Husky Energy

White Rose Extension Project

Drill Cuttings and WBM Operational Release Modelling

June 2012

Husky Energy SUNCOR ENERGY nalcor energy

Environmental Impact Assessment

White Rose Extension Project

Drill Cuttings and WBM Operational Release Modelling

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Executive Summary

Husky Oil Operations Limited (Husky), on behalf of the White Rose Extension Project (WREP) proponents, Husky, Suncor Energy Inc. and Nalcor Energy – Oil and Gas Inc., is leading the development of the WREP. The White Rose field and satellite extensions are located in the Jeanne d'Arc Basin, of the Grand Banks of Newfoundland, 350 km east of St. John's, in approximately 120 m of water. The current focus of the WREP is on the development of West White Rose, with evaluation of options for development, including a wellhead platform (WHP), subsea tiebacks, or a combination of both. All development options will be tied back to the existing *SeaRose* (floating production, storage and offloading) *FPSO*.

As part of the environmental assessment process, this report presents the results of a modelling study undertaken by AMEC to characterize the release and dispersion patterns of drill cuttings and drilling muds during production well drilling over the WREP lifetime. Five base case scenarios were modelled: one each for WHP (40 wells) and subsea (16 wells) options, plus scenarios for two potential new drill centres (West and North, 16 wells each).

The analysis of the drill cuttings discharges was accomplished by using a numerical computer model developed by AMEC to determine cuttings depositions at the time of drilling operations. In the model, a transport computation is employed to simulate the advection of the dispersed drill cuttings materials (the small pieces of rock, ranging in size from gravel to fine sand, created when a well is drilled to reach an oil or gas reservoir; the material is forced up the annulus of the well hole as drilling proceeds) in three dimensions through the water column, following release into the sea, until the particles come to rest on the sea bottom. For the purposes of predicting their physical deposition on the seabed, the cuttings are considered as a composition of particle types or sizes; typically larger cuttings pieces pebbles coarse sand, medium sand and fines. These particle sizes are assumed to be generally representative of the materials likely to be encountered in the area and generated using water-based muds (WBM) for the upper well hole sections and synthetic-based muds (SBM) for deeper hole sections: especially during directional drilling operations where drilling conditions are more difficult and hole stability is critical to safety and success.

Cuttings from drilling the upper two well sections with WBM will all be released as per the Offshore Waste Treatment Guidelines close to the seafloor, under either the WHP option with chute release, or under the subsea option with mobile offshore drilling unit (MODU) riserless drilling. Therefore, there is little time for the cuttings to be transported large distances by the ambient currents.

Under the WHP scenario, the drift of cuttings is restricted to a range generally within 2 to 4 km. The maximum extent is approximately 5 km to the southeast and northeast. Cuttings (exclusively WBM) thicknesses are 1 mm or less over these regions. Cuttings thicknesses directly under the WHP are modelled to be 1.8 m. In the immediate vicinity of the WHP, within 100 m, initial cuttings thicknesses are predicted to be 1.4 cm on average, and as high as 8.6 cm. Due to the large volume of material generated by drilling the (initial) 40 wells, a maximum height of 1.8 m (assuming slumping of the cuttings pile, a maximum height is more likely on the order of 0.5 to 1.0 m) is predicted directly at the WHP. These will be almost exclusively the fast-settling pebbles and coarse sand (a very small percentage of the fines will drift for a time and ultimately settle

near the WHP), whereas at distances greater than about 50 to 200 m, the deposits will be exclusively fines. From 100 to 200 m out from the WHP, thicknesses are predicted to be 1.9 mm on average and a maximum of 3.4 mm. From 200 to 500 m, thicknesses average 1.8 mm and are a maximum of 4.6 mm.

Under the subsea scenario, the footprint of WBM cuttings is smaller than that for the WHP option, with a range generally restricted to within 2 km. The primary difference factor is the reduced number of wells drilled (16 as opposed to 40) and the reduced volume of cuttings material released (267 m^3 per well as opposed to 295 m^3) for the subsea option. Under the WHP option (40 wells), approximately 11,800 m^3 of WBM cuttings are deposited, while the volume under the subsea drill centre option (16 wells) is approximately two-thirds the volume of cuttings (4,272 m^3 of WBM, 4,304 m^3 of SBM).

For drilling of the deeper intermediate and main hole sections - for both WHP and MODU (subsea option and potential future drill centres) - SBM will be used. Under the WHP option, the base case is to use two cuttings reinjection wells into which treated SBM and cuttings will be re-injected (i.e., no return of materials to the sea). Under the subsea drill centre option, the majority of SBM cuttings are deposited quite close to the drill centre, due to the large percentage of large cuttings pieces having fast settling speeds. Patches of light dustings (0.1 mm or less) of fines extend as far as approximately 20 to 25 km to the north and 18 to 20 km to the south. Cuttings thicknesses directly under the MODU are modelled to be 2.2 m. Again, this maximum height does not account for slumping of the cuttings ‘pile’. Assuming a likely angle of repose of approximately 30 degrees, one might estimate from these thicknesses, a maximum height more likely on the order of 0.75 to 1.2 m. Nor is account made of the possibility of cuttings near the cuttings deposits directly about the excavated drill centre(s) being cleared by a seafloor cuttings transportation system and moved to another seafloor location.

In the immediate vicinity of the drill centre, within 100 m, initial SBM cuttings thicknesses, now overlain on top of WBM cuttings from drilling of the top two well sections, are predicted to be 11.7 cm on average, and as high as 98.9 cm. From 100 to 200 m out from the drill centre, thicknesses are predicted to be 1.0 mm on average and a maximum of 6.6 mm. From 200 to 500 m, thicknesses average 0.1 mm and are a maximum of 0.3 mm. Generally comparable values are predicted under the similar MODU drilling for the two other subsea drill centre drilling scenarios.

The environmental effects of released WBMs are generally associated with the potential physical toxicity of fine particulate matter, either barite or bentonite, which are sometimes used to increase the density of the mud mixture, and these additives have greater potential to affect filter feeding organisms as they remain suspended in the bottom boundary layer. The most likely composition of the WBM planned for use during the WREP does not include these weighting agents; therefore, no amount of particulate matter is expected to be introduced to the environment due to the release of WBM during any stage of the drilling process. The anticipated composition of WBM consists primarily of brine, with the possible addition of sodium acid pyrophosphate, a white powder that is water-soluble. No component of the WBM has been identified as potentially toxic; therefore, the dispersion of WBM following the discharges was not treated in further detail.

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1.0 INTRODUCTION

1.1 Project Background

Husky Oil Operations Limited (Husky), on behalf of the White Rose Extension Project (WREP) proponents, Husky, Suncor Energy Inc. and Nalcor Energy – Oil and Gas Inc., is leading the development of the WREP.

The White Rose field and satellite extensions are located in the Jeanne d'Arc Basin, of the Grand Banks of Newfoundland, 350 km east of St. John's in approximately 120 m of water. Initial development was through excavated subsea drill centres, with flexible flowlines bringing production to a centralized floating production platform, the *SeaRose FPSO* (floating production, storage and offloading) vessel.

The current focus of the WREP is on the development of West White Rose, delineated in 2006. Husky and its co-venturers are evaluating options for development of the WREP resources, including subsea tiebacks, a well head platform (WHP), or a combination of both. All development options will be tied back to the existing *SeaRose FPSO*. Additional details are presented in Section 2.0 and in the WREP Project Description (Husky 2012).

1.2 Objectives

As part of the environmental assessment process, this report presents the results of a modelling study undertaken by AMEC to characterize the release and dispersion patterns of drill cuttings and drilling muds during production well drilling over the WREP lifetime.

Drill cuttings are the small pieces of rock, ranging in size from gravel to fine sand, created when a well is drilled to reach an oil or gas reservoir. The material is forced up the annulus of the well hole as drilling proceeds.

Drilling muds are used to keep the well clean, lubricate the drill bit and control pressure within the well. Water-based muds (WBM) are used for drilling of upper well hole sections; synthetic-based muds (SBM) are used in deeper hole sections, especially during directional drilling operations where drilling conditions are more difficult and hole stability is critical to safety and success.

The objectives of this study were:

- To model the deposition pattern of drill cuttings on the seabed (e.g., weight, density, thickness of cuttings) over the WREP lifetime, for the two WREP development options under consideration, by using cuttings particle characterizations and ocean currents as key inputs
- To model the short-term and long-term dispersion and fate in the marine environment of WBM operational releases based on seasonal oceanographic conditions plus a range of different tidal scenarios

2.0 DRILLING PROGRAM

Two development options are being considered for the West White Rose component of the WREP: a WHP, which essentially is a fixed drilling platform; or a subsea drill centre with wells drilled by a mobile offshore drilling unit (MODU). Also as part of the WREP are up to three additional drill centres in other areas of the White Rose field. If a WHP is used in the West, the total number of wells could be up to 88: 40 wells from the WHP, plus up to three additional subsea drill centres, each with up to16 wells (Husky 2012). For the subsea drill centre option, the total number of wells could be up to 64: 16 wells each for West White Rose plus up to three additional drill centres (Husky 2012). These wells will be a combination of producing, water injection, gas injection and (WHP option only) cuttings reinjection.

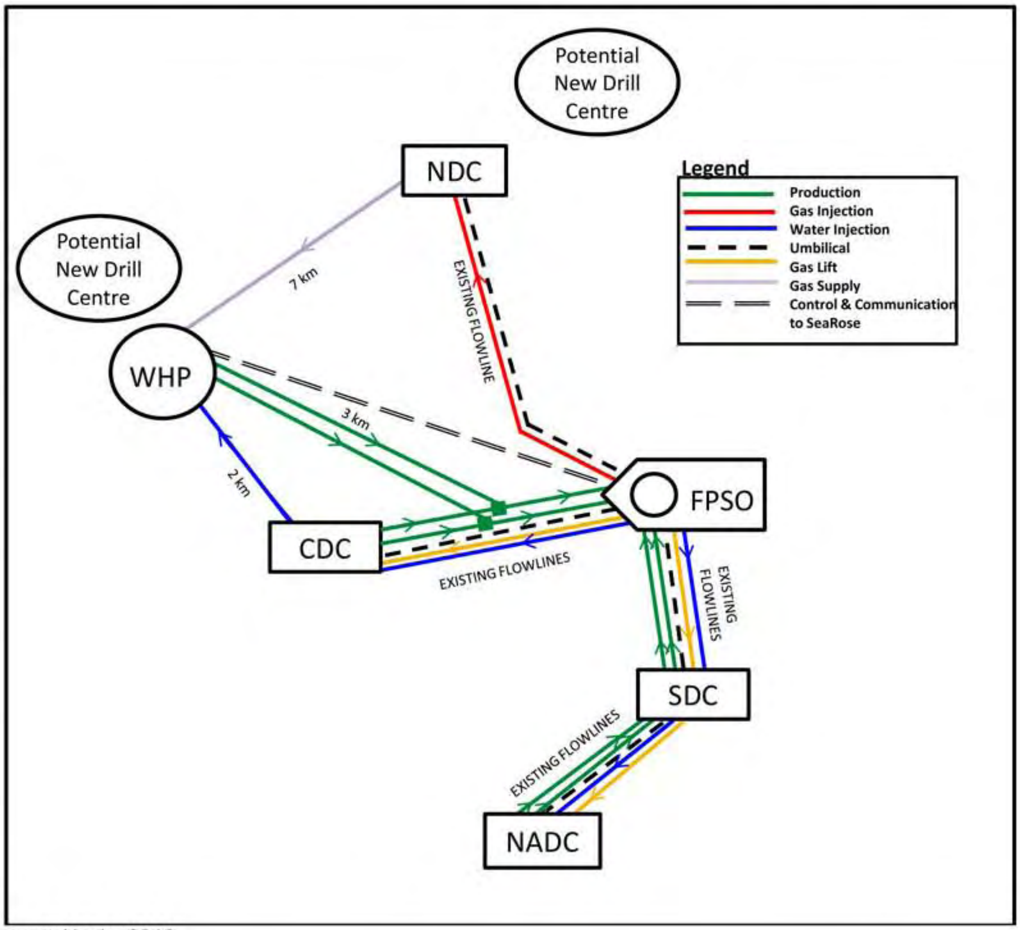
The WHP location and three potential new drill centres are shown, in relation to the existing White Rose FPSO and existing drill centres, in Figure 2-1.

Water-based mud and cuttings associated with drilling the upper two well hole sections (conductor, surface) will be released to the sea. Under the WHP option, the preliminary design is for the mud and cuttings materials, to be returned to the rig floor and released via an exit chute above the seafloor. Under the subsea drill centre option, the conductor and surface hole sections will be drilled in an open circuit manner without a riser in place; mud and cuttings will be released to the seafloor. In the future, the resultant mud and cuttings deposits about the excavated drill centre may have to be cleared from the drill centre to another seafloor location.

WBM will be used exclusively in drilling of the upper two well sections. At the conclusion of this drilling, there will be a bulk ‘instantaneous’ release of WBM as part of a swap out to SBM for drilling of the deeper well sections.

For drilling of the deeper intermediate and main hole sections - for both WHP and MODU drilling - SBM will be used. Under the WHP option the base case is to use two cuttings reinjection wells into which treated SBM and cuttings will be re-injected (i.e., no return of materials to the sea).

For MODU drilling (subsea option and potential future developments), a riser will be installed after completion of the top two hole sections, which will then keep the drilling fluids as a closed loop system and bring the SBM and cuttings back to the rig. Cuttings are processed on the rig in order to recover a large portion of the mud to be reused; however, a small portion of the mud will remain attached to the cuttings and will be discharged with, in accordance with the Offshore Waste Treatment Guidelines (OWTG) (National Energy Board (NEB) et al. 2010).



Source: Husky 2012

Figure 2-1 Potential Wellhead Platform Concept Integration into Existing White Rose Facilities

Well hole section sizes and depths are listed in Table 2-1. All MODU values (subsea option and potential future developments) represent a per well basis. Well lengths assumed are for a typical producing well from a MODU, which is approximately 5,500 m (mKB). The WHP will have a similar well design to the subsea wells; the main difference for the purposes of this modelling is the conductor size (1,067 mm for WHP and 914 mm for MODU).

Table 2-1 Well Hole Sections

Well Hole Section	Hole Size (mm)	Casing Setting Depth (mKB)
Conductor WHP	1,067.0	230
Conductor MODU	914.0	230
Surface	406.0	1,200
Intermediate	311.0	3,500
Main	215.9	5,500
Source: J. Swain pers. comm.		

The associated estimated drill cuttings and drill mud volumes and release locations for the WREP wells, for both WHP and subsea development options, are presented in Table 2-2 and Table 2-3, respectively.

Table 2-2 Drill Cuttings Volumes and Release Locations

Well Hole Section	WHP		Subsea	
	Volume (m^3)	Release Location	Volume (m^3)	Release Location
Conductor	107	shale chute (A)	79	seafloor (B)
Surface	188	shale chute (A)	188	seafloor (B)
Intermediate	--	treat and inject	192	subsea (C)
Main	--	treat and inject	77	subsea (C)

Notes:
(A) Elevation of chute exit from WHP estimated at 20 m above seafloor: to be confirmed during WHP design
(B) WBM cuttings for top two sections estimated release at 10 m above seafloor
(C) SBM cuttings treated prior to release. Estimated release at 20 m below sea surface
Source: J. Swain pers. comm.

Table 2-3 Drill Mud Volumes and Release Locations

Well Hole Section	WHP		Subsea	
	Volume (m^3)	Release Location	Volume (m^3)	Release Location
Conductor	214 WBM	shale chute (A)	158 WBM	seafloor
Surface	470 WBM	shale chute (A)	440 WBM	seafloor
Intermediate	--	SBM returned to surface: treated and re-injected	26 SBM on cuttings --	subsea (B)
Main	--	SBM returned to surface: treated and re-injected	14 SBM on cuttings --	subsea (B)

Notes:
(A) Elevation of chute exit from WHP estimated at 20 m: to be confirmed during WHP design
(B) There is no discharge of SBM on its own. On release is residual SBM left on cuttings after treatment.
Source: J. Swain pers. comm.

Mud volumes have been specified for mud loss during hole cleaning and displacement during cementing for the conductor section and for hole cleaning and swapping out on completion of the surface section, when switching from WBM to SBM. While each hole section may require specific hole cleaning and mud conditioning, that will be determined during the actual drilling process.

3.0 DRILL CUTTINGS DEPOSITION

The drill cuttings deposition primary model considered sequences of wells to be drilled for the WREP – both WHP and subsea development options - and the sequence of cuttings discharges. The subsequent path of the discharged cuttings (with advection as a result of the ambient ocean current) to their ultimate fate on the seabed was predicted with a three-dimensional sedimentation computer model.

3.1 Methods

3.1.1 Advection Dispersion Model Description

The analysis of the drill cuttings discharges was accomplished by using a numerical computer model developed by AMEC to determine cuttings depositions at the time of drilling operations. The AMEC Advection Dispersion Model (ADM) software is written in Visual Fortran and developed based on previous corporate experience and modelling algorithms including those from the Hibernia (Hodgins 1993) and White Rose (Hodgins and Hodgins 2000) cuttings fate modelling studies. The ADM model has also been used as part of the Hebron Project environmental assessment (AMEC 2010).

