APPENDIX H

SBM Accidental Spill Modelling (Amec Foster Wheeler 2017)

FINAL

Nexen Energy ULC
Flemish Pass Exploration Drilling Program, SBM Accidental Spill Modelling

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8 January 2018

Amec Foster Wheeler Project #: TF1695301

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EXECUTIVE SUMMARY

Nexen Energy ULC (Nexen) is planning to conduct a program of petroleum exploration drilling and associated activities in the eastern portion of the Canada-Newfoundland and Labrador Offshore Area over the period 2018 to 2028 (hereinafter also referred to as the Project). The proposed Project Area includes two Exploration Licences (ELs 1144 and 1150) in the Flemish Pass region for which Nexen is the operator and is currently the sole interest holder, and which have not yet been subject to exploration drilling activity to date pursuant to these licences.

Two phases of the planned exploration drilling within ELs 1144 and 1150 will involve the use of synthetic-based muds (SBMs), due to their unique performance characteristics, as well as their low toxicity and relatively low environmental effects compared to oil-based muds (OBMs). Namely, the use of SBM is anticipated during the intermediate riser connected drilling phase, and during the production riser connected drilling phase. In support of the Project's Environmental Assessment, in the present study Amec Foster Wheeler has implemented a numerical SBM spill dispersion model to simulate the advection of dispersed SBM droplets in three dimensions through the water column, following accidental releases into the sea during varying seasonal conditions. With the potential to drill multiple wells and at any time during the year, thousands of potential spill events are considered throughout a full year period, to capture the associated seasonal variation in ocean currents at each location.

Two plausible worst-case accidental SBM release modes have been identified and considered in the modelling study:

- Inadvertent surface release of the entire volume (64 m^3) of the active mud system, over a period of 1-2 hours; and
- Subsurface SBM release from the marine riser and associated transport lines, during an emergency BOP disconnect event (255 m^3 at EL-1144, 89 m^3 at EL-1150), over a period of about 2 hours

Ambient ocean currents for input to the SBM dispersion model were derived from seasonal average currents at near-surface, mid-depth and near-bottom depths through the water column using the WebDrogue CECOM (Canadian East Coast Ocean Model) model (DFO 2015a), and tidal predictions for a full year derived from the WebTide model (DFO 2015b).

Wu et al. (2012) conducted an extensive comparison of the CECOM model results and 11 years of observational data, including both qualitative visual comparisons, and quantitative methods based on statistical analysis. Their comparisons indicated that the main circulation features from the observations were successfully reproduced by the model. Furthermore, the comparison indicated particularly good levels of agreement between model and observations in the regions of the Labrador Shelf, Newfoundland Shelf, and the Flemish Pass, with a mean correlation coefficient of 0.91 (ideal value is 1) across all seasons and depths within the Flemish Pass, and an average ratio of kinetic energy difference to the observations of 0.12 (where a lower value is better, and the value of 0.5 indicates "a fair agreement").

The SBM footprint statistics for the intermediate drilling phase at the deepwater site, EL-1144, indicate that most SBM spills at the surface would reach the seafloor within a maximum of 1 km from the drilling site, with the median spill center distance ranging from 184 m to 743 m from the drilling site. The variability of footprint locations among seasons is due to differences in the magnitude and direction of the mean seasonal currents. However, the median and maximum footprint sizes are comparable among seasons, due to the relatively small variability of currents within the brief SBM release periods, with footprint length (along the longer axis) median values of up to 124 m, and maximum values of up to 220 m for the surface release scenarios. Total SBM footprints for the surface spill scenarios are predicted to have median areas of about 4500 m^2 and maximum areas of 9000 m^2, resulting in initial SBM spill deposits with average thicknesses of 1.7 cm, and maximum thicknesses of 7.1 cm.

The surface spill statistics are similar for the two SBM density values considered at EL-1144, though the slightly denser SBM is expected to be transported to slightly shorter distances (median values of 136 m in summer, and 554 m in fall) from the drilling site than the lighter, intermediate phase SBM. The footprint lengths and areas for the production phase are also correspondingly smaller than in the intermediate phase, with median lengths of up to 98 m, and maximum lengths of about 168 m. Footprint areas for the production phase surface releases are smaller than those for the intermediate phase, with median values of 3600 m^2 and maximum values of 7200 m^2 for all seasons.

At the EL-1150 shallow water site, the modelled spill center distances from the site are generally shorter compared to the EL-1144 deepwater site, with median footprint center distances ranging from 106 m to 201 m, and maximum distances ranging from 322 m to 424 m. Footprint length scales at the EL-1150 site are slightly shorter than at the deepwater site, with median values ranging from 81-84 m across seasons, however the maximum lengths are slightly higher than at the deep site, ranging from 237 m to 250 m. These findings can be attributed to a slightly larger range of current variability at the shallow water site compared to the deepwater site, resulting in a wider range of individual spill sizes within each seasonal scenario. This is also reflected in the modelled footprint areas, with median values of 2700 m^2, and maximum values of 9900 m^2. Due to the lower median footprint sizes, the average SBM deposit thickness is higher at about 2.6-2.7 cm, but the maximum thickness of 7.1 cm is comparable to the deepwater site.

The seasonal probability maps of spill center locations indicate that SBM spill deposits are most likely to reach the seafloor within the quadrant northeast of EL-1150, and the areas to the west-southwest of EL-1140, consistent with the prevailing seasonal mean currents at each location.

The SBM originating from a potential BOP disconnect scenario at EL-1144 for both drilling phases is expected to contact the seafloor much closer to each drilling site (within about 40-60 m in all seasons), resulting in smaller initial footprint areas, but potentially larger initial SBM layer thicknesses. The relatively small vertical distance to the seafloor, and the low ambient near-bottom currents result in low SBM dispersion rates and similar outcomes for all seasons and SBM densities.

It should be noted that the modelled SBM footprints represent only preliminary dimensions of the projected landing area for the SBM droplets, and the estimated SBM layer thickness if the full spill volume landing in each model cell were to be equally distributed within that cell. The subsequent fate and the footprint are likely to evolve in a less predictable fashion, as the negatively buoyant SBM droplets are expected to coalesce into streams or pools, and flow under the influence of gravity and the local bathymetric features. As there is a trade-off between the area covered by the spill and the thickness of the spill, it can be expected that an area of the seafloor that is relatively flat and with few roughness features is likely to result in a thinner and widely distributed SBM layer, while a localized depression in the seafloor could retain the received SBM as a thicker layer within a smaller area.

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APPENDIX A-1: OCEAN CURRENTS FOR MODELLING LOCATIONS

1.0 INTRODUCTION

Amec Foster Wheeler Environment & Infrastructure, a Division of Amec Foster Wheeler Americas Limited (Amec Foster Wheeler), has been contracted by Nexen Energy ULC (Nexen) to complete modelling of potential synthetic-based mud (SBM) accidental spills from the proposed Flemish Pass Exploration Drilling Program, for use in the Project's Environmental Assessment.

1.1 Background

Nexen is planning to conduct a program of petroleum exploration drilling and associated activities in the eastern portion of the Canada-Newfoundland and Labrador Offshore Area over the period 2018 to 2028 (hereinafter also referred to as the Project). The proposed Project Area (Figure 1-1) includes two Exploration Licences (ELs 1144 and 1150) in the Flemish Pass region for which Nexen is the operator and is currently the sole interest holder, and which have not yet been subject to exploration drilling activity to date pursuant to these licences. The Project will include exploration drilling within these ELs, possible appraisal (delineation) drilling in the event of a hydrocarbon discovery, vertical seismic profiling (VSP), well testing, eventual well decommissioning and abandonment or suspension procedures, and associated supply and service activities.

Over the course of the anticipated 11 year duration of the Project, it is estimated that up to 10 wells could be drilled, with specific well site locations being selected as planning and design activities progress. Once a well site location has been identified, drill site clearance has been completed and the Mobile Offshore Drilling Unit (MODU) has been positioned the initial top hole drilling commences, which is a large diameter hole that is drilled without a riser in place. The initial sections are drilled using a water-based mud (WBM), where mud and cuttings are returned to the seabed in accordance with the Offshore Waste Treatment Guidelines (OWTG) (NEB et al 2010). When the top conductor and surface section drilling has been completed to the depth where the rock formation strength is sufficient, the structural casing is run and cemented and the wellhead is installed at seabed. Synthetic-based muds (SBM) are used for deeper hole sections. Once the riser has been installed, drilling mud and cuttings are returned to the MODU deck in a closed loop system, where the drilling fluids and cuttings are separated; the cuttings are treated prior to discharge overboard and the drilling fluids are continually reconditioned and reused throughout drilling of the well.

SBMs are defined as drilling muds in which the continuous phase consists of a synthetic base fluid, while the dispersed phase consists of brine and other additives. SBMs have been developed as a more environmentally friendly alternative to oil-based muds (OBMs), as the synthetic fluids that comprise the continuous phase exhibit low toxicity to aquatic life and are more biodegradable in marine sediments than OBMs. SBMs exhibit several performance advantages over the more commonly used WBMs; therefore, they are commonly used for challenging wells in deep water, or wells with highly deviated wellbores. They serve several essential functions during the drilling process: transport of cuttings to the surface; cooling, cleaning and lubrication of the drill bit; maintaining a pressure balance between the geological formation and the borehole; reduction of friction in the borehole; sealing of permeable formations; and maintaining stability of the borehole walls (Burke and Veil 1995).

A numerical SBM droplet dispersion model, developed by Amec Foster Wheeler, employs a transport computation to simulate the advection of dispersed SBM droplets in three dimensions through the water column, following accidental release into the sea, until the particles come to rest on the sea bottom. Key inputs for the model include SBM droplet characterizations and ocean currents. The primary outputs are predictions of the probable area and locations of the SBM footprints on the seabed for each seasonal scenario (e.g., footprint length, area, thickness and distance from the drilling site).

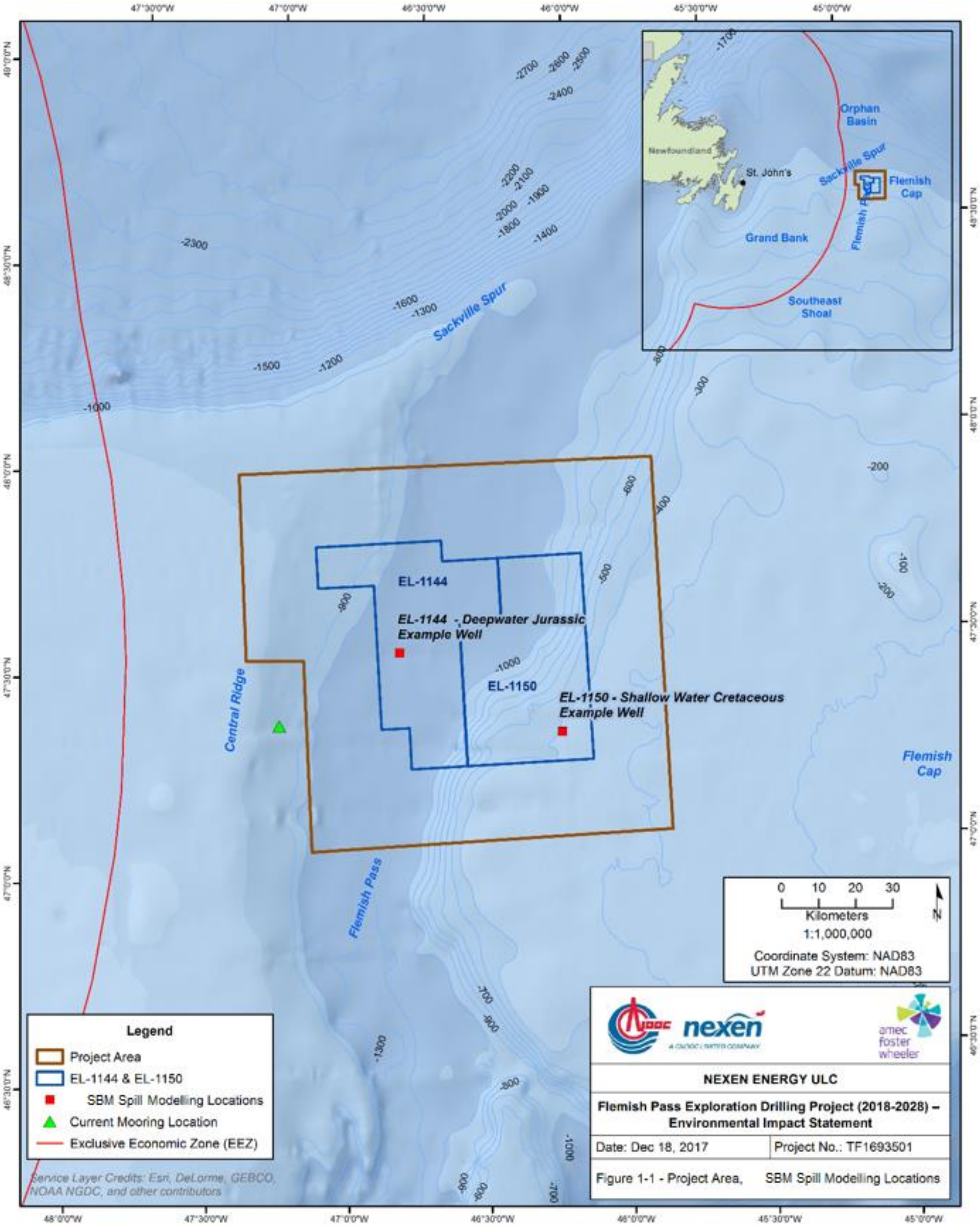
1.2 Objectives

The objective of this study is to model potential accidental SBM spills from exploration well drilling in the Project Area with the results intended to support the Environmental Assessment of the Project.

