for MUDMAP simulations. The size distribution of discharged solids varies as a function of the geology, the type of drilling fluid, and the treatment of cuttings. The Particle Size Distributions (PSD) and the associated settling velocities used for operational drilling simulations are presented in Table 2-3. Eight (8) size classes are used to characterize sediments ranging from very coarse sands to very fine silt-clays. Values for the WBM cuttings particle diameters were provided by RPS based on the Wentworth (1922) grade scale and their associated settling velocities were calculated using MUDMAP. Measured weight percent material values for each size class were provided by Stantec (2019), based upon dried drill cuttings samples from a representative well from Terra Nova (E-19). RPS was provided specific PSDs to use for simulations involving SBM, as well as the measured weight percent of material for each size class. The sizes of the SBM particles were averaged for each size class based on the provided information from Stantec. Using these sizes and the bulk density, settling velocities for the SBM particles were calculated using MUDMAP. Section specific PSDs are presented, allowing for the simulation of discharges resulting from unique sections separately to more accurately characterize the seabed deposition (Table 2-3).

Given the absence of local sample data, representative size distributions based on published values from Brandsma and Smith (1999) were used to characterize the WBM fluids released during the top-hole stages (Table 2-4).

Table 2-3. Particle size distributions and falling velocities for operational discharge simulations.

Cuttings Type, Well Section	8 VERY COARSE SAND	7 COARSE SAND	6 MEDIUM SAND	5 FINE SAND	4 VERY FINE SAND	3 COARSE-MEDIUM SILT	2 FINE SILTS-CLAYS	1 VERY FINE SILTS-CLAYS
WBM Particle diameter (mm)	1	0.595	0.297	0.149	0.074	0.031	0.005	0.0039
WBM Cuttings Fall Velocity (cm/s)	10.2	6.185	2.880	1.002	0.247	0.043	0.001	<0.001
SBM Particle diameter (mm)	1	0.75	0.375	0.188	0.094	0.039	0.009	0.0039
SBM Cuttings Fall Velocity (cm/s)	11.668	8.503	3.967	1.747	0.437	0.075	0.004	0.001
	Measured Weight Percent Material							
WBM, conductor and surface	0.0	0.0	0.2	1.0	4.9	3.9	90.0	0.0
SBM, intermediate (445 mm)	5.2	2.4	3.3	6.4	6.5	37.5	22.8	15.9
SBM, production (311 mm)	8.2	4.4	6.9	9.7	9.0	21.5	13.1	27.2
SBM, reservoir (216 mm)	6.0	4.2	6.9	12.4	12.1	31.6	12.0	14.8

Table 2-4. Water based mud (WBM) settling velocities (Brandsma and Smith, 1999).

Size Class	Percent Volume	Settling Velocity (cm/s)	Settling Velocity (m/day)
1	7.01	2.74×10^{-3}	2.37
2	7.99	6.10×10^{-3}	5.27
3	5.00	1.48×10^{-2}	12.77
4	10.00	3.00×10^{-2}	25.94
5	13.26	4.36×10^{-2}	37.66
6	13.26	5.12×10^{-2}	44.24
7	19.24	6.40×10^{-2}	55.30
8	19.24	8.23×10^{-2}	71.10
9	4.00	4.27×10^{-1}	368.69
10	1.00	1.12	969.12

2.5 Thresholds of Concern

2.5.1 Sedimentation Effects and Thresholds

Although sediment deposition is a natural process, the rate of sedimentation is variable, depending on the oceanographic characteristics within the area. Deep sea habitats are generally characterized by low-energy currents and slow sediment accumulation rates of approximately 1 – 100 mm per thousand years (Gage and Tyler, 1991; Glover and Smith, 2003). Benthic organisms associated with these environments are generally adapted to tolerate a range of conditions and sedimentation rates. Rapid increases in sedimentation associated with mud and cuttings discharges can have direct and indirect effects on benthic infauna communities in deep sea habitats. Direct effects can include smothering, toxicity exposure, and physical abrasion. Indirect effects include habitat alterations and changes to community assemblages (Ray et al. 2005). The severity of sedimentation effects on organisms depends on factors including burial depth, burial rate, burial time, species-specific tolerances, the grain size of the deposited sediments, and seasonal timing (Kjeilen-Eilertsen et al., 2004). For example, higher mortality can occur in the summer than in the winter (Smit et al. 2008). Higher mortality has been observed at higher temperatures in mesocosm and lab studies of burial for mussels and gastropods, possibly due to greater oxygen demand at higher temperatures (Chandrasekara and Frid, 1998; Hutchison et al. 2016). However, there is great variability, as taxonomic groups react differently and have varying levels of tolerance to sedimentation. Sessile and attached organisms typically have the lowest tolerance and highest mortality rate during sedimentation events (Ray et al. 2005; Gates and Jones, 2012).