In the model, a transport computation is employed to simulate the advection of the dispersed drill cuttings materials in three dimensions through the water column, following release into the sea, until the particles come to rest on the sea bottom. For the purposes of predicting their physical deposition on the seabed, the cuttings are considered as a composition of particle types or sizes; typically larger cuttings pieces pebbles coarse sand, medium sand and fines. These particle sizes are assumed to be generally representative of the materials likely to be encountered in the area and generated using WBM or WBM.

At any given time, a particle is assumed to be subject to independent displacing forces due to the ocean current and to a fall velocity that is constant for a given particle type. A term to model turbulent diffusion is added to the displacements. Over the time-step of the available ocean current data, the displacements are calculated and added to yield a new particle position. Vector additions are computed over each successive time step until the simulation terminates with deposition on the sea bottom (which may be some time after well drilling has terminated).

A model grid is selected to encompass the drilling area and possible domain for the deposition of the cuttings. The model tracks the fate and deposition of the particles. In addition to each particle’s path, the weight of material is tracked. This is the primary particle attribute. After completion of a model run, when all particles have settled, or have reached the model grid boundaries (in which case, they are taken to have drifted outside the domain and are tabulated as ‘lost’), each particle is binned in one of the model grid cells and the total weight, W, is calculated. In addition, the following other parameters are calculated for each grid cell:

$$C = W \times 1000 / A \quad (1)$$

$$T = C / \gamma \quad (2)$$

$$OC = OC_{initial} \times W / \left(A \times h \times (1 - n) \times \gamma_s\right) \quad (3)$$

where W = cuttings weight (kg)
C = cuttings density (g/m^2)
T = cuttings thickness (mm)
OC = oil concentration on cuttings (mg/kg)
A = area of one grid cell (m^2)
γ = in situ bulk density (1,850 kg/m^3)
$OC_{initial}$ = initial oil concentration
h = sediment mixing depth (0.08 m)
n = seabed porosity (0.4)
γ_s = specific weight of cuttings (2,596 kg/m^3)

The approach for calculating T and OC follows that employed by Hodgins and Hodgins (2000). The oil concentration on cuttings, OC, is the weight of material times its initial concentration, divided by the volume of an assumed thin benthic layer in which the cuttings are assumed to settle and mix with the seabed sediments. Oil concentration is only applicable where SBM are discharged during MODU drilling. All cuttings are assumed to be adequately treated to reclaim oil as required by present regulations. Oil content on cuttings produced during drilling with SBM, $OC_{initial}$ was set to 7.4 g / 100 g, equal to 6.9 g / 100 g oil on wet solids, as per the OWTG (NEB et al. 2010).

3.2 Model Input

3.2.1 Scenarios, Well Sequences, Well Types

Five base case scenarios were modelled:

- WHP option: 40 wells drilled from a WHP at West White Rose (WWRX1)
- Subsea option: 16 wells drilled from a MODU at West White Rose (WWRX1)
- Three potential new drill centres - as introduced in LGL (2007) – now with 16 wells each drilled by a MODU:
    - South White Rose Extension (SWRX)
    - West White Rose Extension – a second drill centre (WWRX2)
    - North White Rose Extension (NWRX)

Drilling may commence potentially in Q4 2016 for the WHP or Q4 2015 for the subsea drill centre (subsea) (Husky 2012) (i.e., a Q4 seasonal start for either option). The potential additional subsea drill centres (SWRX, WWRX2, NWRX) could be developed in a similar timeframe or later in the WREP life (Husky 2012).

While a drilling schedule has not been developed, the average well time is estimated to be 93 days. This assumes a straight drill and complete operation for each well with no batch drilling. Within this period, the associated operational mud and cuttings releases, for this modelling exercise, are estimated to take place as shown in Table 3-1, as applicable for the WHP or subsea options, and for each of the three potential additional subsea drill centres drilled with MODU.

While the exact timing within the estimated 93 days is not critical, to simulate when in this interval the release of materials takes place, the four well hole section discharges are simulated to take place at days 3, 20, 40, and 60 (of 93).

Table 3-1 Discharge of Mud and Cuttings

Well Hole Section	Duration of Discharge (days)	Comments
Conductor	1	- half of the volume released during hole cleaning, drilling time of duration ~ 7 h - plus similar length of time estimated for displacement of hole section contents (second half of volume released) during cementing - therefore, estimate approximately 1 day total as the period over which material is released to sea. Note that these times do not include time for preparing to spud, drilling, circulating, tripping, casing, cementing
Surface	2	- half of the volume released during hole cleaning, drilling time of duration ~ 42 h - followed by bulk ‘instantaneous’ release of similar volume upon fluid (mud) swap out - these times not include time for preparing to spud, drilling, circulating, tripping, casing, cementing
Intermediate	3	- estimate
Main	8	- estimate

With an average of 93 days, there will be no temporal overlap between successive wells, with respect to mud and cuttings dispersion. Distribution of wells over the seasons (up to 88 or 64 wells for WHP or subsea drill centre options, respectively) is accounted for by running scenarios using seasonal current and density fields.

Approximate duration of each step is also provided. Interruptions will occur during or between steps, so that the total duration of the program will exceed the sum of the individual durations; however, in terms of mud dispersion, an uninterrupted program is the most conservative, worst case scenario.

Two generic well types were considered for cuttings release:

- a WHP-drilled well consisting of WBM cuttings for conductor and surface sections
- a MODU-drilled well consisting of WBM cuttings for conductor and surface sections (as for the WHP) and SBM cuttings for intermediate and main sections

The cuttings compositions for both well types are presented in Section 3.2.2.

3.2.2 Cuttings Particle Characterization

No cuttings particle size distributions that would quantify the composition of different mineral materials as a function of well depth are available. The actual compositions will depend on rate of penetration, rotary table speed, hydraulics, bit selection and the geology of the well.

Information for the Hibernia K-18 well is available from a sieve analysis performed by AGAT Laboratories (1993) and details depths of 900 to 5,010 m. This has been employed in the previous cuttings modelling for Hibernia, Terra Nova and White Rose (Hodgins 1993; Hodgins and Hodgins 1998, 2000), and Hebron (AMEC 2010), with estimates of percentage pebbles, coarse sand, medium sand and fines, and is the best available source of information.

Experience with both SBM and WBM has shown that SBM systems are not dispersive; cuttings are large, and they remain intact until deposited on the seabed. Conversely, the Hibernia K-18 well was drilled with a dispersive water-based drilling fluid to total depth. This would explain the very high percentage of fines seen in the Hibernia K-18 samples[1]. Experience with oil-based drilling fluids is that shales do not disperse, they become oil coated and remain hydrophobic up to and including when they are deposited on the seabed. This will then result in a much higher slip or settling velocity as particle sizes remain large (C. Mazerolle, pers. comm.).

For the WBM-drilled sections, mean percentages of the cuttings composition based on these Hibernia K-18 measurements for the sampled depths corresponding approximately to the WREP conductor and surface section depths are employed (Table 3-2, Table 3-3).

Cuttings drilled with SBM will be large, on the order of 2.5” in length, 1” wide, and 1/8” thick. To characterize these large cuttings as spherical particles for the model, their volume corresponds to a particle diameter of about 1 to 3 cm. This large cutting size type was added to the pebbles, coarse sand, medium sand and fines types used to characterize the WBM-cuttings noted above. It was assumed that most (approximately 70 percent) of the cuttings will be large, approximately 20 percent 0.5 to 1 cm, 5 percent 0.1 cm, with the remaining 5 percent being very fine particles, with diameters of 0.01 cm (Table 3-3).

[1] mean values of 87 percent for well depths less 1,400 m, 61 percent from 1,500 to 4,000 m, and 44 percent for 3,710 to 5,010 m

Table 3-2 Particle Size Distributions Used for Shallow Water-based Mud Drilled Wells

	Measured Weight Percentage Mineral			
Depth (m)	**Pebble**	**Coarse Sand**	**Medium Sand**	**Fines**
900	14.1	0.9	0.7	84.3
1,000	14.1	0.9	0.7	84.3
1,110	4.8	2.9	0.7	91.6
1,200	11.5	3.6	0.6	84.4
1,300	6.0	2.2	0.6	91.2
1,400	8.5	1.6	1.0	88.9
Mean	9.8	2.0	0.7	87.4
Median	10.0	1.9	0.7	86.6
Maximum	14.1	3.6	1.0	91.6
Minimum	4.8	0.9	0.6	84.3
Standard Deviation	4.0	1.1	0.2	3.5

Table 3-3 Cuttings Particle Size Composition

Well Type	Measured Weight Percent Material				
	Large Cuttings	**Pebbles**	**Coarse Sand**	**Medium**	**Fines**
WBM drill cuttings		10	2	1	87
SBM drill cuttings	70	20	5		5
Notes:					

It is assumed that the cuttings will enter the sea in a disaggregated form. The model considered the large cuttings, pebble and sand materials to remain disaggregated in their fall to the seabed. Any fines were assumed to aggregate into flocs of size of approximately 0.1 mm and settle with a constant speed.

Particle fall velocities, w, were estimated from the particle diameter using the following relationships, from Sleath (1984):

$$w = 4.2\sqrt{D}, D > 0.0001m \tag{4}$$

$$w = 12x10^4 D^2, D \le 0.0001m \tag{5}$$

where w is the fall velocity in m/s and *D* is the diameter in m.

For the five particle types considered, this yields the values reported in Table 3-4.

Table 3-4 Cuttings Particle Size Characterization

Particle Parameter	Cuttings Material				
	Large Cuttings	Pebbles	Coarse Sand	Medium Sand	Fines
Particle diameter (mm)	20	7	1	0.25	0.1
Particle fall velocity (m/s)	0.594	0.351	0.133	0.066	0.0012

3.2.3 Ocean Currents

Together with particle settling velocities, horizontal current is the other key factor in determining how far cuttings may potentially be dispersed, so it is important to employ a good characterization of the local current behaviour as a driving force for the model. Since the cuttings will settle through the water column, a characterization of the currents as a function of depth is required.

The temporal coverage of the current data record allows application of the drilling well sequences and provides some statistical reliability of conclusions drawn from analysis of the current data. The regularity of time spacing is essential due to the structure of the advection calculations in the model.

The ocean currents at White Rose are characterized by high variability, most of which is associated with the ocean's response to various atmospheric disturbances, ranging from atmospheric pressure systems, wind forcing during storms, to the influence of tropical cyclones tracking in the area. In contrast, the highly-predictable tidal current components play a relatively minor role, and explain approximately 20 percent of the current variability in the area (Oceans Ltd. 2011). In order to capture the full range of ocean current variability, including components driven by factors that are difficult to predict, it was deemed appropriate to adapt a subset of the currents measured throughout the full water column at White Rose over the past several years.

The ADCP datasets for the three year period from 2008 through 2010 were analyzed by AMEC for completeness of coverage in each season, and the 2010 dataset was found to be the most complete, with only three gaps in temporal coverage during the year. These gaps lasted approximately 3 days and 8 h, with the last missing period spanning from mid-November to the end of 2010. In order to build a representative time series spanning a full year of uninterrupted coverage, the gaps in the 2010 data were filled with current data from the 2008 dataset from the representative periods. It was found that the raw data contained a high-frequency (at periods less than 1 h) variability, particularly pronounced in the upper half of the water column, that is likely attributable to measurement errors related to unfavorable sampling conditions, rather than real physical processes.

In order to eliminate this unexplained variability, as well as to produce a uniform sampling interval for use in the modelling, the raw time series were resampled at a uniform sampling rate of 10 minutes; they were then low-pass filtered by using a 30-point Finite Impulse Response (FIR) filter to eliminate signals with period smaller than two hours; finally, the filtered signal was resampled at the original 10 minute interval. Three ADCP depth bins, at depths of 28, 60 and 112 m, were selected to represent the conditions at the surface, mid-depth and near the bottom. The seasonal statistics for the processed current for the three depth layers are presented in Table 3-5.

Table 3-5 Seasonal Current Statistics for the Processed Currents Used as Model Inputs

Season	Depth	Max Speed (cm/s)	Mean Speed (cm/s)	Mean Velocity (cm/s)	Direction (to) (°True N)
Winter	Near surface	62	15	4	180
	Mid-depth	62	14	3	178
	Near bottom	40	13	4	165
Spring	Near surface	43	12	2	173
	Mid-depth	26	10	0	175
	Near bottom	31	10	2	170
Summer	Near surface	65	12	1	187
	Mid-depth	51	10	1	183
	Near bottom	31	8	1	174
Fall	Near surface	61	20	4	175
	Mid-depth	47	15	2	179
	Near bottom	40	12	5	163
Source: ADCP data from Oceans Ltd. 2011.					

Illustration of the currents is also provided in Appendix A.

It is assumed that the currents are representative of the WREP locations and are uniform over the deposition grids modelled.

Model Application of Currents

In the model algorithm, as each day of drilling and possible discharge is followed, a corresponding day of current data is input from the year time series file and is used to advect the particles as per equations (6) and (7) in Section 3.2.5. It was assumed that drilling would commence in the fall, for either the WHP or subsea development option, and so an October 1 start date was selected for the modelling of the first well, with each consecutive well beginning 93 days after the last At such time as any well drilling starts or continues into a new calendar year, the one year of currents is reused.

An assumed 93 day well duration translates into a period of approximately 21 years and six months for the WHP development option; approximately six years less for the subsea option, provided the wells are drilled consecutively

3.2.4 Model Geometry

The transport (and spatial extent) and fate of the cuttings was modelled as a function of time. A given well sequence as a number of days drilling was employed. For each day, and for each different size class of material (i.e., the large cuttings, pebbles, coarse sand and fines in Table 3-4), a collection of particles were discharged. Particles were assigned a weight apportioned on the number of days drilling (Table 3-1) and the volume of cuttings associated with the particular well section. A time step was assigned appropriate for the geographic scale and model grid of the study area and the ambient current conditions. It was also necessary to choose time steps appropriate for each of the different particle types which exhibit a range of fall velocities. At each time step in the model, a new location for a given particle was calculated. Selection of too large a time step may yield inaccurate results. Too small a time step makes for overly intensive computations in the model. For the given White Rose domain, the time steps employed are provided in Table 3-6 and Table 3-7.

Table 3-6 Model Time Steps for Water-based Mud Cuttings

	Cuttings Material			
	Pebbles	Coarse Sand	Medium Sand	Fines
Time Step, Δt (s)	20	40	60	600
# Particles per Δt	1	2	3	30
# Steps per day	4,320	2,160	1,440	144

Table 3-7 Model Time Steps for Synthetic-based Mud Cuttings

	Cuttings Material			
	Large Cuttings	Pebbles	Coarse Sand	Fines
Time Step, Δt (s)	20	20	40	600
# Particles per Δt	1	1	2	30
# Steps per day	4,320	4,320	2,160	144

It is instructive to consider these time steps together with the particle settling velocities presented in Section 3.2.2. Their application in the model has a direct bearing on the deposition predictions. For WHP discharge 20 m above the seafloor, the particles will settle to the seabed in times that range from one minute for pebbles and three minutes for the coarse sand, to as long as five hours for the fines. This is further evidence of the large influence of the particle size composition assumptions. A grid was employed in the model to track the spatial extent of the deposition. The model grid was a Cartesian grid centred on the White Rose field and extending out a finite distance both in X (or East-West) and Y (or North-South) directions. A grid consisting of a 2000x2000 array of grid cells each of 32 m x 32 m was selected. This covers any given discharge location for ±32 km. An additional grid cell size of 8 m was also employed to characterize the model domain ±8 km to a higher resolution.

The model runs were conducted for each of the four unique WREP origins: WHP location; and SWRX, WWRX and NWRX potential future subsea drill centres. The subsea development option differed from the WHP option only in that West White Rose was drilled with a MODU rather than from the WHP; and 16 wells as opposed to 40 were drilled with the subsea option. For visualizations of combined scenario results (e.g., for the WHP option, 40 wells at the WHP, plus 16 wells at the SWRX, for a total of 56 wells), model output grids were added, translating the grids in X and Y (to the east or north) to yield the proper distance and orientation between drill centres. Well centre locations presented in the White Rose new drill centre and construction environmental assessment (LGL 2007) were used.

A uniform average depth of 120 m was assumed for the model grid.

3.2.5 Model Algorithm

The path of each particle released is tracked by calculating at each new time step, n+1, its position (*x,y,z*) based on its position at the previous time step, n, as given by equations (6) to (8):

$$x_{n+1} = x_n + u \times \Delta t + x' \times R_x \quad (6)$$

$$y_{n+1} = y_n + v \times \Delta t + y' \times R_y \quad (7)$$

$$z_{n+1} = z_n + w \times \Delta t + z' \times R_z \quad (8)$$

where x = the particle position in the east-west horizontal distance (m)
y = the particle position in the north-south horizontal distance (m)
z = the particle position, or depth, in the vertical distance (m) (depth positive downwards)
u = east-west component of the ocean current (m/s)
v = north-south component of the ocean current (m/s)
Δt = time step for the given particle type (s)
w = fall velocity for the given particle type (m/s)
R_x, R_y, R_z= random numbers in the range (-1,1)

and where the $x'R_x$ terms, and similarly for *y* and *z*, are included to simulate an element of turbulence in the current drift of the particles.

