Technical Appendix Q1

Draft Environmental Impact Statement/Environmental Review and Management Programme for the Proposed Wheatstone Project

July 2010

Wheatstone Project

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Title: Draft Environmental Impact Statement/Environmental Review and Management Programme for the Proposed Wheatstone Project: Technical Appendix Q1

Appendix Q1

Dredge Spoil Modelling

Tables

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Appendices

Abbreviations

Abbreviation	Description
ADCP	Acoustic Doppler Current Profiler
BHD	Backhoe Dredger
BPP	Benthic Primary Producers
BPPH	Benthic Primary Producer Habitat
Chevron	Chevron Australia Pty Ltd
CIRIA	Construction Industry Research and Information Association
CPU	Central Processing Unit
CSD	Cutter Suction Dredger
DDP	Dredging and Disposal Plan
DEC	Western Australia Department of Environment & Conservation
DEWHA	Department of Environment, Water, Heritage and the Arts
DMMER	Des Mills Marine Environmental Reviews
Domgas	Domestic gas
DRL	Dredging Research Limited
DSDMP	Dredging and Spoil Disposal Management Plan
EIA	Environmental Impact Assessment
EIS	Environmental Impact Statement
EPA	Western Australia Environmental Protection Authority
ERMP	Environmental Review Management Program
GEMS	Global Environmental Modelling Systems
km	kilometre
LNG	Liquefied Natural Gas
LWI	Lanier-Wallingford International
m AHD	Australian Height Datum (metres)
m LAT	Lowest Astronomical Tide (metres)
MesoLAPS	Australian Mesoscale Limited Area Prediction System
MEB	Marine Ecosystems Branch, DEC
MOF	Materials Offloading Facility
MTPA	Million Tonnes Per Annum
NTU	Nephelometric Turbidity Units
NWS	North West Shelf
PAR	Photosynthetically Active Radiation
PIANC	World Association for Waterborne Transport Infrastructure
PLF	Product Loading Facility
SKM	Sinclair Knight Merz
SSC	Suspended Sediment Concentration
StDev	Standard Deviation
SW	Spectral Wave

T	Tonne
TSHD	Trailing Suction Hopper Dredgers
TSS	Total Suspended Solids
URS	URS Australia Pty Ltd
WA	Western Australia
WODCON	World Dredging Congress

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Wheatstone Project

Dredge Spoil Modelling

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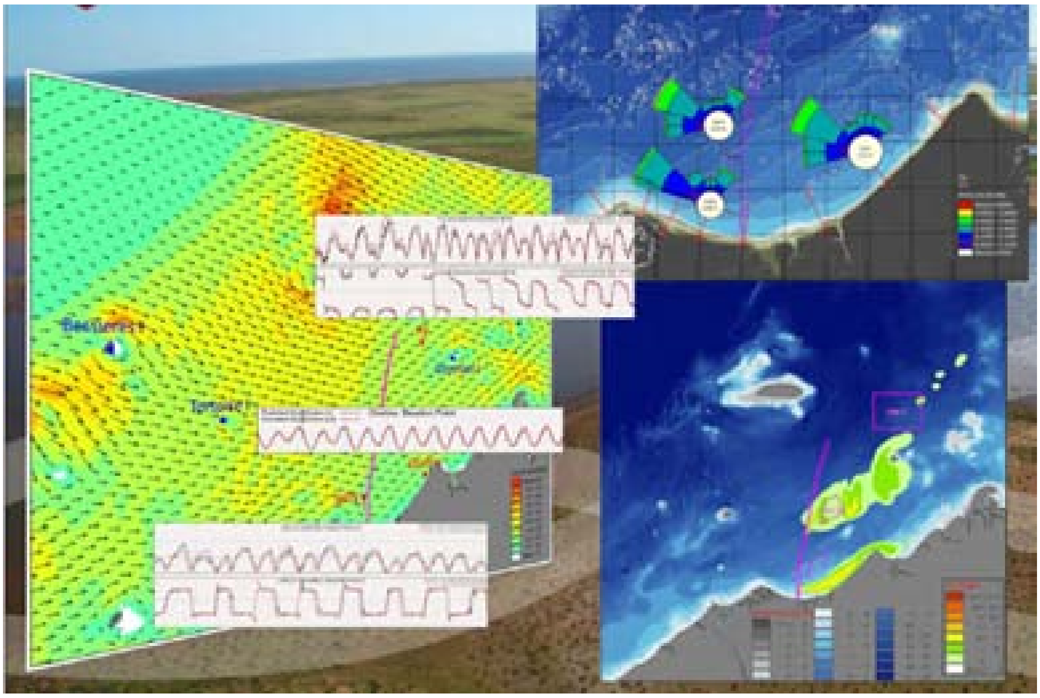

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Wheatstone Project
Dredge Spoil Modelling

May 2010

11th Floor, Hill-View Side
Wisma Perindustrian
Jalan Istiadat, Likas
88400 Kota Kinabalu

Tel: +60 88 260 780
Fax: +60 88 260 781
e-mail: dhikk@tm.net.my
Web: www.dhi.com.my

Client	Client's representative
Chevron Australia	Mr. Ceri Morgan

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Authors	**Date**
Aaroun Azra Leiking Amy Ling Cesar Rocha Dr. Claus Pedersen Dr. Darlene Heuff Dr Jacob Hjelmager Jensen Yvonne Chung	19 May 2010
	Approved by
	Dr. Claus Pedersen

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1	Draft Dredge Spoil Modelling	ALC	CLP	CLP	14/05/2010
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EXECUTIVE SUMMARY

DHI has conducted dredge spoil modelling in support of the Wheatstone Project EIA. The study involved the modelling of the dredging of the MOF, PLF, navigation channel, and the pipeline. Additionally, consideration has been given to assessing the stability of the dredge material placement sites and the eventuality of channel backfilling.

Results from this study have been used to develop zones of impact within the study region. The impact assessment was outside the scope of the works presented here. The methodology and findings of the impact assessment are presented in DHI (2010c)

A summary of key points and/or findings of this study is made below.

Methodology

The methodology adopted for this study was developed based on consideration of:

- The study objectives;
- The details of the dredge program; and
- The characteristics of the ambient environment.

It was concluded that a scenario approach using an Eulerian, coupled, sediment transport and two-dimensional depth averaged hydrodynamic model was appropriate for the modelling of the transport and fate of dredge sediment within the study region.

The modelling methodology has incorporated a number of assumptions and/or components that contribute to the overall conservatism of the model results including:

- The use of two-dimensional depth averaged hydrodynamics for the purposes of representing the impacts associated with a 'line source' of sediment (i.e. the navigation channel);
- The initialisation of the sediment model with fines to support re-suspension within the modelling domain;
- The assessment of both high and low spill rates;
- The selection of an appropriate set of representative worst-case climate scenarios; and
- Determining the envelope of impacts for each dredge scenario under a range of worst case ambient conditions based on the climate scenarios.

A number of studies have been undertaken in support of the adopted methodology. Results from these studies are reported in the appendices to this report.

Channel Dredging

Based on the proposed Dredging and Disposal Plan (LWI 2009a), seven base-case Dredge Scenarios (1-7) were defined. An eighth Dredge Scenario (7A) that incorporates restricted overflow zones within the region covered by Dredge Scenario 7 was also modelled. The incorporation of restricted overflow zones in regions where dredging-activities may potentially lead to adverse impacts at key sensitive receptor locations has been demonstrated to be an effective mitigation measure.

In total, 192 simulations were conducted for the purposes of assessing impacts from the dredging of the navigation channel. These simulations involved eight Dredge Scenarios, six climate scenarios, two spill rates, and two sets of hydrodynamics (one driven by Onslow wind-fields and one driven by MesoLAPS wind fields).

Output from the sediment transport modelling was used as input into the Dredge Plume Impact Assessment (DHI 2010c); results of the impact assessment are reported there too.

Pipeline Dredging

The six climate scenarios were used in simulations involving two trunkline dredging scenarios. The trunkline scenarios were selected based on the proximity of dredging activities to key sensitive receptor locations, namely Ashburton Island and Bessieres Island. Spill rates for the trunkline dredge scenarios were based on the contingency plan as opposed to the preferred option and therefore results presented will be conservative.

Output from the sediment transport modelling was used as input into the Dredge Plume Impact Assessment (DHI 2010c); results of the impact assessment are reported there too.

Spoil Site Stability

An assessment of dredge material placement site stability suggests that there will inevitably be some migration of placed material away from the placement site in the directions of dominant transport mixing into the natural transport pathways that already exist. For dredge material site A and site B, small amounts of fine sand placed at the sites would, at times, be transported towards the Onslow Salt Channel to the east and towards the Wheatstone Navigation Channel to the west. Rates of such transport are unlikely to be significantly greater than that presently occurring because of the distances involved and the presence of fine sand fractions on the seabed in these areas.

Some emission of fine sediments will initially occur from the dredge material placement areas. This will gradually reduce to background levels as the fines are weaned out and the material consolidates. Sediment concentrations from re-suspension from the dredge material placement areas are small compared to the sediment plumes due to spills from dredging and placement.

1 INTRODUCTION

Chevron Australia Pty Ltd (Chevron) proposes to construct and operate a multi-train Liquefied Natural Gas (LNG) and domestic gas (Domgas) plant 12 km south west of Onslow on the Pilbara Coast (Figure 1.1). The LNG and Domgas plant will initially process gas from fields located approximately 200 km offshore from Onslow in the West Carnarvon Basin and other yet-to-be determined gas fields. The project is referred to as the Wheatstone Project and "Ashburton North" is the proposed site for the LNG and Domgas plant. The Project will require the installation of gas gathering, export and processing facilities in Commonwealth and State Waters and on land. The LNG plant will have a maximum capacity of 25 Million Tonnes Per Annum (MTPA) of LNG.

The Wheatstone Project has been referred to the State Environmental Protection Authority (EPA) and the Commonwealth Department of Environment, Water, Heritage and the Arts (DEWHA). The investigations outlined in this report have been conducted to support the environmental impact assessment process.

DHI has been commissioned by URS on behalf of Chevron to undertake the modelling of the transport and fate of sediment from dredging activities associated with the Wheatstone Project. The investigations outlined in this report have been conducted to support the environmental impact assessment process being managed by URS Australia Pty Ltd (URS).

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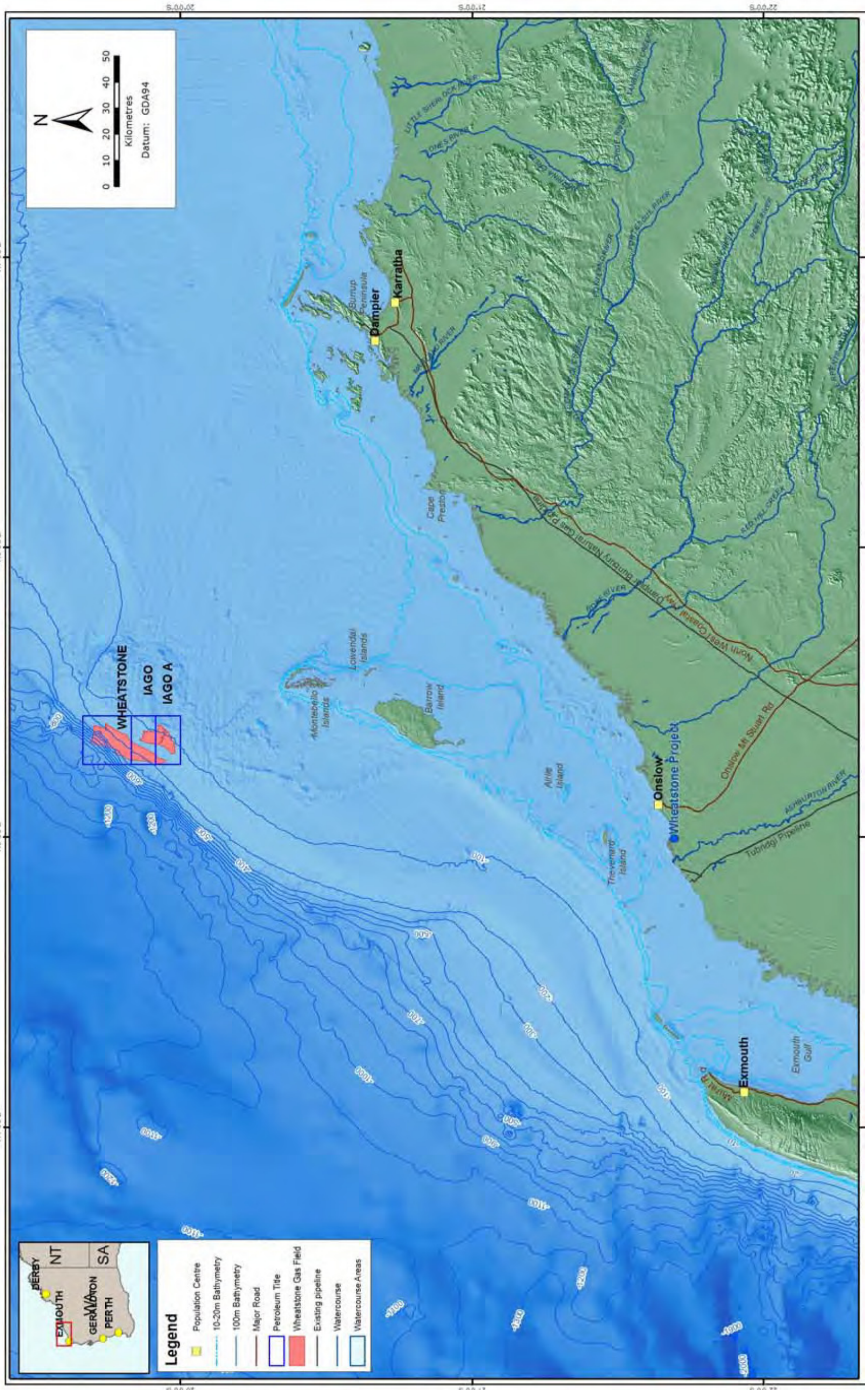

Figure 1.1 Overview of the site location. (Source: URS)

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My5527 Wheatstone – Dredge Spoil Modelling, Revision 0 05-2010

1.1 Dredge Spoil Modelling Scope of Works

The Wheatstone Project involves dredging up to 45 million m^3 of material for installation of berths and turning basins at an inshore Materials Offloading Facility (MOF) and a Product Loading Facility (PLF) as well as access to these through an approximately 16 km long navigation channel. Dredge plume impacts have been rated as a key environmental risk for the project.

Dredge plume modelling is the key tool used to identify areas that may be adversely impacted upon due to dredging activities associated with the Wheatstone Project. Results of the modelling are particularly useful in identifying worst-case ambient conditions such as prolonged periods of relative stagnant ambient conditions which leads to elevated levels of suspended sediment concentration and/or periods of prolonged elevated current velocities which result in the potential for adverse impacts at some distance from the source.

Additionally, modelling plays an important role in the assessment of the relative effectiveness of potential mitigation options.

The scope of works under taken by DHI in relation to the modelling of the transport and fate of disturbed sediment associated with dredge activities included (but was not limited to):

- Development of a calibrated/validated set of regional and local hydrodynamics;
- Development of a calibrated/validated wave model;
- Development of a calibrated/validated sediment transport model;
- Determine the envelope of the dredge plume under worst-case and typical spill rates;
- Assess dredge plumes associated with dredging for the trunkline;
- Assess the relative improvement in environmental outcome associated with potential mitigation options compared with an established base case;
- Assess the potential for channel back filling;
- Assess dredge material site stability; and
- Provide recommendations and suggestions for mitigation if required

Results from the dredge spoil modelling have been used by DHI to conduct an assessment of potential impacts at sensitive receptor locations. The methodology and findings of the impact assessment have been undertaken separately and is outside the current scope of works. The reader is directed to DHI (2010c) for further information relating to the dredge plume impact assessment.

1.2 Report Structure

This report provides an overview of the adopted modelling motivation, methodology, development of modelling tools and results of the dredge spoil modelling. Additional information is provided in the supporting appendices.

Information is presented utilising the following report structure:

Chapter 1 provides an overview of the report including a brief project description, an outline of the study scope of works and relevant documentation. This is followed by an outline of the report structure and a summary of the report review process. The chapter closes with a discussion regarding both the general and study-specific limitations of the study.

Chapter 2 focuses on relevant information relating to the dredging activities. The chapter begins with an overview of the dredging and disposal plan. This is followed by the characterisation of in-situ sediment from both core samples taken within the proposed navigation channel and sediment grab samples obtained throughout the study region including the locations of the proposed dredge material placement sites. The characterisation of in-situ material is followed by a characterisation of dredge sediment. The chapter closes with estimates of high (i.e. worst-case) and low (i.e. realistic) spill rates.

Chapter 3 provides an overview of the modelling methodology that has been adopted for this study. A number of studies that have been undertaken in support of the adopted methodology are outlined.

Chapter 4 presents the development of the key modelling tools, namely the hydrodynamic model, the wave model and the sediment transport model. Discussions relating to model grid development, model inputs, boundary conditions and model calibration and/or validation are presented. Applications of the model setup specific to the Wheatstone Project close out this chapter.

Chapter 5 outlines the climate scenario selection criteria and presents current roses highlighting the ambient conditions captured within each of the six climate scenarios used in this study.

Chapter 6 presents the body of work surrounding the modelling of the dredging of the navigation channel. In particular the scenario selection criteria and the development of the dredge scenarios are presented. In total, seven dredge scenarios are defined. A variation of one of the dredge scenarios has been identified which incorporates mitigation measures designed to reduce impacts at key sensitive receptor locations. Results for the mean suspended sediment concentration are presented for both high and low spill rates for each of the climate scenarios, for each of the dredge scenarios. Additionally, composites of all climate scenarios for each dredge scenario are presented. Results from the full set of dredge and climatic scenarios are combined to develop an envelope of worst-case impacts for low (realistic) spill rates. The chapter closes with a discussion on the issues associated with backfilling of the channel resulting from the natural migration of sediment within the ambient environment.

Chapter 7 presents the dredge scenarios associated with the dredging of the trunkline. Results associated with the contingency dredge program are presented. The preferred trunkline dredge option which involves significantly lower sediment spill rates has not been assessed.

Chapter 8 investigates the stability of the dredge material placement sites. A summary of the findings are included within the chapter.

Chapter 9 presents a summary of the study including a brief overview of the methodology, channel dredge modelling, trunkline dredge modelling, and the dredge material placement site stability assessment.

1.3 Report Review Process

In addition to the internal review processes within DHI, URS, and Chevron, three reviews have been carried out on the modelling component of this study:

1. Input during the course of the study by Lanier Wallingford International (LWI = HR Wallingford) who are providing downstream engineering consultancy.

2. An independent review by Des Mills Marine Environmental Reviews (DMMER) commissioned by Chevron. Input to the study from this review process has been provided through several meetings and in writing throughout the study period. The DMMER review process has provided valuable input on the ambient conditions and available data and information for the North West Shelf as well as advice on “typical” and expected modelling procedures in Western Australia (Appendix JJ).
3. A review by HR Walllingford of the modelling approach (Appendix II).

1.4 Study Limitations

1.4.1 General

DHI has prepared this report in accordance with the usual care and thoroughness of the consulting profession for the use of Chevron Australia Pty Ltd and only those third parties who have been authorised in writing by DHI to rely on the report. It is based on generally accepted practices and standards at the time it was prepared. No other warranty, expressed or implied, is made as to the professional advice included in this report.

The methodology adopted and sources of information used by DHI are outlined in this report. DHI has made no independent verification of this information beyond the agreed scope of works and DHI assumes no responsibility for any inaccuracies or omissions. No indications were found during our investigations that information contained in this report as provided to DHI was false.

This report was prepared between 01/01/2009 and 10/05/2010 and is based on the conditions encountered and information reviewed at the time of preparation. DHI disclaims responsibility for any changes that may have occurred after this time.

This report should be read in full. No responsibility is accepted for use of any part of this report in any other context or for any other purpose or by third parties. This report does not purport to give legal advice. Legal advice can only be given by qualified legal practitioners

1.4.2 Project Specific Limitations

The key project-specific limitations of the current study are associated with:

- The uncertainties associated with the Project description at the time of this assessment which includes (but is not limited to) the representativeness of spoil rates applied in relation to proposed dredging activities;
- The limitations inherent to the use of numerical modelling tools such as MIKE 21 HD, MIKE 21 SW and MIKE 21 MT. It is important to note that all numerical models that are based on approximating a governing set of equations will inherently be associated with some degree of error. The more complex the physical model, the greater the number of physical processes which must be parameterised. This frequently results in a large number of adjustable parameters within the model. There exists extensive expertise in the use of the MIKE suite of modelling tools within DHI and our modellers make every reasonable attempt to ensure that model results are of the highest possible standard.

This study necessarily relies on the accuracy of the following information and/or data sets:

- Project-related information provided by Chevron.
- Details of the dredging and disposal plan.

- Geotechnical data used to characterise in-situ material properties
- Bathymetry data used to develop the model grids
- Sediment data
- Current data used to calibrate and validate the performance of the hydrodynamics
- Wind data (both observational and MesoLAPS) used to drive the hydrodynamic and wave models
- Ambient temperature and salinity data used to establish the uniformity of the water column and lack of significant stratification
- Wave and swell data used as inputs into the wave model (MIKE 21 SW)
- Sea surface elevations developed using the KMS model
- MODIS Images used to assess the frequency and severity of elevated levels of sediment within the study region due to existing environmental conditions.

Project information and data sets have been obtained from a number of sources including (but not limited to):

- Chevron Australia Pty Ltd
- The Australian Government's Bureau of Meteorology
- Lanier-Wallingford International (LWI)
- Global Environmental Modelling Systems (GEMS)
- Metocean Engineers Pty Ltd
- GeoScience Australia

2 DREDGING

2.1 Dredge Disposal Plan

The Dredging and Disposal Plan (DDP) (LWI 2009a) contains a detailed description of the dredging to be carried out, including information on type of equipment, procedures, cycle times and spill rates. This information is well suited for establishing shorter term modelling scenarios. It is noted that there have been recent changes to the dredge schedule and procedures which are not captured in the DDP produced in December 2009. The dredging program as described in the present document is therefore not fully in line with LWI (2009a). Additional information is provided in Appendix A - Dredging and Disposal Plan.

An overview of the channel, the nearshore placement sites (site A, site B and site C), and the offshore placement sites (site D and site E) is provided in Figure 2.1, with details of the nearshore components in Figure 2.2.

The latest dredge plan from the Capital Dredging Monitoring and Management Plan (LWI 2009b) is provided in Figure 2.3. The revised indicative schedule has a large Cutter Suction Dredger (CSD) operating in the nearshore area for a period of 5.75 months to fully establish the MOF basin, MOF channel and dredge the PLF down to -9.4 m AHD. Two 10,000 m^3 and one 5,000 m^3 Trailing Suction Hopper Dredgers (TSHDs) will dredge the PLF and PLF approach channel down to -14.9 m AHD. A tabulated summary of the main dredging components is provided in Table 2.1.

It is noted that the DDP includes options for onshore placement. The scenario modelling presented in this report assumes no onshore placement, which is conservative in terms of marine impacts.

Table 2.1 Summary of key dredging activities.

Activity		Plant	Average Production (m^3/week)	Disposal Site	Time (months)
#	Description				
1	Temporary Access Channel to MOF and barge access to -3m LAT contour in PLF	CSD*	155,000	Site A/C	1.75
2	Dredging PLF Maneuvering Area to -9.4m AHD follow on from Temp Access channel dredging	CSD*	Sand: 250,000 Rock: 170,000	Site C	2.0
3	MOF and MOF approach channel. Follow-on from PLF Maneuvering Area dredging.	CSD*	Sand: 250,000 Rock: 170,000	Site C	2.0
4	Dredging PLF approach channel to -10.4m AHD	5,000 m^3 TSHD**	180,000	Site C	2.0
5	Dredging PLF Basin from -9.4 to -14.9m AHD (installed depth + siltation allowance)	10,000 m^3 TSHD**	Sand: 385,000 Rock: 70,000	Site C	12.75
6	Dredging PLF approach channel to -14.9m AHD (installed depth + siltation allowance)	10,000 m^3 TSHD**	Sand: 385,000 Rock: 70,000	Site C	36.0
7	PLF Basin Rock Dredging	BHD***	28,000	Site B/C	0.75
8	Approach Channel Rock Dredging	BHD***	28,000	Site B/C	1.5
9	Clean-up dredge, MOF (after activities 3 & 4)	5,000 m^3 TSHD**	55,000	Site D	0.25
10	Clean-up dredge PLF (after activity 5)	10,000 m^3 TSHD**	100,000	Site D	2.0

Notes: ** CSD = Cutter Suction Dredger*
*** TSHD = Trailer Suction Hopper Dredger*
**** BHD – Back Hoe Dredger*

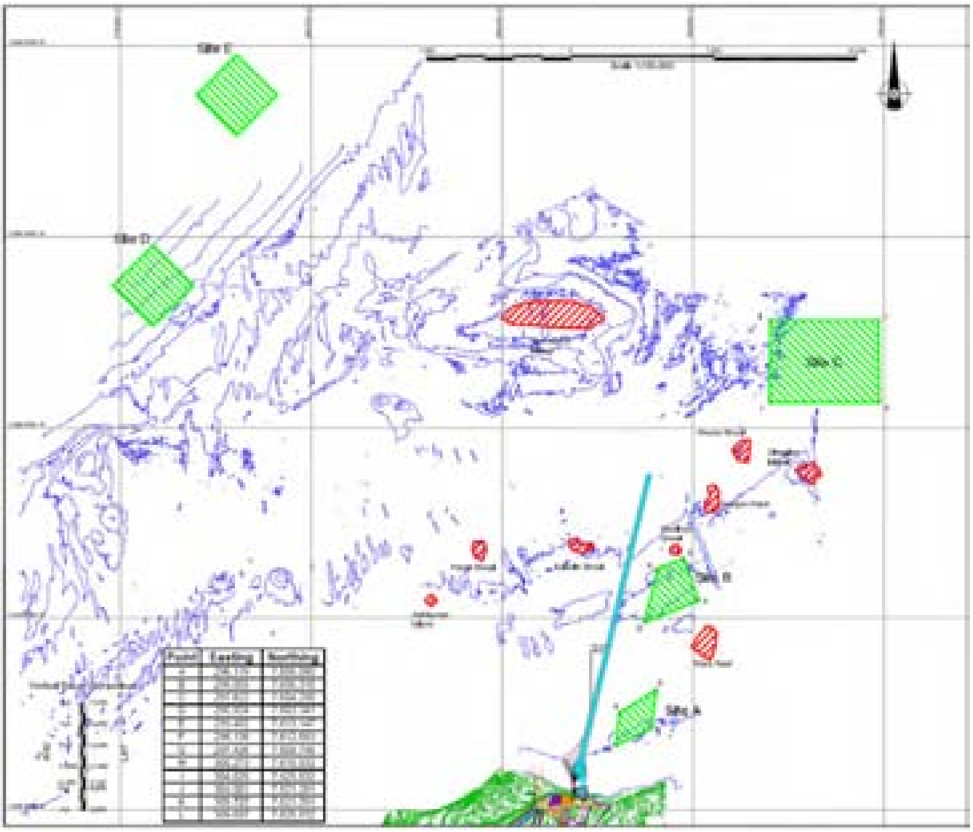

Figure 2.1 Outline of navigation channel, nearshore dredge material placement sites (Site A, Site B and Site C) and offshore dredge material placement sites (Site D and Site E).