Observations from previous research conducted on sedimentation and recovery of benthic infauna in Newfoundland, Canada, was used to demonstrate an increased abundance and biomass in some polychaete species and declines in others in the area around the studied drill site. Reduced abundance was observed to extend approximately 1 – 2 km from the drill site for some species (Paine et al., 2014). This aligns with findings from an extensive literature review that documented biological effects (such as changes in benthic community structure) at distances of 200 – 2,000 m from platforms using water-based drilling fluids (Ellis et al., 2012). The range of effects from synthetic-based drilling fluids was found to be somewhat smaller, with detected biological effects from 50 – 1,000 m from the drill site (Ellis et al., 2012).

Specific sedimentation thresholds tested and reported by Smit et al. (2008) indicate that epibenthic, sessile, filter-feeding species cannot survive sediment burial depths over 10 mm. Meanwhile, infauna taxa that are adapted to habitats covered in sediment may escape from burial under 100 mm of sediment or more (Kjeilen-Eilertsen et al., 2004). In a mesocosm and field study, Trannum et al. (2011) observed that 24 mm of water-based drill cuttings lowered oxygen availability and reduced the abundance of macrofauna in the sediment. Overall, Smit et al. (2008) estimated that mortality of 5% of benthic organisms (including mollusks, polychaetes, and crustaceans) would occur at burial depths of 6.3 mm (3.1 – 10.6 mm), and mortality of 50% would occur at burial depths of 54 mm (37 – 79 mm).

Benthic invertebrates are broadly considered to be unaffected by nontoxic sediment burial depths less than 6.5 mm, based on tolerances to burial, oxygen depletion, and change in sediment grain size (Amec Foster Wheeler, 2017; Kjeilen-Eilertsen et al., 2004; Smit et al., 2006; 2008). However, some more sensitive species are considered more susceptible to shallower burial depths (1.5 mm), and thus 1.5 mm is suggested as a more conservative predicted no-effect threshold.

Studies on the recovery of benthic infaunal communities post-sedimentation present varying results. The ability of a benthic community to recover after sediment deposition depends on larval settlement, the rate of bioturbation, and sediment mixing by currents (Smit et al., 2008; Trannum et al., 2011). Because many benthic species have drifting pelagic larvae, resettlement can occur within months post-disturbance. Trannum et al. (2011) observed reestablishment of species-rich communities within six months of sedimentation and noted that the most successful colonizers were species in the Spionidae family of polychaete worms. In studies from the North Sea, recolonization of cuttings piles from the edges of the piles occur in 1-5 years (Kjeilen-Eilertsen et al., 2004). Areas with the thickest deposition will likely rely on larval transport and resettlement for recolonization, as survival of buried organisms is unlikely. In areas with lower levels of deposition, reestablishment by surviving organisms that burrow or sift through sediment to feed is possible, as they mix mud and cuttings with native sediments and slowly return habitats to pre-drilling conditions (Smit et al., 2008; Gates and Jones, 2012).

For this study, we report a minimum deposition threshold of 0.1 mm but focus on the area of deposition at or above 1 mm, 1.5 mm, 6.5 mm, and 10 mm.

2.5.2 Turbidity and TSS Effects and Thresholds

Smit et al. (2006, 2008) described an increase in the concentration of total suspended solids (TSS) and water column turbidity due to the discharge of drilling cuttings and fluids, which could potentially affect pelagic organisms. Particulates in drilling muds come from bentonite clay and barite, which are toxicologically inert, but can be suspended in the water column. Suspended clay particles of less than 0.01 mm diameter settle very slowly and can potentially persist in the water column for weeks or months (Smit et al., 2008).

Increased turbidity decreases the light availability for phytoplankton in the water column (IOGP, 2016). Phytoplankton were negatively affected at concentrations of 10 mg/L bentonite clay or 1,000 mg/L barite, but these concentrations are unlikely to occur in a discharge plume greater than 25 m down-current (IOGP, 2016). In general, drilling fluid and cuttings solids rapidly disperse, dilute, and settle out of the water column, which reduces the risk of adverse effects on water column organisms because exposure to elevated turbidity or TSS is intermittent and brief (IOGP, 2016).

Benthic suspension feeders (e.g., molluscs) are sensitive to mud and cuttings discharges because they are sessile organisms that cannot escape discharge plumes, and fine suspended particles interfere with feeding and growth (Ray et al. 2005; Smit et al. 2008). Filter-feeding zooplankton and algae were also more sensitive, likely due to greater exposure in the water column from drifting with the currents and therefore with portions of the discharge plume that encounter surface currents. Benthic crustaceans and siphon-feeding molluscs were relatively insensitive to suspended particulates, likely because they have evolved to inhabit the benthic boundary layer comprising mobile sediments and water that is naturally highly turbid (Smit et al. 2008). However, the quality of data available to evaluate TSS thresholds are poor, with few lab studies on bentonite or barite suspended clays.

Synthetic non-aqueous base fluids are not considered toxic to phytoplankton, zooplankton, and other water column marine organisms (IOGP, 2016). Certain chemicals within synthetic base fluids (primary emulsifier and fluid loss agent) elicited sublethal exposure responses in biomarkers of juvenile pink snapper fish, which suggests that chronic exposure from chemicals leaching out of cuttings piles may have some effect on fish over several days (Bakhtyar and Gagnon, 2012). However, a transient exposure to drilling fluids as they pass through the water column is unlikely to be toxic to mobile pelagic organisms.