3.2.6 Model Output

Following each well run, an output file was generated containing an *x,y* grid of the model domain with the following variables calculated for each grid cell:

- *x*, *y*, origin of cell (km), relative to discharge (*x,y,z*) origin: (0,0,110) for the WHP scenario, (0,0,20) for the MODU drilled wells
- range (km) and bearing (°T) from origin

- and for each of WBM cuttings, SBM cuttings, and total (WBM+SBM) cuttings:
- total weight of cuttings (kg)
- cuttings density (g/m^2)
- cuttings thickness(mm)
- number of particles of each of four types (pebble, coarse sand, medium sand, fines).

A run log file was also generated that echoes key model inputs and reports the total weight of cuttings (WBM and SBM) deposited on the seabed and the amount of cuttings which drift outside the model grid; there were no losses for the grid and grid cell sizes employed.

3.3 Results

The cuttings model tracks and outputs separately, the WBM, SBM and total (WBM plus SBM) deposition results. Section 3.3.1 presents the water-based mud cuttings results; Section 3.3.2 presents results for synthetic-based mud cuttings with an additional presentation of total cuttings thickness statistics.

3.3.1 Water-based Mud Cuttings

Cuttings from drilling the upper two well sections with WBM will all be released as per the OWTG (2012) close to the seafloor, under either the WHP option with chute release, or under the subsea option with MODU riserless drilling. Therefore, there is little time for the cuttings to be transported large distances by the ambient currents.

Figure 3-1 and Figure 3-2 present the WBM cuttings deposition predicted following completion of WHP option (40 wells) and subsea option (16 wells) drilling at the West White Rose location (WWRX1). Cuttings thicknesses of 0.1, 0.2 and 0.5 mm, 1, 2 and 5 mm and 10 mm are shown. The locations of the White Rose FPSO and potential second West White Rose Extension drill centre (WWRX2) are shown for reference.

Under the WHP scenario, the drift of cuttings is restricted to a range generally within 2 to 4 km. The maximum extent is approximately 5 km to the southeast and northeast. Cuttings (exclusively WBM) thicknesses are 1 mm or less over these regions.

Cuttings thicknesses directly under the WHP are modelled to be 1.8 m. In the immediate vicinity of the WHP, within 100 m, initial cuttings thicknesses are predicted to be 1.4 cm on average, and as high as 8.6 cm. Due to the large volume of material generated by drilling the (initial) 40 wells, a maximum height of 1.8 m is predicted for the model grid cell at the WHP origin. These will be almost exclusively the fast-settling pebbles and coarse sand (a very small percentage of the fines will drift for a time and ultimately settle near the CGS) whereas at distances greater than about 50 to 200 m, the deposits will be exclusively fines. This maximum height of 1.8 m does not account for slumping of the cuttings ‘pile’. Assuming a likely angle of repose of approximately 30 degrees, one might estimate from these thicknesses, a maximum height more likely on the order of 0.5 to 1.0 m.

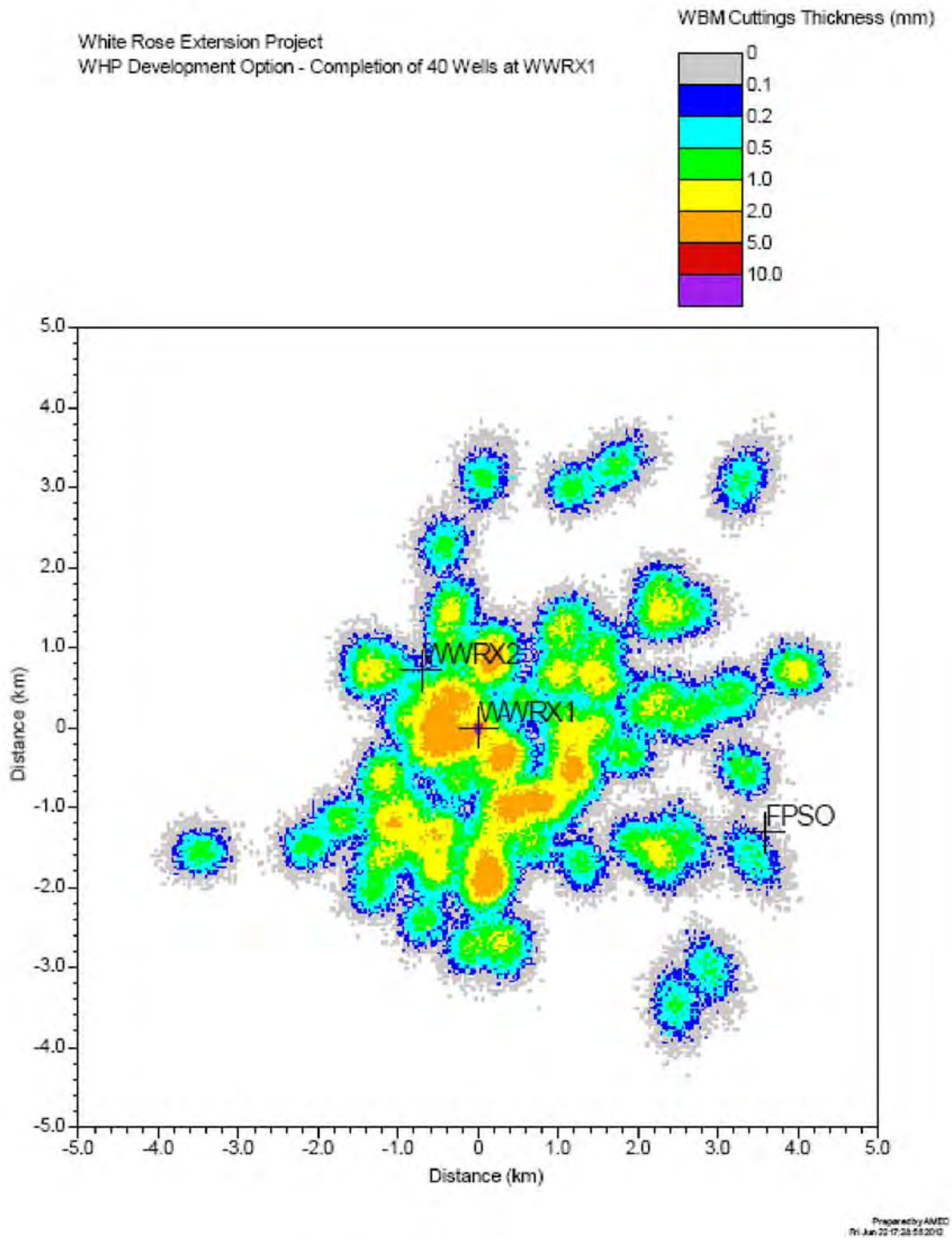


Figure 3-1 Water-based Mud Cuttings Deposition Following Wellhead Platform Option Drilling of 40 Wells, 5-km View

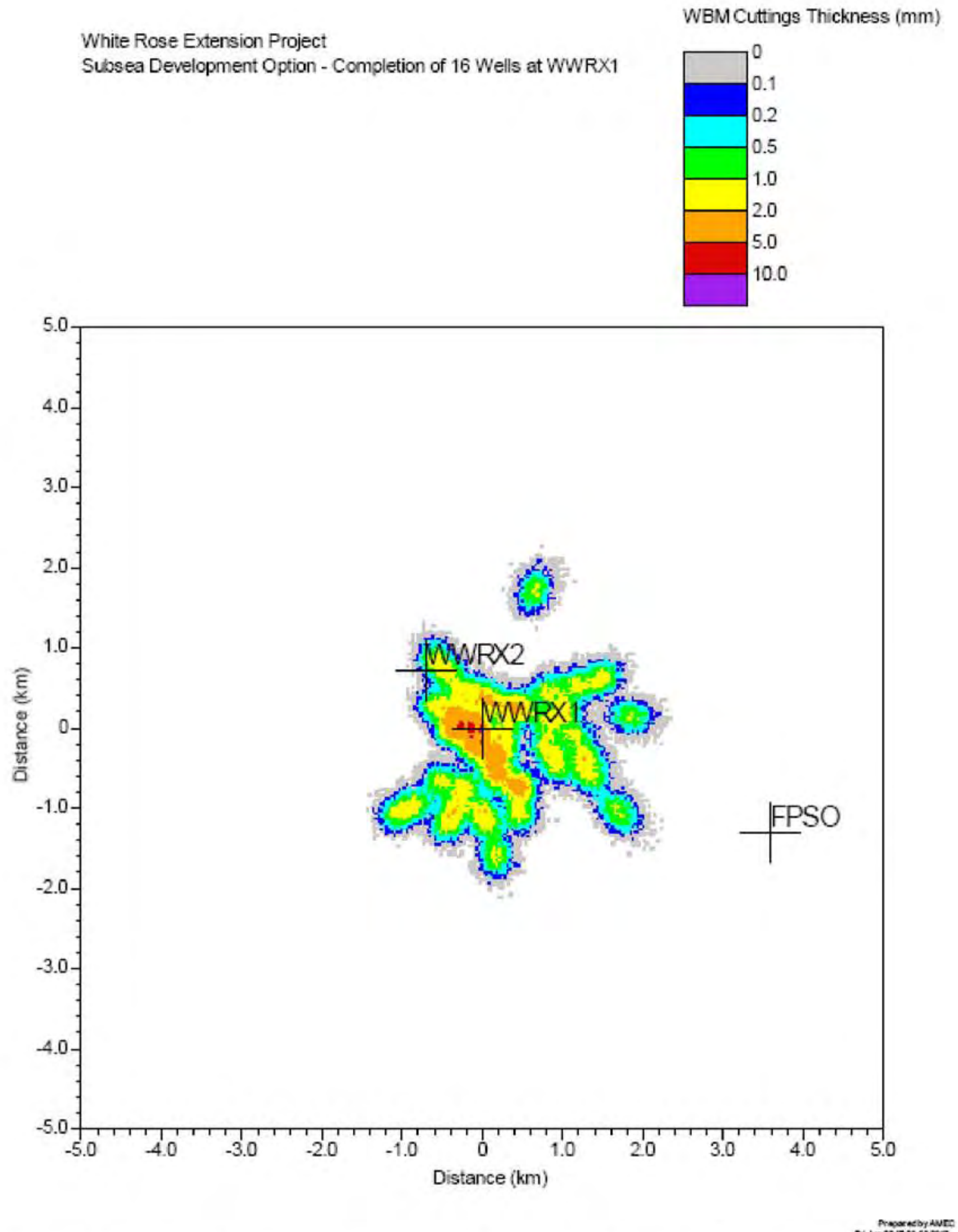


Figure 3-2 Water-based Mud Cuttings Deposition Following Subsea Option Drilling of 16 Wells, 5-km View

From 100 to 200 m out from the WHP, thicknesses are predicted to be 1.9 mm on average and a maximum of 3.4 mm. From 200 to 500 m, thicknesses average 1.8 mm and are a maximum of 4.6 mm.

Table 3-8 and Table 3-9 and corresponding figures Figure 3-3 and Figure 3-4 present the mean and maximum WBM cuttings thicknesses for distances out to 25 km from the well centre/origin. All five case drilling scenarios of the WHP option, subsea option, and three potential subsea drill centres are shown. The figures show thicknesses in mm on a logarithmic scale. Zero values correspond to thicknesses less than 0.01 mm (10 microns) (i.e., the size of the finest particles considered).

Table 3-8 Mean Water-based Mud Cuttings Thickness (mm)

	Distance from Origin (m)							
	0	**16 to 100**	**100 to 200**	**200 to 500**	**500 to 1,000**	**1,000 to 1,500**	**1,500 to 2,500**	**2,500 to 25,000**
WHP Development Option; 40 Wells at WWRX1	1,765.4	14.2	1.9	1.8	1.0	0.9	0.5	0.3
Subsea Development Option; 16 Wells at WWRX1	717.2	5.0	3.2	2.0	0.8	0.6	0.3	0.0
New Subsea Drill Centre; 16 Wells at SWRX	715.1	3.5	1.8	1.6	1.0	0.6	0.3	0.3
New Subsea Drill Centre; 16 Wells at WWRX2	698.9	3.4	1.4	1.4	0.9	0.6	0.4	0.2
New Subsea Drill Centre; 16 Wells at NWRX	701.2	5.0	2.6	1.4	0.8	0.6	0.3	0.3

Table 3-9 Maximum Water-based Mud Cuttings Thickness (mm)

	Distance from Origin (m)							
	0	16 to 100	100 to 200	200 to 500	500 to 1,000	1,000 to 1,500	1,500 to 2,500	2,500 to 25,000
WHP Development Option; 40 Wells at WWRX1	1,765.4	86.2	3.4	4.6	4.3	3.9	4.4	1.9
Subsea Development Option; 16 Wells at WWRX1	717.2	19.2	5.8	5.5	3.5	2.4	1.7	0.0
New Subsea Drill Centre; 16 Wells at SWRX	715.1	18.3	3.0	3.4	3.4	3.5	2.4	2.0
New Subsea Drill Centre; 16 Wells at WWRX2	698.9	19.8	3.0	3.8	3.5	3.5	2.4	1.5
New Subsea Drill Centre; 16 Wells at NWRX	701.2	27.7	5.7	5.2	3.4	3.0	1.8	1.6

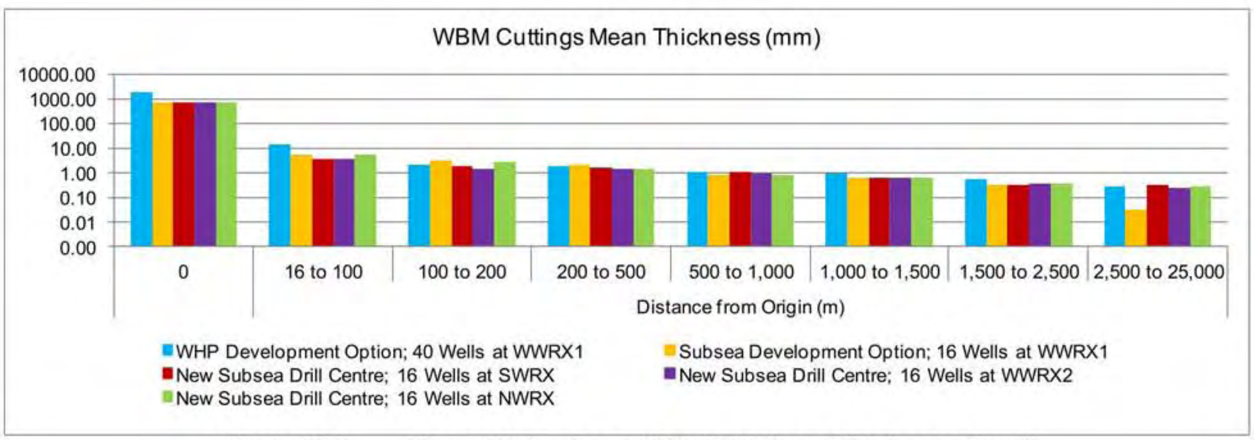


Figure 3-3 Mean Water-based Mud Cuttings Thickness (mm)

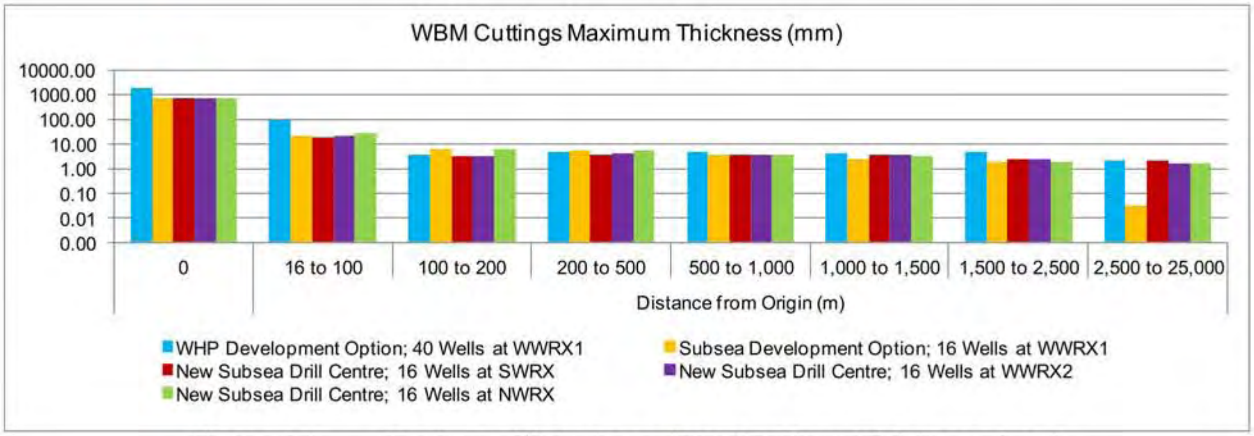


Figure 3-4 Maximum Water-based Mud Cuttings Thickness (mm)

Under the subsea scenario, the footprint of WBM cuttings is smaller than that for the WHP option just described, with a range generally restricted to within 2 km (Figure 3-2). The primary difference factor is the reduced number of wells drilled (16 as opposed to 40) and the reduced volume of cuttings material released (267 m^3 per well as opposed to 295 m^3 - see Table 2-2) for the subsea option. Under the WHP option (40 wells), approximately 11,800 m^3 of WBM cuttings are deposited, while the volume under the subsea drill centre option (16 wells) is approximately two-thirds the volume of cuttings (4,272 m^3 of WBM, 4,304 m^3 of SBM).