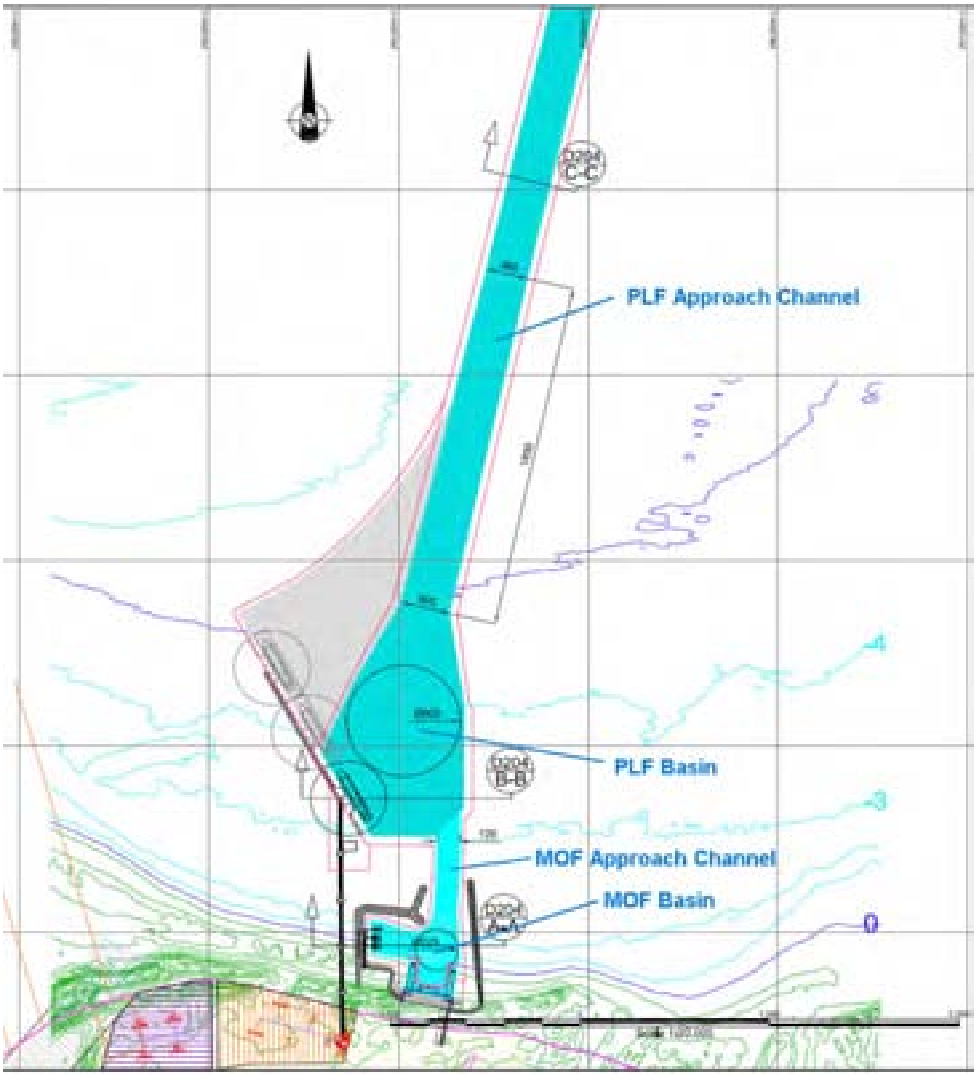

Figure 2.2 Details of MOF, PLF and inner section of PLF approach channel.

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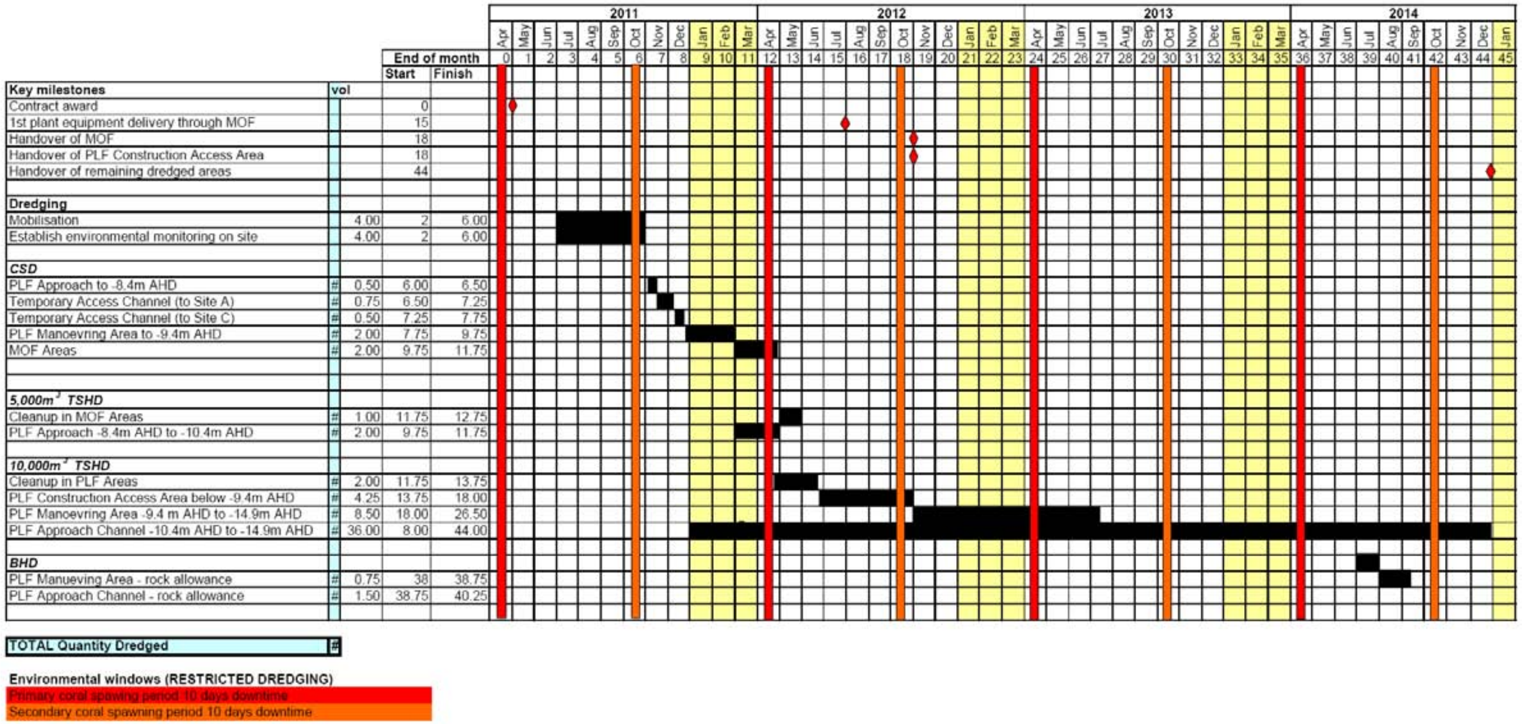

Figure 2.3 Outline indicative dredge schedule from Dredge Disposal Plan LWI (2009a).

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2.2 Characterisation of Sediments

2.2.1 In-Situ Sediment

An accurate characterisation of the material to be dredged is critical for input into the dredge sediment modelling and prediction of potential impacts. The disintegration of the material and the subsequent spill material will be highly dependent upon the equipment type and the strength of the material to be dredged. The soil properties vary along the channel and for different depths, and corresponding significant variations in spill rates will therefore be experienced.

2.2.1.1 Core Samples

Soil and borehole information provided in the DDP (LWI 2009a) is shown in Figure 2.4. This shows predominantly sandy/loose soil conditions along the outer third of the PLF approach channel, weak rock and mud components along the central part of the PLF approach channel, and mixed layers of sandy and rocky soils along the inner part of the PLF approach channel. The PLF basin and MOF approach channel have predominantly loose soils, while the MOF seems to have a larger proportion of consolidated (weak rock) material. It is noted that there are considerable variations along the channel.

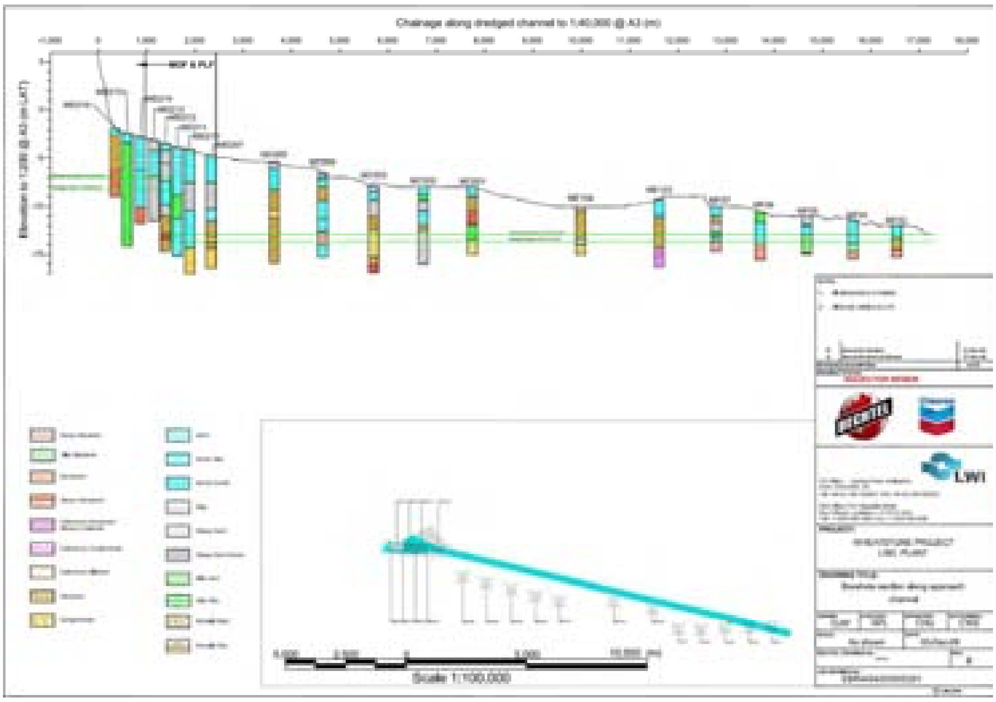

Figure 2.4 Soil classification along dredge corridor based on borehole logs. LWI Drawing No EBR4454/0330/D201 (LWI 2009b)

2.2.1.2 Sediment Grab Samples

Several grab sampling campaigns have been undertaken and mean grain sizes have been obtained within the Wheatstone area in general (see Figure 2.5 and Figure 2.6) and within preliminary nominated dredge material placement grounds for sediment analysis in particular (Figure 2.7).

Measured mean grain sizes throughout the region are indicated on the figures. They show that the mean grain sizes vary throughout the region, but are generally associated with sandy surface material.

According to LWI (2009b) the offshore dredge material placement areas are predominantly composed of sand or coarser material. The percentage of sand/gravel here is close to 80% with only small amount of fines. Using a Shields parameter stability criterion and the simulated bed shear stresses (exceeded 5% of time) indicates that material with a grain size smaller than 0.1 mm is mobile.

Table 2.2 Percentages of sediments within proposed dredge material placement areas (LWI 2009b)

Mean Sediment Grain Size in Wheatstone Dredge Area and Proposed Dredge Material Placement Areas					
Proposed Dredge Material Placement Areas	Cobbles (%) (>6 cm)	Gravel (%) (>2 mm)	Sand (%) (0.062-2 mm)	Silt (%) (2-60 µm)	Clay (%) (<2 µm)
Bechtel Dredge Material Placement Area Site A	0	15.8	58	9.6	16.6
Bechtel Dredge Material Placement Area Site B	0	12.6	60.6	10.2	16.6
Bechtel Dredge Material Placement Area Site C	0	9.2	70.8	6.7	13.3
Bechtel Dredge Material Placement Area Site E	0	3	82	6.6	8.4
Bechtel Dredge Material Placement Area Site D	0	4.6	69.8	12.2	13.4

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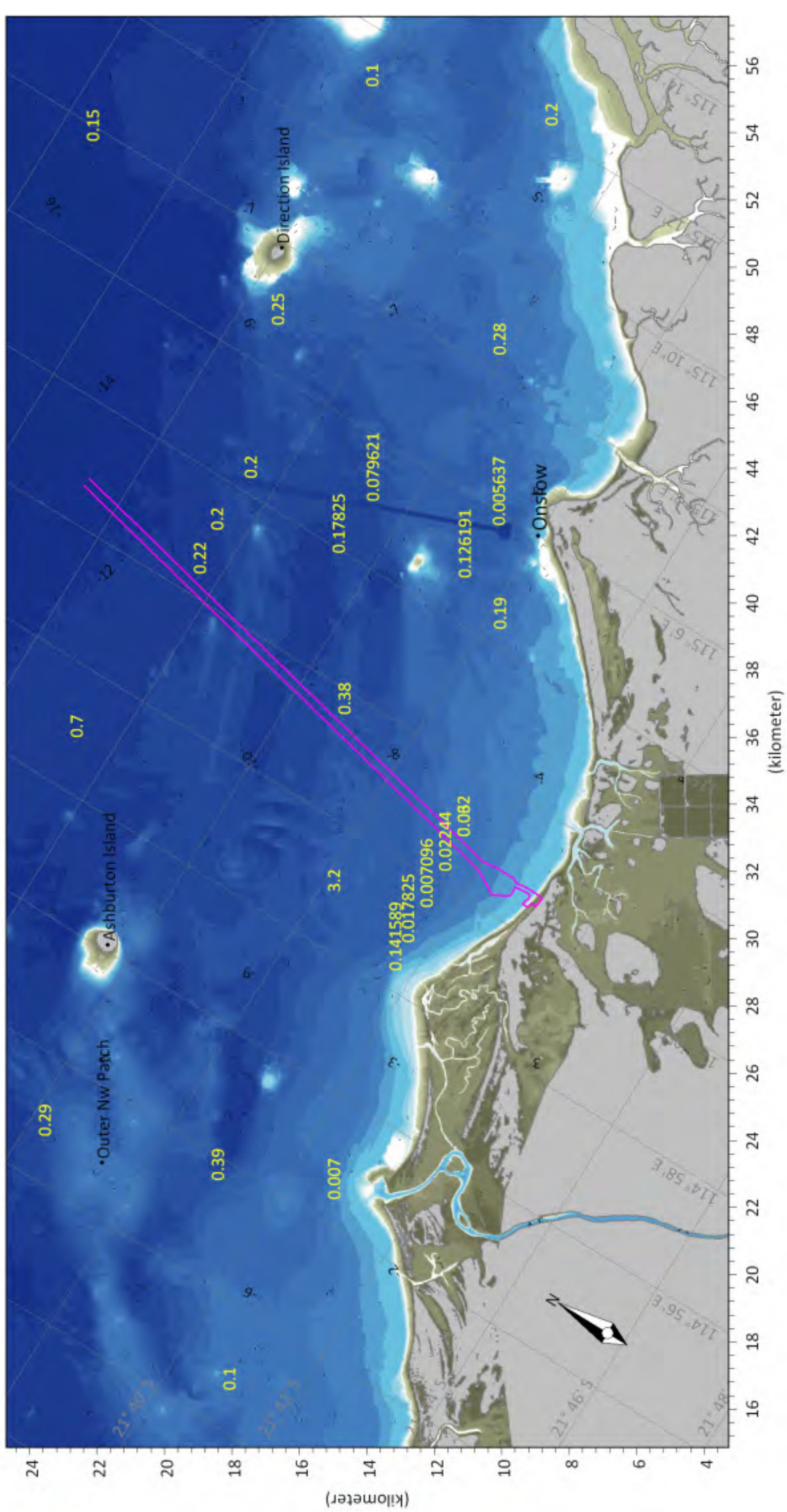

Figure 2.5 Mean grain sizes (mm) throughout the Onslow region.

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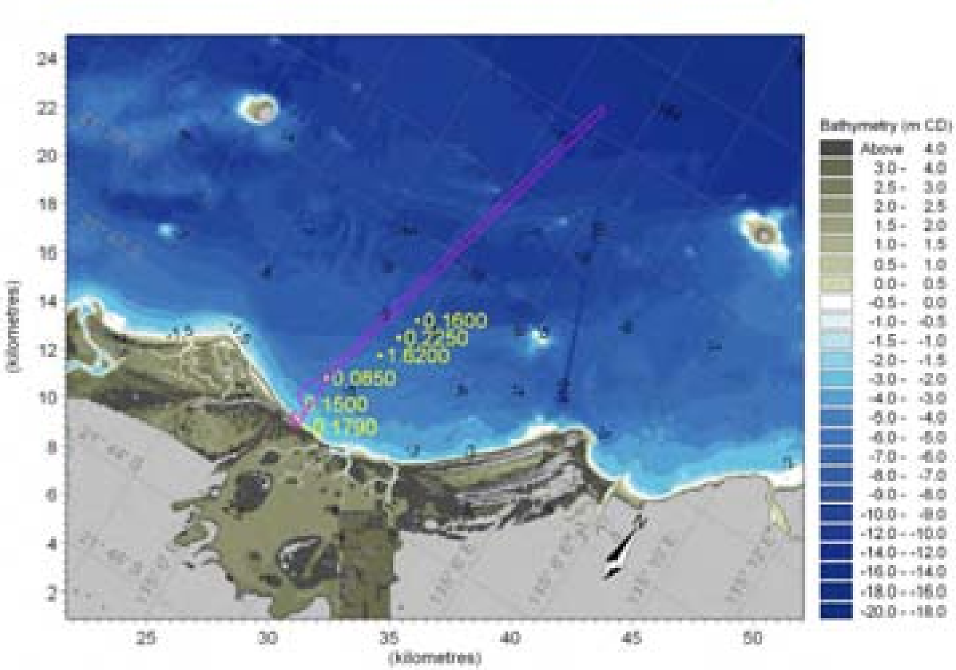

Figure 2.6 Mean grain sizes (mm) in the nearshore area at the Project site.

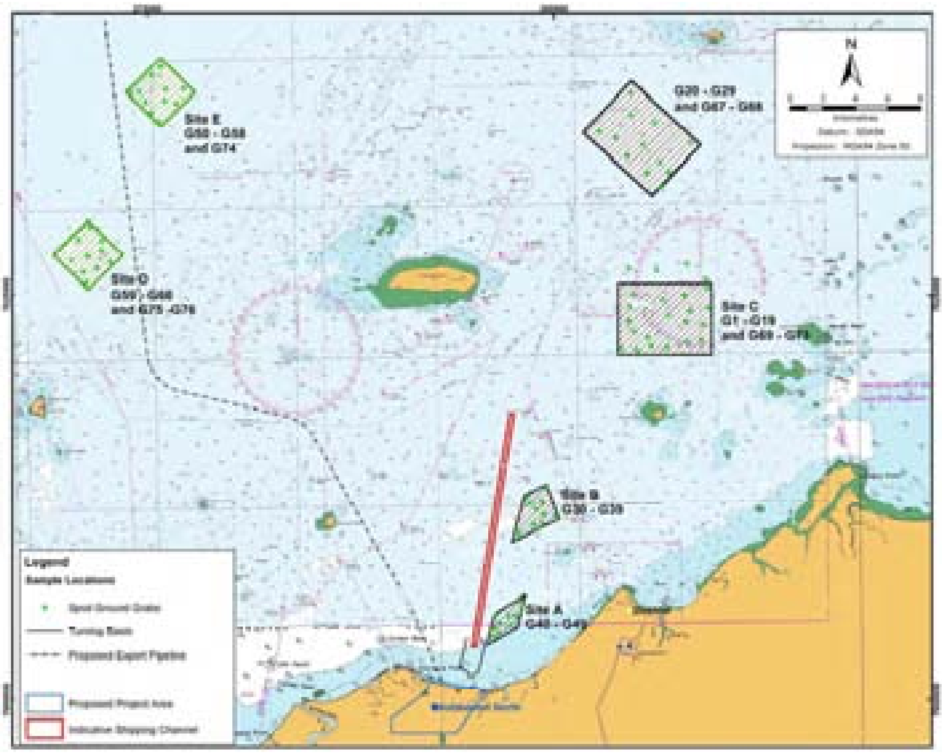

Figure 2.7 Locations of dredge material placement area grab samples for sediment analysis

2.2.2 Characterisation of Spoil Sediment

The DDP from LWI (2009a) includes assumed particle size distributions for the material to be disposed. This is based on analysis carried out on samples taken within the dredge area (boreholes MD207 and MD210 to MD216) which show that the silt and clay fractions of the sandy material to be dredged are highly variable. Silt fractions may vary between 20% and 60%, while the corresponding clay fractions in samples could range between 10% to over 30%. The assumed particle size distribution in Table 2.3 (from Table 7, LWI 2009a) shows that only 16% of the material is coarser than 0.2 mm. This indicates that more than 80% of the material on average will be mobile based on Shields stability criterion.

Table 2.3 Assumed particle size distribution for sand. (Source: LWI 2009a)

Particle size (µm)	PSD 1 (sand)
<20	20
20 – 60	14
60 – 80	8
80 – 100	12
100 – 150	18
150 – 200	12
200 – 300	8
300 – 400	5
400 – 600	2
600 – 1000	1
1000 – 2000	0
2000 – 4000	0
>4000	0
Total	100
Fines (% < 75 µm)	40
Bulk density (kg/m^3)	1,950

2.3 Dredge Spill Rates

There are currently significant uncertainties associated with the spill rates that may occur during dredging. In order to address this uncertainty, two spill rates have been defined for each type of operation and for two soil classes (sand and weak rock) for the dominant planned activity comprising a 10,000 m^3 TSHD. The spill rates are classified as:

1. A “low” (or realistic) spill rate which represents the best estimate representative spill rate for extended periods of dredging.
2. A “high” (or worst-case) spill rate which may occasionally occur for individual cycles, but which is considered highly conservative when maintained for extended periods of time.

The low spill rates combined with the high production rates (assuming “sand”) throughout a month of dredging represent the best estimate of the sediment source that will leave the immediate dredge area in suspension, leading to conservative but realistic impacts over extended periods of times. The high spill rates combined with the high production rates represent sediments leaving the work area in suspension that can occur during shorter periods of time with non-favourable combinations of climatic, dredge and soil conditions. Maintaining these rates for a full month as included in the simulations is considered highly conservative. The low spill rates will therefore be used for the main impact assessment, while the high spill rates will used to derive impact zones that show the limits for impacts in a worst case scenario with no mitigation.

Confirmation of the spill rates and composition of the material can only be fully addressed for the project and site specific conditions after start of dredging.

Low (i.e. realistic) and high (i.e. worst-case) spill rates for each type of operation and each source have been estimated for the relevant soil conditions based on the extensive combined experience of DHI and HR Wallingford from monitoring and modelling of dredge operations. LWI have applied their dredging module to derive spill rates, and DHI have checked against monitoring data from similar conditions. The resulting matrix is provided in the DDP (LWI 2009a) and relevant items included in Table 2.4. Please note that the values in Table 2.4 include minor adjustments over the DDP that have been agreed between DHI and LWI. The separate assessments by LWI and DHI are presented in Appendix B - LWI and DHI Spill Rate Assessments.

Table 2.4 LWI and DHI agreed Low and High estimates for spill rates for extended periods.

Activity		**Source term for plume in suspension**					
		Sand			**Weak Rock**		
#*	**Description**	**Time per cycle**	**Low** Realistic	**High** Worst case	**Time per cycle**	**Low** Realistic	**High** Worst case
1	CSD dredging temporary access channel	Continuous	19 kg/s	39 kg/s	n/a	n/a	n/a
1	CSD discharging by near bed diffuser (Site A)	Continuous	5 kg/s	5 kg/s	n/a	n/a	n/a
2,3	CSD dredging in PLF, MOF & MOF access channel	Continuous	31 kg/s	63 kg/s	n/a	n/a	n/a
1,2, 3	Overflow from barge filled by CSD	40 min	24 kg/s	53 kg/s	n/a	n/a	n/a
4	5,000 m^3 TSHD overflow	86 min	33 kg/s	73 kg/s	n/a	n/a	n/a
4	5,000 m^3 TSHD draghead and prop disturbance	114 min	24 kg/s	24 kg/s	n/a	n/a	n/a
4	5,000 m^3 TSHD disposal Site C	5 min	161 kg/s	805 kg/s	n/a	n/a	n/a
5,6	10,000 m^3 TSHD overflow	50 min	87 kg/s	194 kg/s	335 min	12 kg/s	26 kg/s
5,6	10,000 m^3 TSHD draghead and prop disturbance	75 min	29 kg/s	30 kg/s	355 min	4 kg/s	12 kg/s
5,6	10,000 m^3 TSHD disposal, Site C	5 min	376 kg/s	1,878 kg/s	5 min	53 kg/s	263 kg/s

** Numbers relate to Activities in Table 2.1*

3 MODELLING METHODOLOGY OVERVIEW

When developing an appropriate modelling methodology for any given project, it is important to consider:

- The objectives of the study;
- The availability and quality of input data;
- The issues and challenges associated with the marine environment; and
- The important spatial and temporal scales associated with the problem.

Developing an appropriate methodology therefore requires the establishment of not only a good understanding of the baseline climatic, hydrodynamic and sedimentological conditions, and plume-generating activities but also the governing mechanisms involved in the advection, dispersion and settling processes for the sediments. It is equally important to understand the capabilities and limitations of the models available in relation to the scales at hand i.e.:

- Is it possible to achieve a very detailed model for the near-field of the dredger which may require resolution in the order of meters or less and at the same time cover the entire potential impact area which may be in the order of tens of kilometres?
- Is additional information gained through a detailed near-field model, or is the key objective to establish a model that can reliably simulate the fate of the plume from the near-field to the entire impact area?

It is therefore vital in the scoping and choice of approach to identify and focus on the key parameters in order to optimise the value of the assessment.

3.1 Objectives

The use of numerical models has two main objectives:

1. Extending and supplementing the baseline information in order to describe the temporal and spatial distribution of physical processes that have an impact on the environment in a manner that may result in development constraints. Numerical models allow the spatial extrapolation of limited primary and secondary data.
2. Providing the tools necessary for addressing engineering problems and testing the performance of identified management strategies. Numerical models allow consideration of the effects of future development on the environment

For dredging operations, the numerical models allow prediction of the extent and concentrations of sediment plumes generated, which in turn allows an assessment of the impacts on environmental receptors.