3 MODEL RESULTS

The fate of mud and cuttings released from operational drilling activities at EL 1161 were assessed using representative deterministic scenarios corresponding to the drilling period and discharge volumes provided by Suncor (Table 2-1). One deterministic simulation was performed for each of the five (5) drilling sections for both of the seasonal scenarios, totaling twenty (20) individual simulations. MUDMAP was used to simulate the trajectory of cuttings and fluid particles from operational releases and to track the far field dispersion, accounting for the prolonged settling time associated with very fine particles within the water column. Based on the depth at EL 1161 (~100 m), the settling velocities, and measured weight percent of the finer sediments, several simulated days were required to allow for the majority of particles to reach the seabed.

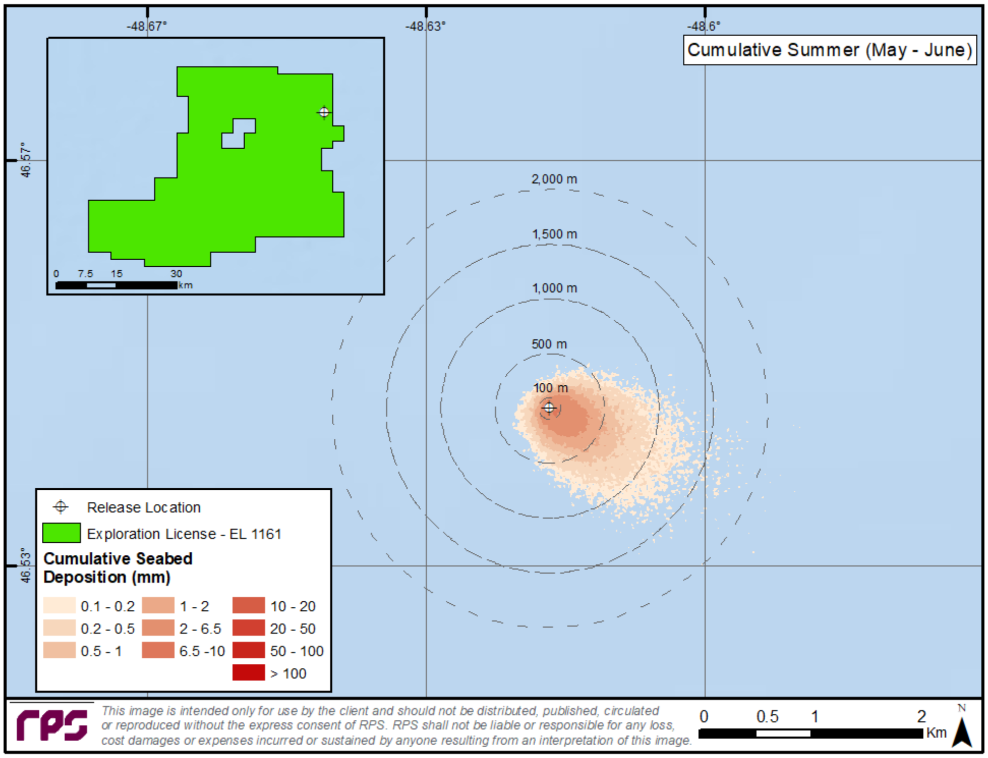
3.1 Operational Discharges

3.1.1 Predicted Seabed Deposition

The output of each MUDMAP simulation is a predicted concentration grid that estimates the loading to the seabed associated with each drill section. These grids were aggregated outside of the MUDMAP model to produce maps of cumulative and riserless deposition from the discharged sections. Figure 3-1 and Figure 3-2 depict the model-predicted deposition patterns from an aerial view. While the MUDMAP model was used to simulate deposition down to 0.01 mm, Table 3-1 and Figure 3-3 summarize the cumulative and riserless spatial extent of seabed deposition for operational discharge simulations ≥0.1 mm. Deposition thicknesses were calculated based on mass accumulation on the seabed, sediment bulk density, and the assumption of no voids (i.e., zero porosity) (Table 3-2).

The predicted deposition patterns were very different in size, shape, and depositional thickness between the modelled scenarios at EL 1161 (Figure 3-1 and Figure 3-2). The differences in deposition patterns resulted from differences in met-ocean conditions between scenarios, despite identical release volumes and durations. During both scenarios, fine blankets of mud/cuttings (≥0.1) were deposited no more than 2.5 km from the drill site, with the furthest deposits ≥0.1 mm thick predicted to range from 1.8 km from the wellhead in the summer (May-June) to 2.5 km during the fall (October-November) season (Table 3-2). For both scenarios, the predicted deposition of muds and cuttings equal to or exceeding 1 mm was predicted to remain within 0.62 km covering an area of 0.26 km^2 during the summer and 0.76 km covering an area of 0.20 km^2 during fall (Table 3-1 and Table 3-2). Depositional thicknesses at or above 1.5 mm ranged from 0.47 km during the summer to 0.55 km during the fall. However, the area above 1.5 mm was predicted to be much greater during the summer, covering 0.18 km^2, when compared to only 0.08 km^2 predicted during the fall (Table 3-1). Depositions at or above the threshold of 6.5 mm (Smit et al., 2008) were predicted to occur during the summer but not during the fall. Thicknesses at or above 6.5 mm were predicted to extend a maximum of 0.11 km from the wellhead and cover an area of no more than 0.003 km^2 during the summer. Depositional thicknesses were not predicted to reach the 10 mm threshold in any simulation. The maximum thickness of 7.3 mm was predicted for the summer scenarios and 2.6 mm for the fall scenarios. The low predicted depositional thicknesses can be attributed to the strong current regimes at this site and long settling times associated with finer particles such as silts/clays, which made up majority of the muds and cuttings released at both the seabed and the surface.