Cuttings thicknesses directly under the MODU (subsea option) are modelled to be 72 cm (less than half that of the WHP option). Comparable values are predicted under the similar MODU drilling for the three other subsea drill centre drilling scenarios (SWRX, WWRX2, NWRX) (e.g., 1st column in Table 3-8).

Within 100 m of the subsea drill centre origin, initial cuttings thicknesses are predicted to be 5.0 mm on average, and as high as 19.2 mm. From 100 to 200 m out from the drill centre, thicknesses are predicted to be 3.2 mm on average and a maximum of 9.8 mm. From 200 to 500 m, thicknesses average 2.0 mm and are a maximum of 5.5 mm (Table 3-8 and Table 3-9). Thickness statistics are comparable for the three potential other subsea drill centres. In general, the MODU drilling results in mean WBM cuttings thicknesses out to 100 m that are approximately one third to one quarter that for the WHP drilling; there is little difference outside of 100 m.

Modelled cuttings releases resulting from drilling with synthetic-based muds (exclusively for MODU drilling) are presented in Section 3.3.2.

3.3.2 Synthetic-based Mud Cuttings

For drilling of the deeper intermediate and main hole sections - for both WHP and MODU (subsea option and potential future drill centres) - SBM will be used. Under the WHP option the base case is to use two cuttings reinjection wells into which treated SBM and cuttings will be re-injected (i.e., no return of materials to the sea). In the summary statistics presented in this section the WHP option is listed together with the subsea and future drill centre options for completeness; however, the SBM cuttings thicknesses are all zero or not applicable for the WHP. For MODU drilling, SBM cuttings will be treated and released in accordance with the Offshore Waste Treatment Guidelines (OWTG) (National Energy Board (NEB) et al. 2010)

Figure 3-5 and Figure 3-6 present the modelled SBM cuttings deposition predicted following completion of the subsea option (16 wells) drilling at the West White Rose location (WWRX1) on both 5 km and 28 km scales.

Due to the large percentage of large cuttings pieces (Table 3-3) having fast settling speeds, the majority of SBM cuttings are deposited quite close to the drill centre. Patches of light dustings (0.1 mm or less) of fines extend as far as approximately 20 to 25 km to the north and 18 to 20 km to the south.

Cuttings thicknesses directly under the MODU are modelled to be 2.2 m. Again, this maximum height does not account for slumping of the cuttings ‘pile’. Assuming a likely angle of repose of approximately 30 degrees, one might estimate from these thicknesses, a maximum height more likely on the order of 0.75 to 1.2 m. Nor, is account made of the possibility noted in Section 2.0 of cuttings near the cuttings deposits directly about the excavated drill centre(s) being cleared by a seafloor cuttings transportation system and moved to another seafloor location.

In the immediate vicinity of the drill centre, within 100 m, initial SBM cuttings thicknesses, now overlain on top of WBM cuttings from drilling of the top two well sections, are predicted to be 11.7 cm on average, and as high as 98.9 cm. Table 3-10 and Table 3-11 and corresponding figures Figure 3-7 and Figure 3-8 present the mean and maximum SBM cuttings thicknesses for distances out to 25 km from the well centre/origin. All five case drilling scenarios of the WHP option (no SBM cuttings), subsea option, and three potential subsea drill centres are shown. The figures show thicknesses in mm on a logarithmic scale. Zero values correspond to thicknesses less than 0.01 mm (10 microns).

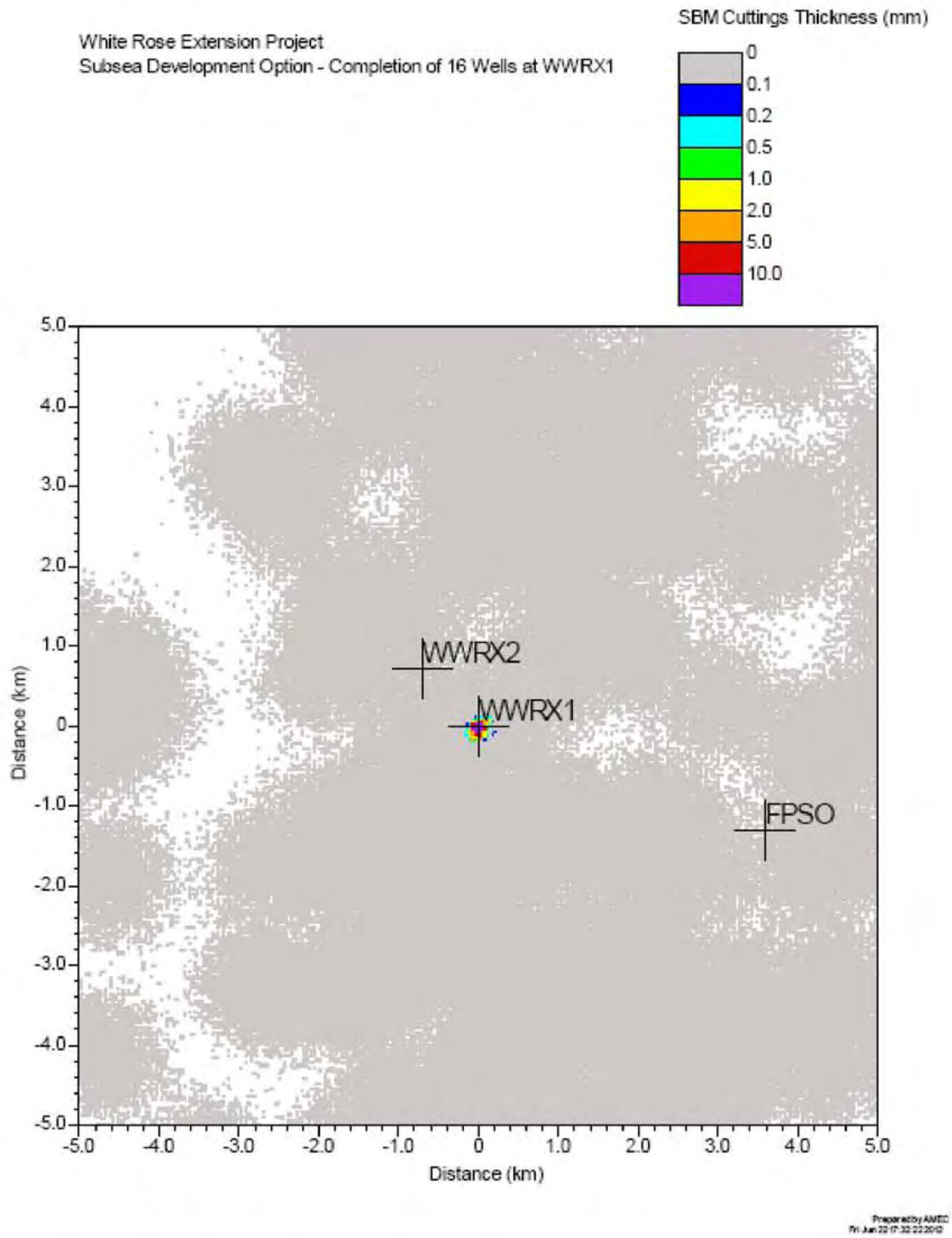


Figure 3-5 Synthetic-based Mud Cuttings Deposition Following Subsea Option Drilling of 16 Wells, 5-km View

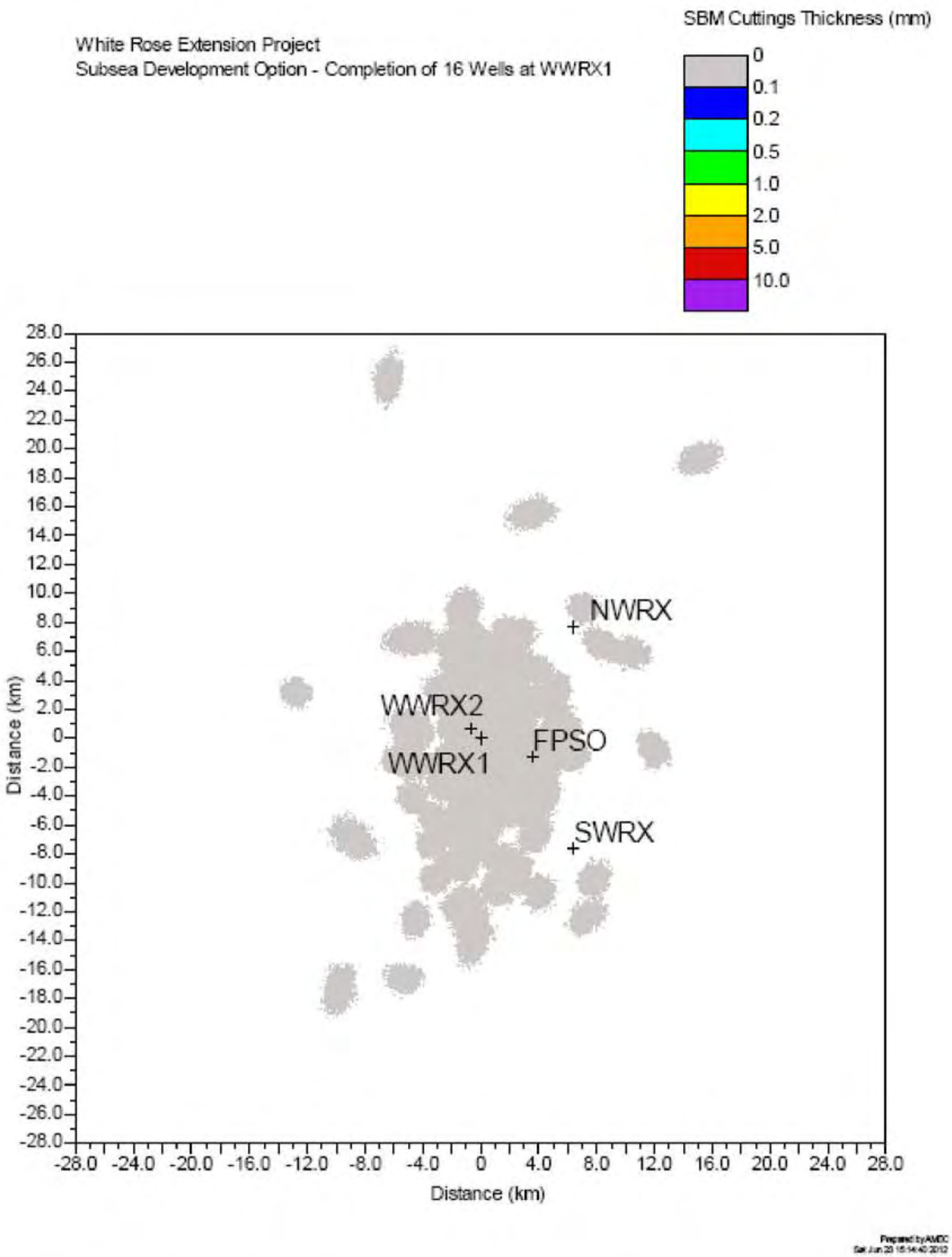


Figure 3-6 **Synthetic-based Mud Cuttings Deposition Following Subsea Option Drilling of 16 Wells, 28-km View**

Table 3-10 Mean Synthetic-based Mud Cuttings Thickness (mm)

	Distance from Origin (m)							
	0	16 to 100	100 to 200	200 to 500	500 to 1,000	1,000 to 1,500	1,500 to 2,500	2,500 to 25,000
WHP Development Option; 40 Wells at WWRX1	no SBM cuttings released to sea							
Subsea Development Option; 16 Wells at WWRX1	2,234.53	116.84	1.02	0.01	0.00	0.00	0.00	0.00
New Subsea Drill Centre; 16 Wells at SWRX	2,206.66	116.88	1.23	0.02	0.00	0.00	0.00	0.00
New Subsea Drill Centre; 16 Wells at WWRX2	2,533.13	106.10	0.99	0.02	0.01	0.00	0.00	0.00
New Subsea Drill Centre; 16 Wells at NWRX	2,154.99	118.97	1.27	0.02	0.00	0.00	0.00	0.00

Table 3-11 Maximum Synthetic-based Mud Cuttings Thickness (mm)

	Distance from Origin (m)							
	0	16 to 100	100 to 200	200 to 500	500 to 1,000	1,000 to 1,500	1,500 to 2,500	2,500 to 25,000
WHP Development Option; 40 Wells at WWRX1	no SBM cuttings released to sea							
Subsea Development Option; 16 Wells at WWRX1	2,234.5	989.33	6.55	0.29	0.02	0.02	0.02	0.03
New Subsea Drill Centre; 16 Wells at SWRX	2,206.7	756.90	10.36	1.49	0.01	0.01	0.02	0.02
New Subsea Drill Centre; 16 Wells at WWRX2	2,533.1	644.18	8.56	1.98	0.03	0.03	0.02	0.02
New Subsea Drill Centre; 16 Wells at NWRX	2,155.0	701.97	10.14	1.54	0.02	0.01	0.02	0.03

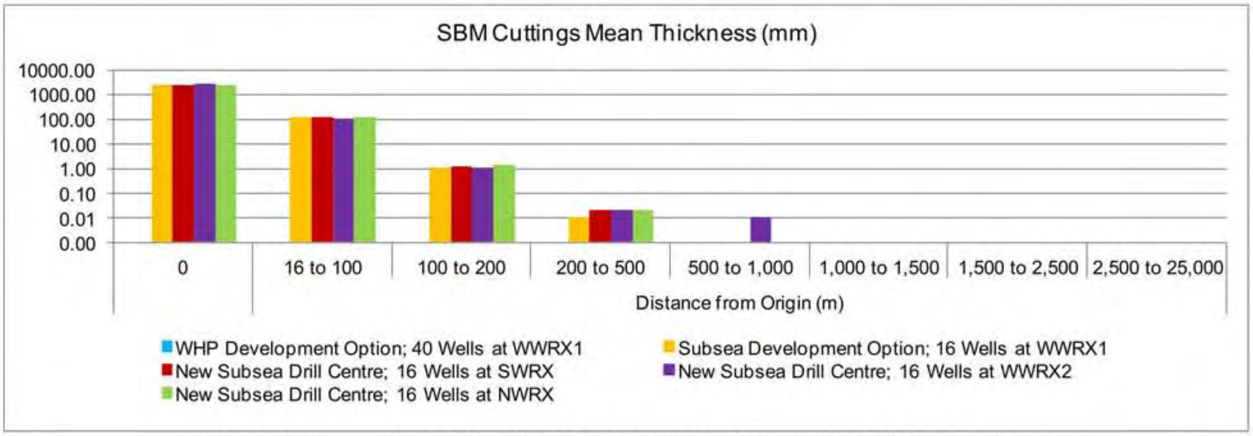


Figure 3-7 Mean Synthetic-based Mud Cuttings Thickness (mm)

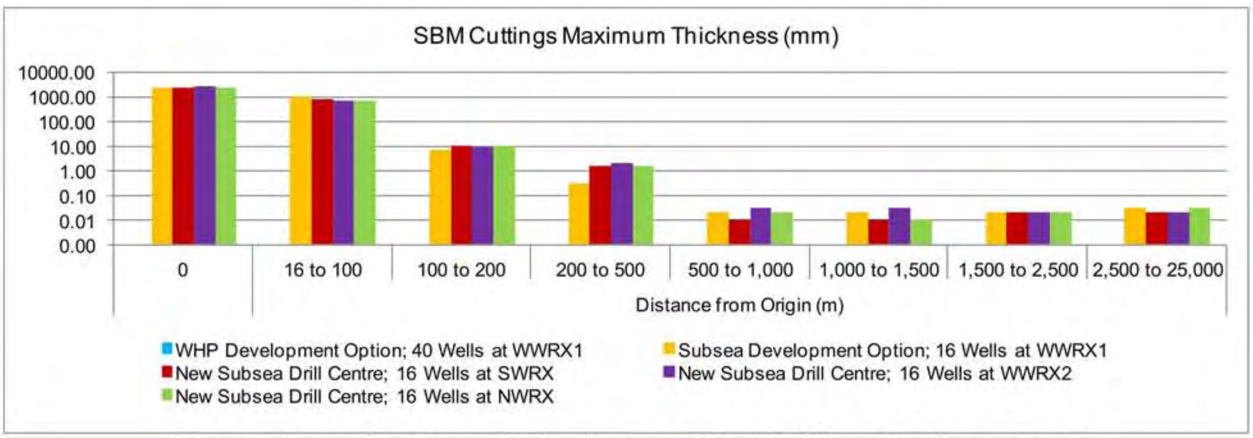


Figure 3-8 Maximum Synthetic-based Mud Cuttings Thickness (mm)

From 100 to 200 m out from the drill centre, thicknesses are predicted to be 1.0 mm on average and a maximum of 6.6 mm. From 200 to 500 m, thicknesses average 0.1 mm and are a maximum of 0.3 mm. Generally comparable values are predicted under the similar MODU drilling for the three other subsea drill centre drilling scenarios (SWRX, WWRX2, NWRX): a maximum thickness of 10.4 mm out to 200 m is modelled for SWRX, compared with 6.6 mm for WWRX1, and a maximum thickness of 2.0 mm out to 500 m is modelled for WWRX2, compared with 0.3 mm for WWRX1.