3.2 Strategy Motivation

This section presents an overview of the motivation for the modelling strategy that has been adopted for this project. A detailed discussion of methodology options are presented in Appendix C - Modelling Methodology Options.

The modelling strategy that has been adopted for the Wheatstone Project has been motivated by the need to ensure that the results of the modelling adequately provide a conservative upper bound on the potential impacts from dredge plume sediment based on the degree of uncertainty that is inherent in the project description. The key uncertainties associated with the proposed dredging program that have been identified are:

1. The actual sediment release rates and spill characteristics that will occur. This is highly dependent upon the type of dredging equipment used and the local sediment characteristics;
2. The final details of the dredging program which will ultimately be defined by the dredging contractor;
3. The precise nature of the climatic conditions that will be experienced across the entire dredge footprint during the three years of actual dredging program as well as the impact of climatic conditions on the dredging program schedule.

In recognition of the uncertainty in the actual dredge program, it is crucial that the modelling and impact assessment are sufficiently flexible to cover a range of plausible dredge programs.

The uncertainty in the spill rate that will occur at the time of dredging has been addressed by the assessment of potential impacts associated with both a 'high' (i.e. worst-case) and 'low' (i.e. realistic) rate of sediment spillage resulting from dredging activities.

In order to address the limitations of the study associated with uncertainties in the details of the dredge program that will be implemented, a scenario approach has been adopted that identifies key stages within the dredging program and assess impacts from each component in isolation.

Uncertainty associated with the climatic conditions that will be experienced at the time of dredging has been accommodated for by the use of a climate scenario approach which includes a range of worst-case climatic conditions.

By investigating the transport and fate of sediment for each dredge scenario under a range of worst-case climatic conditions, the sequencing of dredging activities becomes unimportant thereby reducing the influence of uncertainties associated with the dredge program.

The modelling strategy that has been adopted for this study follows that recommended by The World Association for Waterborne Transport Infrastructure (PIANC) and involves the modelling of the dredging program using combinations of short-term climate scenarios, dredge scenarios, and spill rates in order to ensure that the bounds of the range of plausible conditions are adequately assessed.

In addition to assessing the impacts and risks associated with a given dredge program, the scenario approach can readily be used for:

- Assessing impacts of changes to a given dredge program, both in terms of timing and use of different approaches if the associated spill rate can be assessed.
- Identifying critical stages or components of the dredging program.
- Optimisation of dredge program to minimise impacts (e.g. avoiding dredging in critical areas during certain climatic conditions, minimising spill in critical sectors, etc.)
- Quantifying the effectiveness of potential dredging-related mitigation options designed to reduce the potential for adverse environmental impacts.
- Establishing limits on control variables. For example, the use of a spill budget which determines the maximum allowable sediment spill for defined zones and conditions on critical variables, e.g. variable with climatic conditions.

Thus the adopted scenario approach for the modelling of the transport and fate of dredge sediment maintains a large degree of flexibility as it relates impacts to the spill generated, irrespective of how this is generated.

Motivated by the results of the analysis of available observational ambient data and the configuration of the dredge program, the hydrodynamics used to drive the sediment model have been developed using a two-dimensional depth-averaged approach. A 2D model is conservative when used in combination with the scenario modelling approach where worst-case climatic and spill conditions are modelled along the entire channel, see Appendix E - Sediment Transport Modelling using 2D vs. 3D Hydrodynamics.

3.3 Studies Undertaken in Support of Modelling Methodology

The modelling methodology has incorporated within it a number of assumptions and/or components that contribute to the overall conservatism of the model results including (but not necessarily limited to):

- The use of two-dimensional depth averaged hydrodynamics for the purposes of representing the impacts associated with a 'line source' of sediment;
- The value of the dispersion coefficient used in the hydrodynamic model;
- The initialisation of the sediment model with fines to support re-suspension within the modelling domain;
- The assessment of both high and low spill rates;
- The selection of an appropriate set of representative worst-case climate scenarios;
- Determining the envelope of impacts for each dredge scenario under a range of worst case ambient conditions based on the defined climate scenarios; and
- Exclusion of consolidation of sediment within the ambient environment thereby maintaining the potential for re-suspension of fine sediment.

DHI have undertaken an extensive number of studies in order to ensure that the modelling tools that have been developed for this project will meet the objectives of this study. A significant number of these studies were associated with the model calibration and validation phase of the project and a summary of model performance based on the final configuration of the hydrodynamic model is presented in Appendix D - Hydrodynamic Model Validation and Calibration. Although it is not practicable to report on all investigations undertaken, a number of key demonstrations of the appropriateness of the adopted methodology for the Wheatstone Project are presented in the following appendices:

- Appendix E: Sediment Transport Modelling using 2D vs. 3D Hydrodynamics. This appendix highlights the differences in the impact zones predicted based on the results of the sediment transport model that are driven by two-dimensional hydrodynamics and three-dimensional hydrodynamics.
- Appendix F: Studies in Support of the Scenario Approach. This appendix highlights the advantages and/or disadvantages of the use of scenario approach compared with the simulation of the long term dredge program.
- Appendix G: Characterisation of Sediment within the Sediment Transport Model. This appendix documents that the number of sediment fractions in the model used for representation of the assumed settling velocity curve for the fines that are suspended in the water column is adequate.

4 MODELLING TOOLS

The numerical models applied for the dredge plume modelling for the Wheatstone Project belong to a suite of world-leading models for the marine environment that have been developed over more than 40 years and are undergoing continued research and development.

The suite of software tools include modules for all components of sediment transport and fate modelling that have been extensively applied to dredge management projects throughout the world. See http://www.dhisoftware.com for general info on software suite and applications.

DHI has extensive experience in conducting sediment transport modelling such as that undertaken for the Wheatstone Project. DHI has the expertise to develop appropriate project-specific methodology and to select the best numerical modelling tools to meet the unique circumstances and challenges of individual projects.

For this study the following models from the DHI suite of modelling tools have been utilised:

- Hydrodynamic model – MIKE 21 HD
- Wave model - MIKE 21 SW
- Sediment transport model - MIKE 21 MT

These software tools and their set up, calibration and validation are discussed in the following sections. Details are provided in the supporting appendices.

4.1 Development of Local and Regional Hydrodynamics

An assessment of the data for the Project (URS 2010) has demonstrated that the ambient environment is well represented by well mixed flow conditions over the depth of the water column within the relatively shallow coastal area traversed by the navigation channel. Apart from minor wind effects and seasonal variations, the data suggests that there exists significant uniformity of temperature and salinity properties within the sampled water column within the region of interest of this study.

A regional two-dimensional (2D) hydrodynamic model has been developed to capture the regionally dominant tidal and wind driven processes for use as input into the sediment transport model. The use of 2D depth averaged hydrodynamics in conjunction with the adopted scenario modelling approach supports the conservative modelling methodology adopted for this study (Section 3) (Appendix E: Sediment Transport Modelling using 2D vs. 3D Hydrodynamics).

An overview of the hydrodynamic model set up, validation and calibration are included in this section.

Additional information and supporting discussions are provided in:

- Appendix C - Modelling Methodology Options
- Appendix D - Hydrodynamic Model Validation and Calibration
- Appendix E - Sediment Transport Modelling Using 2D vs. 3D Hydrodynamics
- Append H - 3D Hydrodynamic Model Setup and Validation
- Appendix I - MIKE 21 HD Scientific Documentation

4.1.1 Modelling Tool

The hydrodynamic model MIKE 21 HD is a general numerical modelling system for the simulation of water levels and flows in estuaries, bays and coastal areas. It simulates unsteady two-dimensional flows in one layer (vertically homogeneous) fluids and is based on the vertically integrated conservation of mass and momentum equations.

The hydrodynamic module simulates water level variations and flows in response to a variety of forcings including:

- bottom shear stress;
- wind shear stress;
- barometric pressure gradients;
- Coriolis force;
- momentum dispersion;
- sources and sinks;
- evaporation;
- flooding and drying; and
- wave radiation stresses.

For this study, MIKE 21 HD has been used to develop two-dimensional depth averaged hydrodynamics using a coupled, nested rectangular grid approach.

Details of the mathematical formulation of MIKE 21 HD including a description of the numerical solution technique are included in Appendix I - MIKE 21 HD Scientific Documentation.

4.1.2 Numerical Grid

A significant amount of effort was required in order to develop the numerical representation of the local bathymetry. DHI reviewed and incorporated information contained in a large number of input data sets in order to piece together a bathymetric data set that was as comprehensive over the study domain as possible. Details of the development of the numerical grid are presented in Appendix J - Development of the Bathymetric Data Set, a brief summary is provided here.

Model bathymetries have been interpolated from available sources of hydrographical data including the electronic database for Nautical Charts "*C-Map*", a gridded database from GeoScience Australia "GA" and several local detailed surveys carried out in the vicinity of the project area (Appendix J) It is noted that local detailed survey data are given on a gridded format implying that the gridded data has been interpolated from measured data points.

A relatively large model domain is required to capture local current patterns due to the somewhat complex current fields along the North West Shelf (NWS) of Australia, which are driven by the interaction of the tidal waves and wind-induced currents in the Indo-Australian Basin, as well as the effects from the variable seasonal wind forcing. In order to ensure sufficient model resolution in the area of interest a coupled, rectangular, nested grid approach has been adopted involving 4 grids with resolutions of 3,645 m, 1,215 m, 405 m and 135 m, respectively. Figure 4.1 presents the 405 m grid showing the location and boundaries of the innermost grid corresponding to a horizontal resolution of 135 m.

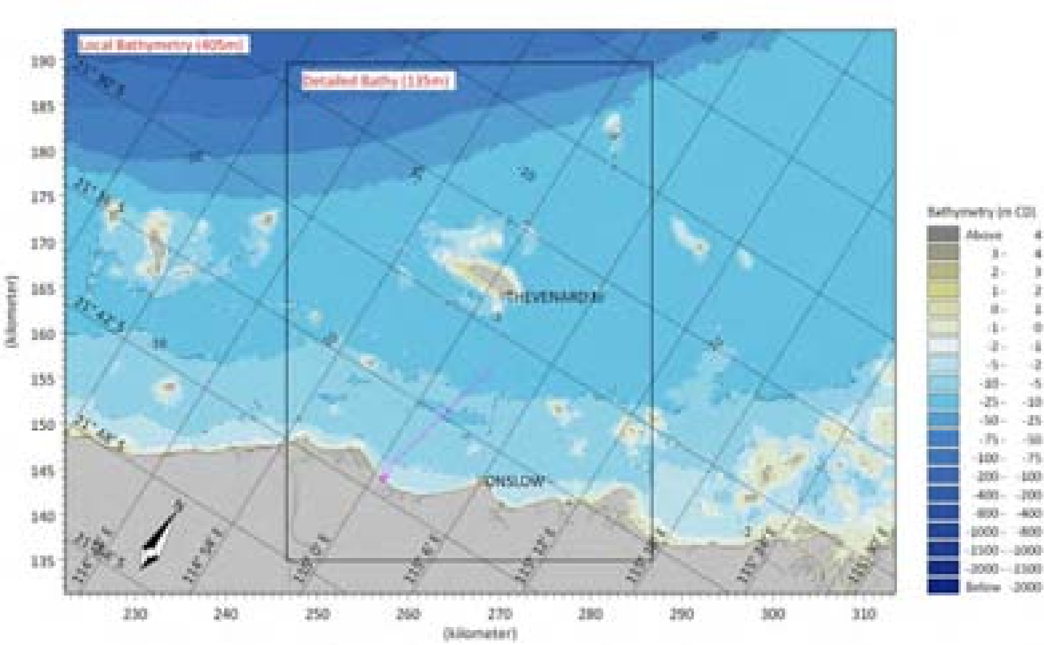

Figure 4.1 Bathymetric model 405 m grid with indication of finer 135m nested grid.

4.1.3 Boundary Conditions

In general, the development of representative hydrodynamics involves the consideration and incorporation of a significant amount of information relating to the ambient environment, including:

- Temporally and spatially varying temperature data;
- Temporally and spatially varying salinity data;
- Temporally and spatially varying wind fields;
- Temporally and spatially varying sea surface pressure; and
- Sea surface elevation.

Due to the lack of apparent significant vertical structure that has been observed within the data obtained for this assessment and reported in URS (2010), MIKE 21 HD has been developed without the specification of ambient temperature and salinity values. Therefore, for this study, boundary conditions for the hydrodynamic model included sea surface elevation and the influence of winds and sea surface pressure. An overview of these data sets is included in the following sections with details included in Appendix D - Hydrodynamic Model Validation and Calibration.

4.1.3.1 Sea Surface Elevations

The regional model is driven by water levels on the open boundaries. Time series of water levels varying along the boundaries have been derived from a global tide model (KMS[1]). The KMS model data (Appendix K - KMS model Tidal Components) representing the

[1] The global tide model data representing the major diurnal (K1, O1, P1 and Q1) and semidiurnal tidal constituents (M2, S2, N2 and K2) with a spatial resolution of 0.25° × 0.25° based on TOPEX/POSEIDON altimetry data. For more information see e.g. Baltazahar (1995).

major diurnal and semidiurnal tidal constituents (with a spatial resolution of 0.25° × 0.25°) have been derived from TOPEX/POSEIDON altimetry data by using a modified orthotide formulation that simultaneously solves for all diurnal and semidiurnal constituents as well as the annual variations in mean sea level (MSL).

Using the KMS data rather than local tide constituents (at fixed tidal stations) has the advantage that the variations along the boundaries can be included in the boundary conditions.

Local sea surface elevation data have been used for model verification (Section 4.1.4 and Appendix D)

4.1.3.2 Wind Fields

DHI undertook a detailed analysis of available wind information to assess the suitability of the data sets for use in driving the hydrodynamic model. This detailed analysis formed part of the model calibration and validation phase of the study (Section 4.1.4 and Appendix D - Hydrodynamic Model Validation and Calibration).

Due to the complexity of the local winds, it was concluded that impacts from the transport of sediment associated with dredging operations would be best represented by the culmination of results from two sets of hydrodynamics driven by different wind fields. The first set of hydrodynamics was driven using monitoring data from the Onslow Meteorological Station and Onslow Airport locations. The second set of hydrodynamics was driven using MesoLAPS wind fields.

The location of the monitoring sites, a brief overview of the MesoLAPS wind fields, and a comparison of wind fields from both Onslow and MesoLAPS (extracted in the vicinity of the Onslow monitoring site) are presented in the following sections.

Monitoring Locations

Presented in Table 4.1 is a summary of the wind data sets that were made available for the purposes of this study. The locations of the monitoring sites are depicted in Figure 4.2.

Table 4.1 List of wind data available to DHI.

Meteorology Station	Period	Description of data
Onslow Town	1997 - 2009	Three hourly wind data for Onslow Town.
Onslow Airport	1997 - 2009	Hourly wind data.
Onslow Meteorological Station	2006 - 2007	BHP Billiton Petroleum Pty Ltd (BHPBP) commissioned MetOcean Engineers Pty Ltd (MetOcean) for this field works. 1 minute interval wind data.
Thevenard Island	1987 - 1998	Sourced from MetOcean site near Administrative Building. 10 minute interval wind data.
	1999 - 2009	Sourced from Bureau of Meteorology site at airport. Hourly wind data.
Barrow Island	1987 - 1999	Sourced from RPS MetOcean site at castle location. 10 minute interval data.
	1999 - 2009	From Bureau of Meteorology site at Barrow Island Airport. Hourly wind data.
Varanus	1999 - 2009	From Bureau of Meteorology site at Varanus Island. Hourly wind data.

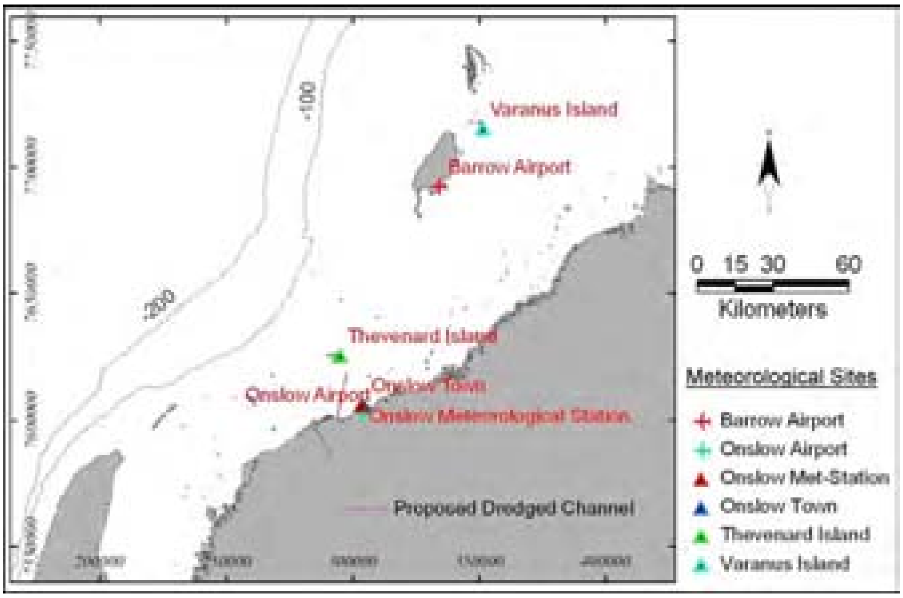

Figure 4.2 Locations of wind speed and wind direction monitoring sites.

MesoLAPS Wind Fields

The Australian Mesoscale Limited Area Prediction System (LAPS) known as MesoLAPS is one of the numerical forecast models operated by the Australian Government's Bureau of Meteorology. The MesoLAPS meteorological fields (including wind speed, wind direction, air temperature, and surface pressure) are provided on a resolution of 0.125 degrees (or approximately 12.5 km).

Initially, 6-hourly MesoLAPS data was made available for this assessment and initial model set up utilised the 6-hourly data set. More recently, 1-hourly MesoLAPS data was made available to DHI. Both the 6-hourly and 1-hourly MesoLAPS data sets will be referred to throughout this document. Reference to MesoLAPS data will necessarily imply the 1-hour data set. Reference to the 6-hourly MesoLAPS data set will include the sampling frequency.

Additional information relating to MesoLAPS is provided in Appendix L - MesoLAPS Information from the Bureau of Meteorology.

Comparison of MesoLAPS and Onslow Airport Wind Fields

In order to assess the spatial representativeness of the wind field data sets, a comparison of MesoLAPS wind fields and observational data from the Onslow Airport is made. This comparison of MesoLAPS wind fields with observational data obtained at the Onslow, Barrow Island and Thevenard Island monitoring locations (Table 4.1) is presented in Appendix M - Comparison of MesoLAPS Wind Fields with Monitoring Data.

As discussed, winds play an important role in the transport of sediment away from the source region. Elevated wind speeds not only contribute to the footprint of the resultant sediment plume but elevated wind speeds also play a significant role in the re-suspension of sediment. It is also important to recall that 'worst-case' conditions in terms of impacts from sediment are associated with both periods of elevated wind and current speeds (in relation to the areal extent of zone of impact) and calm periods (increased sediment loading in the absence of local dispersion). Thus it is important that the wind fields used to drive the hydrodynamics and incorporated into the wave model accurately capture both the magnitude and frequency of elevated environmental conditions as well as calm periods.

Presented in Table 4.2 and depicted in Figure 4.3, are the wind speed percentiles for data from the Onslow Airport and MesoLAPS (extracted at the location nearest to the Onslow Airport monitoring site).

Results highlight the consistent underestimation of the MesoLAPS wind speeds in the nearshore for all percentiles. This consistent underestimation of wind speeds is further highlighted in the time-series of wind speeds for 2007 presented in Figure 4.4.

Table 4.2 Percentiles of wind speed from Onslow Airport Data and MesoLAPS (m/s).

Percentiles	MesoLAPS	Onslow Airport	Percentiles	MesoLAPS	Onslow Airport
100	13.5	15.0	50	4.1	5.3
99	8.6	10.8	45	3.9	5.3
95	7.2	9.2	40	3.7	4.7
90	6.5	8.6	35	3.4	4.2
85	6.1	7.8	30	3.2	4.2
80	5.7	7.2	25	2.9	3.6
75	5.4	6.7	20	2.7	3.6
70	5.1	6.7	15	2.5	3.1
65	4.9	6.1	10	2.2	2.5
60	4.6	5.6	5	1.8	1.9
55	4.4	5.6			

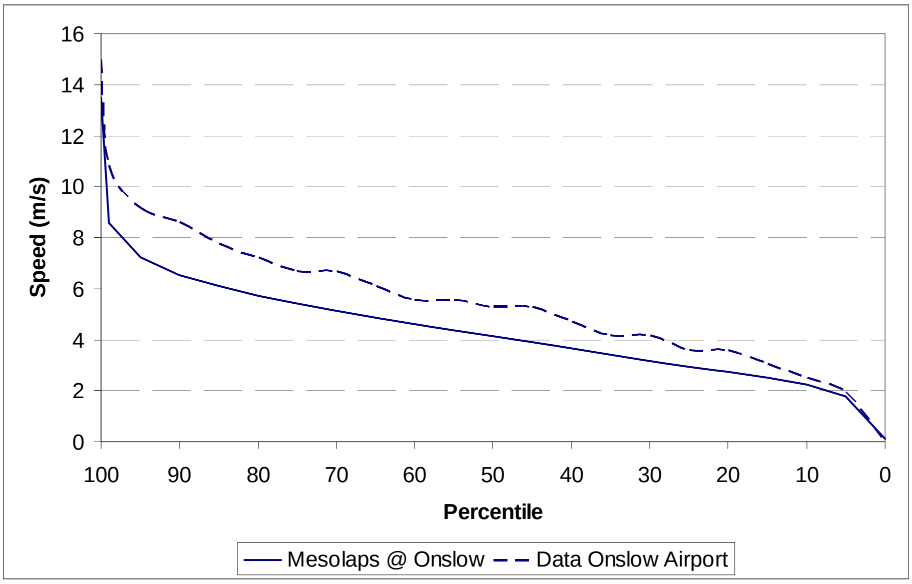

Figure 4.3 Percentile of wind speed from MesoLAPS and Onslow Airport, 2007.

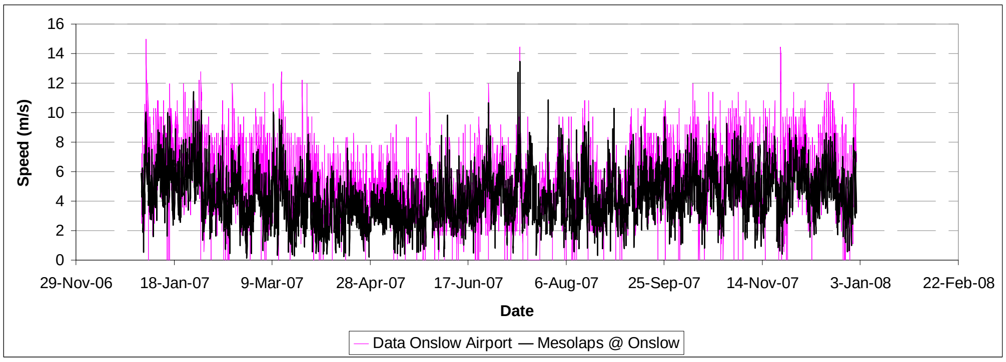

Figure 4.4 Time series of wind speed from MesoLAPS and Onslow Airport, 2007.

Sea/land Breeze Effects

The wind patterns at the study area vary considerably due to the influence of the daily development of the land/sea breeze system. The land/sea breezes are important local-scale weather phenomenon generated by the temperature differences between the land and the ocean. During the night, overnight cooling of the land mass causes early morning land breezes to dominate, and this can continue into the morning hours. During daytime, heating of the land mass leads to a reversal of the circulation, and causes afternoon sea breezes to dominate.

The land/sea breeze cells may extend for up to 100 km from the coast, but more typically, is limited to about 40 km (Meteorological and Oceanographic Measurements Onslow 2007). The daily sea breeze cycle around the study area is generally embedded in the overall trend of westerly winds during summer and easterly winds during winter. The sea/land breeze systems are strongest during summer.

Presented in Figure 4.5 are wind roses of Onslow Airport data from 2007 as a function of the hour of the day. The sea breeze is clearly evident with the shift from southerly in the morning to north-westerly in the afternoon.

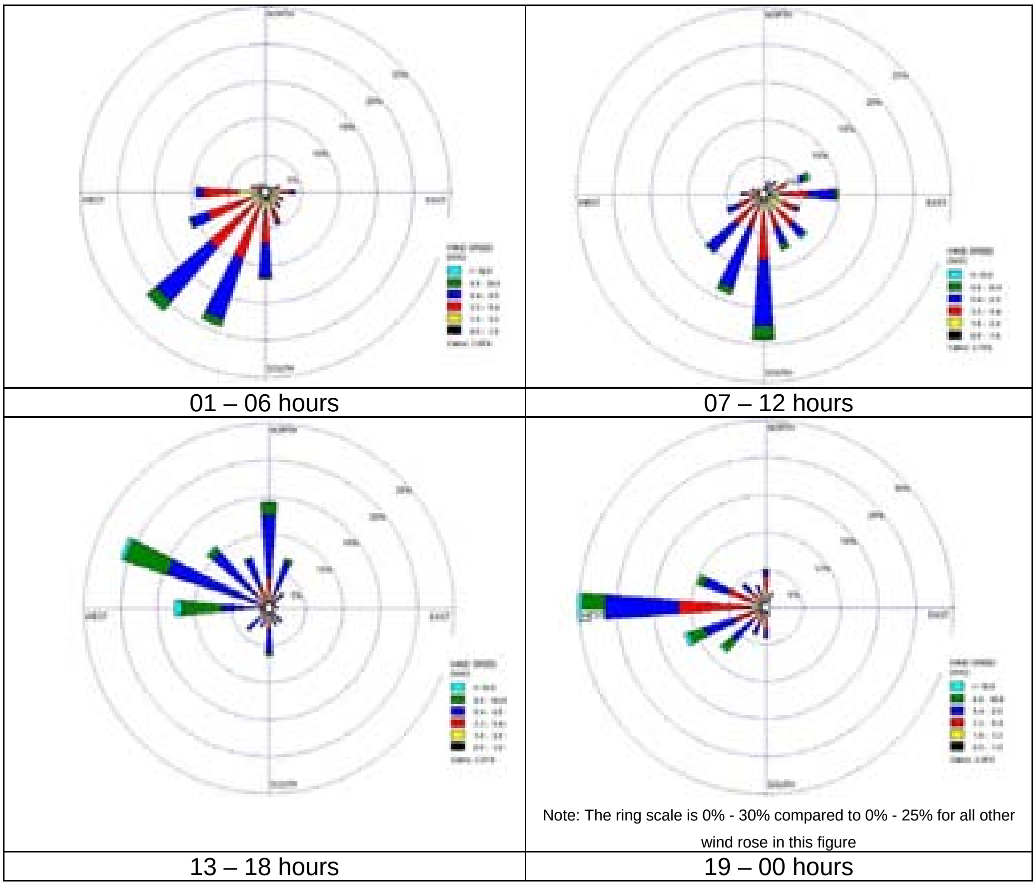

Figure 4.5 Hour of Day wind roses for Onslow Airport, 2007.