As noted above, Nexen is considering two well designs which represent the expected range of wells that could be drilled in the Project Area. These include a Deepwater Jurassic Well Design and a Shallow Water Cretaceous Well Design. There is the possibility either well type is selected for drilling in either of the exploration licences EL-1144 and EL-1150 license blocks. Two phases of the planned exploration drilling within ELs 1144 and 1150 will involve the use of synthetic-based muds (SBMs), during the intermediate riser connected drilling phase, and during the production riser connected drilling phase.

To estimate the potential footprints from accidental SBM spills in the Project Area, two modelling locations are considered with one in each EL. The Deepwater Well Design is selected for EL-1144 and the Shallow Water Design is selected for EL-1150. With the potential to drill multiple wells and at any time during the year, thousands of potential spill events are considered throughout a full year period, to capture the associated seasonal variation in ocean currents at each location. Each scenario model run provides a prediction of the potential SBM spill footprints at the sea floor, and statistical descriptions of the possible outcomes are derived for all four seasons. This report presents details of the model methods, inputs and results.

Figure 1-1 Project Area, Accidental SBM Spills Modelling Locations



2.0 SBM SPILL MODELLING INPUT SPECIFICATIONS

This section provides a summary of key elements of the drilling programs considered in modelling of the accidental SBM releases to the sea.

2.1 Potential SBM Accidental Release Modes

To estimate the potential accidental SBM release in the Project Area, two modelling locations are considered with one in each EL. The locations are shown in Table 2-1 and Figure 1-1. The Deepwater Well Design is selected for EL-1144 and the Shallow Water Design is selected for EL-1150.

Table 2-1 SBM Spill Modelling Locations

Location	Latitude (N)	Longitude (W)	Water Depth (m)
EL-1144 Deepwater Jurassic Example Well	47° 31' 01.23"	46° 43' 09.20"	1,137
EL-1150 Shallow Water Cretaceous Example Well	47° 18' 13.21"	46° 09' 18.53"	378

In order to capture the range of possible accidental spill scenarios, plausible release modes were considered both at the sea surface and under the sea surface at each modelling location.

The worst plausible surface SBM spill scenario could result in the release of the entire SBM volume from the active mud system, due to inadvertent operation of the active mud system valves. The surface SBM spill volume is assumed to consist of the entire capacity of the active mud system of approximately 400 bbl (64 m^3), considered to be applicable at both the deep water and shallow water example wells. The spilled SBM is assumed to reach the ocean at the sea surface, and the discharge would be expected to happen over a period of 1-2 hours.

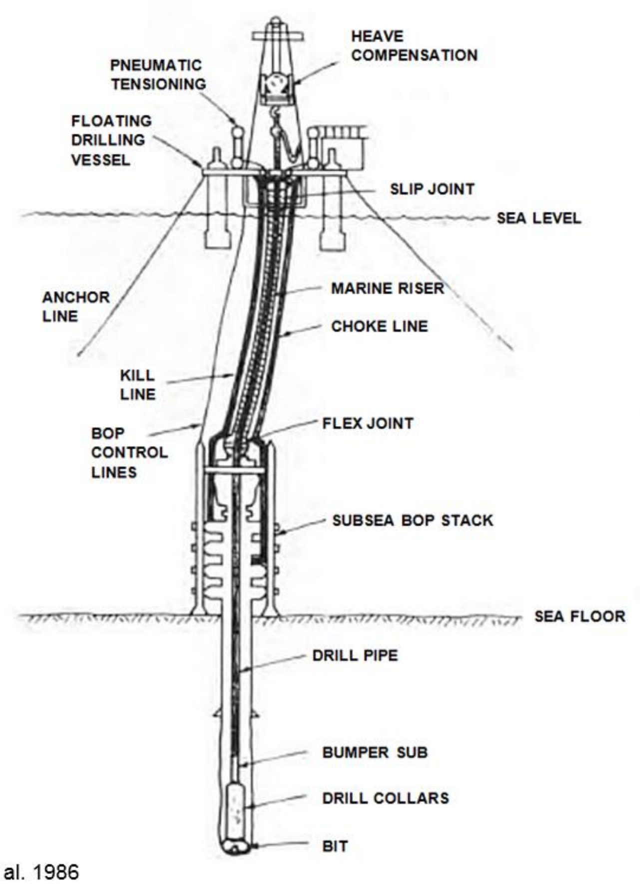
Another potential worst case scenario that could result in a subsurface release of most or all of the SBM contents, from the marine riser and associated transport lines, would be an emergency disconnection of the riser, which might prevent the crew from taking the necessary actions to displace the transport lines with seawater and therefore minimize spill amounts. The components of a typical MODU are illustrated in Figure 2-1, however it is noted that this illustration may not fully represent the final configuration of the MODU, namely the use of anchors is not proposed during the Project activities.

In an emergency BOP disconnection event, it would be expected that the SBM would be released within a relatively short period of time (on the order of two hours), and through large orifices, resulting in a wide and slow jet of SBM being released.

The drilling system assumed for the exploration drilling program is expected to have a combined SBM transport system capacity of 255 m^3 at the EL-1144 Deepwater (DW) site, and a capacity of 89 m^3 at the EL-1150 Shallow Water (SW) site. In a worst case scenario, the potential subsea release of SBM could result in the loss of all the SBM volume at a height of approximately 15 m above the seafloor at each location.

The modes of release and the associated details selected for the modelling study are summarized in Table 2-2 and Table 2-3. The rate of release and the size of the orifices are expected to contribute substantially to the subsequent behaviour and dispersal of the SBM in the environment. While it is difficult to predict the exact mode of failure of mechanical components and their behaviour during rare extreme weather events, the surface and subsea scenarios described here are expected to generally capture the range of possible conditions under which SBMs might be released under extreme conditions.

Figure 2-1 Main Components on a Typical MODU



Source: Bourgoyne et al. 1986

Table 2-2 Modes of Release Selected for Synthetic-based Mud Dispersion Modelling at the EL-1144 Location

Mode of Release	Location of Release	MODU Components Contributing to SBM volume	Total Volume (m^3)	Period of Release (hours)	SBM Flow Type
Surface	Surface (1,137 m above seafloor)	Mud tank	64	1.5	Wide, low-speed jet from large orifice
Subsea (BOP disconnect)	15 m above seafloor	Marine riser; choke, kill, booster, surface lines; mud gas separator	255	2	Wide, low-speed jet from large orifice

Table 2-3 Modes of Release Selected for Synthetic-based Mud Dispersion Modelling at the EL-1150 Location

Mode of Release	Location of Release	MODU Components Contributing to SBM volume	Total Volume (m^3)	Period of Release (hours)	SBM Flow Type
Surface	Surface (378 m above seafloor)	Mud tank	64	1.5	Wide, low-speed jet from large orifice
Subsea (BOP disconnect)	15 m above seafloor	Marine riser; choke, kill, booster, surface lines; mud gas separator	89	2	Wide, low-speed jet from large orifice

For the purposes of this modelling exercise, it is assumed that the drilling operations at EL-1144 and EL-1150 will use SBM that represents an emulsion in which the continuous phase is comprised of Puredrill IA-35, a non-toxic and readily biodegradable synthetic fluid produced by Petro-Canada. The synthetic fluid will comprise approximately 80 percent of the SBM volume, with other additives (barite, viscosifiers, emulsifiers, lime, fluid loss control agents and water) accounting for the rest. The overall density of the SBM is assumed to range from 1140 kg/m^3 (intermediate drilling phase) to 1251 kg/m^3 (production drilling phase) at EL-1144, and from 1100 kg/m^3 (intermediate drilling phase) to 1160 kg/m^3 (production drilling phase) at the EL-1150 well.

2.2 Ambient Ocean Currents

Together with SBM properties, horizontal current is the other key factor in determining how far the SBM spills may disperse, so it is important to employ a good characterization of the local current behaviour as a driving force for the model. Since the SBM is denser than seawater, it is expected to settle through the water column, and a characterization of the currents as a function of depth is required.

No existing current measurements have been found for the Project Area. This includes a query of the Bedford Institute of Oceanography (BIO) Ocean Data Inventory (ODI) database (Gregory 2004, DFO 2017). The nearest current measurements were located about 37 km to the southwest of the EL-1144 Deepwater Jurassic Example Well and unlikely to be representative of the Project Area or either of the modelled locations.

Therefore, ocean currents for input to the SBM dispersion model were derived from seasonal average currents at near-surface, mid-depth and near-bottom depths through the water column using the WebDrogue CECOM (Canadian East Coast Ocean Model) model (DFO 2015a), and tidal predictions for a full year derived from the WebTide model (DFO 2015b). The models yield currents at five depth levels: surface, 100 m, 500 m, 1,000 m and bottom. The depth levels selected for illustration of the currents at the two locations are as noted below.

- EL-1144 Deepwater Jurassic Example Well Location (1,137 m)
- Near-surface: depth level=100 m
- Mid-depth: depth level=500 m
- Near-bottom: depth level=1,000 m

- EL-1150 Shallow Water Cretaceous Example Well Location (378 m)
- Near-surface: depth level=surface
- Mid-depth: depth level=100 m
- Near-bottom: depth level=bottom

Wu et al. (2012) conducted an extensive comparison of the CECOM model results and 11 years of observational data, including both qualitative visual comparisons, and quantitative methods based on statistical analysis. Their comparisons indicated that the main circulation features from the observations were successfully reproduced by the model. Furthermore, the comparison indicated particularly good levels of agreement between model and observations in the regions of the Labrador Shelf, Newfoundland Shelf, and the Flemish Pass, with a mean correlation coefficient in the of 0.91 (ideal value is 1) across all seasons and depths within the Flemish Pass, and an average ratio of kinetic energy difference to the observations of 0.12 (where a lower value is better, and the value of 0.5 indicates "a fair agreement").

In the model algorithm, spills are assumed to be possible at any time during the year, with thousands of separate possible realizations being modelled at 15 minute intervals. For each realized spill event, the corresponding current data is input from the representative year time series file and is used to advect the SBM droplets. It is assumed that the currents are representative of the two locations and are uniform over the SBM spill model domains.

Further illustration of these currents used as SBM model input is presented in Appendix A-1, in the form of monthly current roses for all three depths.

The magnitudes of the modelled ocean currents in the Project Area are low. Near-surface mean current speeds range from 2.6 cm/s in summer to 9.5 cm/s in winter, with maximum values ranging from 4 cm/s in summer to 11.5 cm/s in winter. At greater depths, current speeds are about one half. Annual mean current speeds for mid-depth are about 2.5 cm/s with maximum values of 6 cm/s. Near-bottom mean current speeds range from about 1 cm/s in summer to 3 cm/s in winter, with maximum values ranging from about 3 cm/s in summer to 4.5 cm/s in winter.

Table 2-4 and Table 2-5 present monthly near-surface, mid-depth and near-bottom current statistics for the two locations, one location in EL-1144 on the northwestern slopes of the Flemish Pass at a water depth of 1,137 m, the other in EL-1150 on the western slopes of the Flemish Pass at a water depth of 387 m. On the western side of the Flemish Pass at the modelled EL-1144 location, near-surface (at the surface) mean current speeds range from about 2 cm/s in summer to 9 cm/s in fall, with maximum values ranging from 5 cm/s in summer to 12 cm/s in fall. At greater depths (500 m for mid-depth, 1,000 m for near-bottom), current speeds are about one half to one quarter the near-surface values. For near-bottom, mean currents range from 1 to 3 cm/s year-round with maximum speeds of 3 to 5 cm/s, the largest values again being in the fall.

As illustrated by the current roses in Appendix A-1, the modelled currents are predominantly to the south and southwest in fall and winter at all depths. In spring, the currents near-surface flow predominantly to the south; at mid-depth and near-bottom directions are more evenly distributed to all directions (albeit at the very low current speeds). At near-bottom there is a slight preference to the west. In summer, near-surface currents flow predominantly to the southeast, with conditions mid-depth and near-bottom similar to those in spring.