An additional comparison of SBM cuttings thickness near the drill centre is shown in Figure 3-9 for all four modelled MODU-drilled options. The basic cuttings footprint thicknesses and distribution pattern are comparable for all four scenarios.

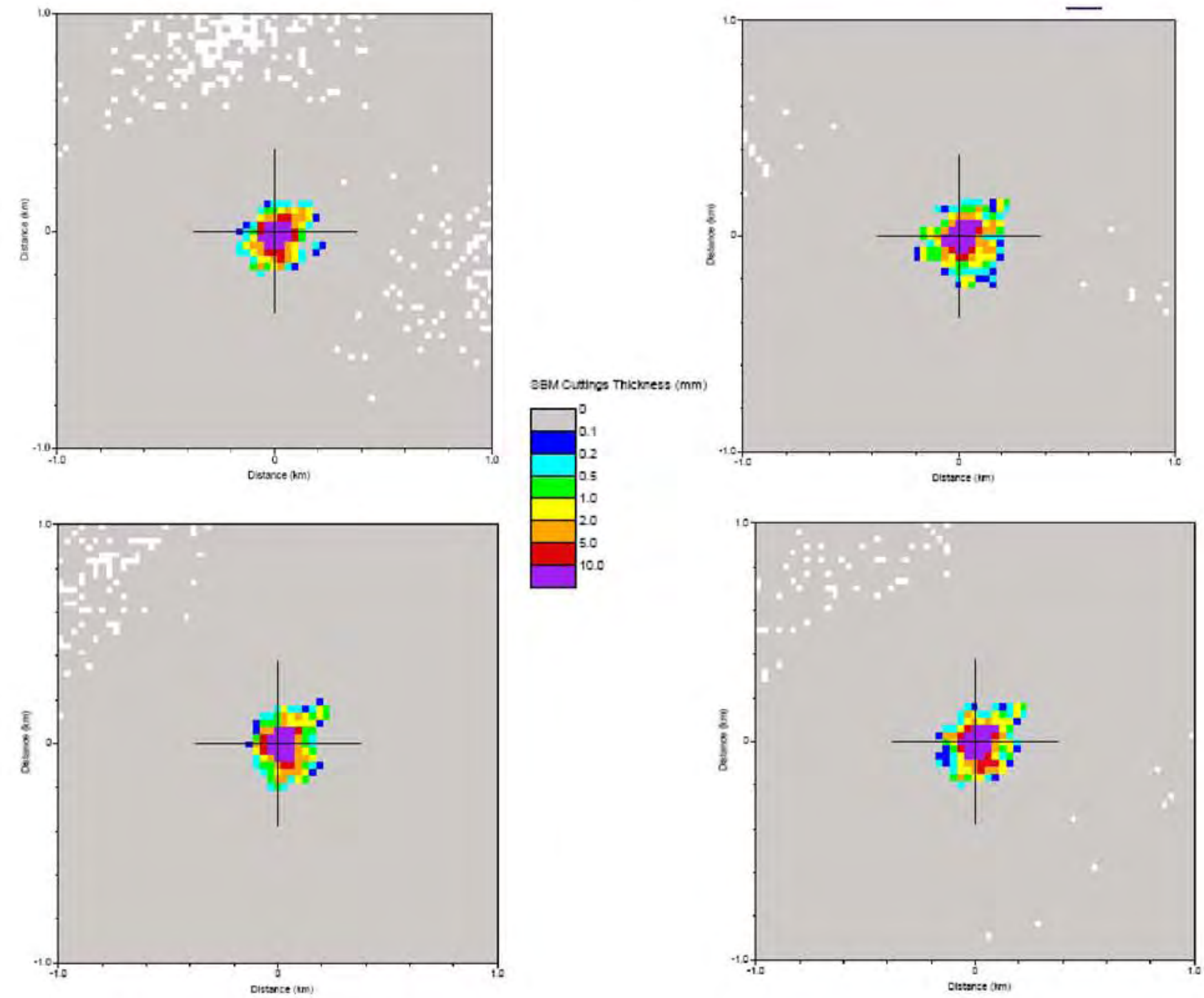


Figure 3-9 Synthetic-based Mud Cuttings Thickness for MODU-Drilled Options, 1-km View. Shown Clockwise from Upper Left are: West White Rose Extension, South White Rose Extension, West White Rose 2 Extension, North White Rose Extension

As noted in Section 3.1.1, the model estimates the oil concentration on cuttings as the weight of the cuttings material times its initial concentration, divided by the volume of an assumed thin benthic layer in which the cuttings are assumed to settle and mix with the seabed sediments (i.e., an oil concentration in the seabed layer is estimated based on the initial oil on cuttings).

Oil concentration is only applicable where SBM are discharged during MODU drilling and is reported in Table 3-12 in mg/kg (equivalent to ppm) and is approximately one to two times the SBM cuttings thickness in microns (e.g., if the thickness is 1,000 microns (1 mm), the oil concentration is approximately 1,000 to 2,000 mg/kg). The mean oil concentration is the average of the oil concentration values for all model grid cells with cuttings deposits within the tabulated radial distance. All five scenarios modelled are summarized.

Table 3-12 Mean Synthetic-based Mud Cuttings Oil Concentration (mg/kg)

	Distance from Origin (m)					
	100 to 200	**200 to 500**	**500 to 1,000**	**1,000 to 1,500**	**1,500 to 2,500**	**2,500 to 25,000**
WHP Development Option; 40 Wells at WWRX1	no SBM cuttings released to sea					
Subsea Development Option; 16 Wells at WWRX1	1,122.9	7.7	3.2	2.6	2.6	1.9
New Subsea Drill Centre; 16 Wells at SWRX	1,350.7	22.2	1.9	2.2	3.7	1.7
New Subsea Drill Centre; 16 Wells at WWRX2	1,092.1	22.6	7.1	4.9	4.4	1.5
New Subsea Drill Centre; 16 Wells at NWRX	1,394.0	17.8	4.0	1.9	2.7	1.9

Closer to the drill centre, cuttings thicknesses will be on the order of tens of centimetres or 1 m or more; estimation of the mean oil concentration (equation 3 in Section 3.1.1) assumes a ‘thin’ benthic layer of approximately 8 cm thickness. This formula is valid where cuttings mix with sediment; not where they accumulate over the sediment. In the latter case (larger cuttings piles near the drill centre), oil concentration is the original one on the cuttings. Therefore, for those situations, a maximum value equal to the original oil concentration of 74,000 mg/kg can be assumed.

As noted in Section 3.3.1, these concentration estimates are initial, ‘worst case’, values: subsequent weathering and fate of material and clearing near the well centres, will further alter the footprints and concentrations.

The oil concentration between approximately 100 m and 200 m from the well centre is predicted to be approximately 1,100 to 1,400 mg/kg. A two orders of magnitude drop is predicted out to 500 m, and outside of this range, 500 m and beyond, oil concentration in the seabed layer is on the order of approximately 2 to 7 mg/kg.

For indication of the cumulative footprint of WBM and SBM cuttings from drilling, Figure 3-10 presents the cuttings deposition predicted following completion of MODU drilling for the scenario of 64 wells (16 wells each at the subsea drill centres WWRX1, SWRX, WWRX2 and NWRX).

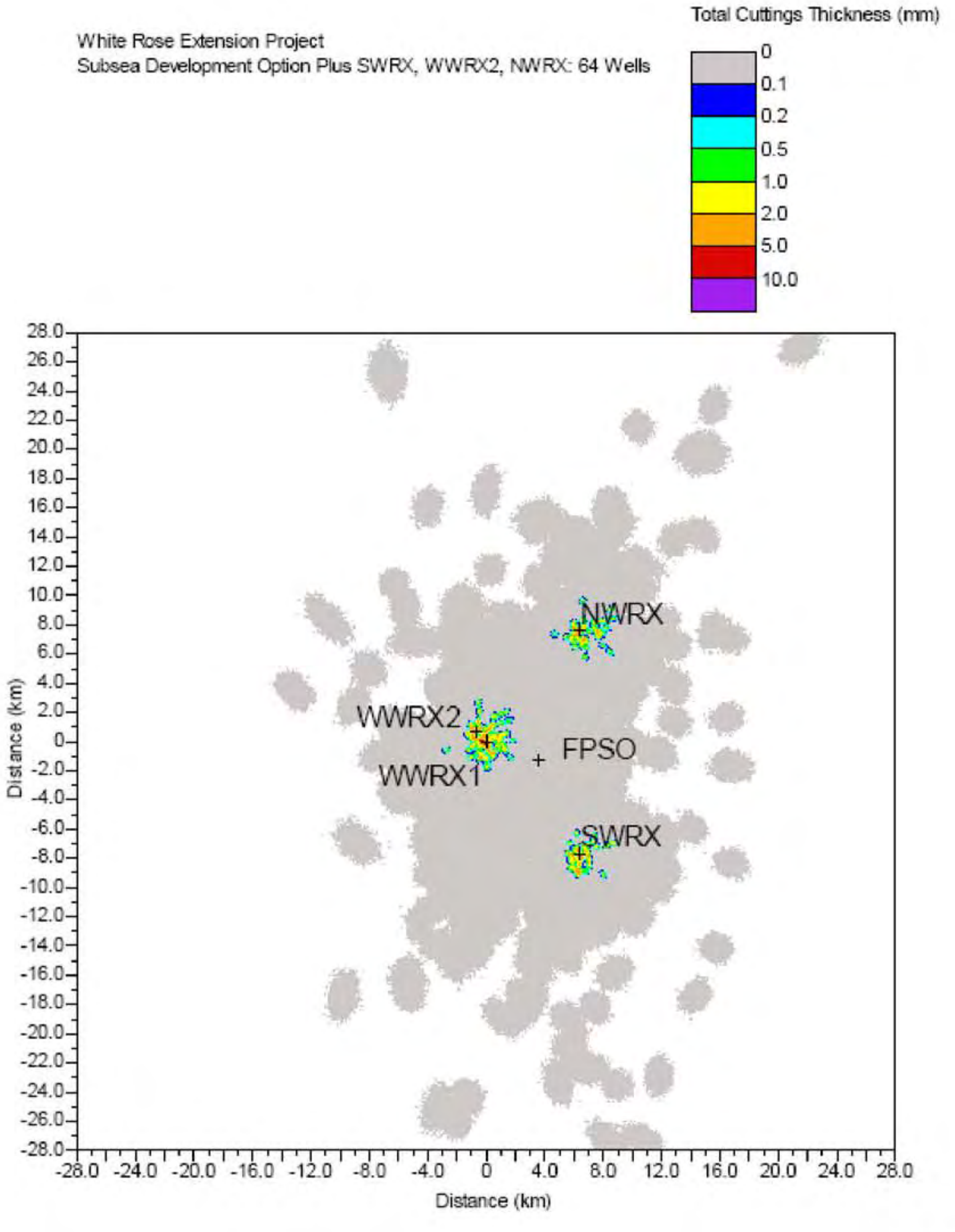


Figure 3-10 Total Water-based Mud and Synthetic-based Mud Cuttings Deposition Following Subsea Option plus Drilling of 64 Wells, 28-km View

The mean and maximum total (WBM+SBM) cuttings thicknesses for distances out to 25 km from the well centre/origin for each of the five scenarios modelled are presented in Table 3-13 and Table 3-14 and corresponding figures Figure 3-11 and Figure 3-12.

Table 3-13 Mean Total (Water-based + Synthetic-based) Mud Cuttings Thickness (mm)

	Distance from Origin (m)							
	0	16 to 100	100 to 200	200 to 500	500 to 1,000	1,000 to 1,500	1,500 to 2,500	2,500 to 25,000
WHP Development Option; 40 Wells at WWRX1	1,765.4	14.2	1.9	1.8	1.0	0.9	0.5	0.3
Subsea Development Option; 16 Wells at WWRX1	2,951.8	121.9	4.2	2.0	0.7	0.4	0.1	0.0
New Subsea Drill Centre; 16 Wells at SWRX	2,921.7	120.4	3.0	1.6	0.9	0.3	0.1	0.0
New Subsea Drill Centre; 16 Wells at WWRX2	3,232.0	109.5	2.3	1.3	0.8	0.3	0.1	0.0
New Subsea Drill Centre; 16 Wells at NWRX	2,856.2	123.9	3.9	1.4	0.7	0.3	0.1	0.0

Table 3-14 Maximum Total (Water-based + Synthetic-based) Mud Cuttings Thickness (mm)

	Distance from Origin (m)							
	0	16 to 100	100 to 200	200 to 500	500 to 1,000	1,000 to 1,500	1,500 to 2,500	2,500 to 25,000
WHP Development Option; 40 Wells at WWRX1	1,765.4	86.2	3.4	4.6	4.3	3.9	4.4	1.9
Subsea Development Option; 16 Wells at WWRX1	2,951.8	1,007.1	10.2	5.5	3.5	2.4	1.7	0.0
New Subsea Drill Centre; 16 Wells at SWRX	2,921.7	770.1	12.0	3.4	3.4	3.5	2.4	2.0
New Subsea Drill Centre; 16 Wells at WWRX2	3,232.0	657.4	9.2	3.8	3.5	3.5	2.4	1.5
New Subsea Drill Centre; 16 Wells at NWRX	2,856.2	721.3	11.7	5.2	3.4	3.0	1.8	1.6

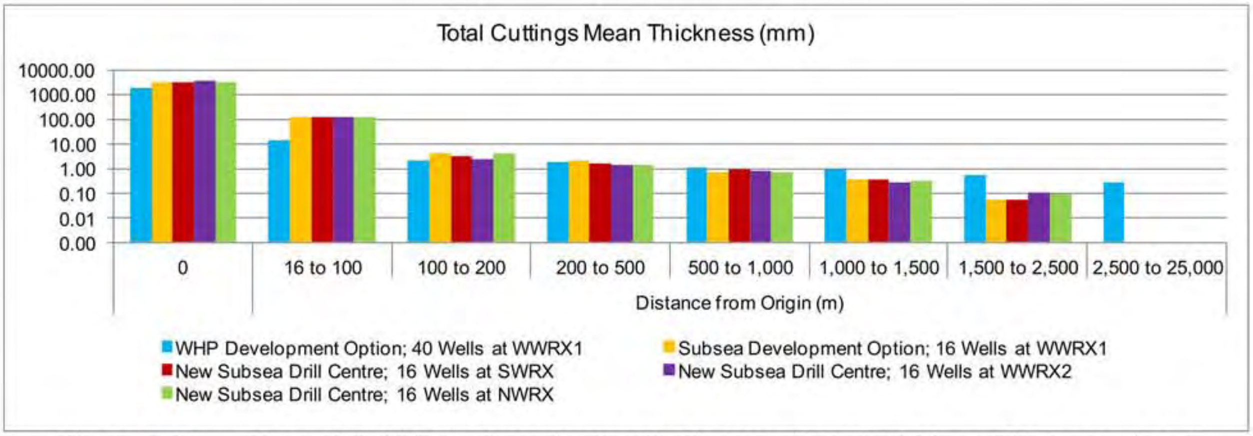


Figure 3-11 Mean Total (Water-based + Synthetic-based) Mud Cuttings Thickness (mm)

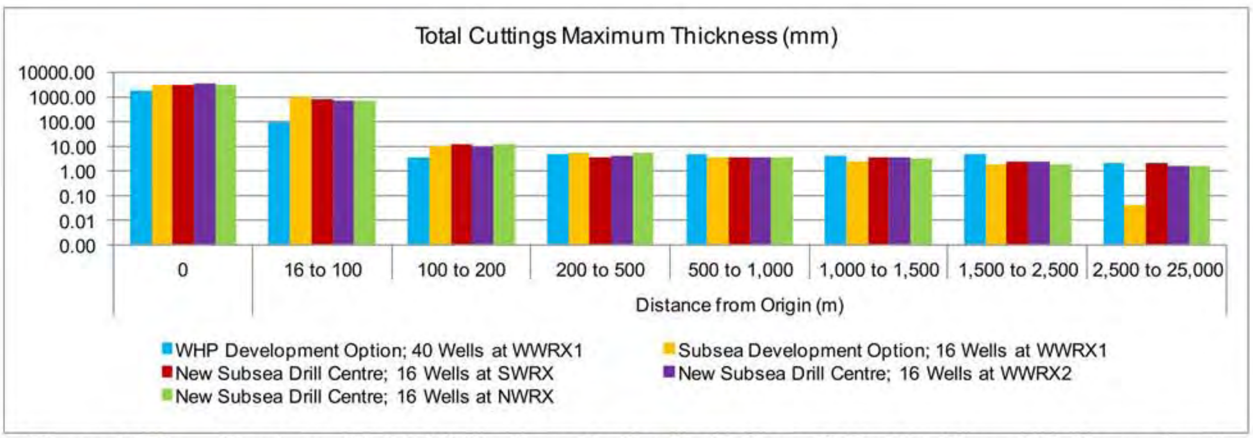


Figure 3-12 Maximum Total (Water-based + Synthetic-based) Mud Cuttings Thickness (mm)

Cuttings thicknesses directly under the MODU at any of the drill centres are modelled to be approximately 3 m. These amounts include the WBM and SBM cuttings. In contrast, the total thickness for WHP drilling is from WBM cuttings alone and a maximum thickness (before slumping of the cuttings 'pile' which will occur) of 1.8 m.