When comparing the depositional patterns from the riserless sections to the cumulative sections within any single scenario, the predicted areal extent of depositional thicknesses ≥0.1 is nearly the same (Figure 3-3 and Table 3-1). During the riserless stages of drilling, approximately 78% of the total mass of all sections combined are predicted to be discharged near the seabed, where they settle rapidly. During the remaining sections of drilling, where the remaining roughly 22% of mass is discharged near the sea surface, smaller particle size fractions with low settling velocities were transported greater distances as they settled through approximately 100 m of the water column. This increased transport resulted in most of this mass being predicted to be carried away from the wellhead and deposited at thicknesses less than 0.01 mm.



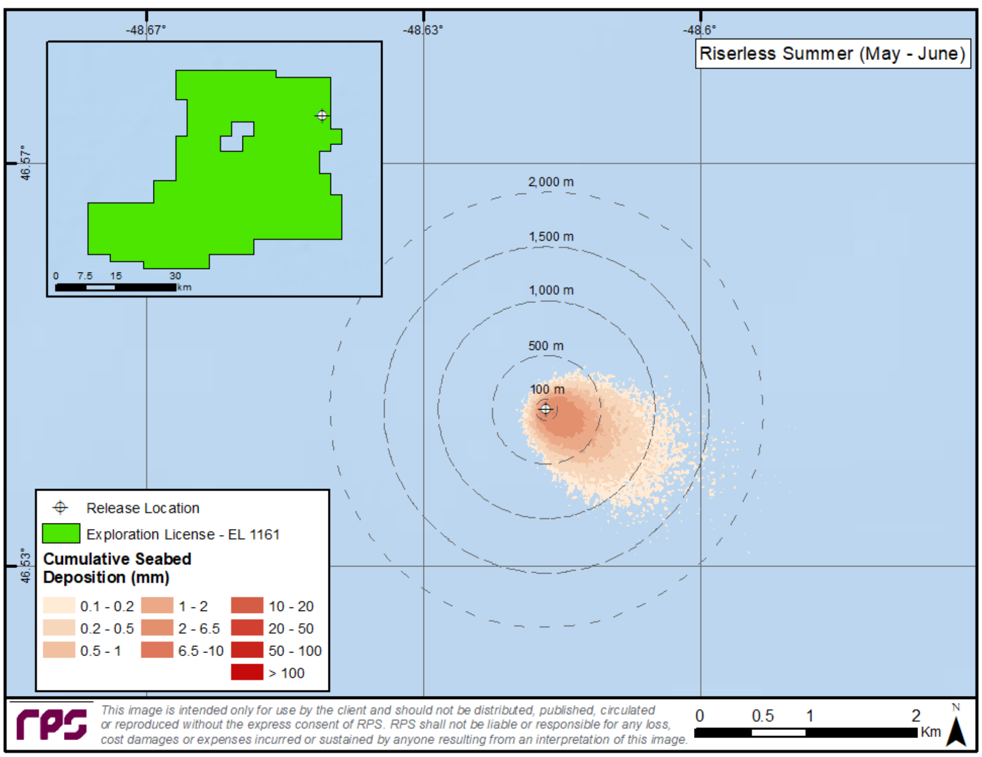
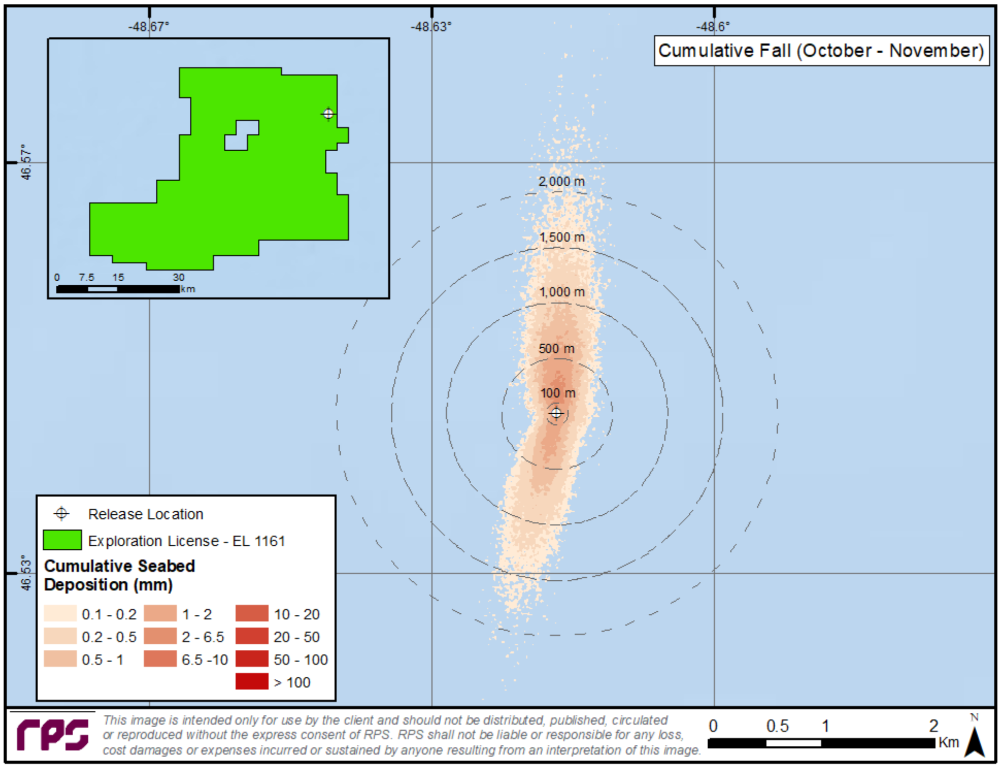