On the eastern side of the Flemish Pass at the modelled EL-1150 location, near-surface (surface) mean current speeds range from about 5 cm/s in summer to 11 cm/s in winter, with maximum values ranging from 10 cm/s in summer to 15 cm/s in winter. At greater depths (100 m for mid-depth and the bottom depth level to characterize near-bottom), current speeds are generally one half to one third the near-surface values. Mid-depth and near-bottom mean currents are 2 to 3 cm/s in all months with maximum speeds ranging from 5 to 7 cm/s, the largest values again being in the winter. The modelled currents near-surface are predominantly to the northeast in fall and winter. In spring the flow near-surface is to the east and northeast, while in summer it is mostly to the east. The generally light (about 2-3 cm/s on average) currents at mid-depth and near-bottom flow primarily to the northeast quadrant (occasionally also to the northwest) in all months.

A regional illustration of the modelled surface and bottom currents is also shown in Figure 2-2 to Figure 2-9. These figures provide a good illustration of the variation in magnitude and direction of currents over the Project Area including the southerly flow through the Flemish Pass near the EL-1144 Deepwater Jurassic Example Well location and the northeasterly flow along the Flemish Cap slopes near the EL-1150 Shallow Water Cretaceous Example Well location.

Table 2-4 EL-1144 Deepwater Jurassic Example Well Location, Monthly Current Statistics

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Near-Surface	Min (cm/s)	6	6	6	5	5	5	1	1	1	8	8	7
	Mean (cm/s)	8	8	8	7	7	7	2	2	2	9	9	9
	Max (cm/s)	10	10	10	9	9	9	5	5	5	12	12	12
	Most Frequent Direction (to)	S	S	S	S	S	S	SE	SE	SE	S	S	S
Mid-Depth	Min (cm/s)	1	1	1	0.1	0.1	0.03	0.1	0.1	0.1	2	2	2
	Mean (cm/s)	3	3	3	1	1	1	1	1	1	4	4	4
	Max (cm/s)	6	6	6	3	3	3	3	3	3	6	6	7
	Most Frequent Direction (to)	SW	SW	SW	S	S	S	N	N	N	SW	SW	SW
Near-Bottom	Min (cm/s)	0.1	0.1	0.1	0.1	0.02	0.1	0.1	0.1	0.01	1	1	1
	Mean (cm/s)	2	2	2	1	1	1	1	1	1	3	3	3
	Max (cm/s)	4	4	4	3	3	3	3	3	3	5	5	5
	Most Frequent Direction (to)	S	S	S	SW	SW	W	W	W	NW	S	S	S

Table 2-5 EL-1150 Shallow Water Cretaceous Example Well Location, Monthly Current Statistics

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Near-Surface	Min (cm/s)	8	8	8	5	5	6	1	1	1	5	5	5
	Mean (cm/s)	11	11	11	9	9	9	5	5	5	8	8	8
	Max (cm/s)	15	15	15	13	13	13	10	10	10	12	12	12
	Most Frequent Direction (to)	NE	NE	NE	E	E	E	E	E	E	NE	NE	NE
Mid-Depth	Min (cm/s)	0.3	1	1	0.3	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.2
	Mean (cm/s)	3	3	3	3	3	3	2	2	2	3	3	3
	Max (cm/s)	7	7	7	7	7	7	6	6	6	6	6	6
	Most Frequent Direction (to)	NE	NE	NE	E	E	E	E	E	E	E	E	E
Near-Bottom	Min (cm/s)	0.1	0.3	0.1	0.1	0.04	0.1	0.01	0.02	0.1	0.3	0.1	0.1
	Mean (cm/s)	3	3	3	2	2	2	2	2	2	2	2	2
	Max (cm/s)	7	7	7	6	5	6	6	6	6	5	5	5
	Most Frequent Direction (to)	N	N	N	E	E	E	E	E	E	NW	NW	NW