In the immediate vicinity of the drill centre, within 100 m, total cuttings thicknesses from any of the MODU-drilled subsea drill centres are an order of magnitude larger than that drilled with the WHP at West White Rose; mean thicknesses are on the order of 12 cm (Table 3-13) compared with 1.4 cm for the WHP; maximum thicknesses are on the order of approximately 66 cm to 1 m (Table 3-14) compared with 8.6 cm for the WHP. The cuttings thickness differences become much less as one moves out from a drill centre.

Between 100 and 200 m away, total cuttings thicknesses are on the order of 2 to 4 mm on average (for WHP and MODU-drilled options); maximum thicknesses are about 10 mm.

It is noted that the modelling predicts the initial deposition of the cuttings only. The subsequent weathering, fate and obliteration of the material accumulated on the seabed is a separate, less-readily predicted, process. In addition, as noted in Section 2.0, cuttings deposits directly about the excavated drill centre(s) will be cleared by a seafloor cuttings transportation system and moved to another seafloor location. In this way, these predictions represent an initial, ‘worst case’, footprint.

3.4 Sensitivity Discussion

Key inputs and sensitivities for the modelled fate of drill cuttings deposition include the following:

- Particle composition
- Particle settling velocities
- Ocean current velocities
- Drill cuttings volumes.

Actual ocean current time series measured over a one-year period were used; confidence in these data is high as they include a good range of the natural variability both in direction and speed that would be encountered.

Sensitivity to the amount of cuttings material is straightforward; in general, the cuttings weights, densities and thicknesses seen over a given area are directly proportional to the volume of materials released. For example, due to injection of cuttings from the deeper two sections, the amount of material released for the WHP drilling of a well is half that for MODU drilling, and is all WBM cuttings.

The most variable parameter associated with the cuttings characterizations is the relative composition makeup assumed for the cuttings material. Fines materials settle to the seabed at much slower rates than the large cuttings, pebbles and sands, which comprise the remainder of the cuttings. The composition is dependent on the stratigraphy of the wells drilled, the type of drilling mud used and the nature of the cuttings treatment applied on the platform or MODU prior to discharge. Deposition is most sensitive to particle size distribution; more fines means greater deposition farther away from the point of discharge, less fines means greater deposition close to the origin.

For example, if the volumes of faster settling large cuttings, pebbles and coarse sand are reduced by half, the resulting cuttings mounds on the seafloor can be expected to be approximately twice as low. Fines drift farther and result in generally homogeneous thin dustings over a large area. If the amount of fines material doubled, the thicknesses can be expected to double though the areas covered should remain about the same.

As noted, the larger cuttings, pebble and sand elements tend to fall much closer to their discharge origin than the slower settling fines. The possible effect of faster settling of the fines can be considered.

In the study of drift and dispersion of suspended drill muds from the Hibernia platform, Tedford et al. (2003) approximate the processes of flocculation and floc breakup by making the settling velocity a function of the bottom stress. Three velocities were employed. A fast-settling velocity of 0.005 m/s was selected for the early stages of the discharge plume and used until the bottom stress exceeded a critical threshold. The flocs were then modelled to break up into their individual components and assume a low settling velocity of 0.0001 m/s. This settling velocity was employed until the bottom stress then fell back below that critical threshold, at which point the material was modelled to flocculate into the background of marine flocs with a larger settling velocity of 0.001 m/s, almost equal to the fines settling velocity of 0.0012 m/s estimated in Section 3.2.2. These latter two settling velocities (0.0001 and 0.001 m/s) were alternately employed depending on the bottom stress.

For the present modelling, one settling velocity is employed for each particle type. For a faster fines settling velocity sensitivity, the value of 0.005 m/s from Tedford et al. (2003) was selected and applied for the scenario of drilling one of the potential future subsea drill centres.

Figure 3-13 and Figure 3-14 show the original 'base case' and sensitivity cuttings footprints, considered for a simulation of 16 wells at the South White Rose Extension (SWRX) subsea drill centre. The total WBM plus SBM cuttings thicknesses are shown. Due to the faster settling speeds, the fines all settle within approximately 4 to 7 km, compared with the original simulation, where the fines can drift as far as approximately 20 to 27 km. A closer, 5-km, view of the total (WBM+SBM) cuttings footprints are shown in Figure 3-15 and Figure 3-16. The distances from the drill centre with cuttings thicknesses greater than 1 cm are about 150 m for the base (Figure 3-15), and now 450 to 500 m for the sensitivity scenario including a 'pile' approximately 660 m to the northeast (Figure 3-16).

In general, under the faster settling of fines sensitivity, a small increase in cuttings thickness is observed; mean thickness increases from 120 to 139 mm from 16 to 100 m, from 3 to 18 mm from 100 to 200 m and from 1.6 to 2.9 mm from 200 to 500 m. Outside of this range, under the sensitivity, there are fewer fines left to settle so that thicknesses are now very slightly less compared to the base case. Minimum and maximum total cuttings thicknesses are shown in Figure 3-17 and Figure 3-18.

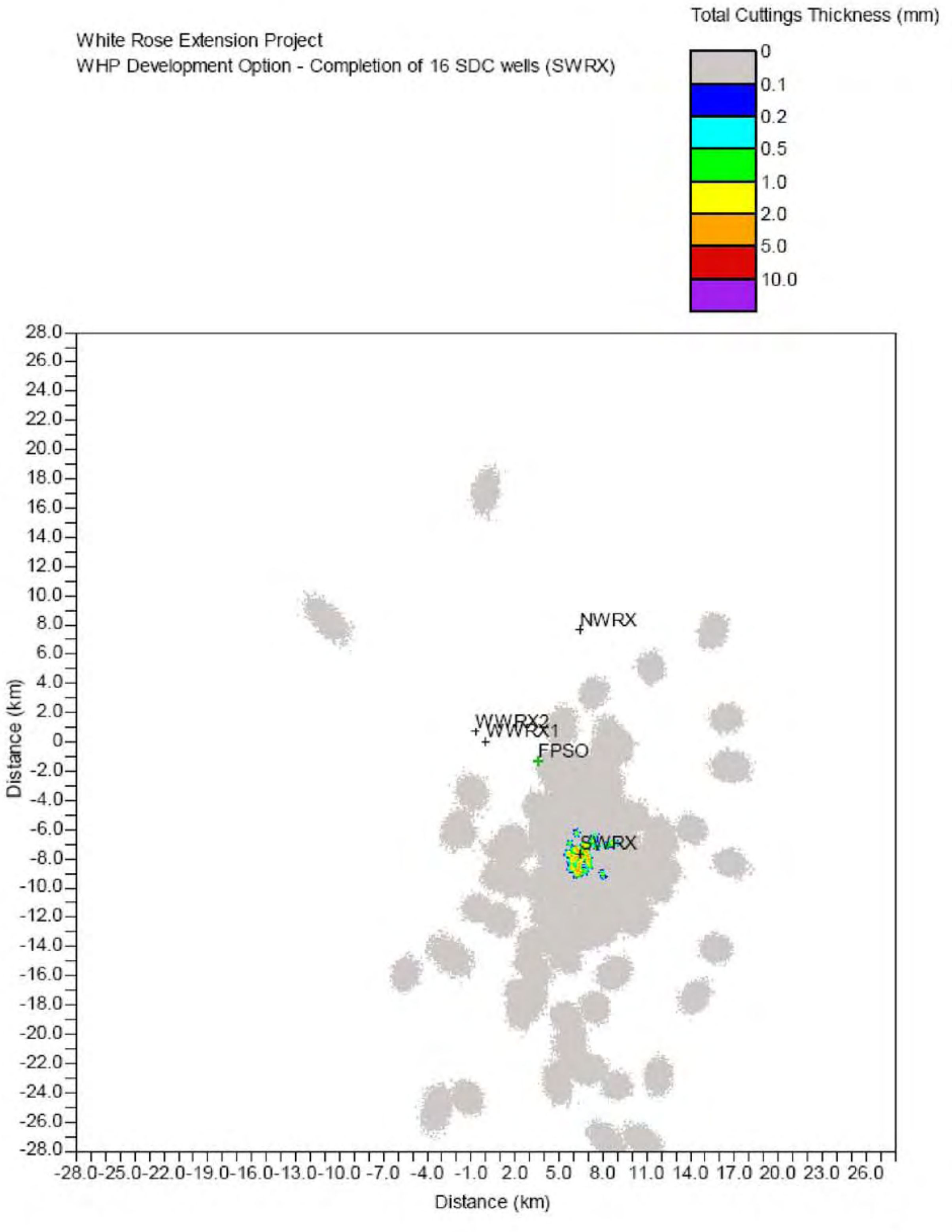


Figure 3-13 Total Water-based Mud and Synthetic-based Mud Cuttings Deposition Following South White Rose Extension Drilling of 16 Wells, 'Base Case', 28-km View

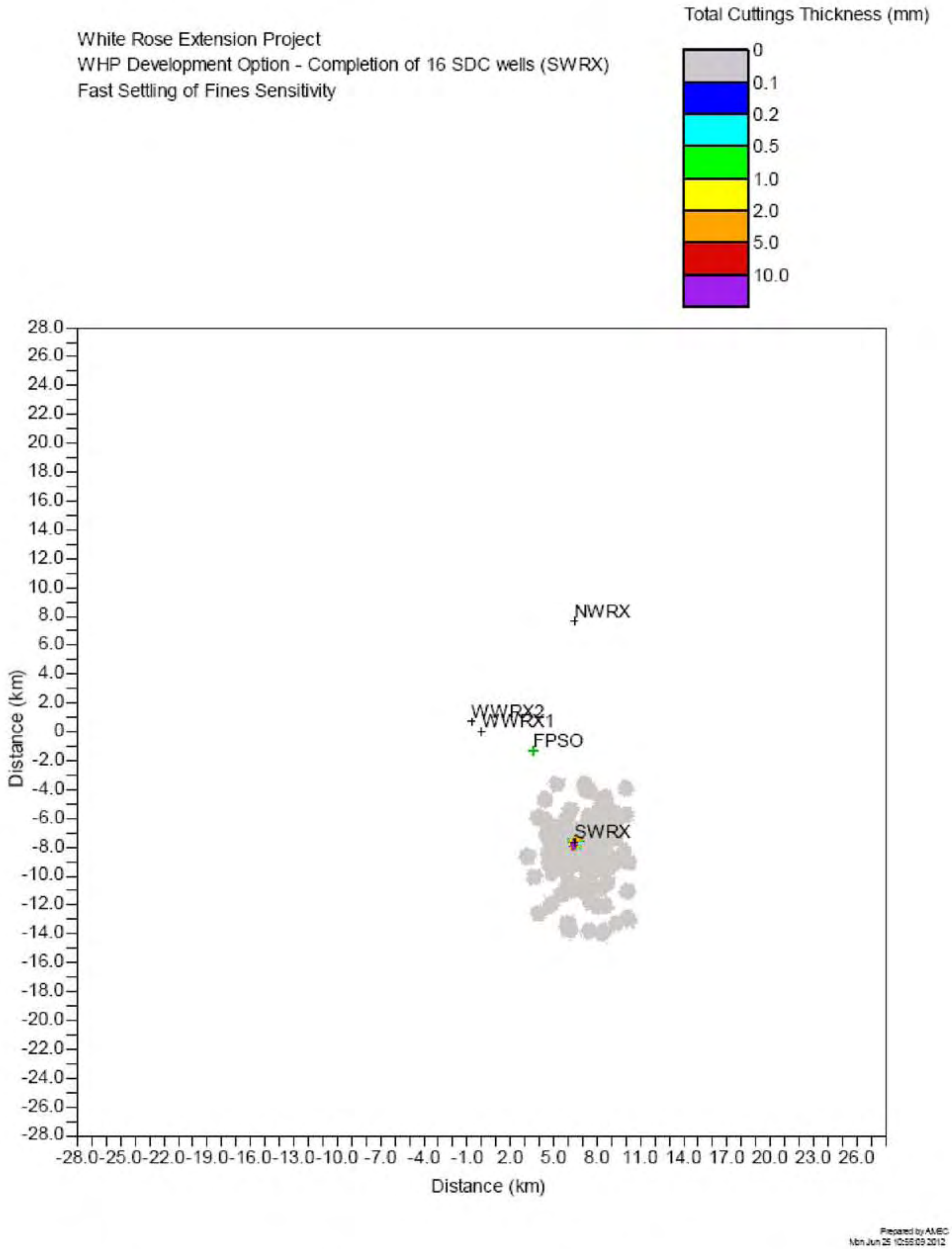


Figure 3-14 Total Water-based Mud and Synthetic-based Mud Cuttings Deposition Following South White Rose Extension Drilling of 16 Wells, 'Fast Settling of Fines Sensitify', 28-km View

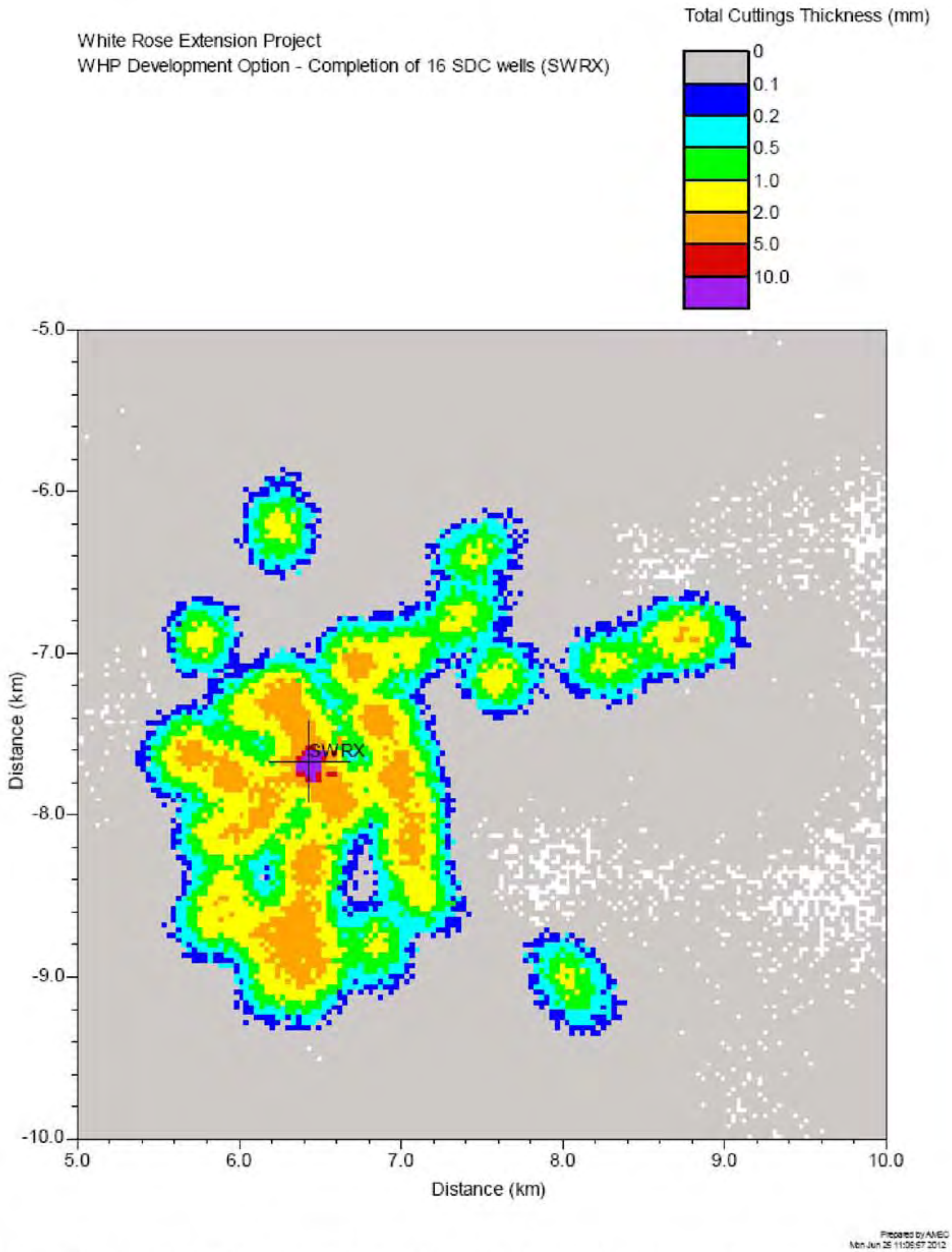


Figure 3-15 Total Water-based Mud and Synthetic-based Mud Cuttings Deposition Following South White Rose Extension Drilling of 16 Wells, 'Base Case', 5-km View