Figure 3-1. Scenario 1: Predicted thickness of seabed deposition of discharged mud and cuttings resulting from all drilling sections (top) and from only the riserless drilling sections (bottom) during the summer at EL 1161.



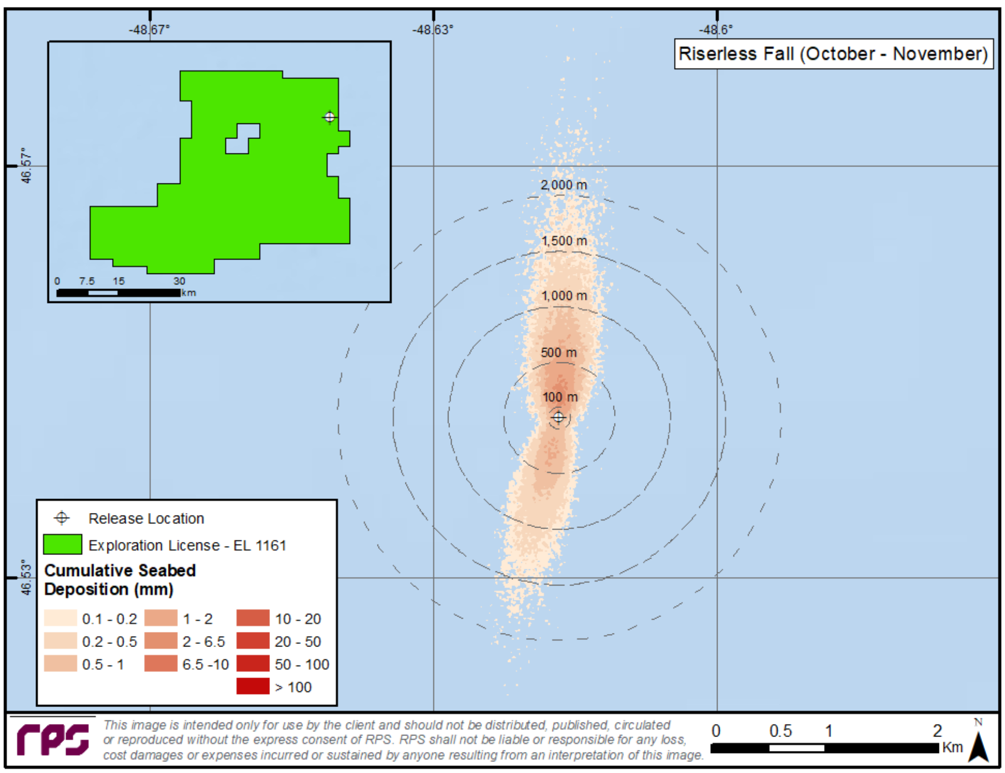


Figure 3-2. Scenario 2: Predicted thickness of seabed deposition of discharged mud and cuttings resulting from all drilling sections (top) and from only the riserless drilling sections (bottom) during the fall at EL 1161.

Table 3-1. Areal extent of predicted seabed deposition (by thickness interval) for operational discharge simulations in Summer and Fall.

Deposition Thickness (mm)	Cumulative Area Exceeding (km^2)			
	Summer		Fall	
	Cumulative Sections	Riserless Sections	Cumulative Sections	Riserless Sections
≥0.1	1.4349	1.3319	2.1381	2.0186
≥0.2	0.8752	0.8310	1.2438	1.1697
≥0.5	0.4574	0.4338	0.5143	0.4722
≥1	0.2616	0.2494	0.1996	0.1507
≥1.5	0.1752	0.1642	0.0777	0.0700
≥2	0.1289	0.1204	0.0269	0.0216
≥6.5	0.0029	0.0005	0.0000	0.0000
≥10	0.0000	0.0000	0.0000	0.0000
Maximum Thickness (mm)	**7.28**	**6.72**	**2.64**	**2.53**