Presented in Figure 4.6 are wind roses from MesoLAPS wind fields as a function of the hour of the day (2007). Although there are some general similarities between these two figures, a comparison of the afternoon wind rose for Onslow Airport and MesoLAPS highlights the underestimation of MesoLAPS wind speeds associated with the afternoon sea breeze. Additionally, MesoLAPS has not captured the more north-westerly direction of the winds during this period.

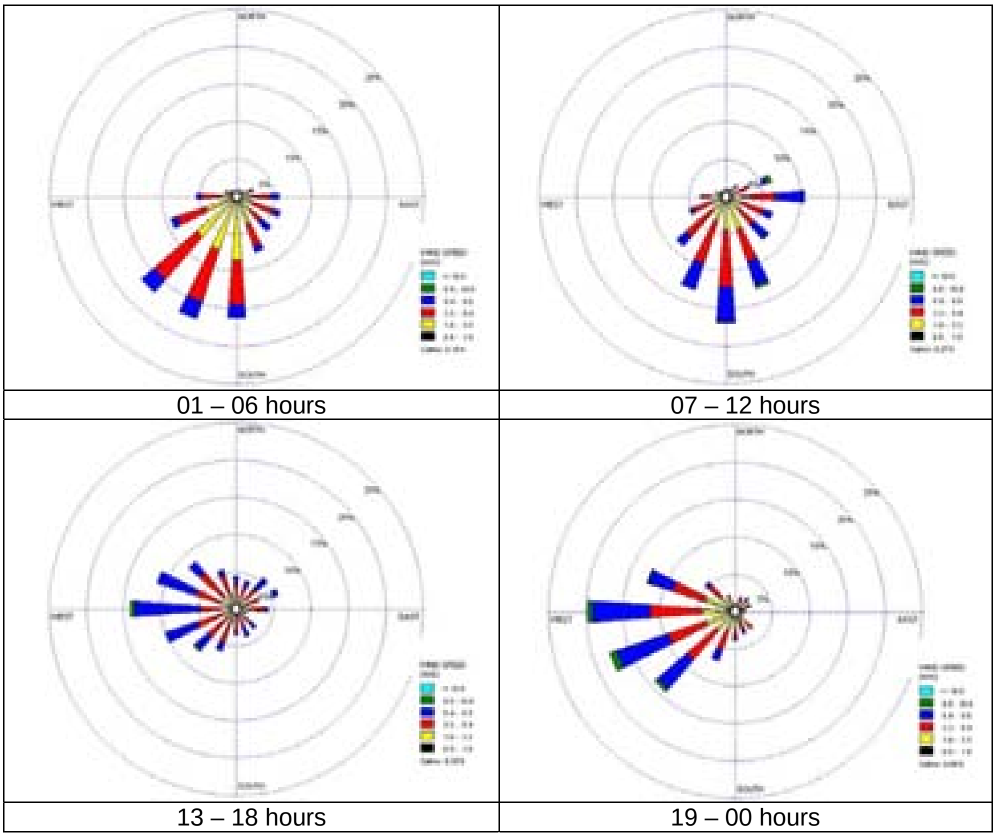

Figure 4.6 Hour of Day wind roses for MesoLAPS, 2007.

4.1.3.3 Sea Surface Pressure

Spatially and temporally varying MesoLAPS sea surface pressures were used to drive the hydrodynamic model.

4.1.4 Calibration and Validation of the Hydrodynamic Model Output

To ensure that the hydrodynamic model produces reliable results it is important that the model is calibrated and that the validity of the model predictions are verified as far as practicable based on the availability of observational data. Calibration is the process by which model parameters are adjusted within reasonable limits so that model predictions match observational data at specified location(s).

In general, the quality of model results is determined by the quality of the model inputs. The key inputs into the hydrodynamic model for this project include bathymetry, tides, and wind fields.

DHI reviewed all available data at the time of the model setup and calibration phases of the assessment and assessed it for its suitability for the purposes of calibrating model parameters and the validation of model output.

The calibration of the hydrodynamic model primarily focused on the refinement of the extensive bathymetric data set and bottom roughness. Bathymetry plays an important role in steering the wind and tidally driven circulations. Refinements on the model bathymetry were assessed against available tidal data at 16 locations within the study region (Table 4.3 and Figure 4.7) and the current data available in the vicinity of the site (Figure 4.8 and Table 4.4).

Table 4.3 Locations of the tidal stations in the regional model

Tidal Station Name	Longitude	Latitude
Tantabiddi	113.9833	-21.9167
Point Murat	114.1833	-21.8167
Exmouth	114.15	-21.9333
Serrurier (Long) Island	114.6833	-21.6
Thevenard Island	115.0167	-21.4667
Onslow, Beadon Point	115.1	-21.6333
Large Islet	115.5	-21.3
Tanker Mooring	115.55	-20.8167
Wapet Landing	115.4667	-20.7167
North West Island	115.5167	-20.3667
Trimouille Island	115.55	-20.3833
Dampier (Hampton Harbour)	116.7167	-20.65
Cape Legendre	116.8333	-20.35
Hauy Islet	116.9667	-20.4167
Port Walcott	117.1833	-20.5833
Port Hedland	118.5833	-20.3

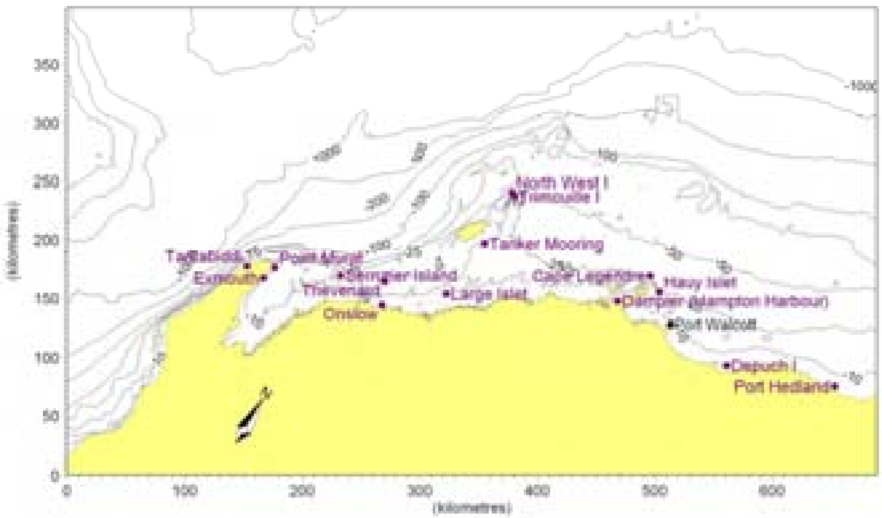

Figure 4.7 Locations of tidal stations used for model calibration and validation.

Table 4.4 Overview of available current measurements.

No.	Location	Id	Period	Water Depth (m)	Longitude (E)			Latitude (S)		
					deg	min	sec	deg	min	sec
1	Basin ADCP	P3	25-01-2006 to 25-02-2006	9.5	115	3	0	-21	38	31.5
2	Bank ADCP	P4	25-01-2006 to 25-02-2006	13.5	115	5	19.8	-21	31	12.9
3	Basin CM04P	P6	25-01-2006 to 25-02-2006	9.5	115	3	27.4	-21	38	14.3
4	Jetty CM04P	P7	25-01-2006 to 25-02-2006	4.5	115	3	50.4	-21	39	37.1
5	Basin CM04p #2	P8-1	26-02-2006 to 22-04-2006	11	115	3	25.6	-21	38	40.3
		P8-2	14-05-2006 to 07-06-2006							
6	Basin CM04p	P9	26-02-2006 to 07-06-2006	11	115	3	25.2	-21	38	17.5
7	Basin CM04p #2	P10	08-06-2006 to 20-09-2006	8	115	3	28.1	-21	38	43.3
8	Basin CM04p #2	P11	21-09-2006 to 01-02-2007	8	115	3	32.0	-21	38	38.8
9	Jet015	Jetty	11-01-2009 to 16-04-2009	8.2	115	0	42.5	-21	39	17.7
	Jet051	Jetty	17-04-2009 to 13-06-09	8.2	115	0	42.5	-21	39	17.7
	Jet052	Jetty	26-07-2009 to 10-09-2009	8.2	115	0	42.5	-21	39	17.7
10	Spoil Ground		10-01-2009 to 16-04-2009	51	114	51	6.8	-21	21	51.5
11	Channel		24-07-2009 to 12-09-2009	15	115	2	56.4	-21	30	6.18

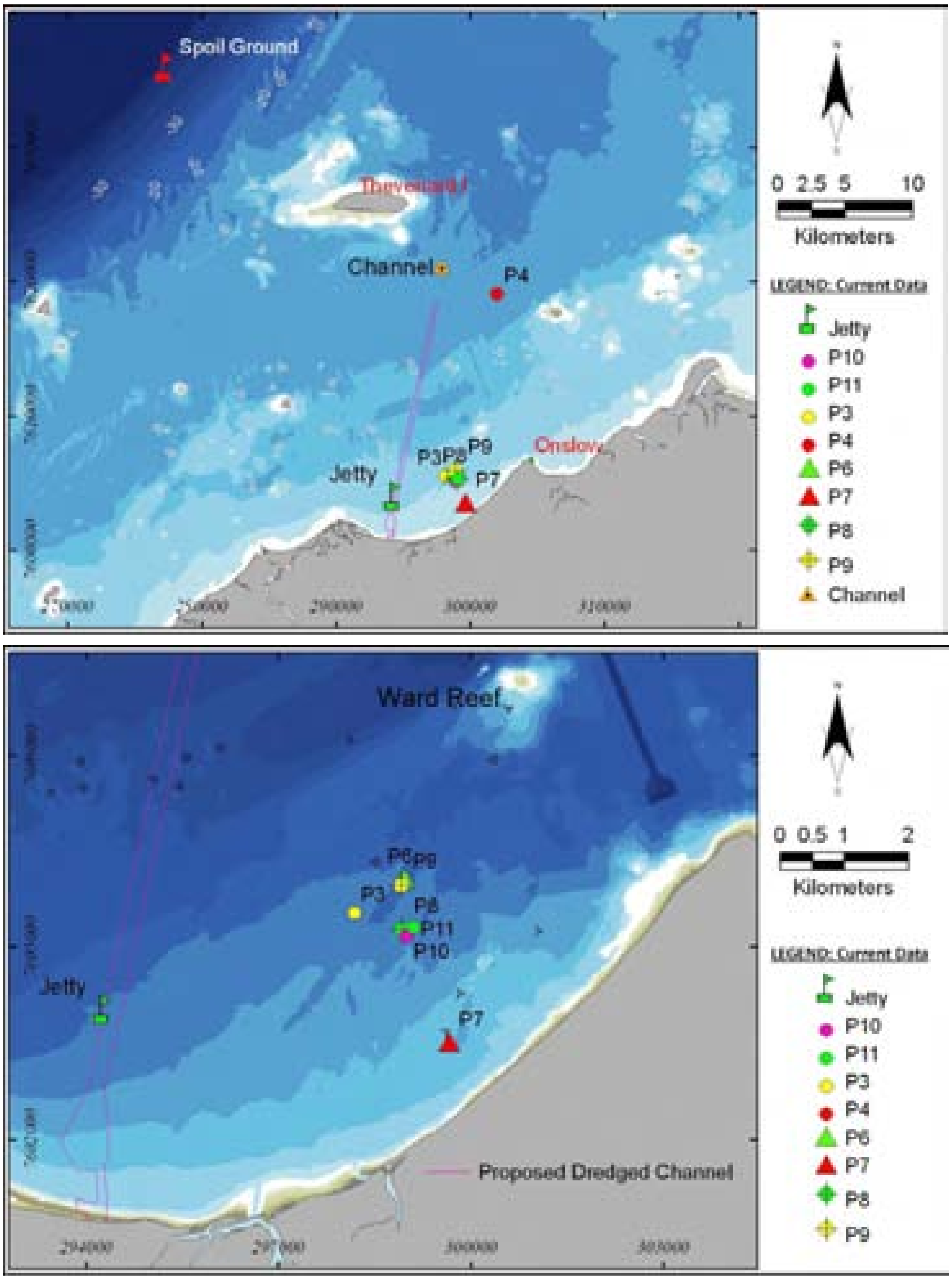

Figure 4.8 Locations of current measurements that were available for the study for model calibration and validation. See Table 4.4 for details of measurements.

Two sets of wind data have been used to drive the model:

- Measured data from Onslow Met-station;
- MesoLAPS wind fields.

A common calibration has been used for the two sets of wind data, and model validation has been carried out for both sets. Visual comparisons to time-series of water levels and currents demonstrate that:

- The model fully captures the large gradients in tidal amplitude through the model domain.
- The model reproduces the tidal amplitudes and phases well throughout the model domain.
- The model generally reproduces the current amplitudes and phases well for the available validation data.
- The magnitudes and patterns of wind driven net currents are captured through the combination of MesoLAPS and Onslow winds.

For quantification of the model performance, DHI has applied the internationally recognised UK Foundation for Water Research (UKFWR) Guidelines for quantitative assessment of the adequacy of the hydrodynamic model setup, calibration and validation (*UK Foundation for Water Research* 1993). These guidelines are a series of quantitative measures of the accuracy of numerical hydrodynamic models and have been previously used in international court cases such as the ITLOS Case No. 12 for the dispute over dredging and reclamation impacts between Singapore and Malaysia (UN 2005) to establish the validity of model outputs.

A quantitative measure of model performance has been undertaken using statistical analysis of the differences in modelled and measured flow properties for:

- Tidal elevations and water levels; and
- Current speeds and direction.

DHI's model for the Project has met all of the quantitative criteria specified by the UKFWR. Details of the model calibration and validation methodology and findings are provided in Appendix D - Hydrodynamic Model Validation and Calibration.

4.2 Development of the Wave Model

The dominant impacts of waves are on the coastal morphology. Although less critical, waves are furthermore important for the plume modelling in shallower waters where they are capable of generating additional bottom shear stresses that will play a role in the sedimentation and re-suspension of sediments. Offshore wave conditions at the Project are dominated by swell waves from the Southern Ocean. In deep water off the coast, these waves run basically parallel to the coast, and undergo large-scale refraction into the shallow areas at the site. Model testing has demonstrated that the nearshore waves are predominately generated by local winds, and the offshore waves are of less importance.

The wave model simulates wave propagation from offshore to the Project site based on the offshore wave conditions, local tides and 6-hourly MesoLAPS wind fields.

The following sections outlines the wave model selected for use in this study, the inputs to the model and the works undertaken to calibrate/validate the developed wave model. Details of the model set up, calibration and validation are included as Appendix N - Wave Model Setup and Validation.

4.2.1 Modelling Tool

DHI's MIKE 21 SW model has been utilised for the numerical wave transformation. The model simulates wave propagation from deep water to nearshore areas, including the effects of shoaling, refraction, bottom dissipation, wave breaking, wind generation and directional spreading which are introduced through a parameterisation of the wave spectra. Wave breaking is represented in the model using the approach of Battjes and Janssen (1978).

4.2.2 Numerical Grid

The model bathymetries are built based on the bathymetry data base established for the project as described in Appendix J - Development of Bathymetric Data Set.

The grid used in the wave model was an unstructured finite element grid that allows for spatially varying cells to be defined throughout the study region. Typically, the area of interest and areas with rapidly changing bathymetry are associated with smaller cells in order to resolve the key physical features of the generated wave field.

Figure 4.9 illustrates the model mesh. It is noted that this mesh is coarse in the surf zone as the model is not set up to provide detailed waves in the surf zone.

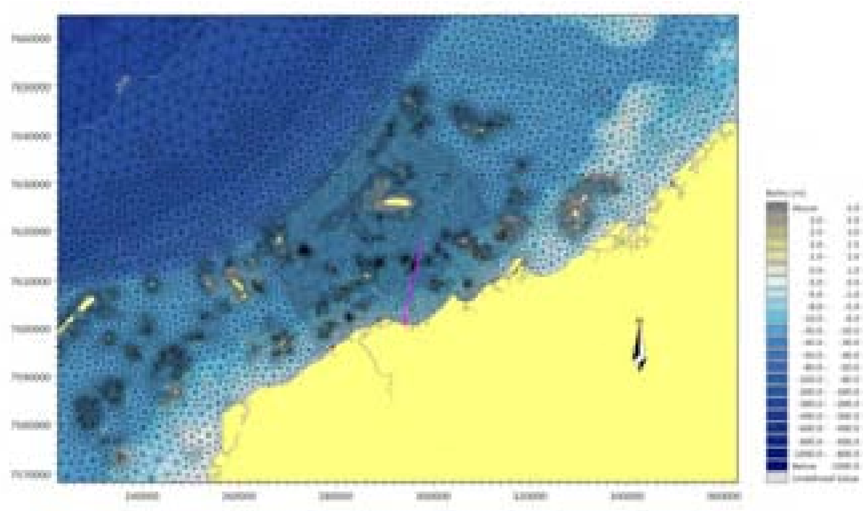

Figure 4.9 Unstructured mesh used in the wave model

4.2.3 Boundary Conditions

4.2.3.1 Sea Surface Elevations

The water level becomes important for the transformation of wave conditions to the nearshore areas as higher water levels result in less wave energy dissipation due to bottom friction and wave breaking. Water levels derived through tidal prediction from a tidal station nearest to the study area has been applied in the wave model.

The sea surface elevations used to drive the wave model are the same as those used to drive the hydrodynamic model and were discussed in Section 4.1.3.1.

4.2.3.2 Sea Swell

Model testing has shown that the penetration of the offshore swell waves into the shallow coastal waters is limited, and locally generated wind waves dominate the coastal wave climate most of the time. Some penetration of small swell waves is present during the winter season with offshore directed winds.

Directional wind and swell wave data from the Exmouth Buoy has been applied on the model boundaries for the set up of the wave model for use as input into the sediment transport modelling. It is noted that the Exmouth wave buoy is not located on the model boundary, but it is located in sufficiently deep water and at a sufficiently exposed location for waves from the dominant directions to be representative of the waves along the model boundary for most conditions.

4.2.3.3 Winds

As waves propagate from the offshore region towards the site, they lose energy through dissipation over offshore shoals, strings of coral reefs located near the site and through large-scale wave refraction. Consequently, energy input from the wind becomes increasingly important. Therefore, for sea waves, it is important to include wind in the nearshore wave simulations.

Observational data suggests that nearshore waves are predominately generated by local winds, and offshore waves are of less importance. This is also demonstrated in the measurements which have the largest offshore swell waves during winter, but the highest nearshore waves during summer with winds predominantly blowing on-shore.

MesoLAPS wind data have been applied in the modelling. This ensures that spatial variability is included in the modelling.

4.2.4 Wave Height Monitoring Locations

At the time of this study, six sources of wave data are available as outlined in Table 4.5 with locations shown in Figure 4.10 and details of nearshore sites in Figure 4.11.

Table 4.5 Overview of available wave data.

Location	MGA-50		App. Water Depth (m)	Overall Period
	Easting (m)	Northing (m)		
"Offshore Wave Data"				
Exmouth	199795.36	7597627.69	54	04-10-2006 to 17-08-2009
Wheatstone Platform	330670.52	7794010.65	100	05-05-2009 to 20-08-2009
Spoil Ground	276916.08	7635601.11	52	10-01-2009 to 12-09-2009
"Nearshore Wave Data"				
Jetty	294253.58	7604050.43	8.2	11-01-2009 to 16-04-2009
Basin DWR	298987.60	7605472.62	10	25-01-2006 to 14-03-2007
Channel	297891.86	7621062.75	15	24-07-2009 to 12-09-2009

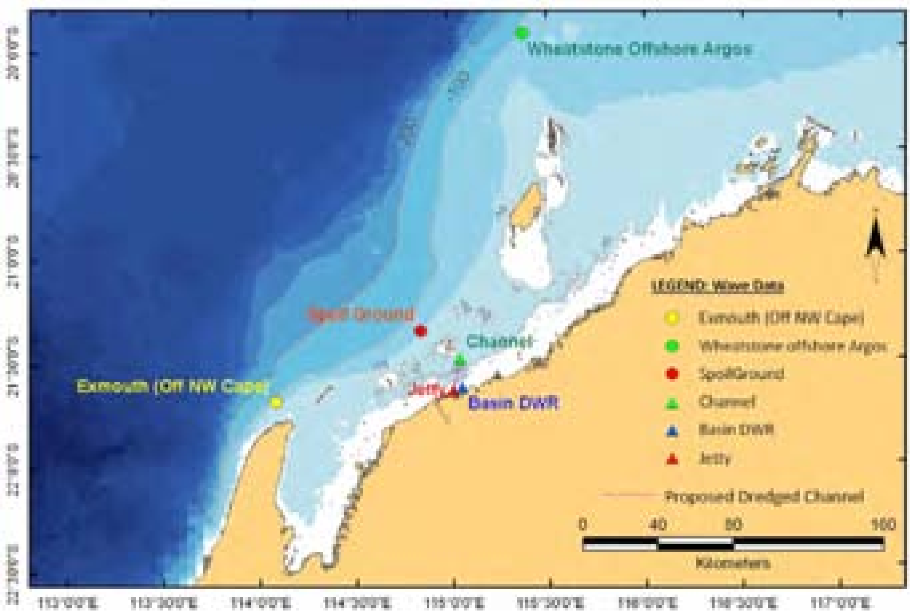

Figure 4.10 Locations of wave data that was available to the project.

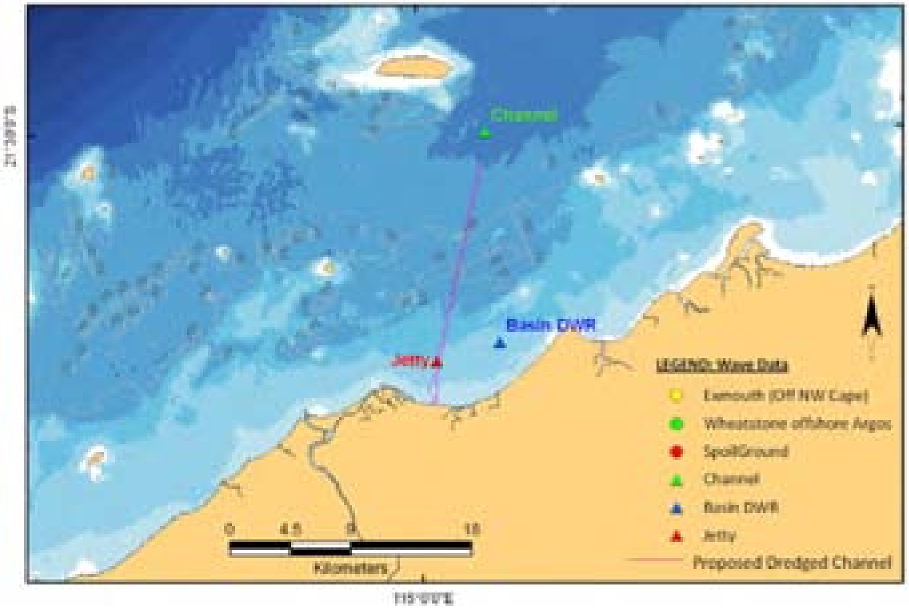

Figure 4.11 Locations of nearshore wave data that was available to the project.

Collection of field data for the Wheatstone Project is ongoing with collection of data at three different locations in the nearshore region. At this stage, the longest data record available is approximately 13 months of wave measurements at the site indicated "Basin DWR" in Figure 4.10 and Figure 4.11.

Shorter term wave data is available at the "Jetty", "Channel" and "Spoil Ground" locations shown on Figure 4.10 and Figure 4.11.

4.2.4.1 Wave Model Validation

Details of the wave model validation are provided in Appendix N -Wave Modelling: Setup and Validation.

The model has been validated against data ranging from nearshore ("Basin DWR" and "Jetty") over mid depths ("Channel") to deeper water ("Spoil Ground") locations. The model validates well for significant wave heights, directions and periods for all locations, and it is concluded that model performance is fully adequate for inclusion in the dredge material modelling.

The model validation includes a full year at the nearshore "Basin DWR" location. The model validation will be expanded with additional data for other locations as it becomes available from ongoing field observations.

4.3 Development of the Sediment Transport Model

Sediments will be released into the water column through the dredging and disposal processes. Apart from the initial density driven settling and mixing in the immediate vicinity of the release point, the main processes taking place through the water column will be settling out and turbulent mixing, and settling out and re-suspension at the bottom. The coarser fractions will settle out relatively quickly and generally remain within or in the vicinity of the dredge corridor, while finer fractions with lower settling velocities may be transported away the site. Flocculation and hindered settling may affect settling of sediment in the vicinity of the source, resulting in high concentrations.

The fines will primarily be transported away from the original spill site (dredging or placement) by the currents. Tidal currents will tend to re-circulate the plume within a distance of the source controlled by the tidal current amplitude, while the wind driven net currents are critical in determining the transport of the plume away from the source and therefore the overall plume excursion.

Available monitoring data presented in URS (2010) suggests that the water column is well mixed within the relatively shallow coastal waters of the project with no significant stratification identified. These observations are confirmed by the very good calibration/validation obtained for the two-dimensional (depth averaged) hydrodynamic model (Section 4.3.2.7 and Appendix D). The main three-dimensional effects will be associated with density driven currents, pressure wave and propeller wash generated by the dredging equipment. The area in the immediate vicinity of the dredge corridor is already considered to suffer 100% receptor mortality, and therefore a detailed representation of the flow and sedimentological details are not required in close proximity to the dredging activities. Thus the focus when developing the sediment model is on the representation of sediment excursion to the mid and far fields in order to determine the boundaries between zones of high and moderate impacts as well as the zone of influence.

The key inputs into the sediment transport model include the hydrodynamics (Section 4.1), waves (Section 4.2) which are particularly critical in the nearshore, and winds.

4.3.1 Modelling Tool

The transport, dispersion and deposition of fine sediments brought into suspension by these activities have been simulated using MIKE 21 MT (Mud Transport). The MT module operates interactively with the hydrodynamic models presented previously, and includes the temporal and spatial effects of waves derived from the detailed wave model (Section 4.2)

The MIKE 21 MT is a combined multi-fraction and multi-layer model that describes erosion, transport and deposition of mud or sand/mud mixtures under the action of currents and waves. Processes that can be included in the simulation include forcing by waves, sliding, salt-flocculation, detailed description of the settling process, layered description of the bed with consolidation processes, and morphological update of the bed.

The sediment transport model is a (semi) three-dimensional sediment transport model in which the vertical shear-structure within the water column was assumed to be associated with a logarithmic velocity profile. This approach to the modelling of the transport and fate of the dredge sediment incorporates key three-dimensional sediment dynamics which result in variations in sediment concentration through the water column. The need to explicitly resolve the vertical shear structure (i.e. the use of fully three-dimensional hydrodynamics) must be guided by the observational data balanced against the increased computational requirements for 3D compared to 2D and the resulting implications for the modelling.