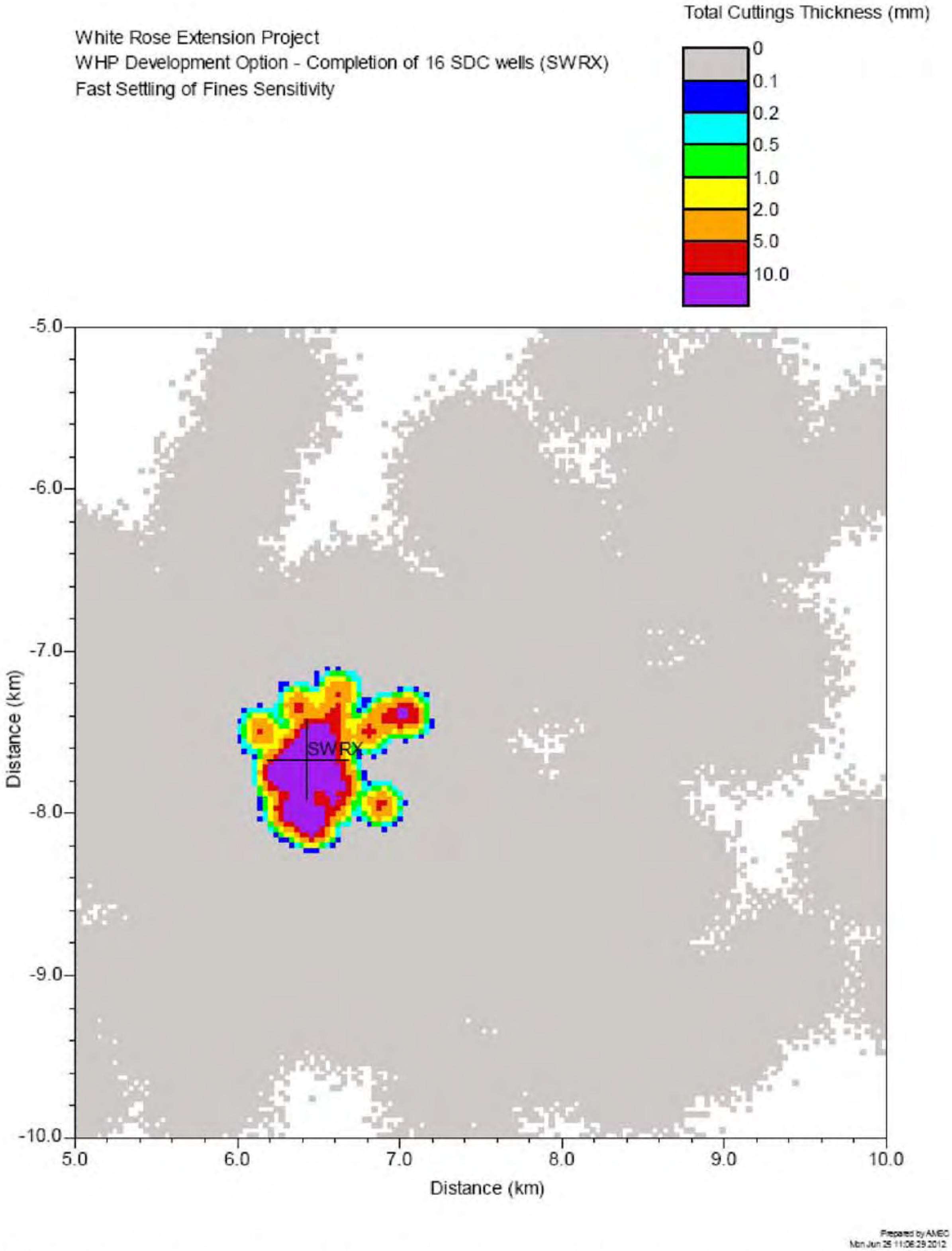


Figure 3-16 Total Water-based Mud and Synthetic-based Mud Cuttings Deposition Following South White Rose Extension Drilling of 16 Wells, 'Fast Settling of Fines Sensitivity', 5-km View

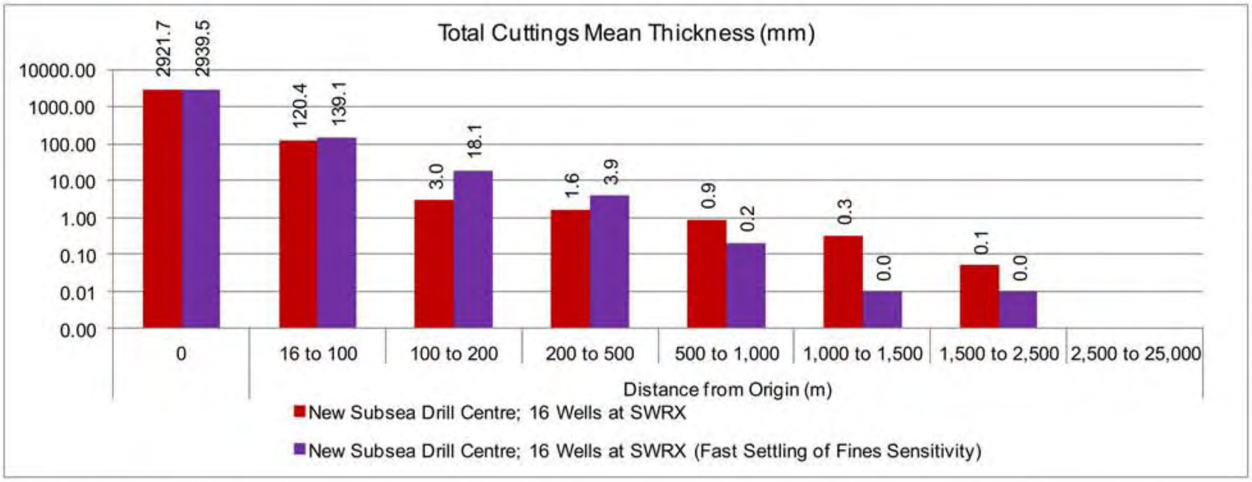


Figure 3-17 Mean Total (Water-based + Synthetic-based) Mud Cuttings Thickness: South White Rose Extension Base Case and Fast Fines Settling Velocity Sensitivity (mm)

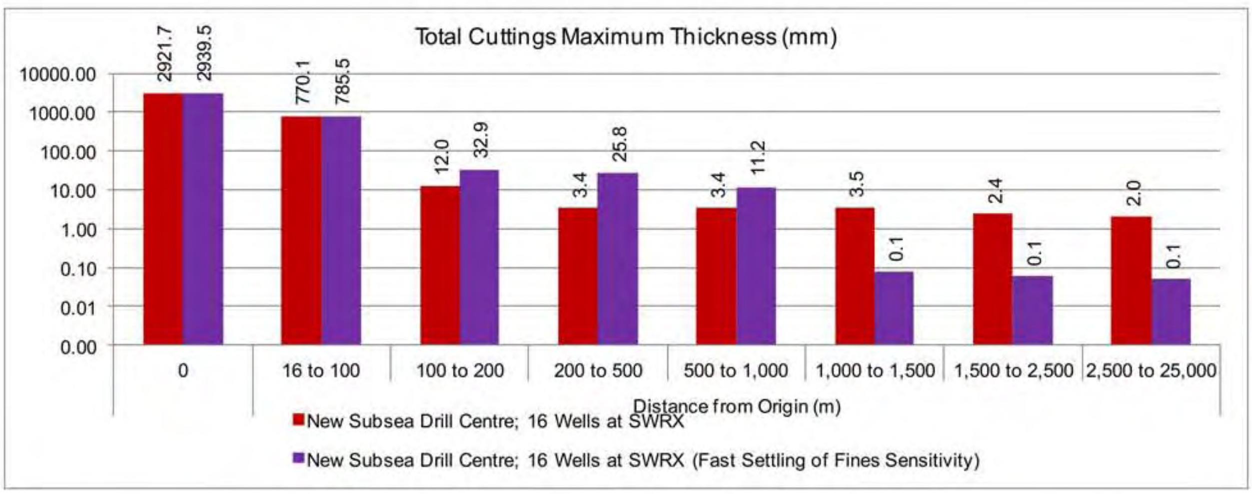


Figure 3-18 Maximum (Water-based + Synthetic-based) Mud Cuttings Thickness: South White Rose Extension Base Case and Fast Fines Settling Velocity Sensitivity (mm)

4.0 Drilling Mud Properties and Discharge Characteristics

The drilling operations will necessitate the use of drilling muds, which 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).

While most of the drilling operations, including the conductor and surface hole sections, will involve the use of water-based mud (WBM), it is anticipated that the drilling operations for the intermediate and main well hole sections will necessitate the use of synthetic-based mud (SBM). The use and disposal of water-based muds are subject to the Offshore Waste Treatment Guidelines (OWTG) (NEB et al. 2010), which state the following:

> Where it is technically reasonable, water based mud (WBM) should be used in the drilling of wells and well sections. Spent and excess WBM may be discharged onsite from offshore installations without treatment.

The amounts and locations of discharge of WBM for each of the well hole sections are outlined in Table 2-3. The discharges associated with the conductor section consist of 214 m^3 and 158 m^3 of WBM released 20 m above the seafloor, and at the seafloor, respectively. The discharges associated with the surface section consist of 470 m^3 and 440 m^3 of WBM released 20 m above the seafloor, and at the seafloor, respectively.

The environmental effects of released WBMs are generally associated with the potential physical toxicity of fine particulate matter, either barite or bentonite, which are sometimes used to increase the density of the mud mixture: as noted by Cranford (2005) these additives have greater potential to affect filter feeding organisms as they remain suspended in the bottom boundary layer.

The most likely composition of the WBM planned for use during the WREP does not include these weighting agents, therefore no amount of particulate matter is expected to be introduced to the environment due to the release of WBM during any stage of the drilling process. The anticipated composition of WBM (Table 4-1) constitutes primarily of brine, with the possible addition of Sodium Acid Pyrophosphate (SAPP). SAPP is a white powder that is water soluble. It is used as a mud thinner and dispersant, and is especially effective for treating cement contamination (MiSwaco 2006). No component of the WBM has been identified as potentially toxic; therefore the dispersion of WBM following the discharges has not been treated in further detail.

Table 4-1 Drilling Mud Components Used for Different Hole Sections

Chemicals	Hole Section and Mud Type					
	Conductor WHP	Conductor MODU	Surface	Intermediate	Main	Total
	WBM	WBM	WBM	SBM	SBM	
Barite (t)	0	0	0	500	0	500
Bentonite (t)	None used					0
Caustic Soda (kg)	None used					0
Lime (kg)	0	0	0	2,340	1,050	3,390
SAPP (kg)	125	125	125	0	0	375
SBM Emulsifiers (kg)	0	0	0	4,446	2,625	7,071
SBM Viscosifiers (kg)	0	0	0	4,680	1,575	6,255
SBM Wetting Agents (kg)	0	0	0	417	0	417
Filtration control (kg)	0	0	0	936	0	936
Base Oil (t)	0	0	0	29	11	40
PHPA (kg)	None used					0
Source: J. Swain pers. comm.						

Drilling operations involving SBMs will be conducted in accordance with the OWTG (NEB et al. 2010), which dictate the following:

> Where there is technical justification (e.g., requirements for enhanced lubricity or for gas hydrate mitigation), operators may use synthetic based mud (SBM) or enhanced mineral oil based mud (EMOBM) in the drilling of wells and well sections. Other than the residual base fluid retained on cuttings as described in the operator's EPP, no whole SBM or EMOBM base fluid, or any whole mud containing these constituents as a base fluid, should be discharged to the sea.

Accordingly, there will be no bulk discharges of SBM during WREP operations. A limited amount of SBM will be retained on the cuttings associated with SBM drilling as discussed in Section 3.3.2. Potential modes of accidental bulk releases of SBM, and the subsequent dispersal in the environment have been treated in an accompanying report (AMEC 2012).

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6.0 Acronyms

Term	Description
ADCP	Acoustic Doppler Current Profiler
C-NLOPB	Canada-Newfoundland and Labrador Offshore Petroleum Board
CNSOPB	Canada-Nova Scotia Offshore Petroleum Board
FPSO	Floating production, storage and offloading vessel
h	hour
kg/m^3	kilograms per cubic metre
m/s	metres per second
mKB	metres below Kelly bushing
MODU	Mobile offshore drilling rig
NEB	National Energy Board
NWRX	North White Rose Extension
OWTG	Offshore Waste Treatment Guidelines
s	seconds
SWRX	South White Rose Extension
SBM	synthetic-based mud (a type of drilling mud)
WBM	water-based mud (a type of drilling mud)
WHP	Wellhead platform
WWRX	West White Rose Extension
WREP	White Rose Extension Project

7.0 Glossary

Word	Definition
ADCP	An instrument designed to measure water flow by making use of the acoustic Doppler effect
Bathymetry	The measurement of depths of water in oceans, seas and lakes; also the information derived from such measurements
Drill Cuttings	Drill cuttings are formation or **reservoir** solids separated from drilling mud by solids control equipment. The cuttings
Drilling Mud	A special mixture of clay, water and chemical additives pumped down the wellbore through the drill pipe and drill bit to cool the rapidly rotating bit, lubricate the drill pipe as it turns in the wellbore, and carry rock cuttings to the surface; may have a **water base** or a **synthetic oil base** fluid
Fall Velocity	The vertical speed at which particles or negatively buoyant droplets fall through the water column
Kelly	A long square or hexagonal steel bar with a hole drilled through the middle for a fluid path. The kelly is used to transmit rotary motion from the rotary table or kelly bushing to the drillstring, while allowing the drillstring to be lowered or raised during rotation. The kelly goes through the kelly bushing, which is driven by the rotary table. The kelly bushing has an inside profile matching the kelly's outside profile (either square or hexagonal), but with slightly larger dimensions so that the kelly can freely move up and down inside (http://www.glossary.oilfield.slb.com/Display.cfm?Term=kelly)
Kelly Bushing	The kelly bushing connects the **kelly** to the **rotary table**
Rotary Table	The revolving or spinning section of the drillfloor that provides power to turn the drillstring in a clockwise direction (as viewed from above). The rotary motion and power are transmitted through the **kelly bushing** and the **kelly** to the drillstring. When the drillstring is rotating, the drilling crew commonly describes the operation as simply, "rotating to the right," "turning to the right," or, "rotating on bottom." Almost all rigs today have a rotary table, either as primary or backup system for rotating the drillstring. Topdrive technology, which allows continuous rotation of the drillstring, has replaced the rotary table in certain operations. A few rigs are being built today with topdrive systems only, and lack the traditional kelly system (http://www.glossary.oilfield.slb.com/Display.cfm?Term=rotary%20table)
Synthetic-based Mud (SBM)	A **drilling mud** in which the continuous phase is a synthetic fluid
Water-based Mud (WBM)	A **drilling mud** in which the continuous phase is water
Water Column	The vertical dimension of a body of water (*i.e.*, the water between a reference point or area on the surface and one located directly below it on the bottom)