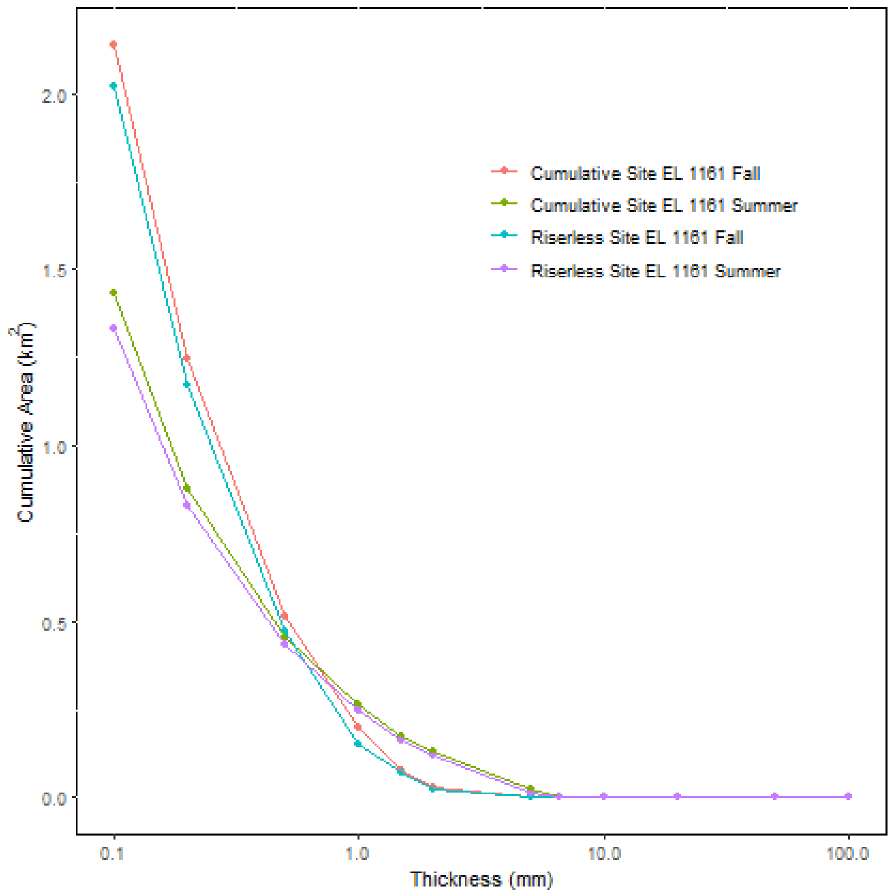


Figure 3-3 Cumulative areal extent of predicted seabed deposition for operational discharge simulations in the Summer and Fall drilling periods.

Table 3-2. Maximum distance of thickness contours (distance from release site) predicted for operational discharge simulations.

Deposition Thickness (mm)	Maximum extent from release site (km)			
	Summer		Fall	
	Cumulative Sections	Riserless Sections	Cumulative Sections	Riserless Sections
≥0.1	1.79	1.76	2.43	2.42
≥1.0	0.62	0.62	0.76	0.75
≥1.5	0.47	0.47	0.55	0.54
≥6.5	0.11	0.09	0.00	0.00
≥10	0.00	0.00	0.00	0.00

4 DISCUSSION AND CONCLUSIONS

In each modelled scenario, the deposition of muds and cuttings from operational discharges onto the seabed was controlled by the settling velocities of particles, the currents within the water column, and the depth of the water column. Modelled operational discharges from EL 1161, with a water depth of approximately 100 m, were predicted to produce a spatially confined depositional area of no more than 2.2 km^2 above 0.1 mm extending less than 2.5 km from the wellhead. Maximum depositional thicknesses were predicted to be 7.28 mm thick during calmer summer conditions, with only 2.64 mm predicted during fall periods, where stronger currents transported material over greater distances. The different current regimes simulated between summer and fall influenced the seabed deposition patterns and thicknesses heavily. Slow settling velocities associated with the fine silts/clays and coarse silts, which make up the largest fractions of the cuttings drilled with WBM and SBM, allowed for greater dispersion before settling out.