Figure 2-2 Winter, Surface Currents

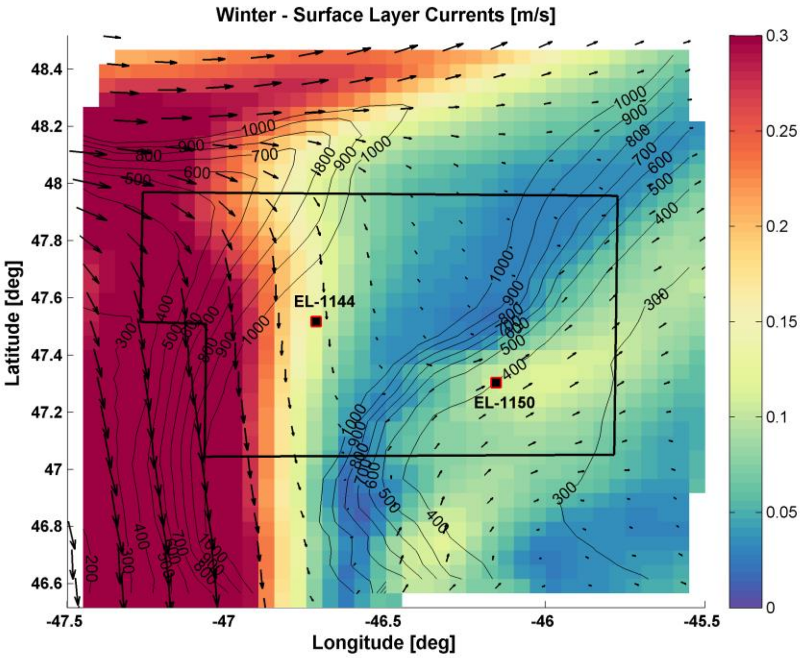


Figure 2-3 Winter, Bottom Currents

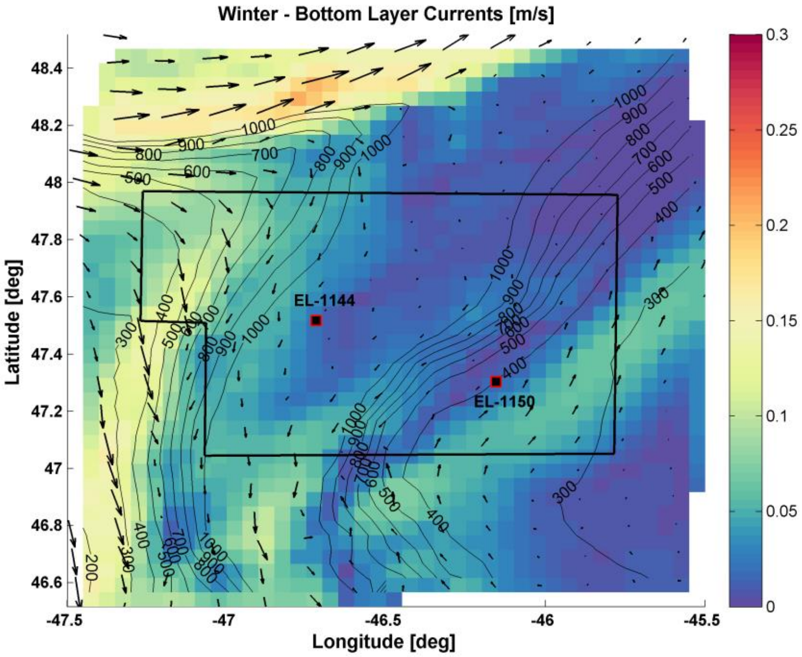


Figure 2-4 Spring, Surface Currents

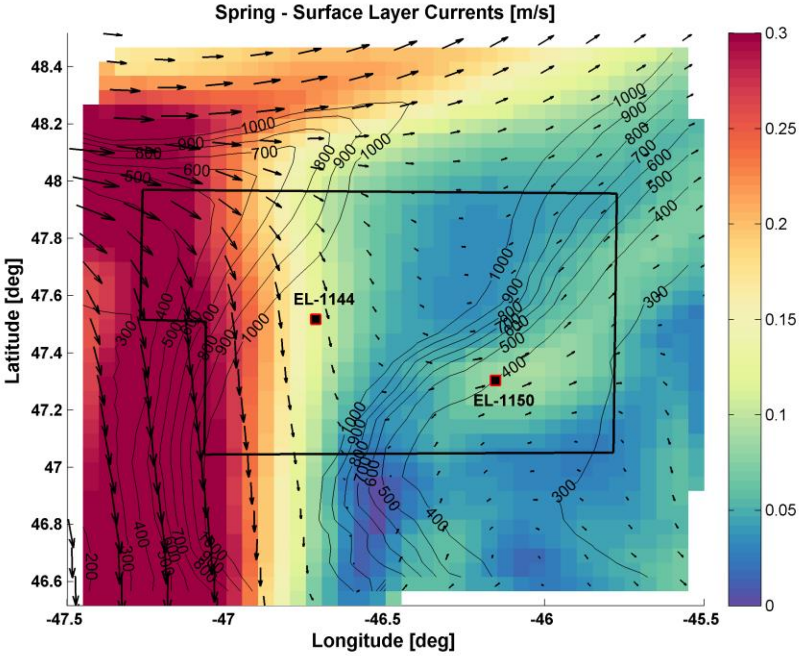


Figure 2-5 Spring, Bottom Currents

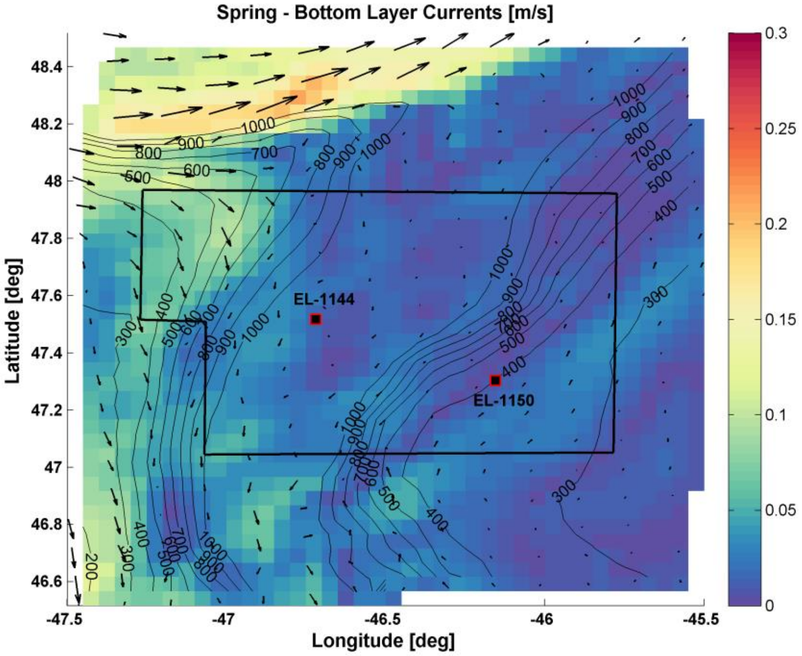


Figure 2-6 Summer, Surface Currents

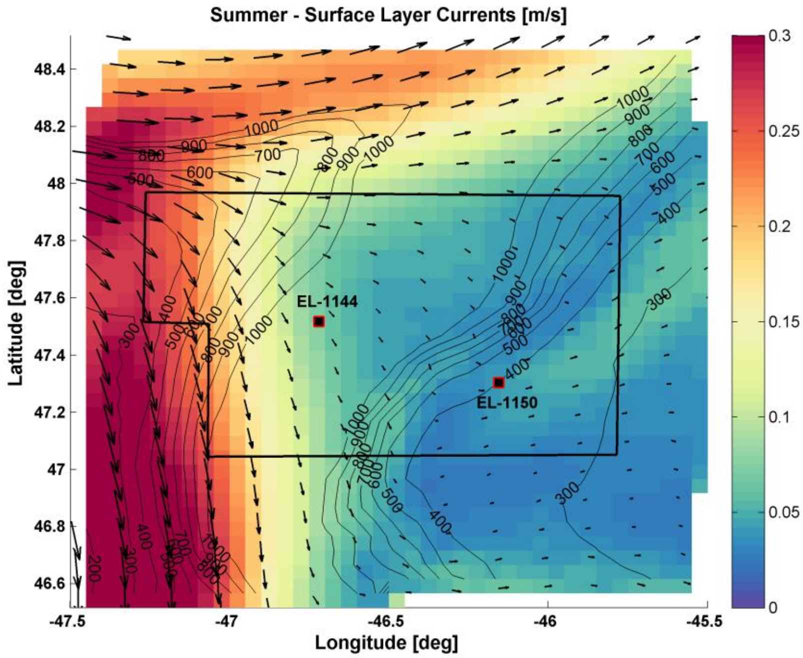


Figure 2-7 Summer, Bottom Currents

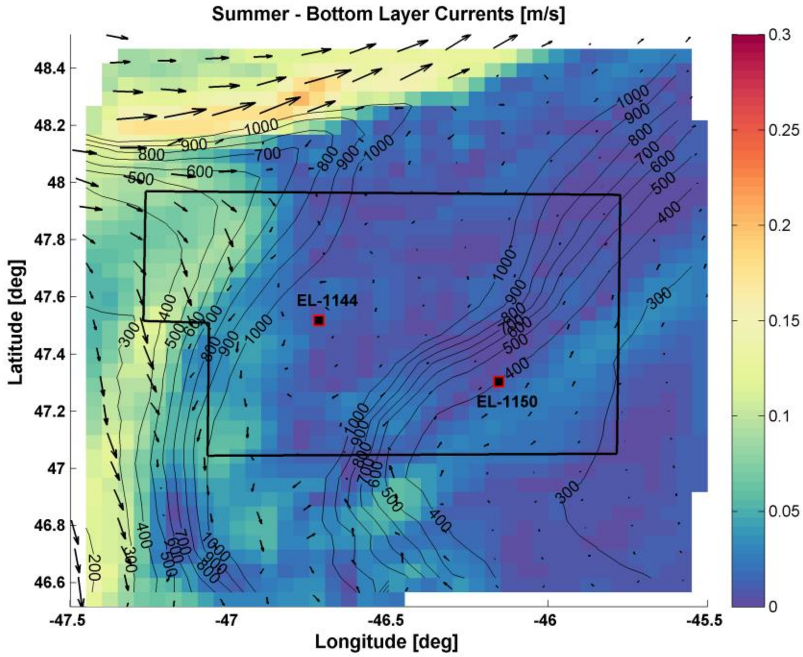


Figure 2-8 Fall, Surface Currents

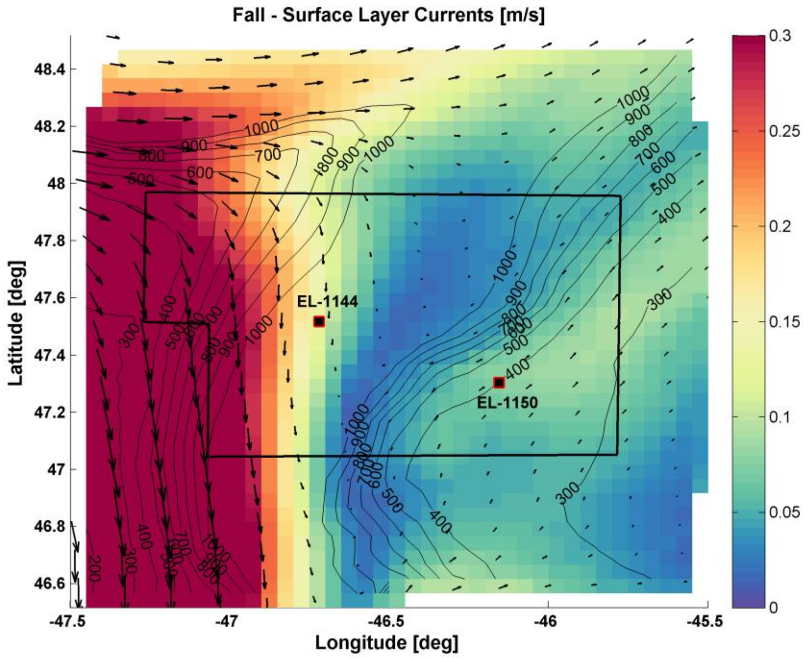
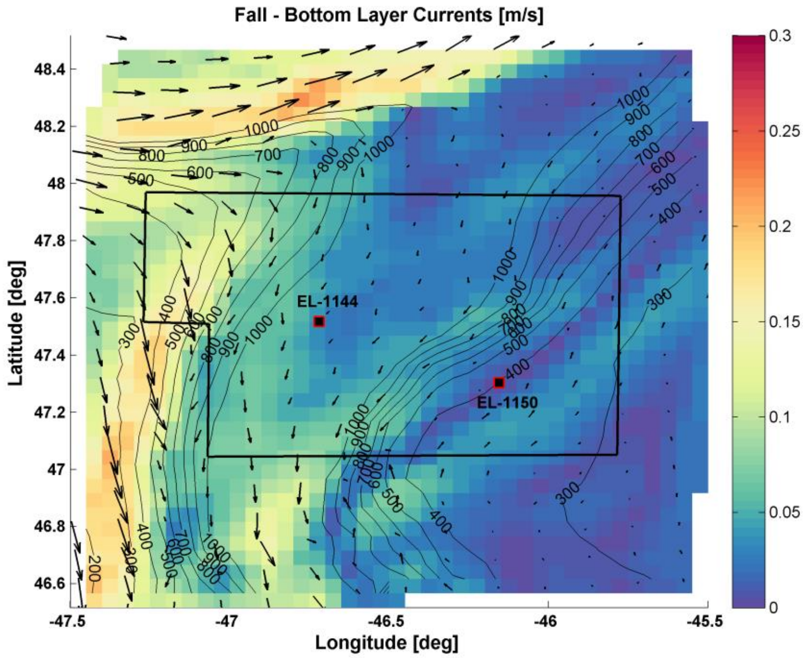


Figure 2-9 Fall, Bottom Currents



3.0 SBM DISPERSION MODELLING METHODOLOGY

Modelling the dispersion of SBM spills in the marine environment requires knowledge of the properties and behaviour of the SBM fluid in the immediate vicinity of the release site under different release scenarios, as well as the subsequent behaviour under the influence of the ambient ocean currents. A literature review of the current state of scientific knowledge of the behaviour of SBM in the marine environment indicate that SBMs exhibit a unique behaviour in the marine environment as they are immiscible in water, and are negatively buoyant. Unlike water-based fluids, they tend to form distinct jets and droplets that fall relatively rapidly through the water column, and they are prone to form visible and clearly-defined streams and pools at the seafloor, where their dispersion is in large part driven by gravity in conjunction with the local seafloor features. The approaches for modelling the dispersion of WBMs and other water-based fluids are therefore not applicable to SBMs.

The present modelling study relies on data from an experimental study of SBM fall velocities under several release scenarios, which was commissioned by the US BOEMRE and conducted by the Southwest Research Institute (SwRI) (2007)[1].

3.1 Synthetic-Based Mud Properties and Behaviour

The drilling operations at the deepwater site EL-1144 and the shallow water site EL-1150 will use SBM based on Puredrill IA-35, a non-toxic and readily biodegradable synthetic fluid produced by Petro-Canada, or a comparable component with the same or similar characteristics. It is assumed that the synthetic fluid will comprise approximately 80 percent of the SBM volume, with other additives (barite, viscosifiers, emulsifiers, lime, fluid loss control agents and water) accounting for the rest. The overall density of the SBM is assumed to range from 1140 kg/m^3 (intermediate drilling phase) to 1251 kg/m^3 (production drilling phase) at EL-1144, and from 1100 kg/m^3 (intermediate drilling phase) to 1160 kg/m^3 (production drilling phase) at the EL-1150 well.

Since SBMs are immiscible in water, once released, they would form droplets of various sizes that are then subject to dispersal by the ocean currents. Some key aspects of the SBM behaviour that determine how it would spread in the marine environment are the breakup of the fluid into droplets of varying sizes and the stability of the SBM emulsion under different release and environmental conditions, as well as the terminal fall velocity of the droplets. For immiscible fluids, there exists a maximum stable droplet size at terminal fall velocity, which is governed by the balance between the interfacial tension holding the drop together, and the deforming force imparted by the buoyant flow (Grace et al. 1978). If the droplets formed in a spill event are larger than the maximum stable size, they will break up as they fall through the water column until they reach a stable size at the final fall

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[1] SwRI (Southwest Research Institute). 2007. *Fall Velocity of Synthetic-Based Drilling Fluids in Seawater*. Final Report, prepared for Minerals Management Service.

velocity. The deforming shear forces are expected to be much larger for higher jet speeds, when it is likely that the SBM would be broken into droplets that are smaller than the stable droplet size.

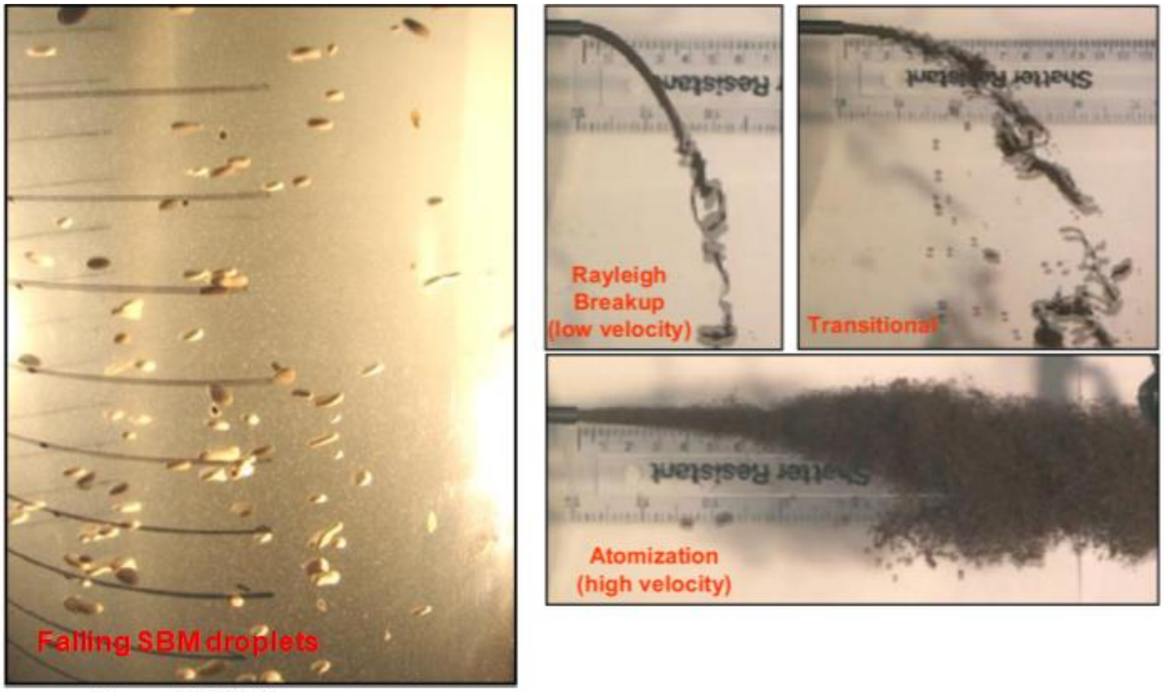
Clift et al. (1978) have shown that droplets fall faster as they grow bigger in diameter, up to a certain threshold size beyond which increasing the droplet size does not increase the fall velocity. This was explained by the fact that drops retain their spherical shape only until a certain threshold in size, beyond which the deforming forces act on the drops to make them flatter and resistant to further increases in fall velocity.

The behaviour of immiscible fluids becomes more complex when they are discharged as jets of varying speed. Kitamura and Takahashi (1986) showed that there are three main flow regimes that a jet undergoes, depending on the fluid properties and the relative speed of the jet and the receiving fluid. At low jet velocities, large drops form from a laminar jet of fluid in which Rayleigh instabilities grow until they pinch off the jet into individual drops – a flow regime named Rayleigh breakup, or laminar breakup. This flow regime results in a relatively uniform distribution of droplet sizes. In contrast, higher speed jets break up into a spray of fine drops that have a wide size distribution – a flow regime called the spray or atomization breakup. Instead of Rayleigh instabilities, the dominant breakup forces in the atomization regime are exerted by the fluid momentum in conjunction with the viscous forces. At intermediate jet speeds, there exists a transitional flow regime in which both the Rayleigh instabilities and the fluid momentum impart a substantial influence on the breakup process.

The SwRI (2007) conducted an experimental study of fall velocities for five different batches of SBM, labelled from A through E, exhibiting a range of densities used by industry in offshore drilling in the Gulf of Mexico. Out of these, the mud samples D (1,402 kg/m^3) and E (1,169.5 kg/m^3) bracket the range of densities of the SBM planned for use during the proposed exploration drilling program, and therefore the experimental data for these mud types were used as most representative for the mud composition assumed in the present study. The SwRI (2007) designed their experiment in such a way as to capture the most frequent spill modes, which they determined partly by conducting an industry survey, and partly by analysis of spill modes in the Gulf of Mexico from BOEMRE database spill statistics. Furthermore, their experimental setup allowed them to simulate overboard spills of SBM (dropped above the sea surface), as well as to capture the different flow regimes (Rayleigh to atomization) for low- and high-speed jets (Figure 3-1) for each of the SBM samples, and to measure the fall velocity distributions for each of the spill scenarios.