Note: Bolded **words within a definition are themselves defined**

Appendix A

White Rose Current

Time Series and Speed vs. Direction Bivariate Statistics

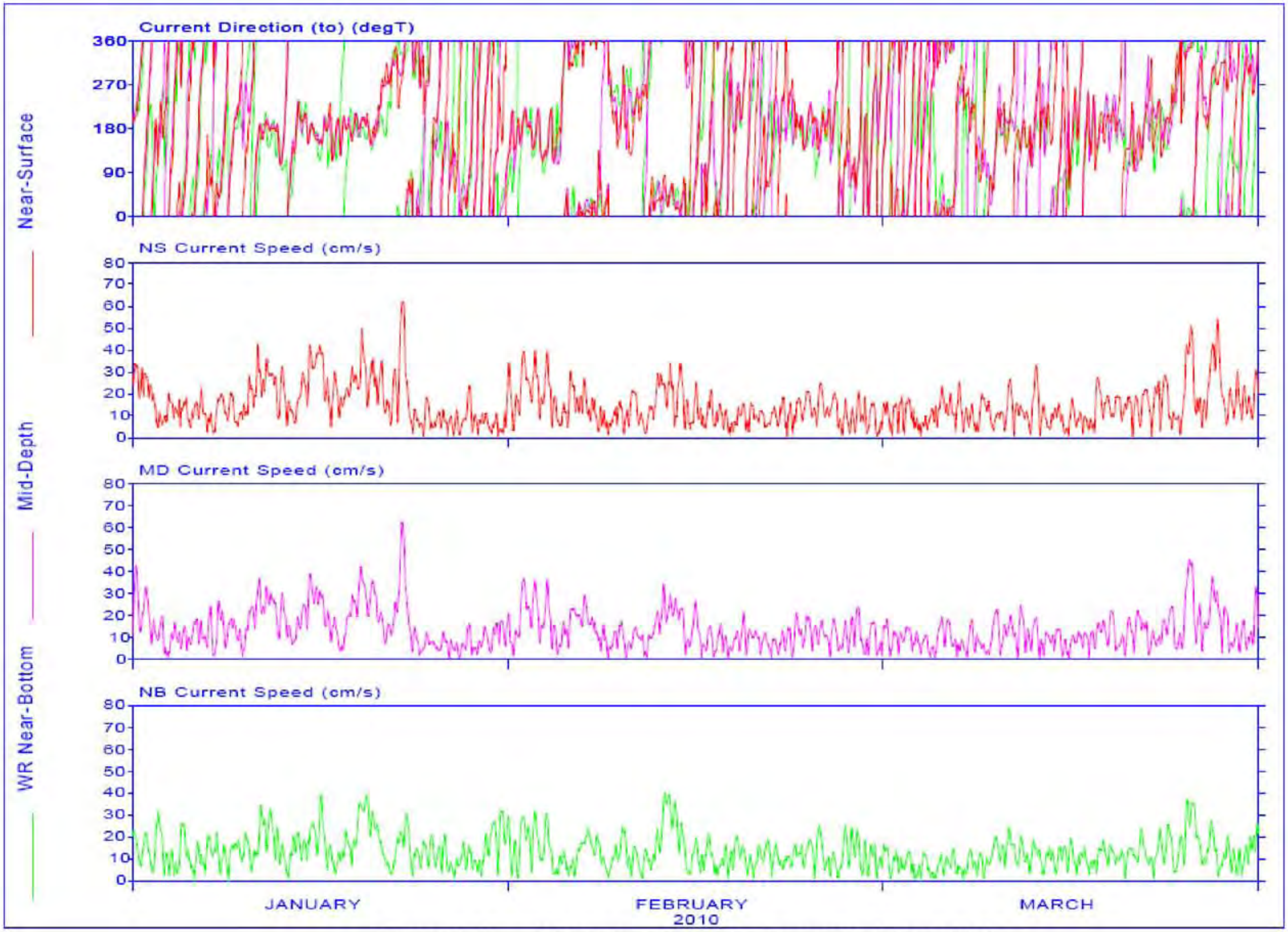

Figure A-1 White Rose Currents, January to March, 2010

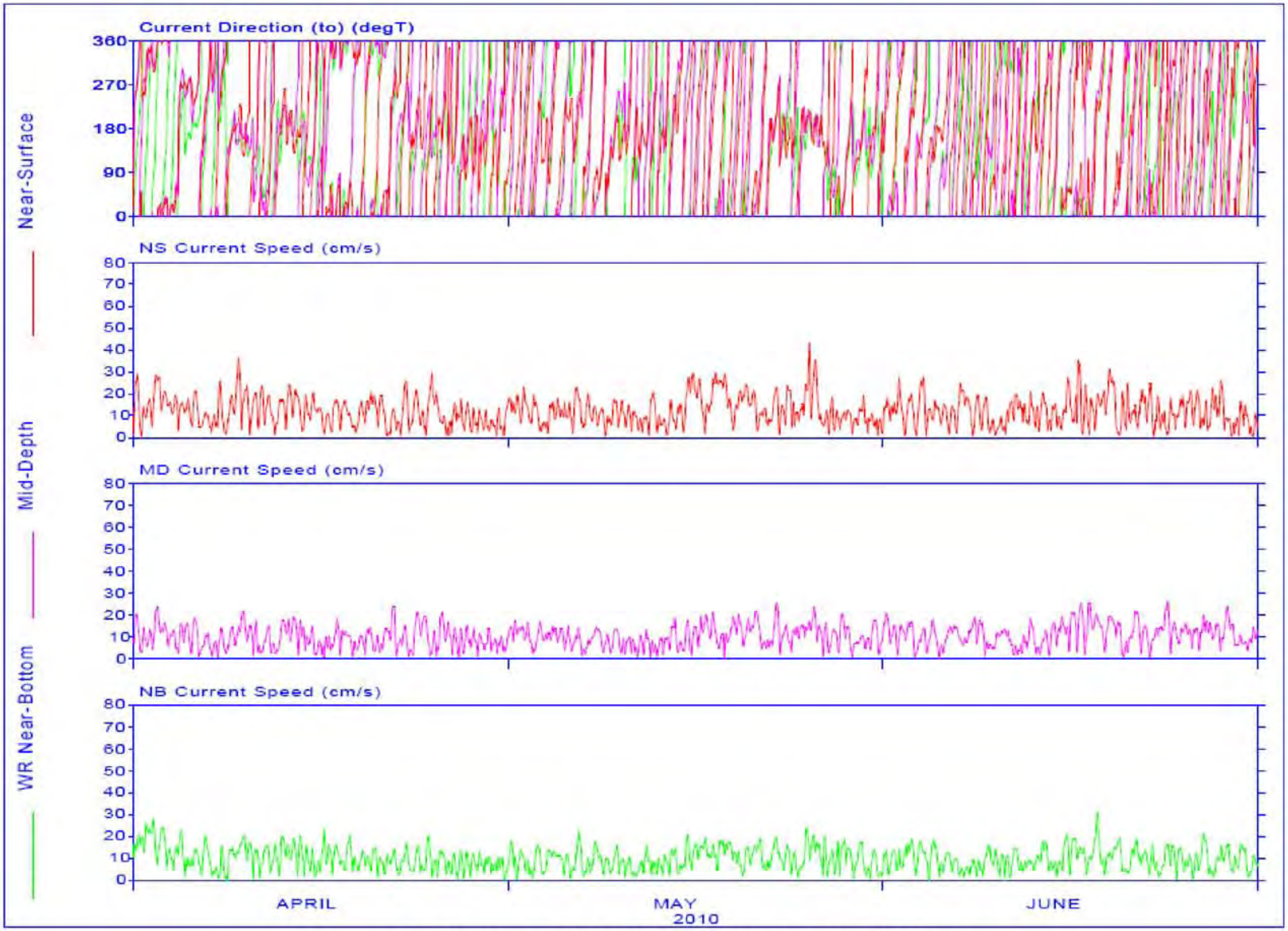

Figure A-2 White Rose Currents, April to May, 2010

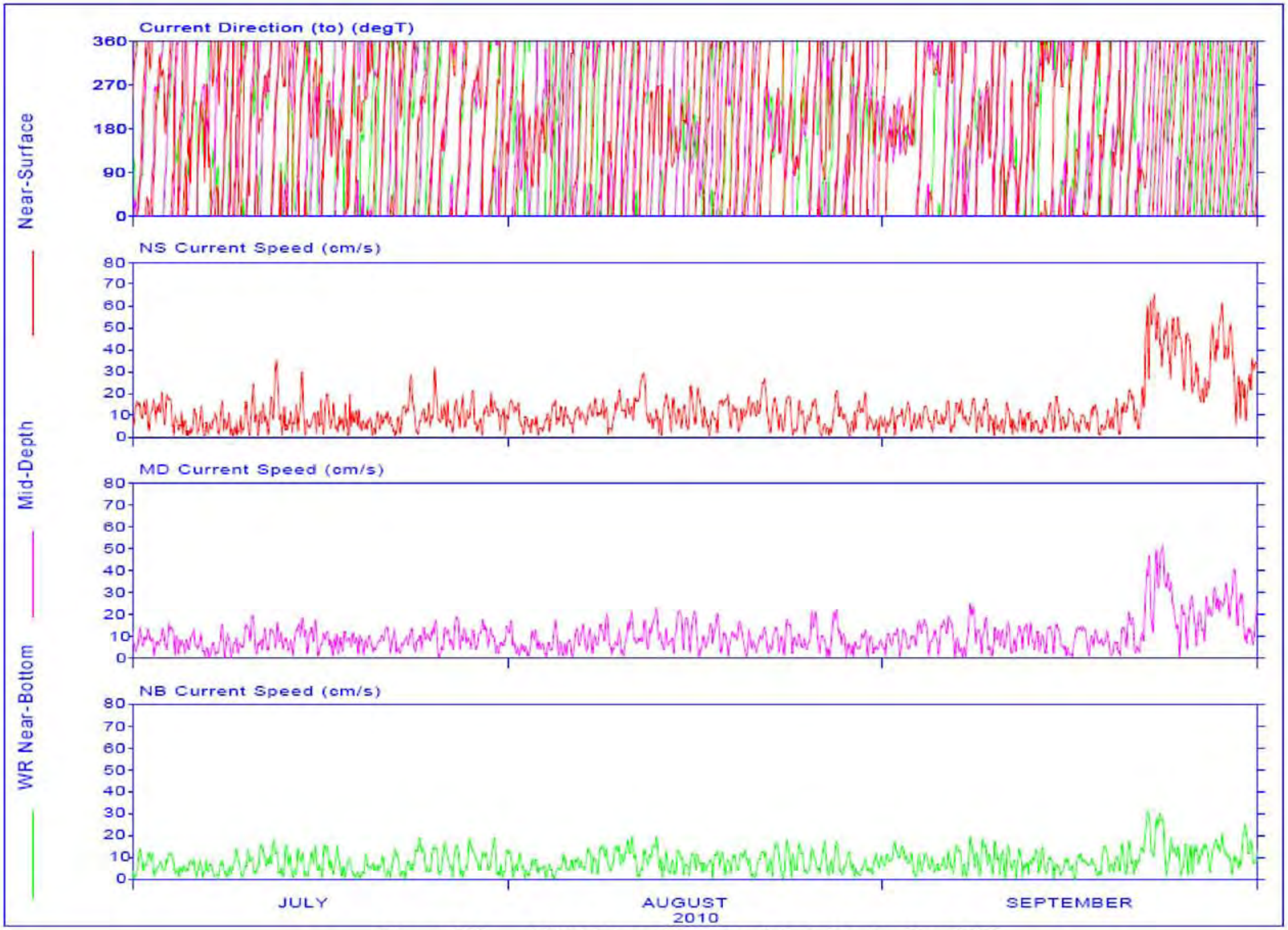

Figure A-3 White Rose Currents, July to September, 2010

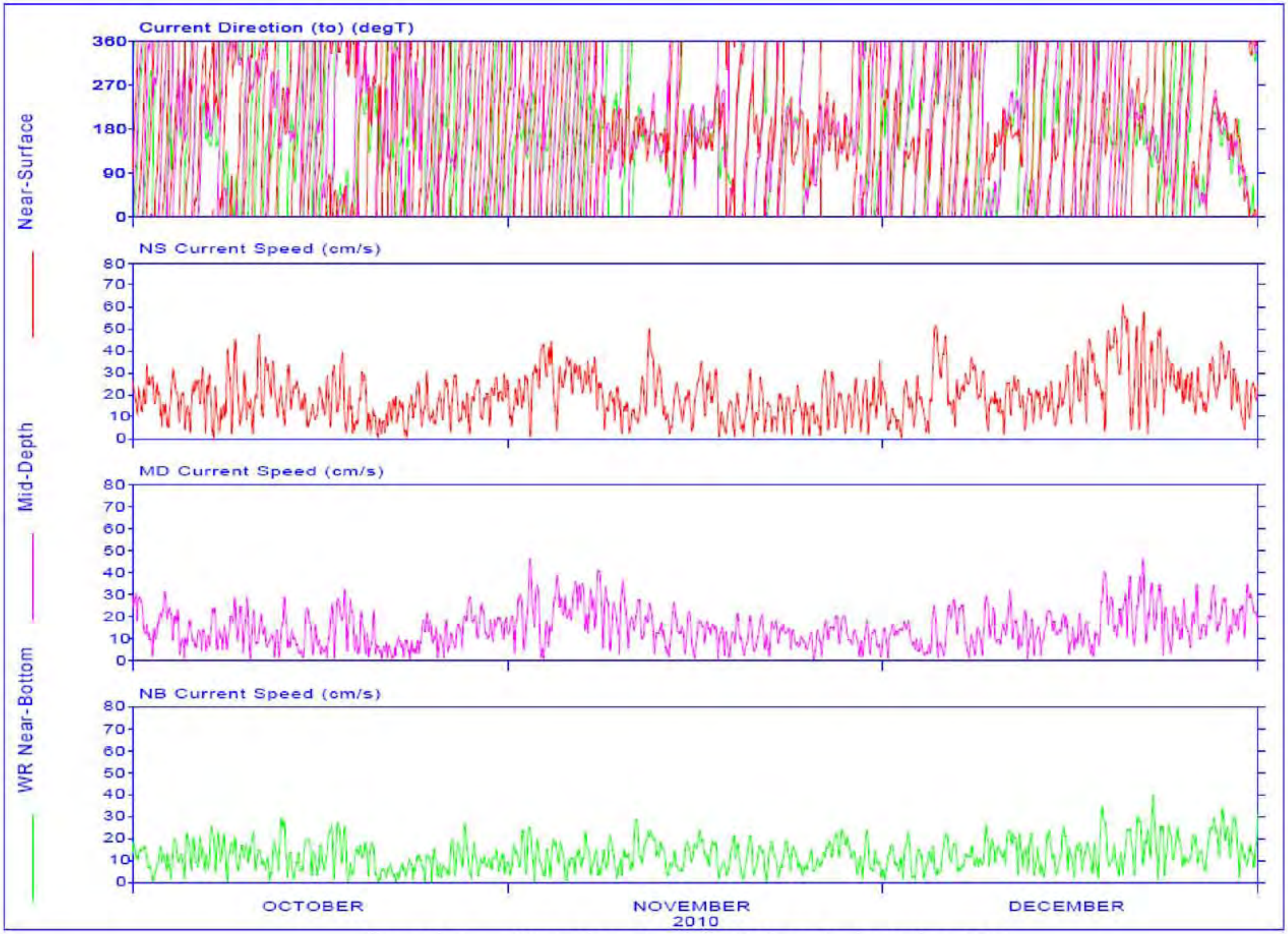

Figure A-4 White Rose Currents, October to December, 2010

Table A-1 White Rose. Annual, Near Surface, Current Speed (cm/s) vs. Direction

Dir (to)	0 to 5	5 to 10	10 to 15	15 to 20	20 to 25	25 to 30	30 to 35	35 to 40	40 to 45	45 to 50	50 to 55	55 to 60	60 to 65	65 to 70	# of Obs	% Total
N	118	208	213	147	61	42	25	13	11	6	6	3	3		856	9.8
NE	127	218	230	160	87	56	29	3	4	6	4		2		926	10.6
E	133	262	239	171	84	58	17	9	9	6	5	2	2	1	998	11.4
SE	142	328	306	269	111	62	36	35	18	8	3	4	1		1323	15.1
S	138	333	302	247	187	135	59	33	25	11	6				1476	16.8
SW	138	311	271	202	125	84	49	26	7	10	7	4			1234	14.1
W	129	269	269	154	76	59	30	22	6	11	12	3	4		1044	11.9
NW	130	233	220	143	64	45	25	14	14	8	3	2	2		903	10.3
Sum	1055	2162	2050	1493	795	541	270	155	94	66	46	18	14	1	8760	100.0
% Exceed	88.0	63.3	39.9	22.8	13.8	7.6	4.5	2.7	1.7	0.9	0.4	0.2	0.0	0.0		
Source: based on ADCP data from Oceans Ltd. 2011.																

Table A-2 White Rose. Annual, Mid-Depth, Current Speed (cm/s) vs. Direction

Dir (to)	0 to 5	5 to 10	10 to 15	15 to 20	20 to 25	25 to 30	30 to 35	35 to 40	40 to 45	45 to 50	50 to 55	55 to 60	60 to 65	# of Obs	% Total
N	5	10	15	20	25	30	35	40	45	50	55	60	65	1053	12.0
NE	163	298	305	127	85	44	10	5	10	5	1			1023	11.7
E	149	293	278	154	92	34	17	2	3	1				1006	11.5
SE	164	338	257	138	72	26	9	2						1114	12.7
S	173	334	282	169	76	39	30	9	2					1348	15.4
SW	149	352	371	222	110	78	39	19	6	2				1115	12.7
W	165	308	286	182	82	32	27	18	9	5	1			1168	13.3
NW	198	348	331	175	62	30	14	5	1	1	2	1		933	10.7
Sum	1301	2573	2372	1267	645	321	156	67	34	15	4	3	2	8760	100.0
% Exceed	85.1	55.8	28.7	14.2	6.9	3.2	1.4	0.7	0.3	0.1	0.1	0.0	0.0		

Source: based on ADCP data from Oceans Ltd. 2011.

Table A-3 White Rose. Annual, Near Bottom, Current Speed (cm/s) vs. Direction

Dir (to)	0 to 5	5 to 10	10 to 15	15 to 20	20 to 25	25 to 30	30 to 35	35 to 40	40 to 45	# of Obs	% Total
N	187	276	195	108	39	23	8	7		843	9.6
NE	160	328	254	127	59	29	11	13	1	982	11.2
E	191	381	369	200	70	15	2	1		1229	14.0
SE	215	400	425	245	82	37	22	5		1431	16.3
S	186	454	472	279	124	41	22	8		1586	18.1
SW	231	423	335	157	57	23	1			1227	14.0
W	188	300	212	67	25	5				797	9.1
NW	167	267	165	41	18	4	3			665	7.6
Sum	1525	2829	2427	1224	474	177	69	34	1	8760	100.0
% Exceed	82.6	50.3	22.6	8.6	3.2	1.2	0.4	0.0	0.0		
Source: based on ADCP data from Oceans Ltd. 2011.											