Summer simulations for the EL 1161 site were predicted to have weaker subsurface current regimes with moderate directional variability, when compared to the fall simulations. This resulted in more even radial footprints for summer simulations, when compared to the more elongated results in the fall simulations. Depositional footprints during the summer simulations typically did not extend as far for thicknesses up to 0.5 mm when compared to the fall simulations. However, extents for thicknesses at or above 1 mm during the summer simulations were greater than those during fall simulations. This was due to the weaker current regimes during the summer season, which transported the discharged cuttings and muds a shorter distance from the wellhead but allowed for greater and localized accumulation of the sediments near the wellhead. This also explains why the maximum depositional thickness was predicted to be greater for simulations in the summer, when compared to the fall. When comparing the riserless simulations to the cumulative simulations, the areal extents were nearly the same during the summer. Only at the 6.5 mm threshold was the areal extent much greater for the cumulative simulation when compared to the riserless simulation. This was due to the fraction of SBM that takes less than a day to settle from the sea surface to the seabed, which makes up approximately 35% of the SBM mass. The remaining roughly 65%, which is made up of finer SBM sediments, was transported far from the wellhead and was deposited at thicknesses less than 0.01 mm. It should also be noted that approximately 78% of the total mass discharged at EL 1161 was discharged during the riserless stages. This explains why the depositional footprints are very similar between the riserless and cumulative simulations. Depositional thicknesses at or above 0.1 mm were predicted to extend to the southeast up to 1.79 km and cover an area up to 1.45 km^2 during the summer. Predicted depositional thicknesses at or above 1 mm extended to a maximum of 0.62 km and covered an area no greater than 0.27 km^2. Depositional thicknesses that reached 1.5 mm in thickness extended less than 0.5 km and covered a maximum area of 0.18 km^2. The deposition at or above the predicted no effect concentrations (PNEC) threshold of 6.5 mm (Smit et al. 2008) was predicted to cover a maximum of 0.003 km^2 and extended up to 0.11 km from the wellhead. The maximum thickness during the summer simulations was predicted to be 7.28 mm. Therefore, the thickness threshold of 10 mm never reached for the summer simulations.

Fall simulations for the EL 1161 site were characterized by stronger subsurface current regimes with greater variability, which led to slightly more elongated depositional footprints, when compared to summer scenarios. While the predominant current directions were southeasterly, the discharge of finer sediments in the WBM cuttings and muds were predicted to be transported by northerly and southwesterly currents that occurred temporarily during the first two drilling sections. This resulted in a broader depositional footprint that was predicted to extend to the north and southwest. During the fall simulations, thicknesses at or below 0.5 mm were predicted to extend further and have greater areal extents than the summer simulations. This was due to the stronger current regime that transported fine sediments with low settling velocities further from the wellhead, which resulted in less accumulation of the sediments over a broader area. When comparing the cumulative and riserless simulations during the fall, the predicted areal extents for all depositional thicknesses were very similar. Depositional thicknesses at or above 0.1 mm were predicted to extend to the southeast up to 2.43 km and cover an area up to 2.14 km^2 during the fall. Predicted depositional thicknesses at or above 1 mm extended to a maximum of 0.76 km and covered an area no greater than 0.2 km^2. Depositional thicknesses that reached 1.5 mm in thickness extended less than 0.6 km and covered a maximum area of 0.08 km^2. The maximum thickness during the fall simulations was 2.64 mm, so the thresholds of 6.5 and 10 mm in thickness were never predicted to be reached.

The variations within predicted results between the seasonal simulations were due to two main factors including: 1) settling velocity associated with different release substances and 2) current patterns (i.e. velocity, which is which is composed of speed and direction). The discharges modelled in this study may be considered representative of other potential discharges in the Project Area, as the depth of the sites (~100 m) are similar in depth to other locations within the Project Area. This dispersion modelling targeted the most likely drilling windows for the Project, which were May-June and October-November. Together, both drilling periods consist of representative current regimes for the area and the predicted results could be applicable to timeframes outside of the modelled temporal windows.

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APPENDIX A: MUDMAP MODEL DESCRIPTION

MUDMAP is a personal computer-based model developed by RPS (ASA at the time of creation) to predict the near and far-field transport, dispersion, and bottom deposition of drill muds and cuttings and produced water (Spaulding et al; 1994). In MUDMAP, the equations governing conservation of mass, momentum, buoyancy, and solid particle flux are formulated using integral plume theory and then solved using a Runge Kutta numerical integration technique. The model includes three stages:

Stage 1: **Convective decent/jet stage** – The first stage determines the initial dilution and spreading of the material in the immediate vicinity of the release location. This is calculated from the discharge velocity, momentum, entrainment and drag forces.

Stage 2: **Dynamic collapse stage** – The second stage determines the spread and dilution of the released material as it either hits the sea surface or sea bottom or becomes trapped by a strong density gradient in the water column. Advection, density differences and density gradients drive the transport of the plume.

Stage 3: **Dispersion stage –** In the final stage the model predicts the transport and dispersion of the discharged material by the local currents. Dispersion of the discharged material will be enhanced with increased current speeds and water depth and with greater variation in current direction over time and depth.

MUDMAP is based on the theoretical approach initially developed by Koh and Chang (1973) and refined and extended by Brandsma and Sauer (1983) and Khondaker (2000) for the convective descent/ascent and dynamic collapse stages. The far-field, passive diffusion stage is based on a particle based random walk model. This is the same random walk model used in RPS' OILMAP spill modelling system (ASA, 1999).

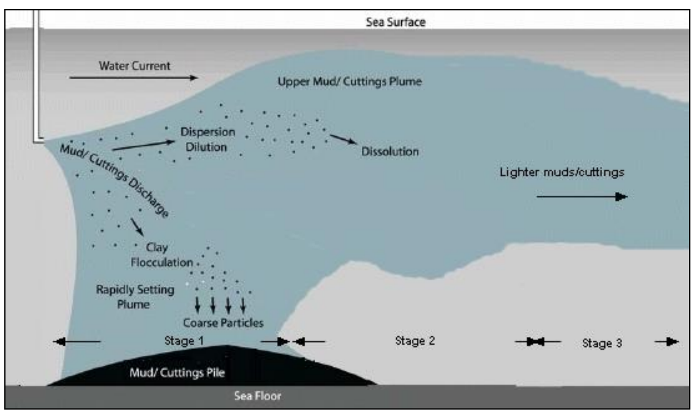

Figure A1. Conceptual diagram depicting the general behavior of cuttings and muds following discharge to the ocean and the three distinct discharge phases (after Neff 2005).