As described in Appendix E, the use of a 2D model in combination with the scenario modelling approach leads to a slightly conservative assessment.

4.3.2 Boundary Conditions

For this study, the model has been set up to simulate excess concentrations of suspended sediments due to the dredging and placement activities only, ignoring ambient concentrations and other sources such as runoff from rivers.

4.3.2.1 Hydrodynamics

The sediment transport model is driven by the two-dimensional hydrodynamics developed in Section 4.1.

In order to account for important three-dimensional sedimentation effects, a logarithmic profile for the vertical component of velocity within the water column has been assumed. The assumption of a logarithmic current profile is generally supported by the current measurements (URS 2010). In deeper water out by the potential offshore dredge material placement areas, the data suggests there is potential for a stronger dominance of wind driven current profiles.

4.3.2.2 Waves and Swell

Waves have two main effects on sediment plume dispersion:

- Introducing additional turbulence and mixing in the water column through wave breaking; and
- Introducing shear stresses on the bottom which will impact the deposition and re-suspension of sediments.

The MT model calculates the bottom shear stresses in combined current and wave action.

The wave model developed in Section 4.2 has been used as input into the sediment transport model. Waves and swell contribute to increases in shear stress, particularly in the nearshore region.

4.3.2.3 Characterisation of Sediment and Sediment Settling velocity

A key parameter for sediment plume modelling is the sediment fractions and associated settling velocities. During dredging, the spill generally contains a significant portion of coarse material in addition to the fines. The coarse material generally settles within the dredge corridor or in the immediate vicinity, and does not contribute significantly to the plume dispersion outside these areas.. This component is disregarded in the modelling which concentrates on the fines (silt and finer fractions), which are more easily transported away from the dredging and placement areas. The spill rates defined in Section 2.3 likewise concentrates on fines leaving the immediate dredge and disposal areas.

The settling velocities of the fine material released during the dredging operation will depend upon many factors including the degree of flocculation within the overflow. It also includes whether these flocs are broken up by the turbulence of the overflow and/or on the boundaries of the density current phases of the setting process where the fine materials are released into the water column. This process will in turn depend on:

- the specific nature of the dredger;

- pumping rates;
- presence of environmental valve (for TSHD);
- the chemical composition of the fine material;
- prevailing water depth;
- current speed; and
- whether the density plume is disturbed by the propeller wash (for TSHD).

The settling characteristics at the present stage of the project development are associated with a significant degree of uncertainty.

DHI has undertaken a large number of settling tube measurements in overflow samples from silty sand material with bed silt/clay content in the 10 - 30% range. Settling tube measurements from overflow samples are provided in Figure 4.12. It is recognised that the percentage fines in the parent material is towards the lower bound of the silt content present in the dredge area for the Project. However, as Figure 4.12 does not indicate any clear trends between lower bed fines and higher bed fines, and in the absence of site specific measurements (which will only become available after start of dredging), Figure 4.12 is considered the best available basis for defining the appropriate settling velocities for the spill material.

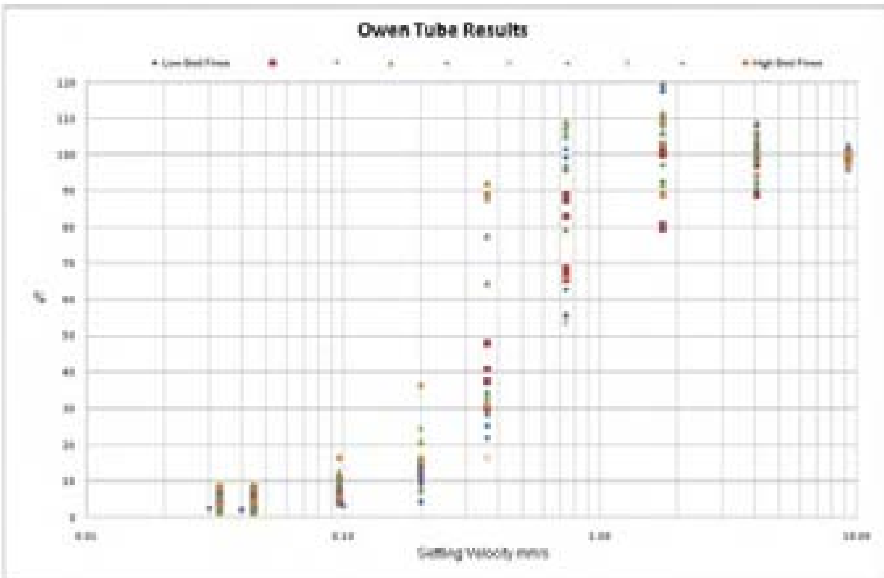

Figure 4.12 Example of measured settling velocity characteristics of sediment plume material escaping the immediate work area

It is noted that Figure 4.12 indicates percentages higher than 100% for some data points. This is an indication of the uncertainties involved in the analysis and is reflective of the heterogeneous nature of the overflow material and the flocculation processes ongoing in the settling tube during the tests. All settling tests are run at a base concentration chosen to mimic concentrations of the material leaving the density plume phase of the overflow and thus the floc size that will be present in the material leaving the immediate work area.

4.3.2.4 Re-suspension and Consolidation of Sediment

The fines originating from the dredging and disposal processes can deposit and re-suspend under the influence of waves and currents. A layer of fine sediment available for re-suspension is introduced in the model at dredged areas and within the placement sites. The layer available for re-suspension within the placement sites and dredge corridor is not limited in thickness within the scenario period.

Simulations have shown that particular combinations of spring tide and strong wind driven net currents can lead to significant and repeated re-suspension of material, which can carry low concentration plumes far from the dredge location. Under the assumption that re-suspension of sediments leads to limited excess concentrations, which generally do not cause mortalities on its own, it is expected that the continued re-suspension of material in the long dredge simulations may lead to an increase in the zone of influence but not any significant increase in the other impact zones. It is thus expected that apart from the zone of influence, the impact zones derived from the full dredge period simulations will lie within the envelope of impact zones developed through the shorter scenario simulation.

Depending on the nature of the ambient environment, cohesive forces and consolidation may gradually prevent a particle from re-suspending. The model can be set up to represent these factors, e.g. by producing a map of critical shear stresses for erosion depending on the type of sediment present. Consolidation can be included through multiple layers with different characteristics and a transfer function between layers.

4.3.2.5 Dispersion Coefficients

The dispersion coefficient adopted in the plume modelling has a distinct bearing on the spatial impact. Higher dispersion coefficients will often lead to the prediction of a wider area of influence however, as concentrations will be reduced by the dispersion process, the severity of impacts associated with higher dispersion are often lower. It is thus critical to adopt an appropriate dispersion coefficient in the plume model. Again, extensive data sets from other dredging sites are used in the absence of site specific data. These data sets include both ADCP sediment flux transects and high resolution remote sensing data.

Although there is considerable variability in the data, those cases with distinct and constant current directions and where propeller wash does not initially disturb the plume, the sediment flux transects indicate a typical plume width in the order of 120 m, 400 - 500 m behind the dredger in an area with prevailing current speed of approximately 1.0 m/s counter to the direction of dredger travel. This equates to a dispersion coefficient of approximately 1.0 m^2/s.

Extensive sensitivity testing of the spatial performance of the sediment plume model against satellite imagery were also carried out as part of the validation of the sediment transport model for dredging projects in Singapore. Results from this work indicate that a dispersion coefficient in the order of 1.5 m^2/s is appropriate. A value of 1.5 m^2/s has been adopted for the Wheatstone Project.

4.3.2.6 Other Model Parameters

Other key model parameters which have a significant effect on the model results are presented in Table 4.6.

Table 4.6 Other key model parameters

Parameter	Value
Critical shear stress for erosion	0.3 N/m^2
Critical shear stress for deposition	0.1 N/m^2
Density of initial deposits*	400 kg/m^3

***Note**: The value is based on the density of sediments recovered from sediment traps and is considered a robust and well validated figure.

Critical shear stresses for erosion and deposition play a key role in affecting the spatial extent of the sediment plume. The parameters presented in Table 4.6 reflect literature values and have proven to be appropriate across a range of monitoring projects carried out in Singapore where DHI has had the opportunity to compare measured and simulated sediment plumes from dredging operations.

4.3.2.7 Model Validation

No site specific data is available for model validation at this stage of the project. For projects where DHI is involved in the Environmental Monitoring and Management phase, it is standard to go through an intensive validation process at the start-up of the project.

4.3.3 Application of Sediment Model to the Wheatstone Project

A brief summary of some of the sediment modelling methodology that is specific to the Project is described in this section.

Scenario Approach

For this study, a number of short-term climate scenarios have been defined (Section 5). Additionally, key elements of the dredge program have been identified and a set of representative dredge scenarios have been defined (Section 6.1.1).

In total, 96 scenarios have been considered and are associated with:

- six climate scenarios
- Eitht dredge scenarios
- two spill rates

Details of the scenario selection criteria and scenario definition will be presented in latter sections of this report.

The 96 scenarios have been run for both MesoLAPS and Onslow winds to drive the HD model, and the total number of scenarios used for the impact assessment is thus 192.

Characterisation of Sediment and Settling Velocity

Based on the settling velocity curves presented in Figure 4.12 it has been chosen to adopt a six-fraction sediment description as described in Table 4.7 with a higher number of fractions on the lower settling velocities.

Table 4.7 Model sediment settling characteristics

Fraction	% Contribution	Settling velocity mm/s
1	5	0.03
2	15	0.24
3	20	0.39
4	20	0.48
5	20	0.68
6	20	1.00

Re-suspension

For the two month scenario modelling, a conservative approach of omitting any consolidation effects and allowing particles to re-suspend throughout the model area has been adopted. Additionally, the model is initialised with fine sediment in key areas within the domain in order to ensure the continual availability of fine sediment in association with potential re-suspension.

Spill Rates

The highest production and associated 'spill rates' (equivalent term to 'release rates') from the dredging activities are expected from the loose, granular material (denoted "sand" in the DDP). To maintain conservatism and capture the highest spill rates in the EIS assessment, the simulated scenarios have concentrated on the spill rates corresponding to granular material (sand) along the entire dredge corridor. The spill rates used in this assessment are presented in Appendix B.

5 CLIMATE SCENARIO SELECTION

With a well calibrated model, tidally driven currents can be accurately predicted for any dredging period. However, when climatic conditions such as wind and pressure fields are important for the overall current conditions, there is a stochastic component that must be accounted for. This is clearly the case at the Project site which has dominant summer and winter conditions with wind driven net currents that cause the sediment plumes to travel in a predominant direction. Due to the variable climatic component, a number of different scenarios are required to develop an envelope of possible impacts.

It is often not clear at the onset of the study which conditions lead to the largest impacts. Mild weather conditions will cause lower dispersion with resulting higher concentrations and sedimentation rates in the near field, which is likely to determine the high impact zone, whereas stronger winds will tend to disperse the plume more rapidly and reduce near-field impacts, but drive the plume further away from the dredge area and thereby define the zone of influence. Climatic scenarios can be defined as:

- **Option (1):** Measured conditions from a given period which exhibits the desired environment;
- **Option (2):** Statistically “made up” conditions representing the desired environment. The simplest example of this is constant wind conditions corresponding to a certain exceedence frequency.

Climatic scenarios may use either or both of the above options. The second option is well suited to represent fairly uniform conditions, e.g. a consistent monsoon wind climate. It is less suitable when there are significant variations within the climatic scenario intended to be simulated.

At the project area, there are significant variations of the wind field during a given season. Both approaches were tested in the sediment plume modelling, and it was concluded that Option (1) which is based on measured conditions leads to a higher degree of variability in the plume dispersion and a more realistic picture. Applying constant winds corresponding to a given exceedence frequency, i.e. Option (2), tends to under-predict lateral plume dispersion.

Therefore, to get as realistic a picture as possible, the various climatic scenarios have been represented by selected measured conditions, i.e. Option (1).

5.1 Selection Criteria

Each scenario has to cover a neap-spring tidal cycle as a minimum because tidal currents are an important parameter in the sediment plume dispersion. To further ensure “established” conditions for statistical analysis, the model requires a “warm-up” period allowing the plume to get established prior to deriving e.g. mean concentrations or exceedences. Each climatic scenario has thus been based on a full month simulation.

The most complete observational wind records available at the time of the study were from 2006 and 2007. Comparison to previous years indicates that these two years follow fairly typical patterns, although 2006 encompassed cyclonic events in March and April, and 2007 had higher than average winds in January (Appendix FF).

In addition to the tides, the main climatic conditions determining the sediment plume dispersion are related to winds and waves. Waves are well correlated to the local winds

(Appendix N) and the scenario selection can thus be based primarily on the winds and the resulting net currents.

Model testing has shown that the net currents are a key factor for the sediment dispersion from the dredge site. To assess the net current patterns, the two years with the best wind records (2006 and 2007) were simulated in a regional model and the net currents over the various months were derived as shown in Appendix FF

The following is noted from the simulated net drift patterns:

- In line with the winds, there is a clear predominance for a net north easterly flow which dominates from September till February.
- Winter leads to shorter duration westerly net currents, dominant in May, June, July in 2006 and only June and July in 2007.
- As expected from the net wind records, January and June for 2007 have relatively high net currents in easterly and westerly direction, respectively.

Based on the regional net current patterns, the periods listed in Table 5.1 have been chosen for the climatic scenarios. Two months have been included for each "season" in order to capture a greater percentage of the observed variability.

Table 5.1 Selected climatic scenarios 2007

Condition Period	Period
Summer A	January
Summer B	February
Winter A	June
Winter B	July
Transition A	April
Transition B	May

Figure 5.1 shows current roses extracted from a location in the vicinity of the navigation channel for each of the six climate scenario periods listed in Table 5.1 (the location is in Section 4 of the navigation channel – see Figure 6.1 for a description of the Sections). Results highlight the dominant easterly flow during summer, the stronger westerly flow during winter, and the relatively equally strong east and west flow during the transitional period. The lack of directionally variability in this area is indicative of the flow observed in the nearshore region.

Figure 5.2 shows current roses for each of the six climate scenarios extracted from a point in the vicinity of the navigation channel that is located further offshore than that in Figure 5.1 (Section 2). Although similar to that presented in Figure 5.1, there is increased directional variability in the currents at this location.

The hydrodynamic and sediment transport models have been set up to model two continuous months for each of summer, transitional and winter conditions. Statistical analysis for input to the impact assessment is carried out for the second 14-day period of each of the months. This in effect means, for each climatic scenario, a "warm-up" period of two weeks for the first period and one and a half months for the second analysis period.

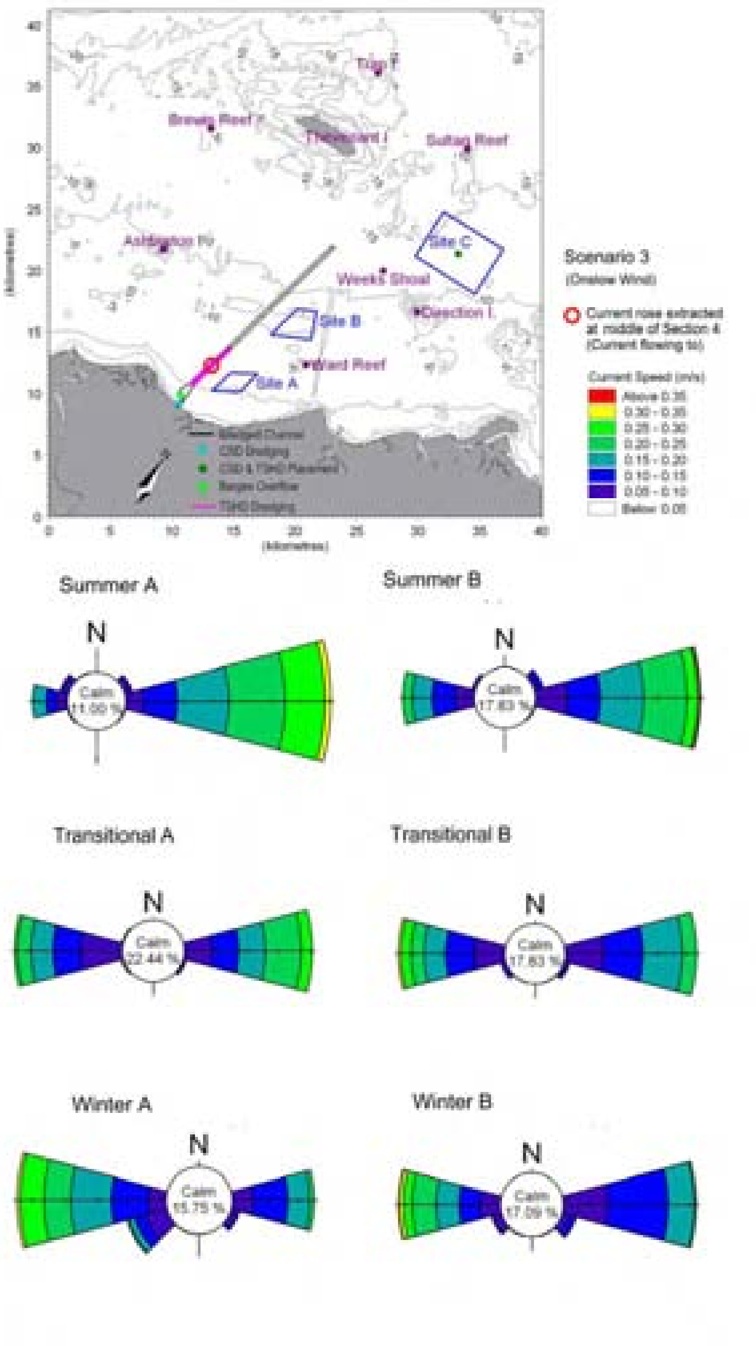

Figure 5.1 *Current roses associated with the six climate scenarios. Location of the current rose within the study region is indicated with a circle in the top image (Navigation channel, Section 4).*

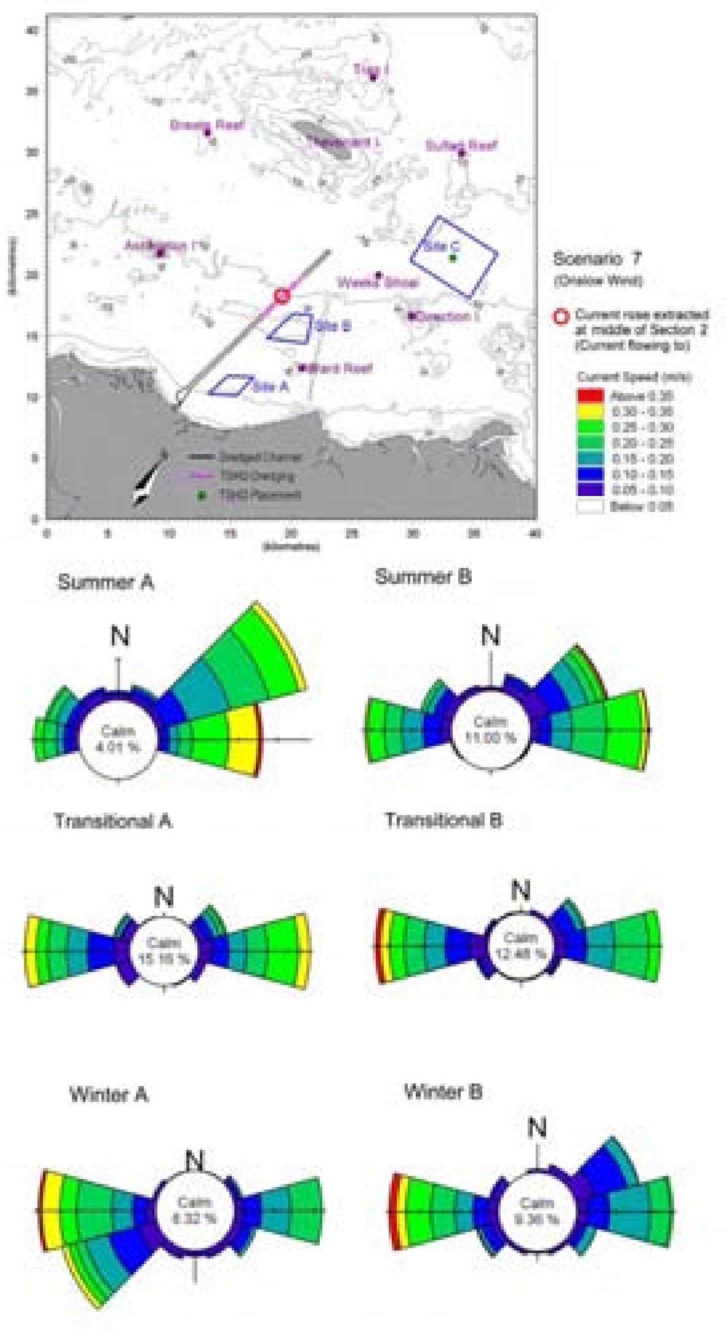

Figure 5.2 *Current roses associated with the six climate scenarios. Location of the current rose within the study region is indicated with a circle in the top image (Navigation channel, Section 2).*

6 DREDGING OF THE NAVIGATION CHANNEL

6.1 Scenario Selection

The LWI dredge schedule (LWI 2009b) specifies a large CSD operating in the nearshore area covering the PLF, MOF and MOF channel for a period of just under six months, and one or two TSHDs operating in the PLF and PLF approach channel for three years. For reference in the present document, the MOF, MOF channel and PLF are referred to as the "nearshore dredging", while the PLF approach channel is referred to as the "offshore" dredging. There is limited overlap in time between the nearshore CSD dredging and the "offshore" TSHD dredging in the DDP schedule.

Some of the principles applied in the selection of the dredge scenarios used in the modelling include:

- Activities along the entire dredge corridor from the MOF to the outer limit of the PLF channel have been included to capture operation in all areas.
- The main focus is on the dredge activities anticipated to lead to the highest spill rates and highest potential for impacts at a given section along the dredge corridor.
- To maintain conservative conditions, the scenarios for TSHD dredging in sand assume double pipe operation.
- The TSHD dredging along the PLF approach channel is likely to encounter variable soil conditions through a single dredge cycle. Production, spill rates and timing may vary between the "pure" sand and weak rock conditions sketched for the dredge cycles and spill rates. To maintain conservatism, the high production and associated spill rates for sand dredging are assumed to occur along all sections of the channel and PLF for up to a month as covered by a climatic scenario. It is noted that this approach is considered highly conservative (worst case).
- Each dredge scenario is simulated for all climatic conditions, even if the scenario only occurs during a limited time period and during a given season according to the schedule provided in the DDP. This is to account for any changes to the schedule.
- Simultaneous activities that could lead to "joint" impacts, e.g. low concentration plumes from different activities overlapping and thereby potentially bringing concentrations over the threshold for impacts, are captured according to the DDP schedule.

All activities have been simulated as realistically as possible. Assumptions that have been applied include:

- TSHD dredge speed of approximately 1 m/s (just under 2 knots),
- Total dredge lengths of 6.85 km for the 5,000 m^3 TSHD, 4.5 km for the 10,000 m^3 TSHD dredging in sand and 21.3 km for the 10,000 m^3 TSHD dredging in weak rock. All lengths are based on the cycle times provided in the DDP.
- 5,000 m^3 TSHD dredge assumed to start from approximate -8 m LAT contour and run through to PLF basin to turn around.
- 10,000 m^3 TSHD dredging in sand is assumed to run straight for 4.5 km along different channel sections. (An approach with a turn-around halfway to dredge twice over a 2.25 km channel section has been tested and showed relatively large, higher concentration plumes, but is not considered likely to be implemented operationally).
- 10,000 m^3 TSHD dredging in weak rock is assumed to run twice along a distance of 10.65 km with a turn-around in the PLF basin.

- All spill sources are timed according to the dredge cycles provided in the DDP.
- The bathymetry is developed progressively, i.e. a representative bathymetry for the stage of the dredging is implemented for each scenario, taking into account all previous dredging according to the DDP.
- When an area has been dredged, a layer of fines is assumed to be deposited in the dredged area. This is included in the model setup as a layer of fines available for re-suspension.
- A layer of fines available for re-suspension is included at the placement sites after they have first been used. The layer is assumed to cover the entire placement area.

Based on the DDP, seven base dredge scenarios have been established to cover the main planned dredging activities in the near- and offshore areas. Each of these is combined with two spill rates (high and low to provide worst case and realistic loads going out of the immediate dredge area) and six climatic conditions, i.e. a total of 84 scenarios. An additional scenario illustrating operational mitigation of plumes developed in a critical section of the PLF approach channel has been developed.

For the PLF approach channel, the TSHD operation in sand leads to the highest spill rates and is likely to determine the impact zones. The dredge distance per cycle for this activity is assumed to be 4.5 km, based on the cycle information from the DDP and a dredging speed of 1 m/s. Four Sections, each 4.5 km, long have been defined for the PLF approach channel (with some overlap between the Sections). The PLF is assumed as a fifth section, half the distance based on a turn-around approach. See Figure 6.1 for channel Sections.

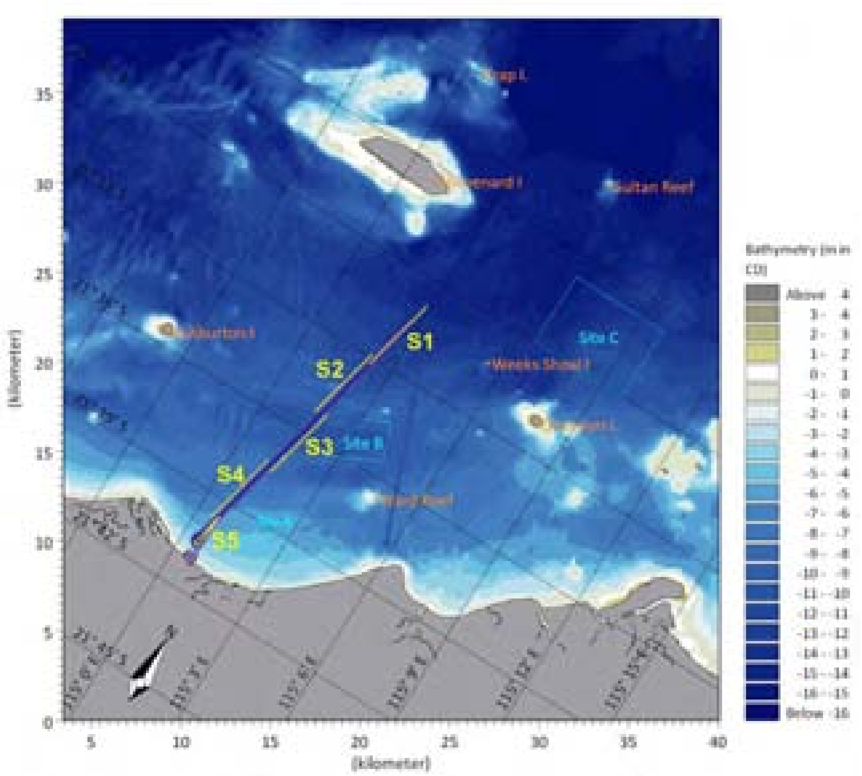

Figure 6.1 Definition of PLF Approach Channel dredge Sections (1 – 4) and PLF Section (5).