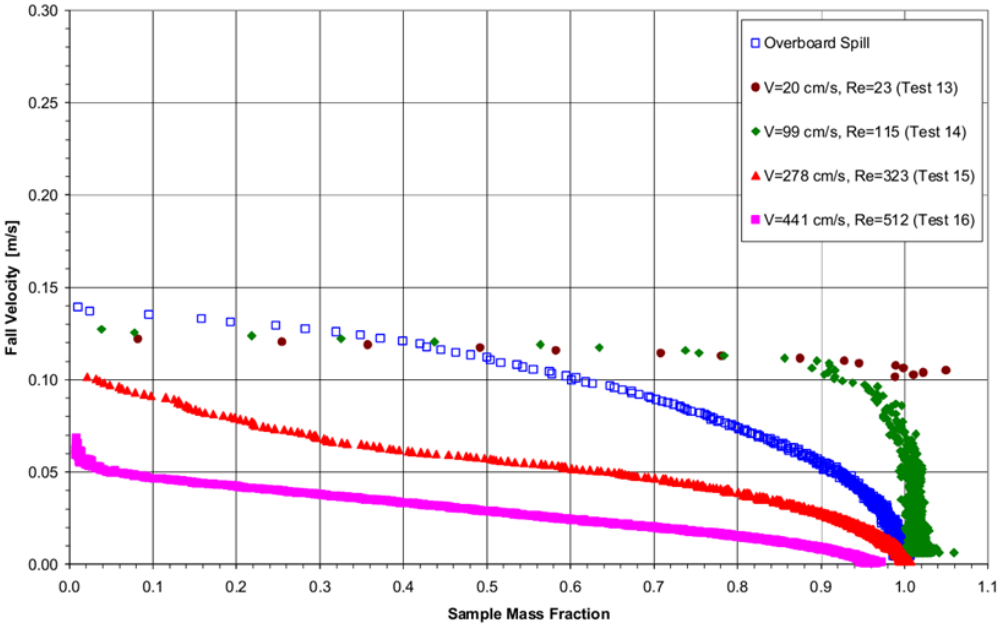
The SwRI (2007) experimental study focused on producing fall velocity distributions instead of the more difficult to measure droplet size distributions, due to the fact that the fall velocity of the resulting SBM droplets is the controlling factor that determines the time period in which they would settle and reach the seafloor. The settling period also represents the time during which they would be subject to horizontal dispersal by the ambient ocean currents. Therefore, the expected terminal fall velocities under each release scenario will be a primary factor in their fate and footprint on the sea bottom. The fall velocity distributions for muds D and E, presented in Figure 3-2 and Figure 3-3, were used as the basis for the SBM dispersion model.

Figure 3-1 Falling Synthetic-based Mud Droplets (left panel) and Jet Breakup Regimes



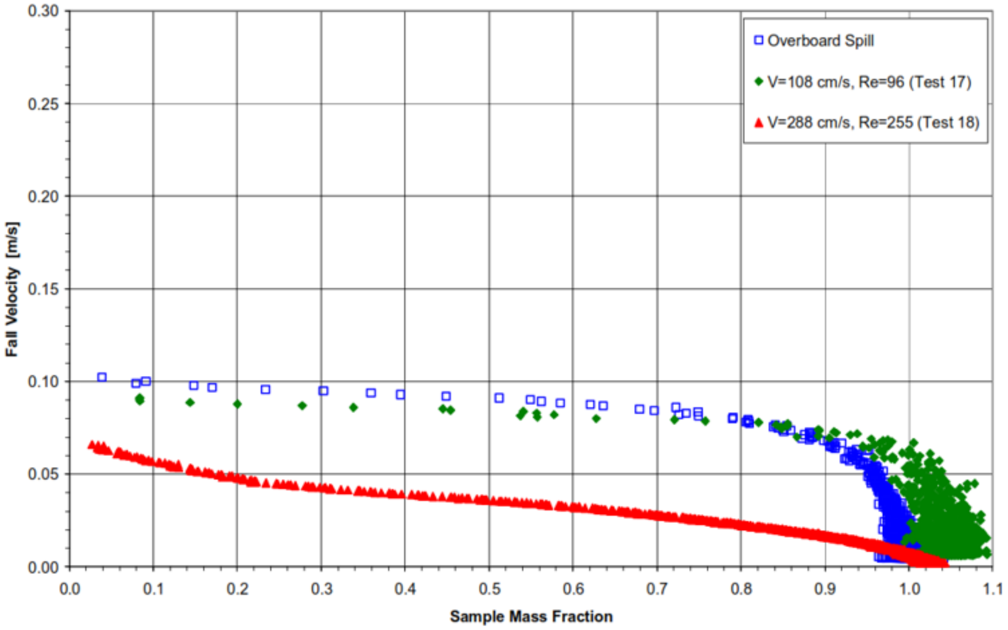
Source: SwRI 2007

Figure 3-2 Fall Velocity Distributions for Synthetic-based Mud Droplets (Mud D) under Different Flow Regimes



Source: SwRI 2007

Figure 3-3 Fall Velocity Distributions for Synthetic-based Mud Droplets (Mud E) under Different Flow Regimes



Source: SwRI 2007

The experimental scenarios representing an overboard spill and with the lowest jet speeds corresponded to a laminar (not turbulent) breakup regime and as such, therefore they are considered representative of the SBM release scenarios involving large orifices or pipes, and the lowest expected jet speeds (e.g., surface release of mud tank contents through pipe; subsea release via BOP disconnect). The denser Mud D sample in the SwRI (2007) experiments was considered to bracket the higher SBM density for the production drilling phase at the EL-1144 site, with average terminal fall velocities of 11 cm/s, while the Mud E was considered as most representative for the intermediate drilling phase at EL-1144 and for all drilling phases at EL-1150, with average terminal fall velocities of 8 cm/s.

3.2 Synthetic-Based Mud Dispersion Model Setup

A model that aims to capture the fate of accidental SBM spills must incorporate in a meaningful way the timing, location and amounts of each potential spill event, as well as the ocean current variability over the duration of the spill event. Moreover, since the timing of the spill cannot be predicted, it should be assumed that the spill can take place at any time during the year. Therefore, the SBM dispersion model runs should take into account the full ocean current time series available. In this context, the modelling approach was based on the consideration of the specific parameters and assumptions for each of the scenarios, which were derived from the details of each of the three selected release modes described in Section 2.1

The modelling procedure included splitting the full spill volume into discrete collections of droplets over the duration of the release. Since the input current series had a time resolution of 15 minutes, the currents were linearly interpolated so that each collection of packages experienced the most up-to-date set of current conditions. To calculate the horizontal trajectory of the droplets, it was necessary to compute the time they would spend in each of the vertical layers. The destination at the seafloor for each collection of droplets experiencing a set of current conditions [(u_s, v_s),(u_m, v_m),(u_b, v_b)] is computed according to the following equations:

$$x = x_0 + u_s \times t_s + u_m \times t_m + u_b \times t_b$$

$$y = y_0 + v_s \times t_s + v_m \times t_m + v_b \times t_b$$

where the subscripts *s, m, b* stand for the nominal *surface, mid-depth* and *bottom layers*, respectively. The time spent in each of the three layers is defined in terms of the initial height above the seafloor, $H_{release}$, the settling velocity, $w_{settling}$, and the fraction of the vertical layer relative to the water depth, f_{layer}, as follows:

$$t_s = \frac{H_{release}}{w_{settling}} \times f_s$$

$$t_m = \frac{H_{release}}{w_{settling}} \times f_m$$

$$t_b = \frac{H_{release}}{w_{settling}} \times f_b \, .$$

Each set of east and north destination components (*x, y*) were fit within a horizontal grid with a 30 m resolution, and the amount of SBM within each grid cell was counted for the full duration of the spill event. Any model grid cell that received any amount of SBM was included within the spill area. The thickness of the initial SBM layer on the seafloor was computed on the assumption that the SBM was equally distributed across the area of each cell. In order to capture the full range of seasonal conditions, approximately 35,000 independent spill events were simulated over the four seasons. The total spill footprint area, length and distance from release site, as well as projected initial SBM layer thickness on the seafloor, were estimated for each simulated event, and seasonal median, maximum and average values were derived. The footprint areas, and the associated footprint lengths, are expected to be influenced by the period over which the SBM is released and the fall velocities, as well as the variability of the currents over the release and settling periods.

4.0 RESULTS

As described in the preceding sections, SBM spill footprint modelling was conducted for the two example sites within the Project Area, considering four seasonal scenarios for the prevailing ambient currents. Two sets of modelling results are presented for the EL-1144 site, due to the relatively distinct SBM density values assumed for the intermediate drilling phase and production drilling phase respectively. Since the SBM densities were relatively similar among drilling phases for the EL-1150 site, one set of modelling results is considered to be representative for the conditions at that location. The results are presented in terms of statistical descriptions of the thousands of seasonal scenarios modelled for each site and SBM type, in order to provide an assessment of the range of potential outcomes under all scenarios.

It should be noted that the modelled SBM footprints represent only preliminary dimensions of the projected landing area for the SBM droplets, and the estimated SBM layer thickness if the full spill volume landing in each model cell were to be equally distributed within that cell. The subsequent fate and the footprint are likely to evolve in a less predictable fashion, as the negatively buoyant SBM droplets are expected to coalesce into streams or pools, and flow under the influence of gravity and the local bathymetric features. As there is a tradeoff between the area covered by the spill and the thickness of the spill, it can be expected that an area of the seafloor that is relatively flat and with few roughness features is likely to result in a thinner and widely distributed SBM layer, while a localized depression in the seafloor could retain the received SBM as a thicker layer within a smaller area.

4.1 SBM Spill Footprints at Deepwater Site EL-1144

The seafloor footprints resulting from the modelled accidental SBM spills at EL-1144 are summarized in Table 4-1 and Table 4-2 for the intermediate and production drilling phases, respectively. The results include the distance of the spill footprint centers from the drilling site, whereby the footprint centers represent the location with the maximum spill thickness per unit area.

The SBM footprint statistics for the intermediate drilling phase at the deep site indicate that most SBM spills at the surface would reach the seafloor within a maximum of 1 km from the drilling site, with the median spill distance ranging from 184 m (in summer) to 743 m (in fall) from the drilling site. The variability of footprint locations among seasons is due to differences in the magnitude and direction of the mean seasonal currents. However, the median and maximum footprint sizes are comparable among seasons, due to the relatively small variability of currents within the brief SBM release periods, with footprint length (along the longer axis) median values of up to 124 m (spring), and maximum values of up to 220 m (summer) for the surface release scenarios. Total SBM footprints for the surface spill scenarios are predicted to have median areas of about 4500 m^2 and maximum areas of 9000 m^2, resulting in initial SBM spill deposits with average thicknesses of 1.7 cm, and maximum thicknesses of 7.1 cm.

The surface spill statistics are similar for the two SBM density values considered at EL-1144, though the slightly denser SBM used during the production drilling phase is expected to be transported to slightly shorter distances (median values of 136 m in summer, and 554 m in fall) from the drilling site than the lighter, intermediate phase SBM. The footprint lengths and areas for the production phase are also correspondingly smaller than in the intermediate phase, with median lengths of up to 98 m (spring and fall), and maximum lengths of about 168 m (summer). Footprint areas for the production phase surface releases are smaller than those for the intermediate phase, with median values of 3600 m^2 and maximum values of 7200 m^2 for all seasons. While the maximum modelled thicknesses of 7.1 cm are the same as in the intermediate phase scenarios across seasons, the average thickness is slightly higher at about 2.2 cm.

In order to illustrate the distribution of the probable landing areas for the SBM spills released at the surface for the EL-1144 site, seasonal probability maps of footprint center locations were produced and presented in Figure 4-1 and Figure 4-2 for the two drilling phases. The results illustrate that for both drilling phases the spills are expected to result in deposits up to several hundred meters to the west-southest of EL-1144, depending on the prevailing ambient current conditions for each season. The modelling results indicate notably narrower spatial distributions of the possible footprint center locations for the denser SBM in the production phase compared to the intermediate phase, consistent with the higher terminal fall velocities and lower travel times.

The SBM originating from a potential BOP disconnect scenario at EL-1144 for both drilling phases is expected to contact the seafloor much closer to the drilling site (within about 40-60 m in all seasons), resulting in smaller initial footprint areas, but potentially larger initial SBM layer thicknesses in the range of 23-28 cm. The relatively small vertical distance to the seafloor, and the low ambient near-bottom currents result in low SBM dispersion rates and similar outcomes for all seasons and SBM densities. The final size and thickness distribution of the SBM footprints in these cases is expected to vary based on the features of the local seafloor.

4.2 SBM Spill Footprints at Shallow Water Site EL-1150

The seafloor footprints resulting from the modelled accidental SBM spills at EL-1150 are summarized in Table 4-3, while seasonal probability maps of footprint center locations are presented in Figure 4-3. The modelled spill distances from the drilling site are generally shorter compared to the deepwater site, with median footprint center distances ranging from 106 m (summer) to 201 m (winter), and maximum distances ranging from 322 m (summer) to 424 m (winter).

Footprint length scales at the EL-1150 site are slightly shorter than at the deepwater site, with median values ranging from 81-84 m across seasons, however the maximum lengths are slightly higher than at the deepwater site, ranging from 237 m (fall) to 250 (summer). These findings can be attributed to a slightly larger range of current variability at the shallow water site EL-1150 compared to the deepwater site EL-1144, resulting in a wider range of individual spill sizes within each seasonal scenario. This is also reflected in the modelled footprint areas, with median values of 2700 m^2, and maximum values of 9900 m^2. Due to the lower median footprint sizes, the average SBM deposit thickness is higher at about 2.6-2.7 cm, but the maximum thickness of 7.1 cm is comparable to the deepwater site.