The model's output consists of calculations of the movement and shape of the discharge plume, the concentrations of soluble (i.e. oil in produced water) and insoluble (i.e. cuttings and muds) discharge components in the water column, and the accumulation of discharged solids on the seabed. The model predicts the initial fate of discharged solids, from the time of discharge to initial settling on the seabed As MUDMAP does not account for resuspension and transport of previously discharged solids, it provides a conservative estimate of the potential seafloor concentrations (Neff 2005).

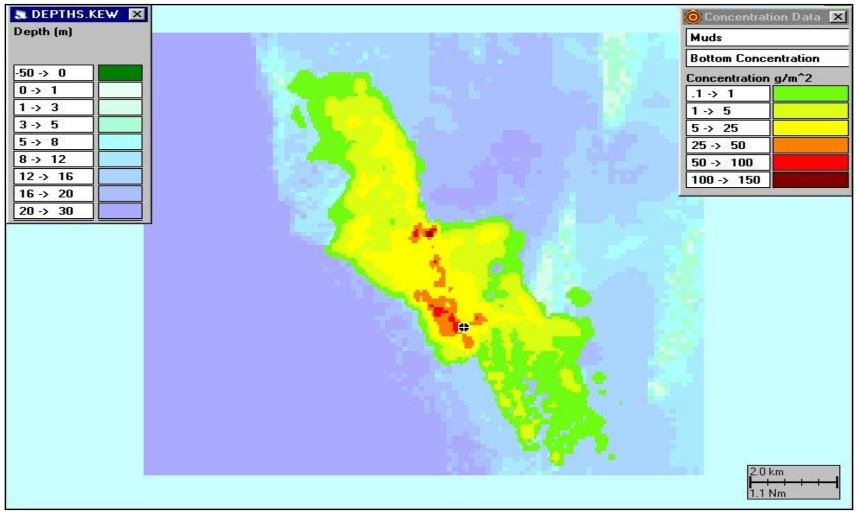

Figure A2 Example MUDMAP bottom concentration output for drilling fluid discharge.

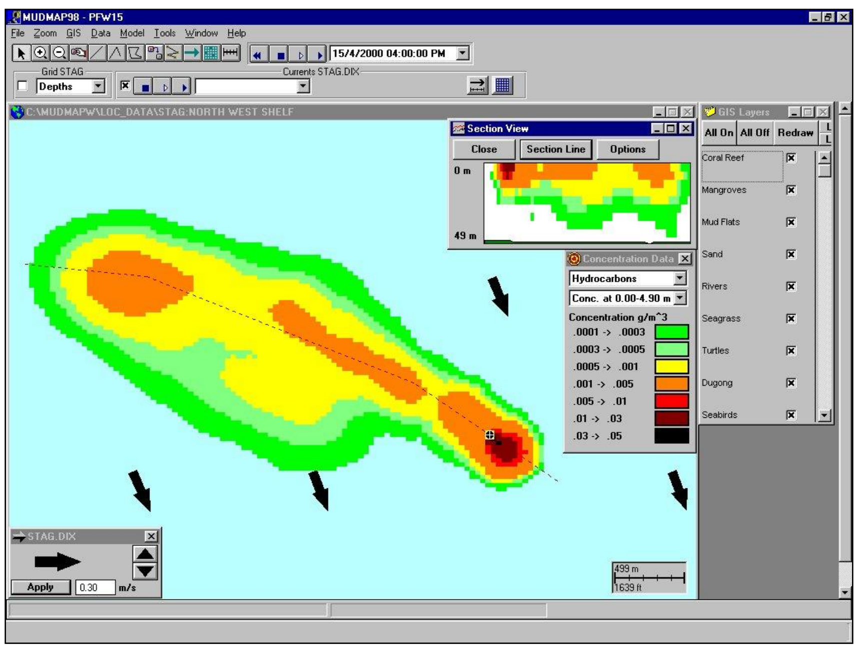

Figure A3. Example MUDMAP water column concentration output for drilling fluid discharge.

MUDMAP uses a color graphics-based user interface and provides an embedded geographic information system, environmental data management tools, and procedures to input data and to animate model output. The system can be readily applied to any location in the world. Application of MUDMAP to predict the transport and deposition of heavy and light drill fluids off Pt. Conception, California and the near-field plume dynamics of a laboratory experiment for a multi-component mud discharged into a uniform flowing, stratified water column are presented in Spaulding et al. (1994). King and McAllister (1997, 1998) present the application and extensive verification of the model for a produced water discharge on Australia's northwest shelf. GEMS (1998) applied the model to assess the dispersion and deposition of drilling cuttings released off the northwest coast of Australia.

MUDMAP References

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