6.1.1 Dredge Scenarios

A total of seven base dredge scenarios were originally identified. Motivated by results of Dredge Scenario 7, an additional dredge scenario was investigated that incorporated dredge spill (i.e. overflow) restrictions along parts of the channel in order to reduce potential impacts at nearby sensitive receptor locations such as Paroo Shoal, Hastings Shoal, Gorgon Patch (ref. Figure 2.1).

A summary of the seven base dredge scenarios (1-7) and the one mitigation scenario (7A) are outlined in Table 6.1.

Table 6.1 Summary of dredging scenarios based on main activities defined in Table 2.1.

Dredge Scenario No.	Dredging Activity Description	
	"Nearshore" Dredging	**"Offshore" Dredging**
1	#1 CSD dredging of barge access channel with placement at site A through bottom diffuser.	
2	#2 CSD dredging in PLF berth pocket loading barges at -3 m LAT contour on western side of MOF channel in footprint of PLF basin.	
3	#3 CSD dredging in MOF area loading barges at -3 m LAT contour on western side of MOF channel in footprint of PLF basin.	#4: 5,000 m^3 TSHD dredging in inner part of PLF approach channel Section 4 with disposal at site C
4	#5 10,000 m^3 TSHD dredging weak rock in PLF (Section 5) with disposal at site C	#6: 10,000 m^3 TSHD dredging sand along PLF approach channel Section 1 with disposal at site C
5		#6: 10,000 m^3 TSHD dredging sand along PLF approach channel Section 3 with disposal at site C #6 10,000 m^3 TSHD dredging weak rock in approach channel Sections 1 & 2 with disposal at site C
6		#6: 10,000 m^3 TSHD dredging sand along PLF approach channel Section 4 with disposal at site C #6 10,000 m^3 TSHD dredging weak rock in along approach channel Sections 3 & 4
7		#6: 10,000 m^3 TSHD dredging sand along PLF approach channel Section 2 with disposal at site C
7A(1)		#6: 10,000 m^3 TSHD dredging sand along defined "no overflow" zone at PLF approach channel Section 2 with disposal at site C. Dredger starts each dredge cycle at centre of "no overflow" zone and dredges along the channel towards shore and offshore on alternate cycles.
Note (1): For each dredge cycle, the TSHD starts dredging at the centre of the "no overflow" zone within Section 2. It takes 25 minutes, corresponding to a sailing distance of 1.5 km for a speed of 1 m/s (app. 2 knots) before overflow starts. The dredger keeps dredging for another 3 km with overflow. The dredger dredges towards south and north, respectively, on alternate trips. This leads to a 3 km section with no overflow with 3 km with overflow on each side, i.e. the total channel section being dredged is 9 km		

Table 6.2 is a summary of the modelling methodology that has been adopted with respect to the representation of the bathymetry and the inclusion of material for re-suspension for each of the dredge scenarios defined in Table 6.1.

Figure 6.2 through Figure 6.9 show pictorial representations of the seven base dredge scenarios (1 – 7) and the one mitigation scenario (7A).

Table 6.2 Summary of dredging scenarios modelling methodology.

Parameter	Scenario							
	1	2	3	4	5	6	7	7A
Bathymetry	Partly dredged access channel.	Fully dredged access channel, including MOF.	Fully dredged, 75 m wide channel to -6 m LAT and barge access channel. Includes MOF breakwaters.	Fully dredged MOF and MOF channel, partly dredged PLF basin to -12 m LAT. Includes MOF dredged basin and MOF breakwaters.	Fully dredged MOF, MOF channel and PLF basin. Partly dredged approach channel along entire length. Includes MOF dredged basin and MOF breakwaters.	Fully dredged MOF, MOF channel and PLF basin. Partly dredged approach channel along entire length. Includes MOF dredged basin and MOF breakwaters.	Fully dredged MOF, MOF channel and PLF basin. Partly dredged approach channel along entire length. Includes MOF dredged basin and MOF breakwaters.	Fully dredged MOF, MOF channel and PLF basin. Partly dredged approach channel along entire length. Includes MOF dredged basin and MOF breakwaters.
Re-suspension material	Dredged channel & PSA.	Dredged channel & PSA, PSC.	Along channel and in placement sites A and C.	Along channel and in placement sites A and C.	All dredged areas and in placement sites A and C.	All dredged areas and in placement sites A and C.	All dredged areas and in placement sites A and C.	All dredged areas and in placement sites A and C.

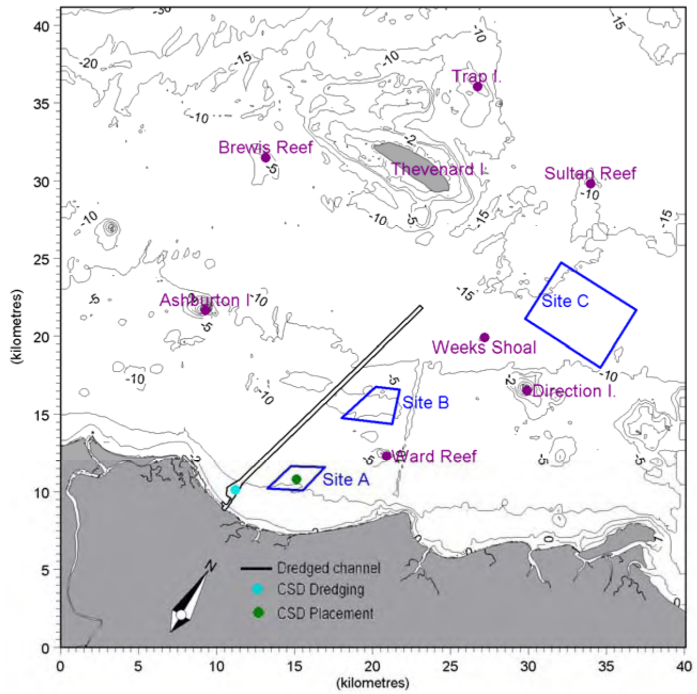

Figure 6.2 *Sketch of locations for Dredging Scenario 1: CSD dredging (blue dot) with placement to site A (dark green dot)*

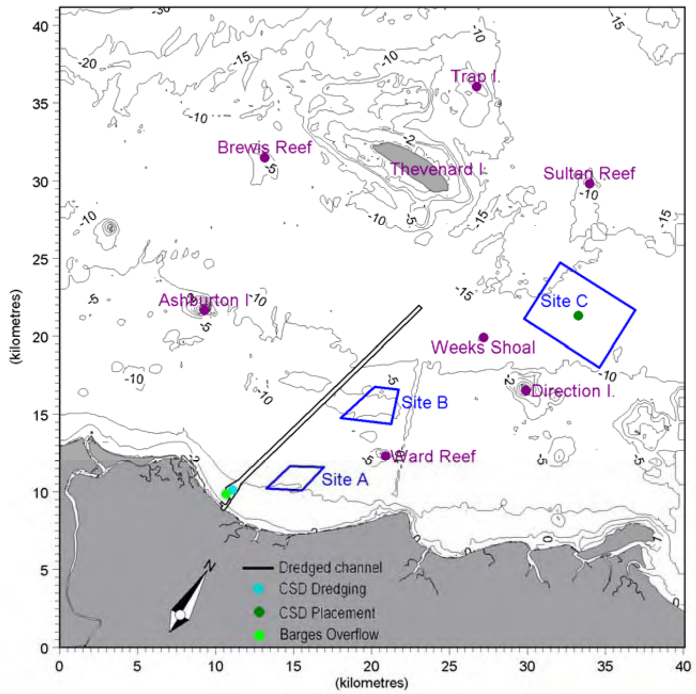

Figure 6.3 *Sketch of locations for Dredging Scenario 2: CSD dredging (blue dot) with loading of barges (light green dot). Placement to site C (dark green dot)*

6-6

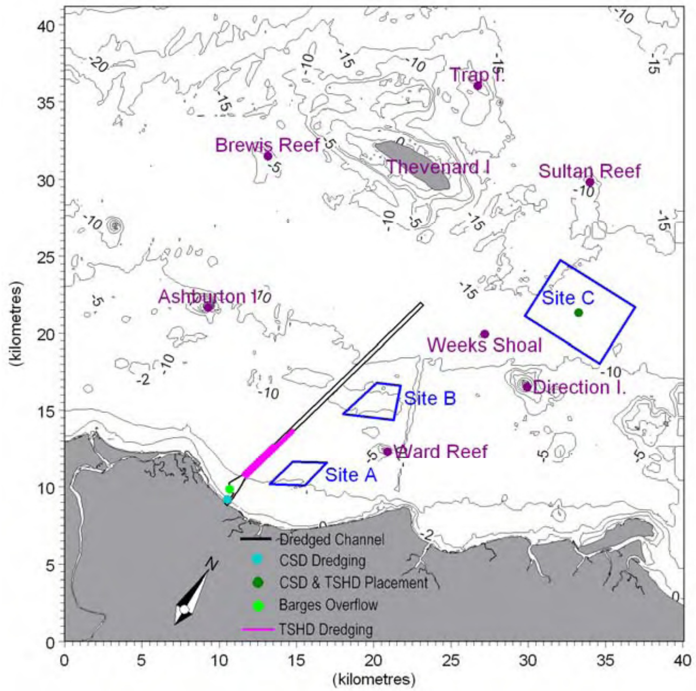

Figure 6.4 *Sketch of locations for Dredging Scenario 3: CSD dredging at MOF (blue dot) with pumping to barges at -3 m LAT contour with overflow (light green dot) and transport to placement site C (dark green dot). 5,000 m^3 TSHD dredging Section 4 (pink line).*

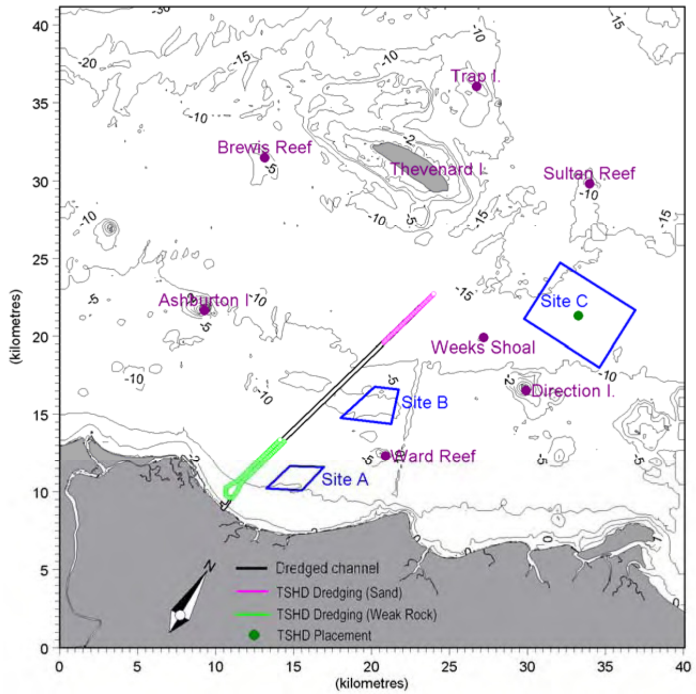

Figure 6.5 *Sketch of locations for Dredging Scenario 4: 10,000 m^3 TSHD dredging weak rock in PLF Sections 4 & 5 (green line) and 10,000m^3 TSHD dredging sand at PLF approach Section 1 (pink line); placement at site C (dark green dot).*

6-7

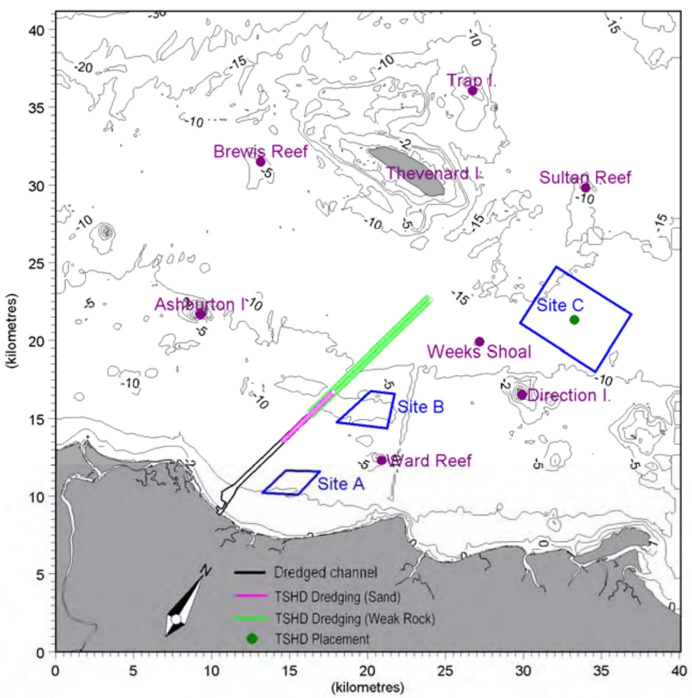

Figure 6.6 Sketch of locations for Dredging Scenario 5: 10,000 m^3 TSHD dredging weak rock in PLF Sections 1 & 2 (green line) and 10,000 m^3 TSHD dredging sand at PLF approach Section 3 (pink line); placement at site C (dark green dot).

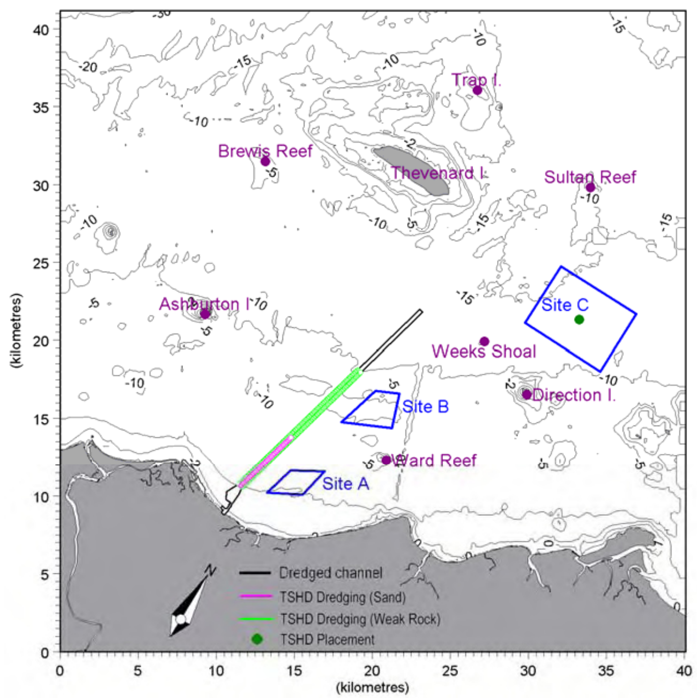

Figure 6.7 Sketch of locations for Dredging Scenario 6: 10,000 m^3 TSHD dredging weak rock in PLF Sections 3 & 4 (green line) and 10,000 m^3 TSHD dredging sand at PLF approach Section 4 (pink line); placement at site C (dark green dot).

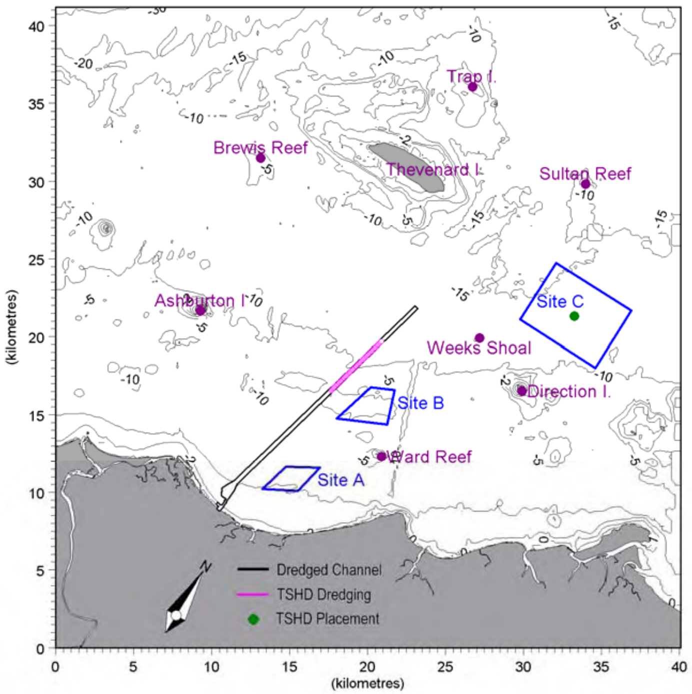

Figure 6.8 *Sketch of locations for Dredging Scenario 7: 10,000 m^3 TSHD dredging sand at PLF approach Section 2 (pink line); placement at site C (dark green dot).*

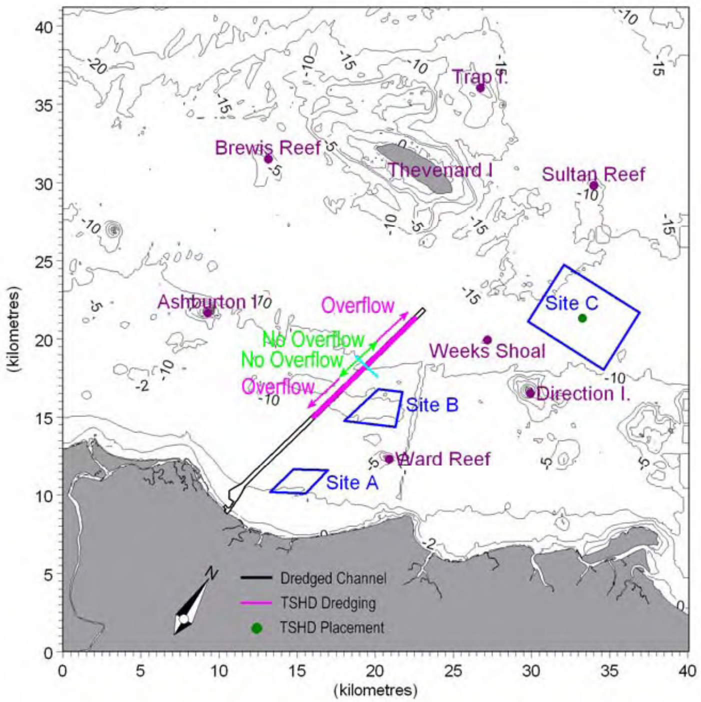

Figure 6.9 *Sketch of locations for Dredging Scenario 7A: TSHD starting in centre of pink line, dredging towards or away from shore on alternate trips with initial 1.5 km section with no overflow followed by 3 km with overflow; placement at site C (dark green dot).*

6.2 Results for the Dredging of the Navigation Channel

Statistics on the model results are used in conjunction with defined impact criteria to derive impact zones. This is reported separately in DHI (2010c). In the present report, the results are illustrated through plots of selected statistical outputs.

Results obtained from the hydrodynamics driven by both sets of wind fields have been used to develop the results presented in this section. This is due to the issues surrounding the limitations associated with the representativeness of either of the Onslow wind fields (which have been shown to be representative in the nearshore region during summer), and MesoLAPS wind fields (which are considered representative of wind fields in the offshore region and during winter). A conservative approach has been adopted when developing the composites, with the resultant contour plot representing the maximum from each of the individual results.

Results based on Onslow wind-driven hydrodynamics are presented in Appendix O (Dredge Scenario 1) through Appendix V (Dredge Scenario 7A). Results for the following statistics are included in the appendices for each of the six climate scenarios and two spill rates:

- Mean excess concentration at two scales;
- Exceedence of 5 mg/l excess concentration at two scales;
- Exceedence of 10 mg/l excess concentration;
- Exceedence of 25 mg/l excess concentration; and
- Net sedimentation rates at two zoomed levels at the site.

Appendix W (Dredge Scenario 1) through Appendix DD (Dredge Scenario 7A) also present results for each of the six climate scenarios and two spill rates based on MesoLAPS wind-driven hydrodynamics for these same statistics.

When interpreting the results presented in the following figures, it is important to note that these are not snapshots in time and therefore do not represent the spatial extent of the dredge sediment plume at any given time. Instead, these plots are the composite of a number of simulated 14-day periods that have been superimposed to give an estimate of maximum footprint associated with each of the dredge scenarios. All plume results presented in the present section are combined for Onslow and MesoLAPS winds, while the individual results for the two sets of wind data are presented in the appendices as outlined above.

6.2.1 Results for Individual Dredge Scenarios

Plume modelling results for the mean suspended sediment concentration (SSC) for each of the eight dredge scenarios, six climate scenarios and two spill rates are presented in this section.

In summary, results suggest that Scenario 3 and Scenario 7 have either the largest and most concentrated plumes, or plumes which have the potential to impact on key sensitive receptor locations. Recall that Scenario 3 is associated with the offshore placement base case, with two dredgers (a CSD and small TSHD) working in close proximity to each other in the nearshore. Dredge Scenario 7 is associated with a large TSHD working in sand adjacent to the coral shoals which occur along the 10 m isobath. These two scenarios are responsible for most of the dredging-related benthic primary producer habitat impacts presented in Section 8.3 of the Wheatstone Project EIA. Results from Dredge Scenario 7A have been included to highlight the potential environmental benefit that can be achieved by incorporating 'no-spill' zones into the dredge program.

6.2.1.1 Low (Realistic) Spill Rates

In general, results for the two summer climate scenarios are associated with plumes that extend eastward driven by the predominately easterly flow during this period. The two winter climate scenarios are generally associated with plumes that extend westward. For a comparison, see the current roses presented in Section 5.1.

The transitional periods are associated in general with plumes with a limited degree of excursion away from the source region. These periods of relative 'calm' are associated with elevated levels of localised sediment. This is because the introduced material experiences less dispersion under these ambient conditions, but may still be kept in suspension by relatively high tidal current velocities during spring tides.

Dredge Scenario 1

Figure 6.10 shows the results for Dredge Scenario 1. Included in the figure is a depiction of the corresponding dredge scenario (top figure). The results for the mean SSC for the six climate scenarios for Dredge Scenario 1 based on realistic spill rates are presented in the lower figures.

Dredge Scenario 1 has a CSD operating in the PLF area with direct pumping to site A.

Results highlight the influence of the predominant easterly flow during the summer climate scenarios with plumes extending along the nearshore. The predominant westerly flow during the winter climate scenarios is also apparent. Limited dispersion takes place from site A for the assumed spill rates for the bottom placement.

A composite of worst-case impacts is obtained by overlaying the results of all six climate scenarios and taking the maximum value at each point within the domain. The result of this analysis is depicted in Figure 6.11 (cf. results presented in Figure 6.10).

Dredge Scenario 2

Dredge Scenario 2 with a CSD operating in loose material in the near-shore area is not dissimilar to Dredge Scenario 1. Apart from a slight difference in the dredge location and bathymetry, the main difference is the fact that the CSD now pumps to barges for transport to site C rather than pumping directly to site A. Barge loading takes place in the inner part of the PLF basin close to the dredging, and the overflow from the barges leads to a higher total spill rate than the placement at site A for Dredging Scenario 1. This is because Dredging Scenario 1 assumes a relatively low spill rate for the bottom placement with a spreader pontoon.

The nearshore plumes in Dredge Scenario 2 is similar to the nearshore plume for Dredge Scenario 1, but with higher concentrations due to the higher combined spill rates from the CSD cutter head and the overflow as outlined above. In addition, Dredge Scenario 2 has a plume from the placement at site C compared to the plume emitted from site A in Dredging Scenario 1.

Scenario 2 has the highest concentration near-shore plumes of the seven base scenarios due to the fact that the CSD works close to the barge overflow and the two spill sources combine to one during overflow.

Dredge Scenario 3

Presented in Figure 6.14 are the results for Dredge Scenario 3. Included in the figure is a depiction of the corresponding dredge scenario (top figure). The results for the mean SSC for the six climate scenarios for Dredge Scenario 3 based on realistic spill rates are presented in the lower figures. Figure 6.15 presents a composite of the results for the six climate scenarios for Dredge Scenario 3.

Dredge Scenario 3 combines CSD dredging in the MOF with overflow to barges with a 5,000 m3 TSHD dredging in the inner part of the PLF approach channel. Both operations dispose the material at site C, which leads to the largest spill rates and plumes from site C among the scenarios.

The MOF dredging assumes the breakwaters are partly in place. Sheltering by the breakwaters leads to lower emission of plumes from the CSD. The overflow of barges within the PLF basin is similar to Dredging Scenario 2.

The spills from the MOF dredging with overflow of the barges and the TSHD dredging in the inner part of the PLF Approach channel combine to create a very wide (up to 5 km) plume along the coastline stretching predominantly eastward during summer and westward during winter.

Dredge Scenario 4

Dredge Scenario 4 combines two 10,000 m^3 TSHDs working in parallel. It is assumed that the first dredges weak rock within the PLF, while the other dredges sand along the outer part of the PLF Approach Channel. Both discharge via bottom placement to site C.

Figure 6.16 presents mean concentrations for the six climatic scenarios, while Figure 6.17 presents a composite of the results for the six climate scenarios for Dredge Scenario 4.

The production and associated spill rates for dredging in weak rock are low compared to dredging in loose material. The plume from the PLF, due to the TSHD dredging in weak rock, is small and low concentration compared to the CSD dredging with overflow in previous scenarios.

The plume emitted from dredging in loose material at the outer end of the PLF Approach Channel tends to combine with the plume from site C, leading to a fairly far-reaching combined plume.

Dredge Scenario 5

Dredge Scenario 5 operates with two 10,000 m^3 TSHDs with the first dredging weak rock and the other dredging sand similar to Dredge Scenario 4, but with the dredger operating at different channel segments.

Figure 6.18 presents mean concentrations for the six climatic scenarios, while Figure 6.19 presents a composite of the results for the six climate scenarios for Dredge Scenario 5.

The plume dispersion has the usual patterns with respect to the climatic scenarios, i.e. eastward extension during summer and westward dispersion during winter. Again, the Summer A plume reaches site C, which leads to a fairly extensive but relatively low concentration plume towards the north-west during these climatic conditions.

Dredge Scenario 6

Dredge Scenario 6 has TSHD dredging in loose material in the inner part of the PLF Approach Channel, overlapping with TSHD dredging of weak rock in the same area.

Figure 6.20 presents mean concentrations for the six climatic scenarios, while Figure 6.21 presents a composite of the results for the six climate scenarios for Dredge Scenario 6.

The combined plume from the two operations leads to a significant plume stretching eastward along the coast during the Summer A climatic conditions.

The combination of the relatively high combined spill rates and the nearshore environment leads to significant re-suspension in the model, and low concentration plumes are found up to 100 km to the north-east of the site and up to 70 km to the west of the site during winter conditions.