The seasonal probability maps of spill center locations indicate that SBM spill deposits are most likely to reach the seafloor within the quadrant northeast of EL-1150, consistent with the prevailing seasonal mean currents at this location.

Table 4-1 EL-1144 Deepwater Jurassic Example Well Location, Seasonal SBM Footprint Statistics, Intermediate Phase

SBM DISPERSION		Distance from Site (m)		Footprint LENGTH (m)		Footprint AREA (m2)		Layer Thickness (cm)	
		max	median	max	median	max	median	max	avg
Surface	winter	620	422	165	95	7200	3600	7.1	2.2
	spring	441	273	157	98	7200	3600	7.1	2.1
	summer	264	136	168	93	7200	3600	7.1	2.2
	fall	726	554	161	98	7200	3600	7.1	2.2
BOP	winter	57	57	32	31	3600	900	28.3	25.1
	spring	57	57	32	31	3600	900	28.3	23.7
	summer	57	41	33	31	3600	900	28.3	23.6
	fall	57	57	32	31	1800	900	28.3	27.2

Figure 4-1 Probability Map of Spill Center Locations for the EL-1144 site, Intermediate Phase

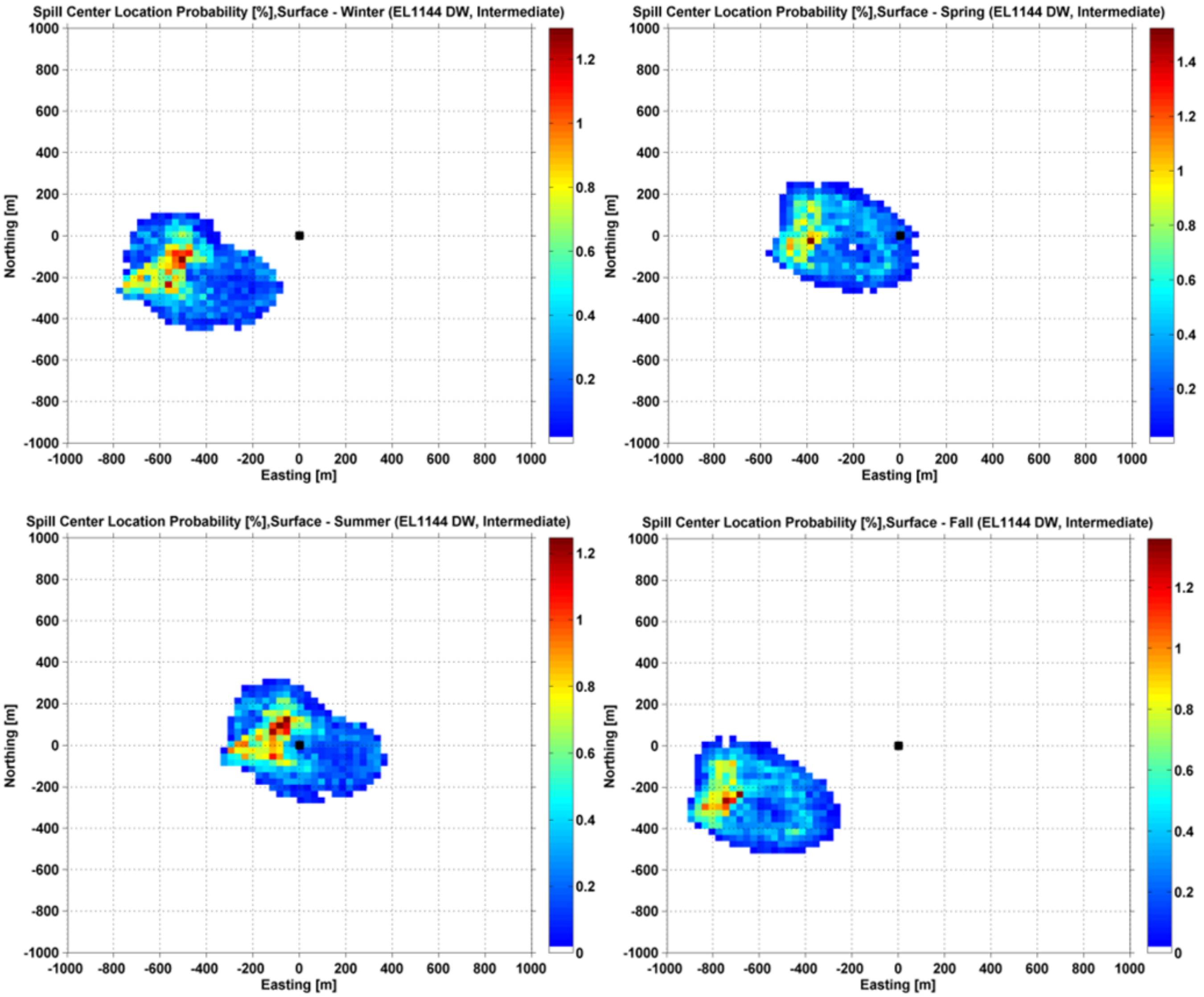


Table 4-2 EL-1144 Deepwater Jurassic Example Well Location, Seasonal SBM Footprint Statistics, Production Phase

SBM DISPERSION		Distance from Site (m)		Footprint LENGTH (m)		Footprint AREA (m2)		Layer Thickness (cm)	
		max	median	max	median	max	median	max	avg
Surface	winter	838	573	215	119	9000	4500	7.1	1.7
	spring	589	370	205	124	9000	4500	7.1	1.7
	summer	364	184	220	117	9000	4500	7.1	1.7
	fall	982	743	210	123	9000	4500	7.1	1.7
BOP	winter	57	57	33	32	3600	900	28.3	25.1
	spring	57	57	33	32	3600	900	28.3	23.7
	summer	57	41	33	32	3600	900	28.3	23.6
	fall	57	57	33	32	1800	900	28.3	27.2

Figure 4-2 Probability Map of SBM Spill Footprint Locations for the EL-1144 site, Production Phase

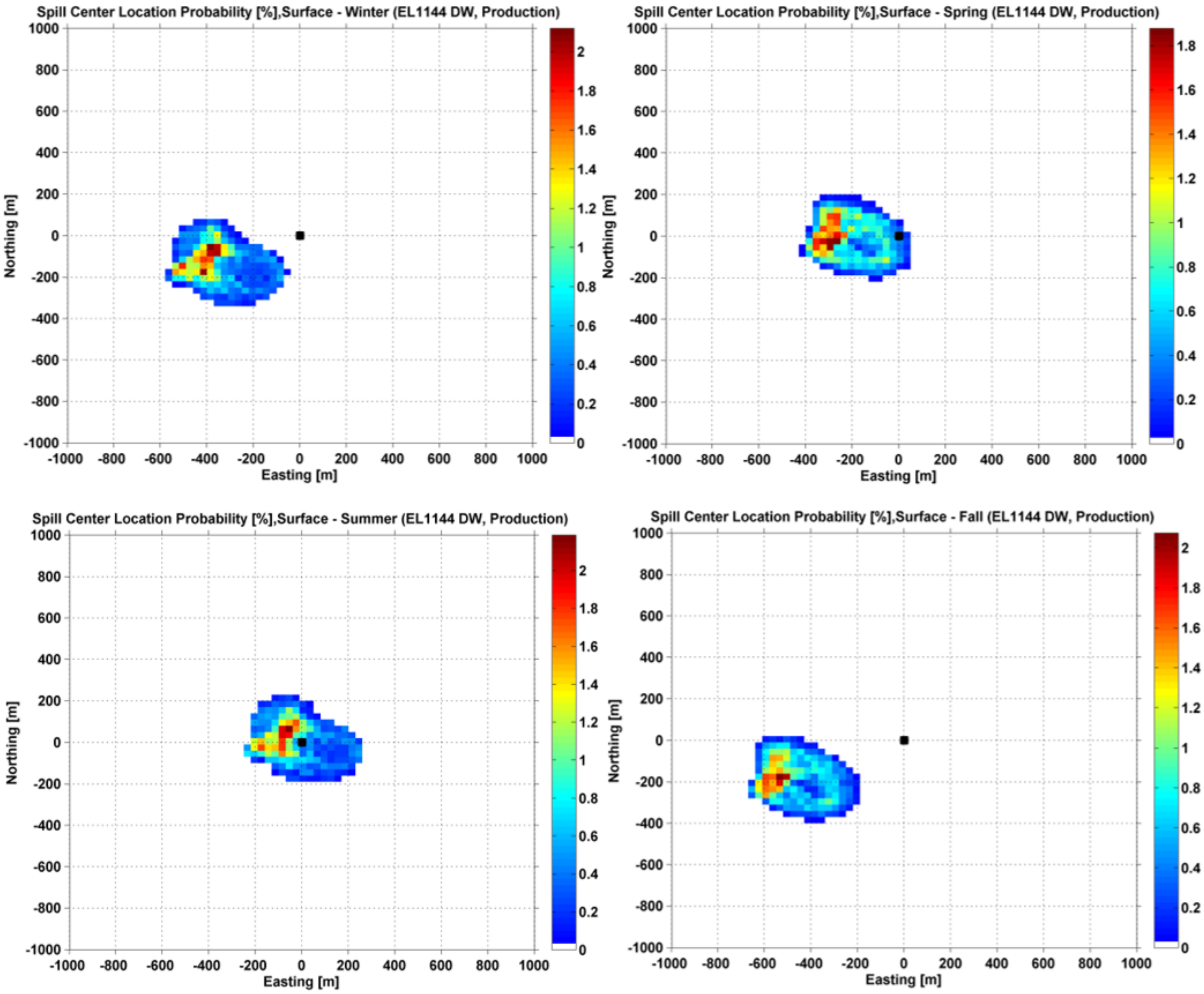
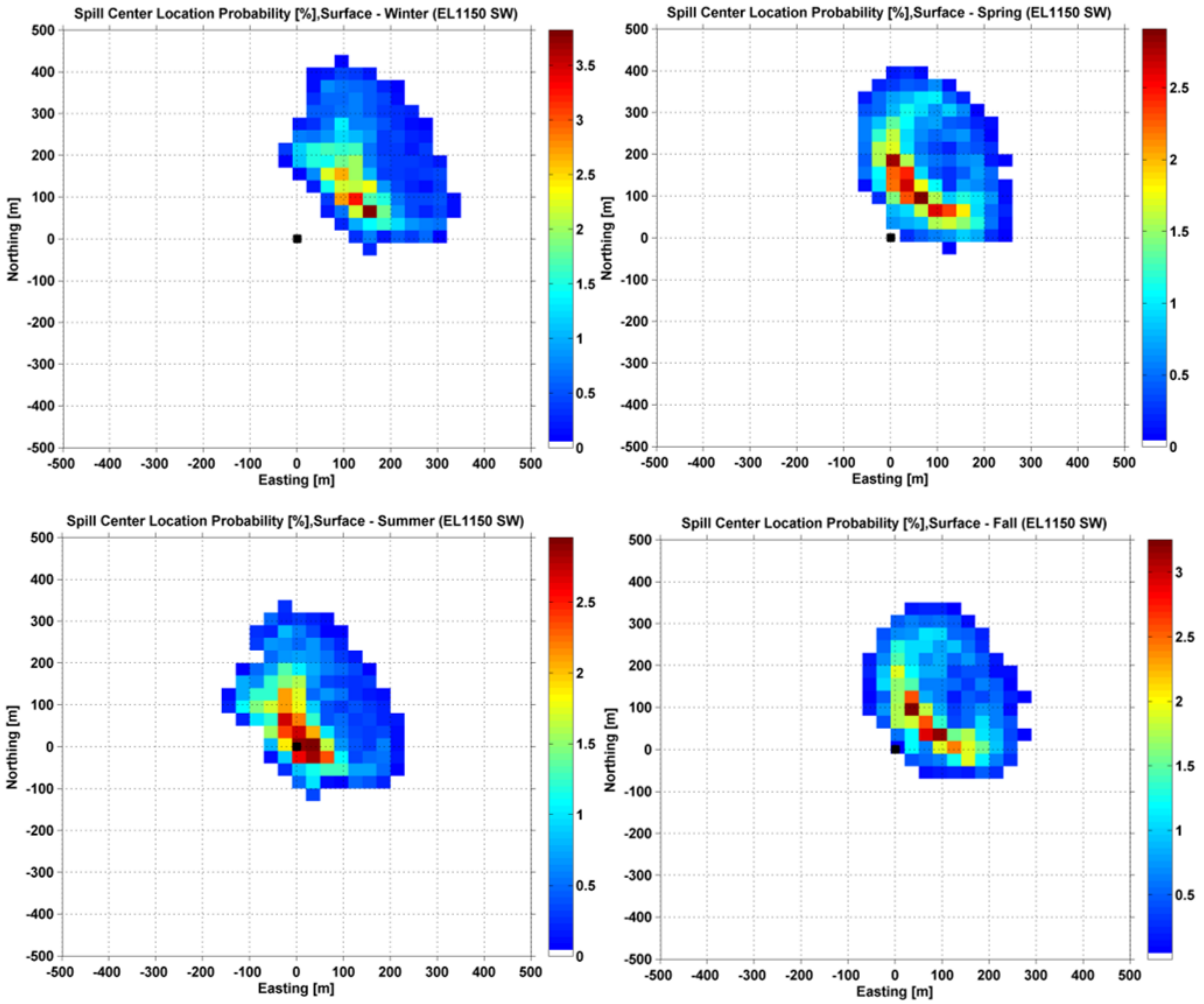


Table 4-3 EL-1150 Shallow Water Cretaceous Example Well Location, Seasonal SBM Footprint Statistics

SBM DISPERSION		Distance from Site (m)		Footprint LENGTH (m)		Footprint AREA (m2)		Layer Thickness (cm)	
		max	median	max	median	max	median	max	avg
Surface	winter	424	201	246	82	9900	2700	7.1	2.6
	spring	388	170	247	84	9900	2700	7.1	2.6
	summer	322	106	250	81	9000	2700	7.1	2.7
	fall	338	146	237	83	9900	2700	7.1	2.6
BOP	winter	41	14	39	33	2700	900	9.9	8.2
	spring	57	41	39	33	2700	900	9.9	7.7
	summer	57	41	39	33	2700	900	9.9	7.9
	fall	57	41	38	33	2700	900	9.9	7.7

Figure 4-3 Probability Map of Spill Center Locations for the EL-1150 site



5.0 CLOSURE

This report presents the data and methods used to model potential accidental SBM release during Nexen exploration drilling at two Flemish Pass example well locations. Results from the modelling are presented which include SBM spill footprint locations, area covered and thickness statistics for four seasonal predictions at each location.