Dredge Scenario 7 and Dredge Scenario 7A

Figure 6.22 shows the results for the six climate scenarios for Dredge Scenario 7 based on realistic spill rates. Included in the figure is a depiction of the corresponding dredge scenario (top figure).

Results highlight the influence of the prevailing winds during the winter and summer periods. Transitional periods are associated with the highest mean SSC values in close proximity to the channel. Sediment plumes associated with dredging activities in this region are predicted to extend westward to Ashburton Island during the winter period and eastward towards Weeks Shoal during the summer period

In order to reduce the potential for impacts from sediment plumes associated with dredging activates in this region, 'no-spill' zones have been proposed and modelling undertaken (Dredge Scenario 7A). Figure 6.23 shows the results for the six climate scenarios for Dredge Scenario 7A based on realistic spill rates. The effectiveness of the 'no-spill' zones is clearly identifiable with reductions in the mean SSC during the winter and summer periods.

Presented in Figure 6.24 are the climate composites for Dredge Scenario 7 (unmitigated) and Dredge Scenario 7A (mitigated option). The effectiveness of the proposed restricted overflow zones is clearly evident with the reduction in the mean SSC in the vicinity of Ashburton Island and Weeks Shoal.

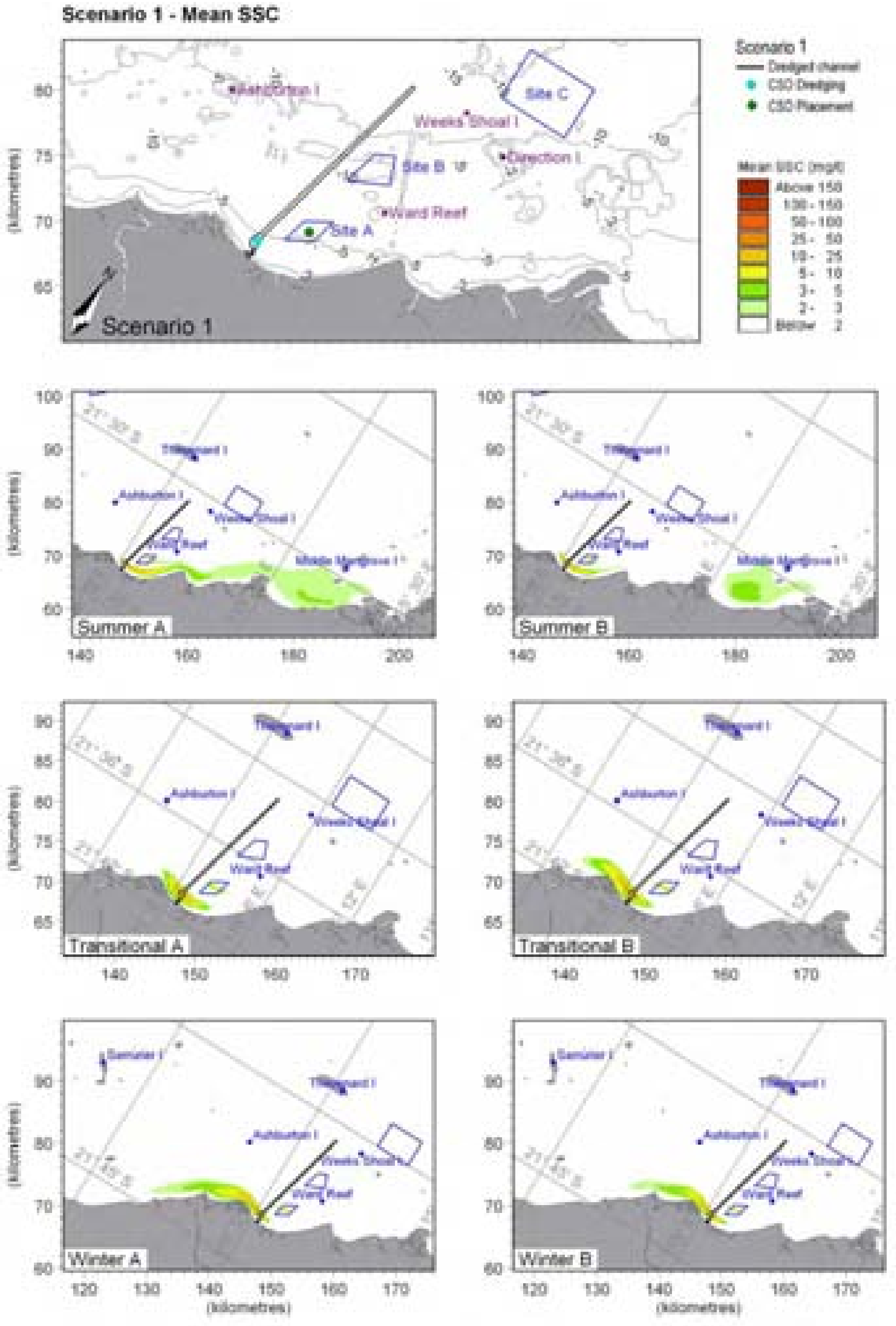

Figure 6.10 Mean SSC for Dredge Scenario 1 with realistic spill rates.

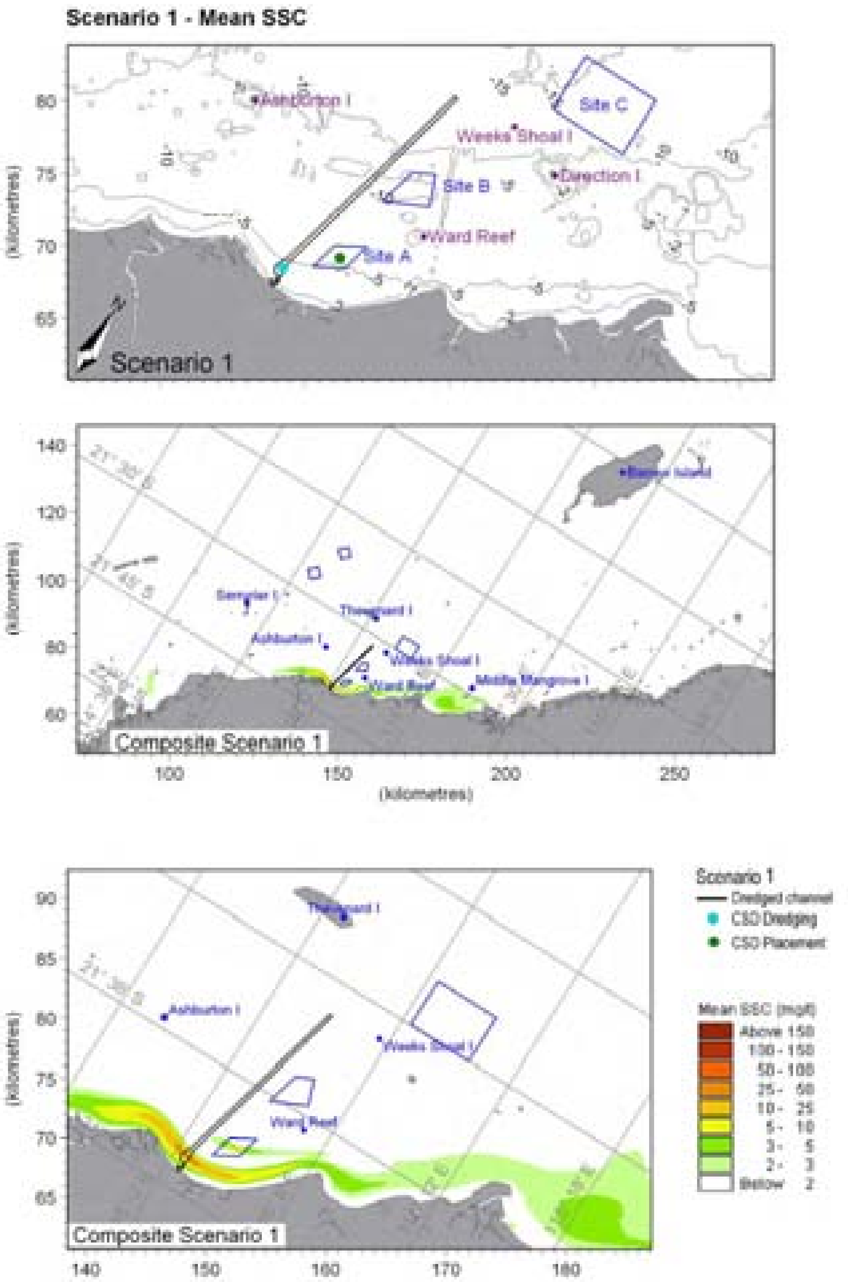

Figure 6.11 Composite of the Mean SSC for Dredge Scenario 1 with low (realistic) spill rates. All climate scenarios combined.

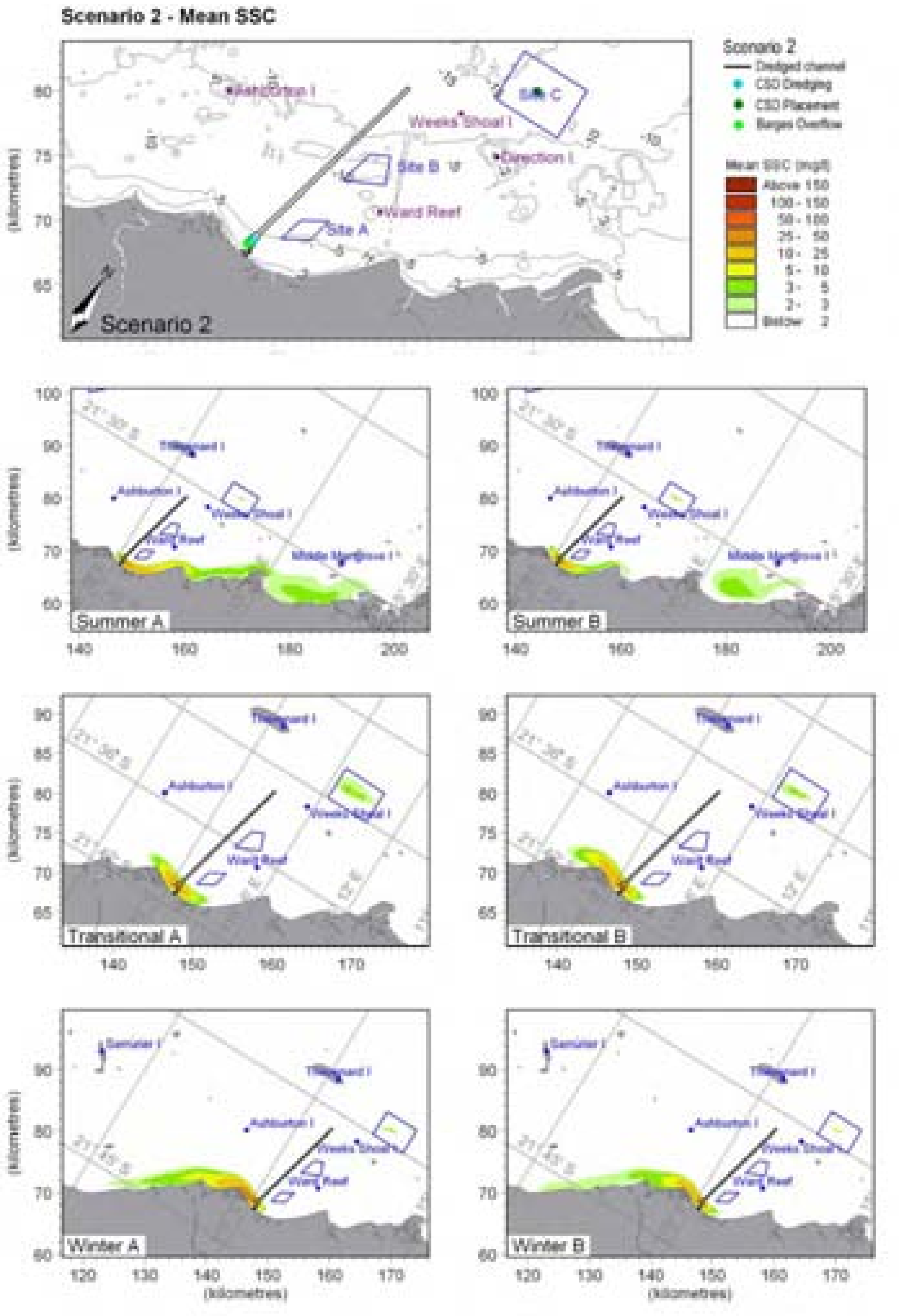

Figure 6.12: Mean SSC for Dredge Scenario 2 with realistic spill rates

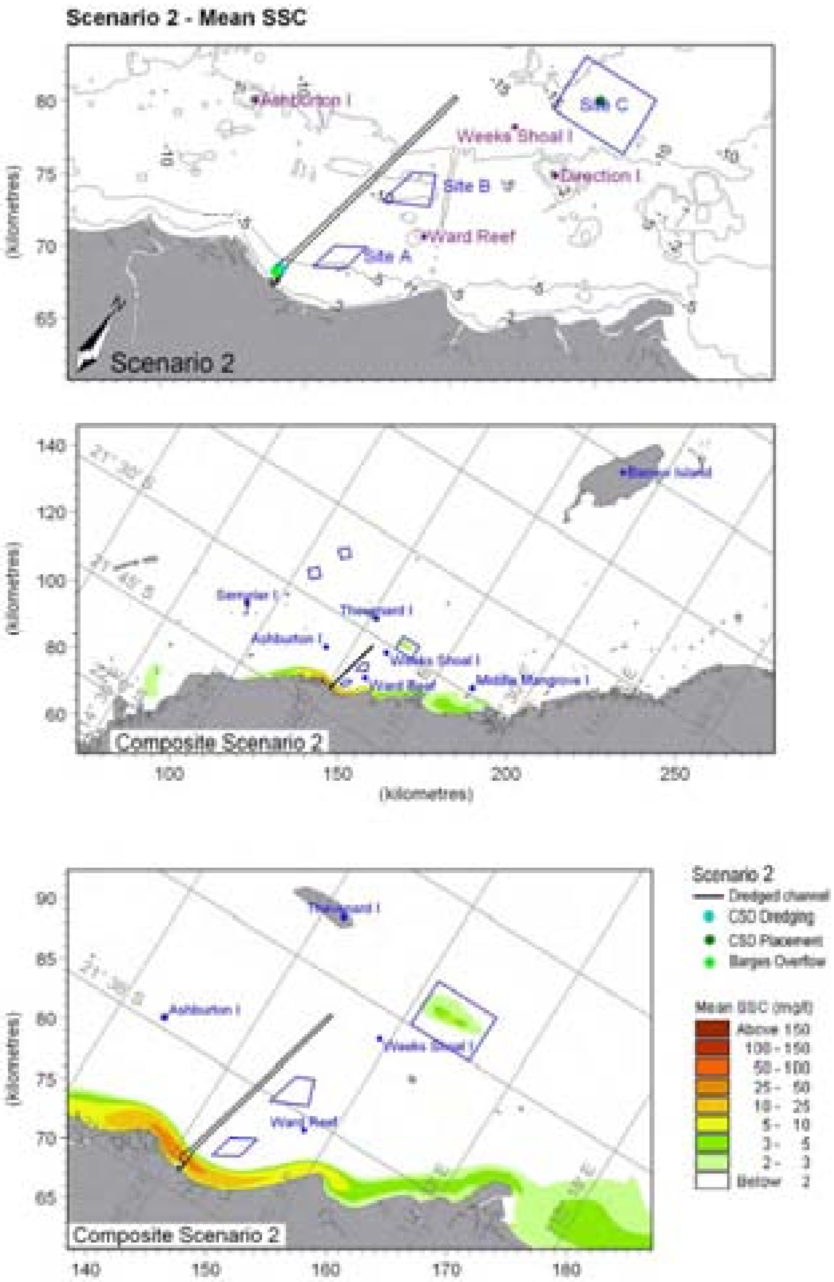

Figure 6.13 Composite of the Mean SSC for Dredge Scenario 2 with low (realistic) spill rates. All climate scenarios combined.

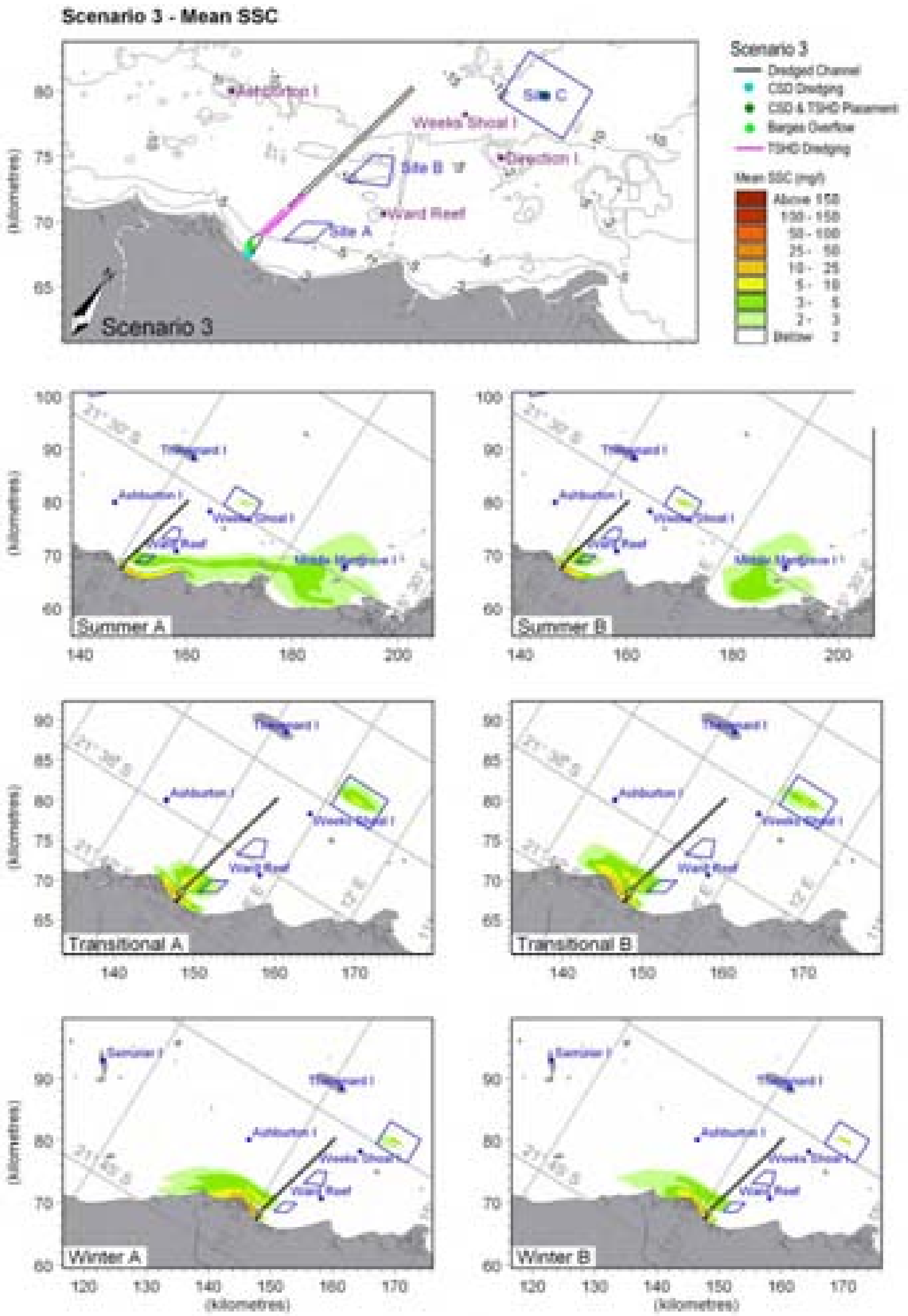

Figure 6.14 Mean SSC for Dredge Scenario 3 with low (realistic) spill rates

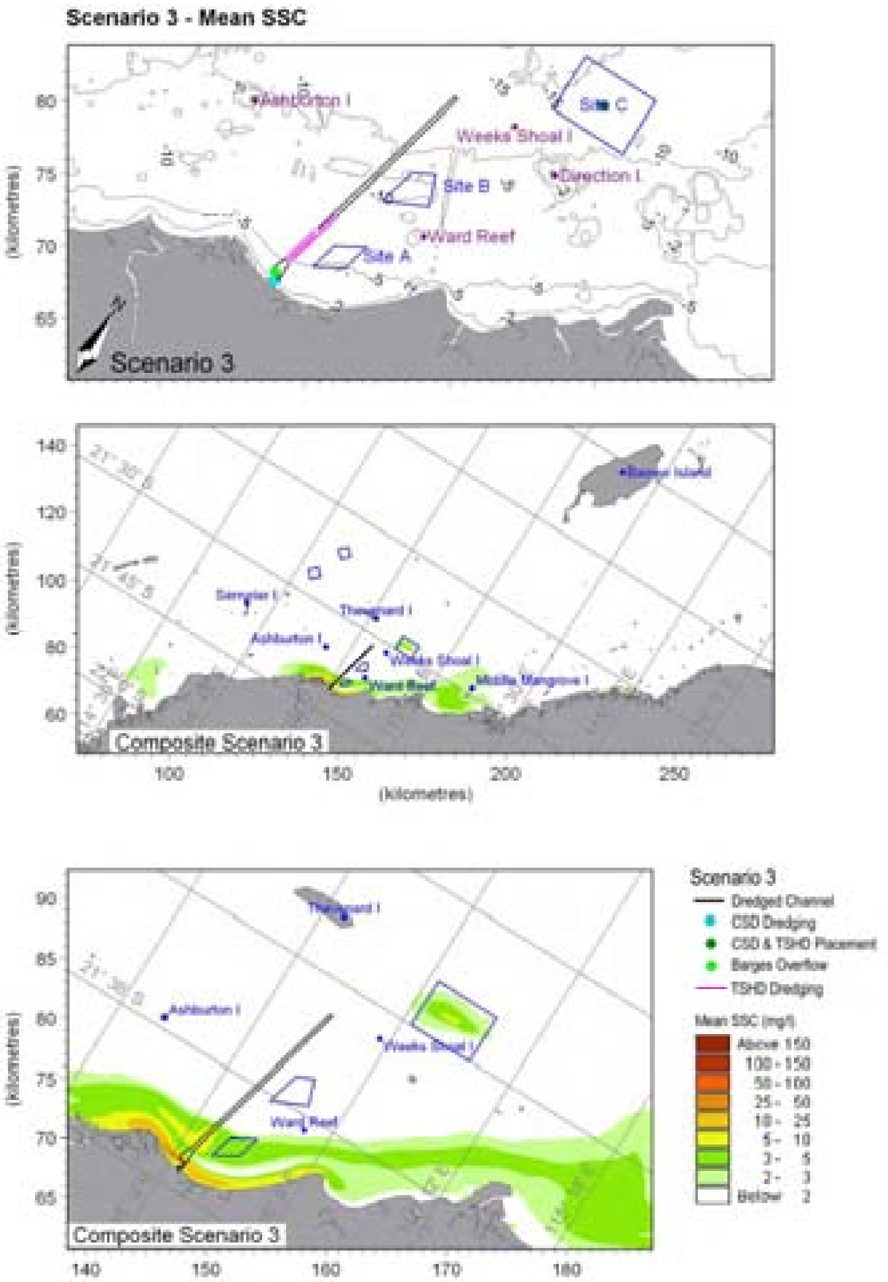

Figure 6.15 Composite of the Mean SSC for Dredge Scenario 3 with low (realistic) spill rates. All climate scenarios combined