Yours sincerely,

Amec Foster Wheeler Environment & Infrastructure,
a Division of Amec Foster Wheeler Americas Limited

Prepared by:	Reviewed by:
<Original signed by>	<Original signed by>
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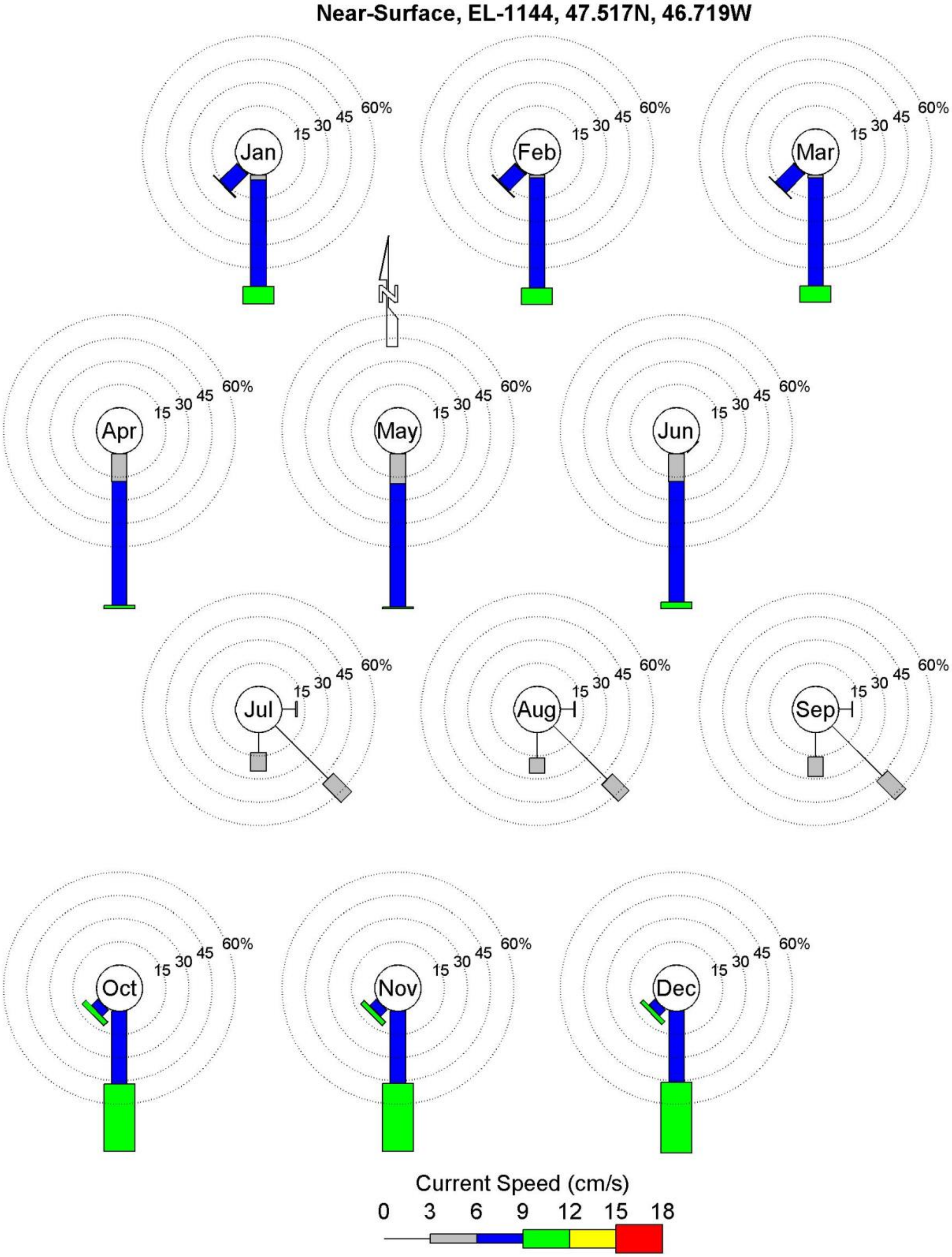
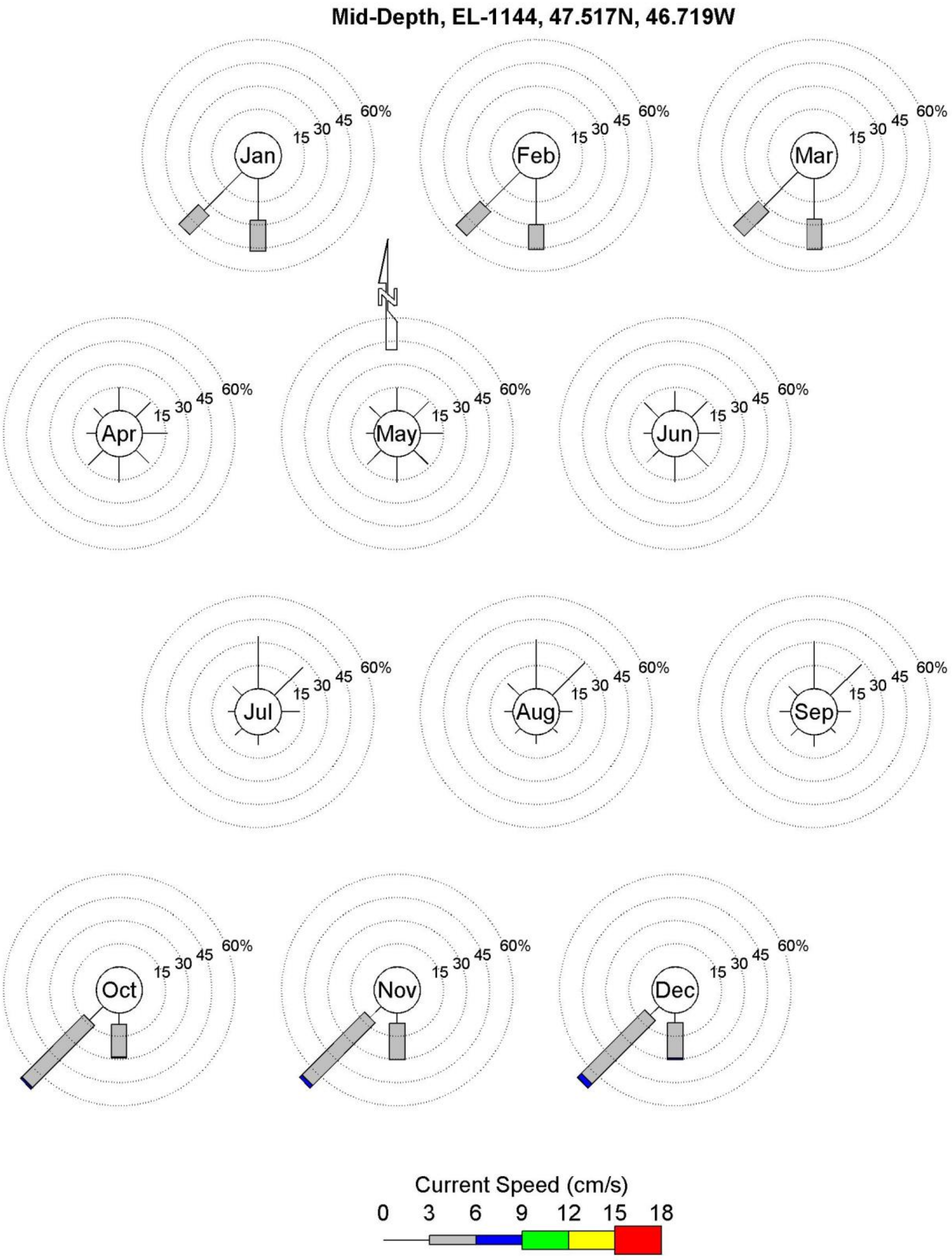
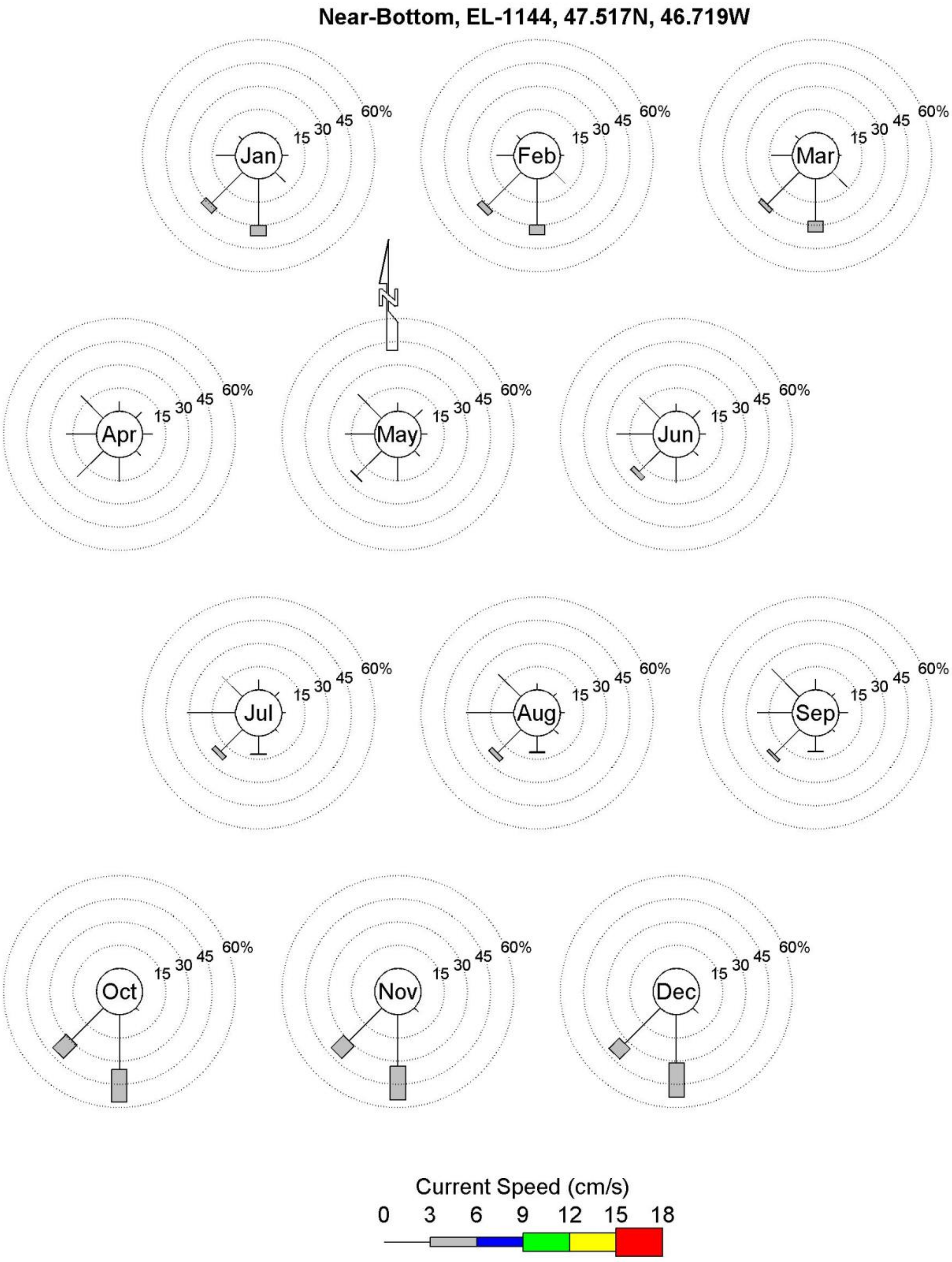
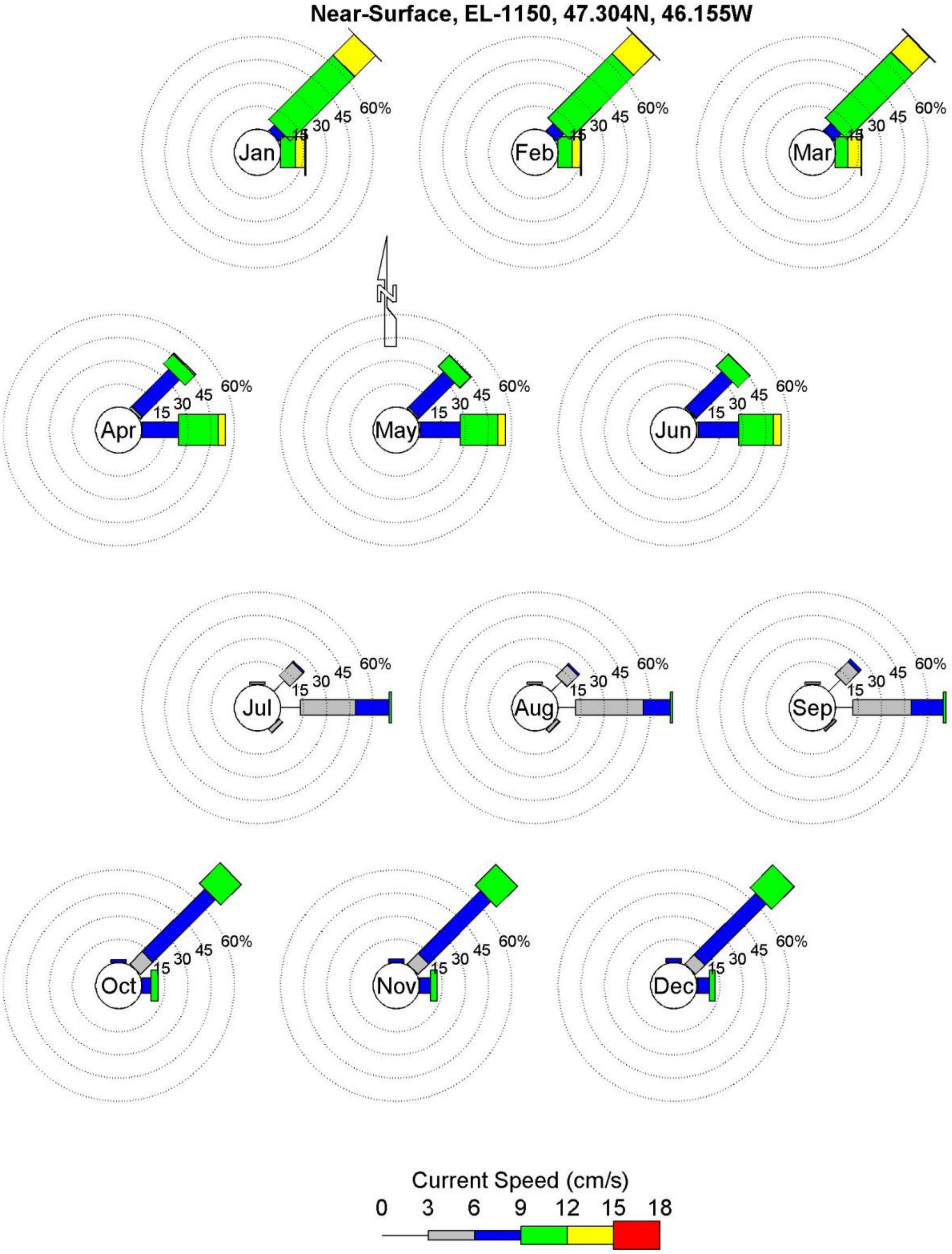
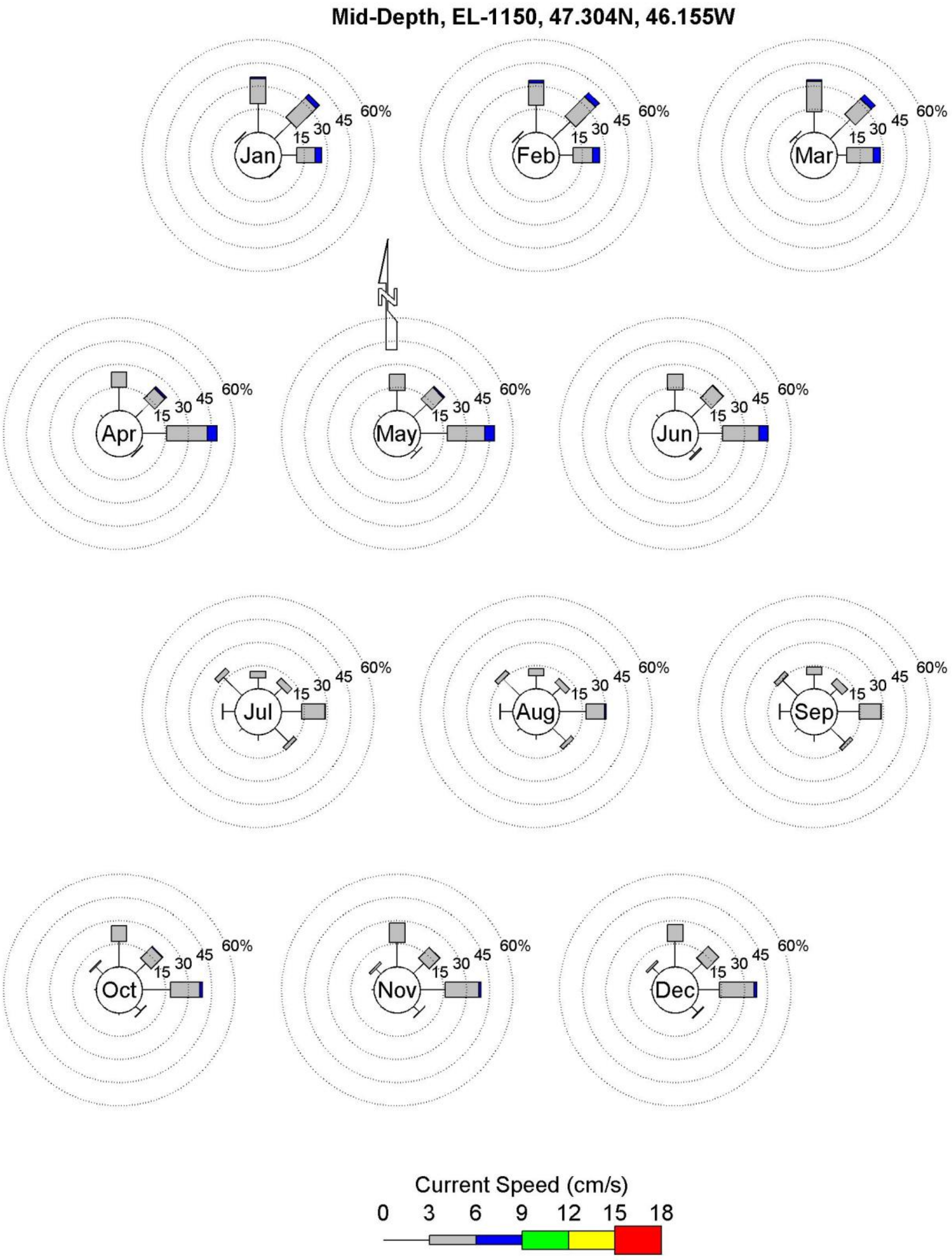
APPENDIX A-1: OCEAN CURRENTS FOR MODELLING LOCATIONS


Near-Surface, EL-1144, 47.517N, 46.719W
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
15
30
45
60%
N
Current Speed (cm/s)
0
3
6
9
12
15
18


Mid-Depth, EL-1144, 47.517N, 46.719W
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
15
30
45
60%
N
Current Speed (cm/s)
0
3
6
9
12
15
18


Near-Bottom, EL-1144, 47.517N, 46.719W
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
15
30
45
60%
N
Current Speed (cm/s)
0
3
6
9
12
15
18


Near-Surface, EL-1150, 47.304N, 46.155W
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
15
30
45
60%
N
Current Speed (cm/s)
0
3
6
9
12
15
18


Mid-Depth, EL-1150, 47.304N, 46.155W
Jan
Feb
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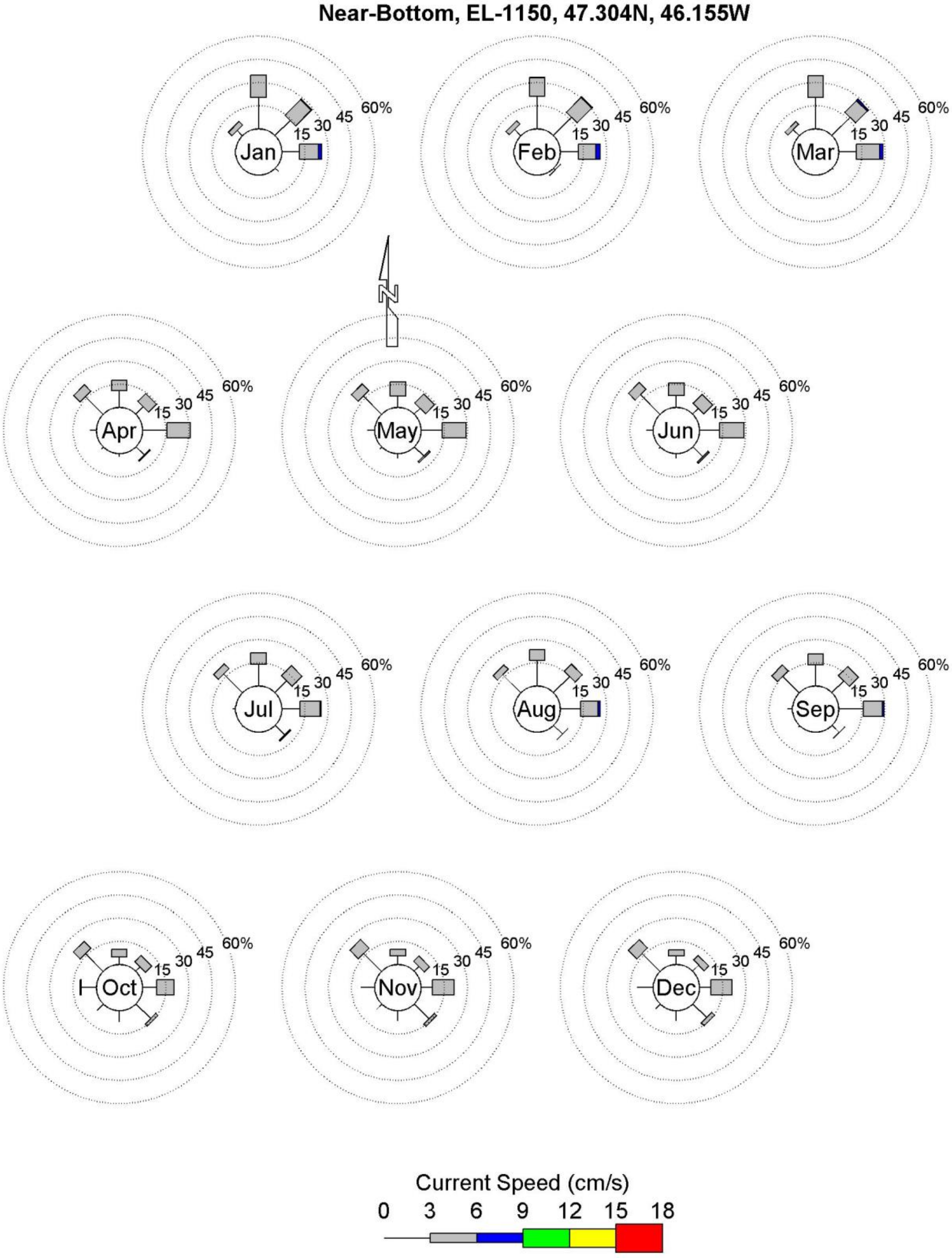
Oct
Nov
Dec
15
30
45
60%
N
Current Speed (cm/s)
0
3
6
9
12
15
18


Near-Bottom, EL-1150, 47.304N, 46.155W
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
15
30
45
60%
N
Current Speed (cm/s)
0
3
6
9
12
15
18