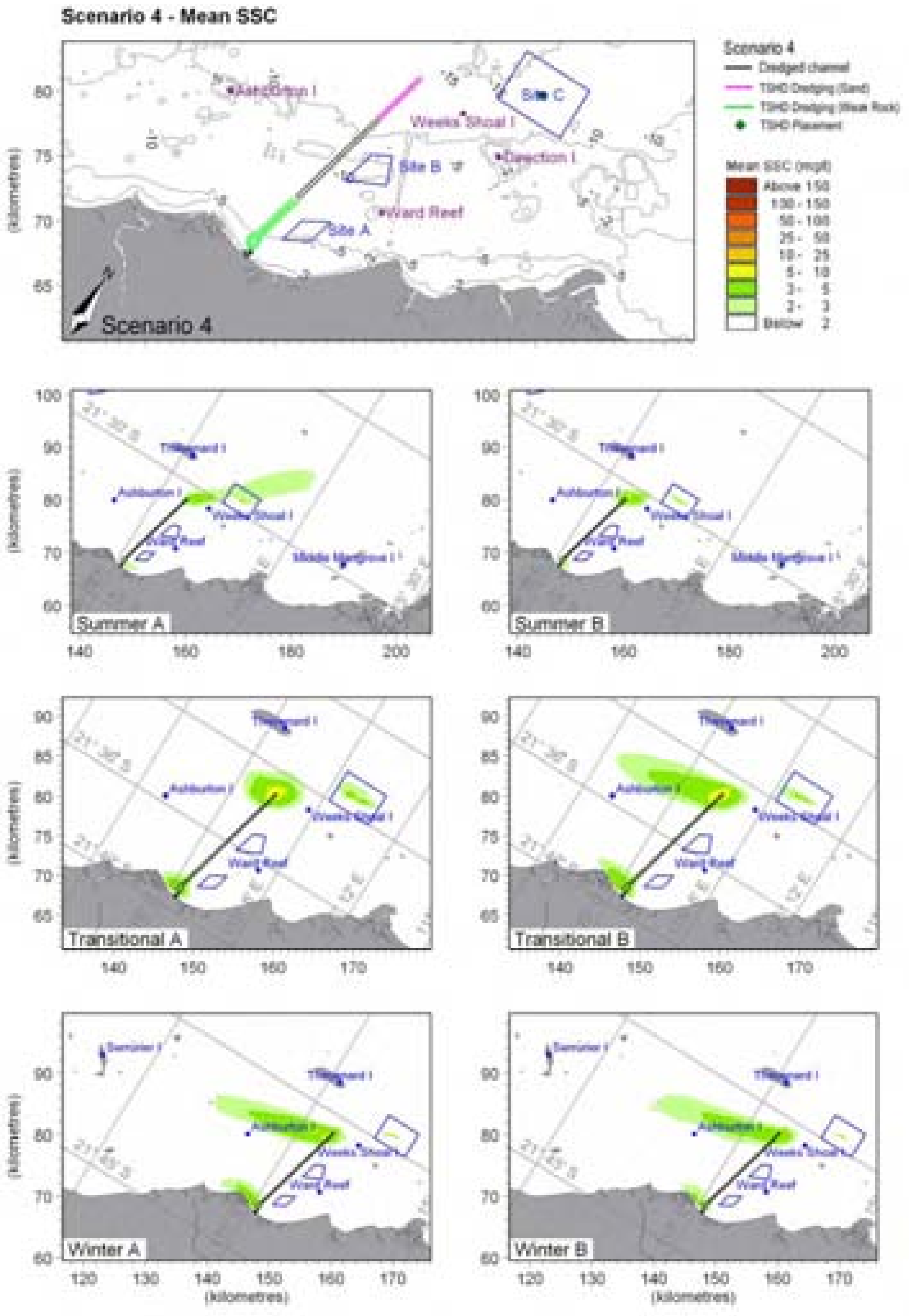

Figure 6.16 Mean SSC for Dredge Scenario 4 with low (realistic) spill rates

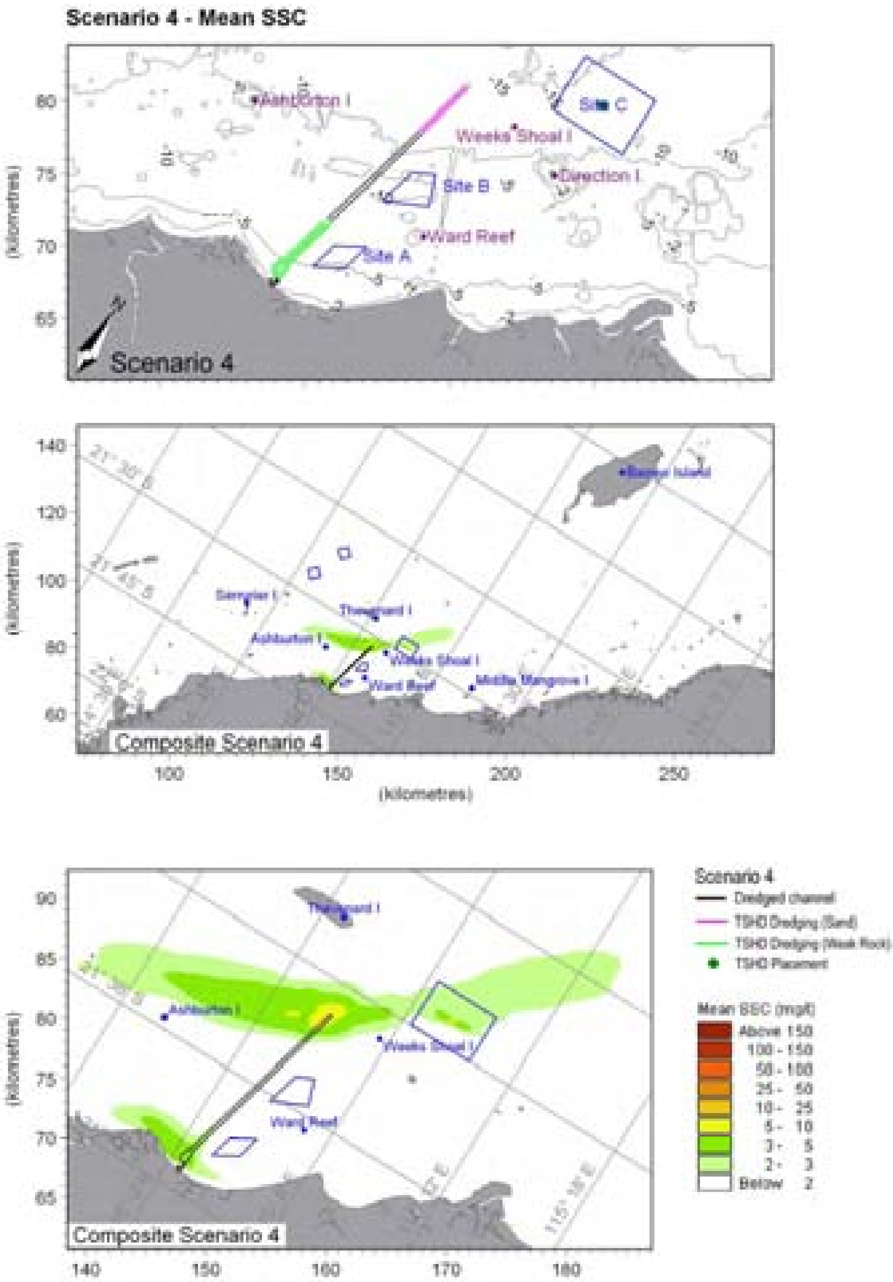

Figure 6.17 Composite of the Mean SSC for Dredge Scenario 4 with low (realistic) spill rates. All climate scenarios combined.

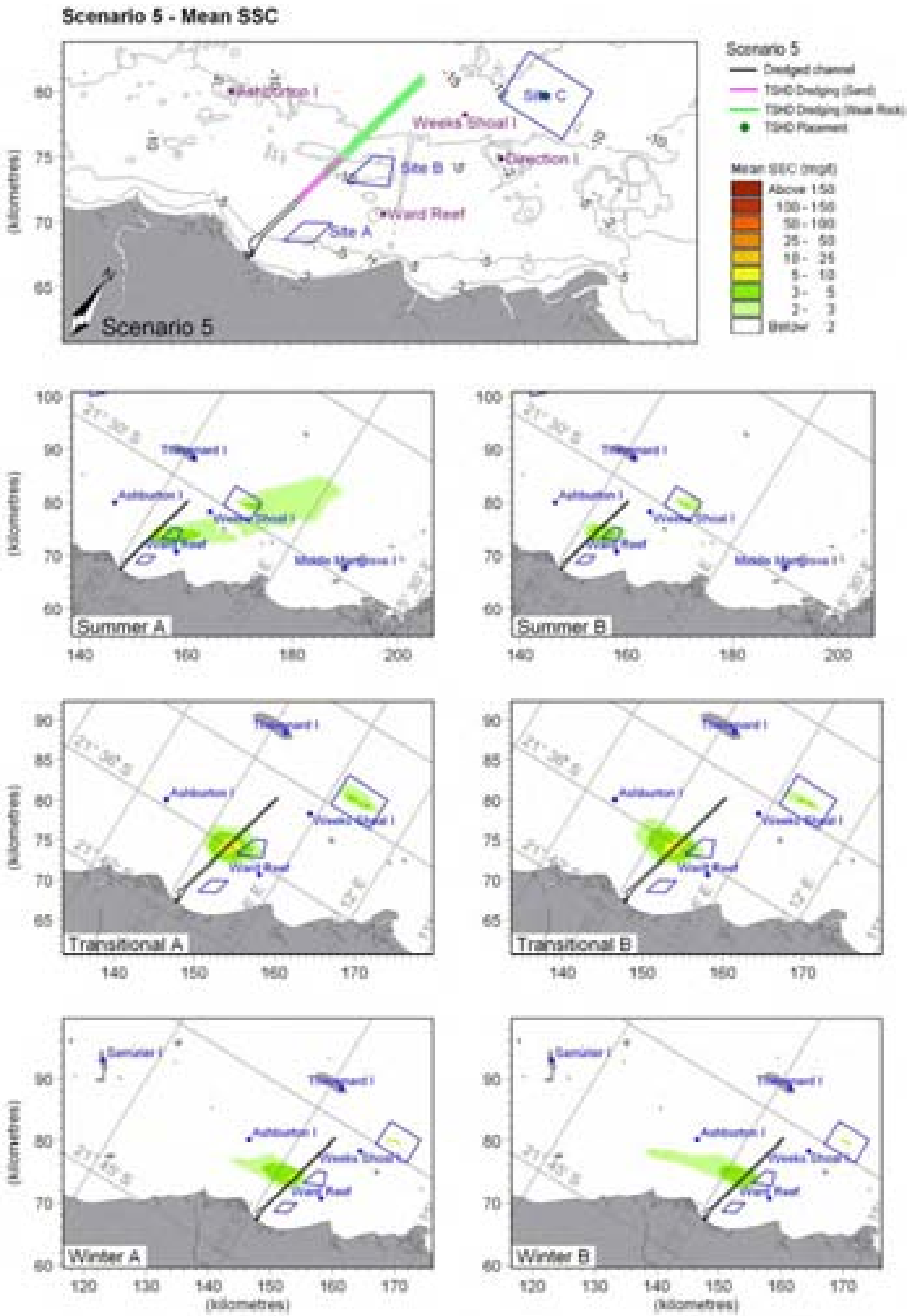

Figure 6.18 Mean SSC for Dredge Scenario 5 with low (realistic) spill rates

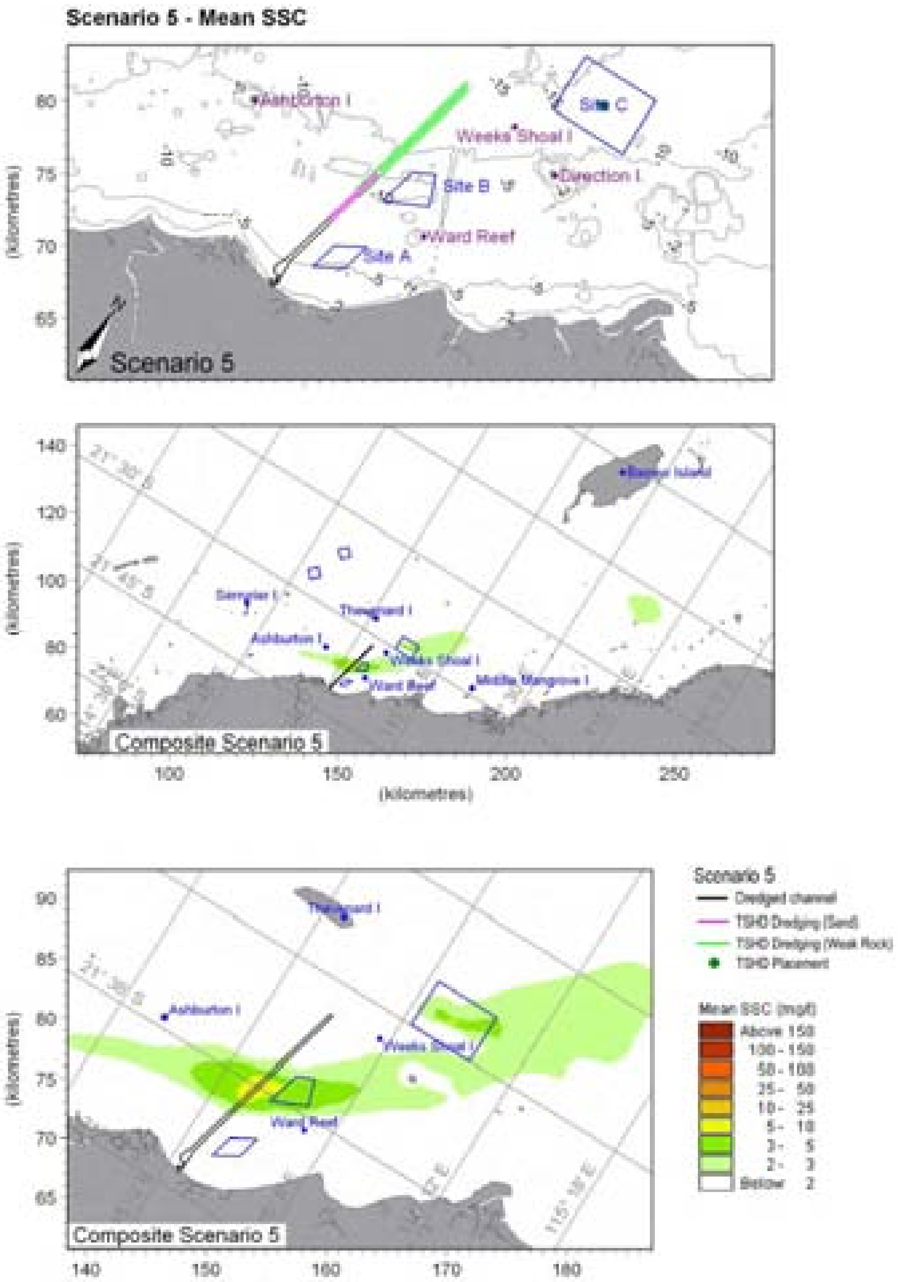

Figure 6.19 Composite of the Mean SSC for Dredge Scenario 5 with low (realistic) spill rates. All climate scenarios combined.

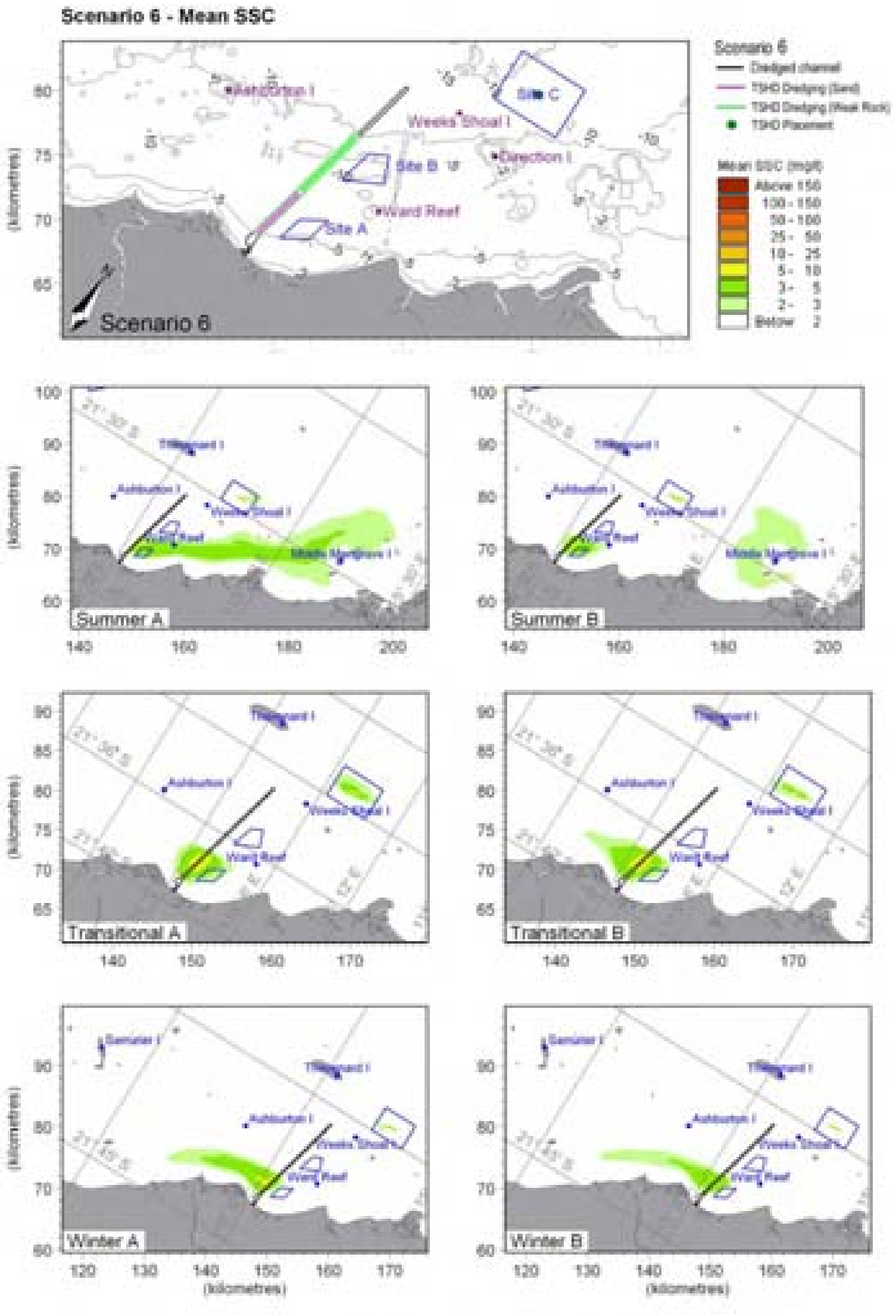

Figure 6.20 Mean SSC for Dredge Scenario 6 with low (realistic) spill rates

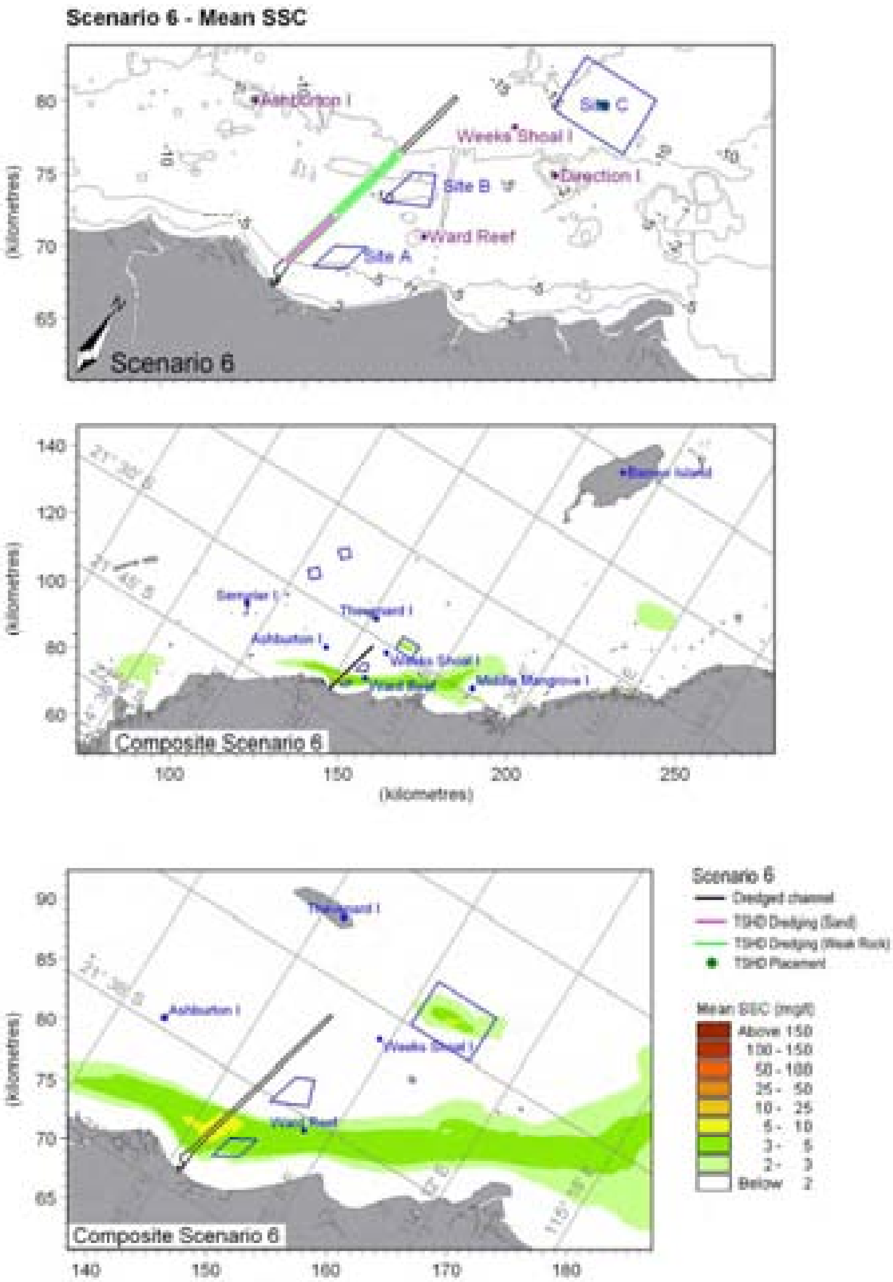

Figure 6.21 Composite of the Mean SSC for Dredge Scenario 6 with low (realistic) spill rates. All climate scenarios combined.

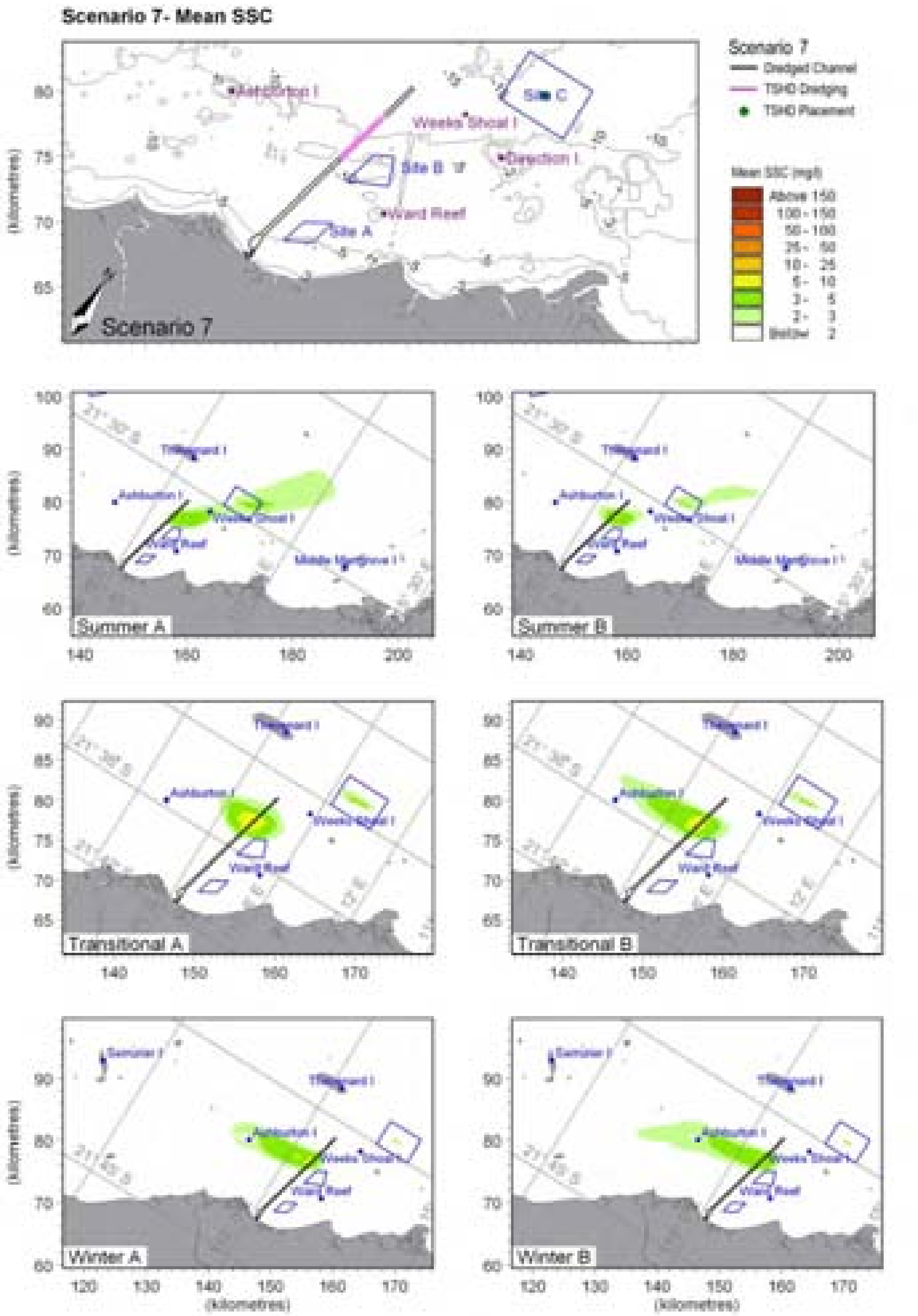

Figure 6.22 Mean SSC for Dredge Scenario 7 with low (realistic) spill rates

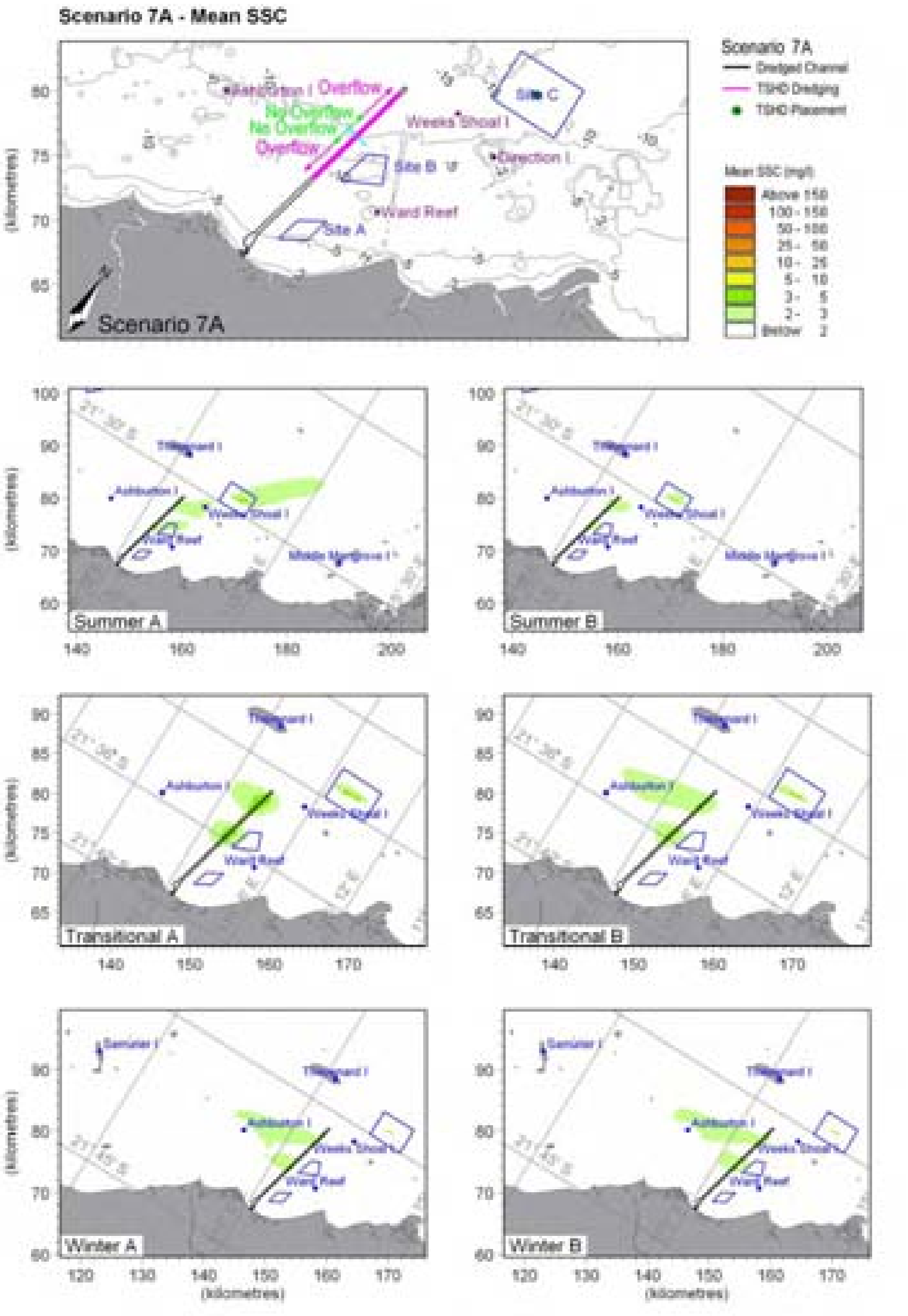

Figure 6.23 Mean SSC for Dredge Scenario 7A with low (realistic) spill rates

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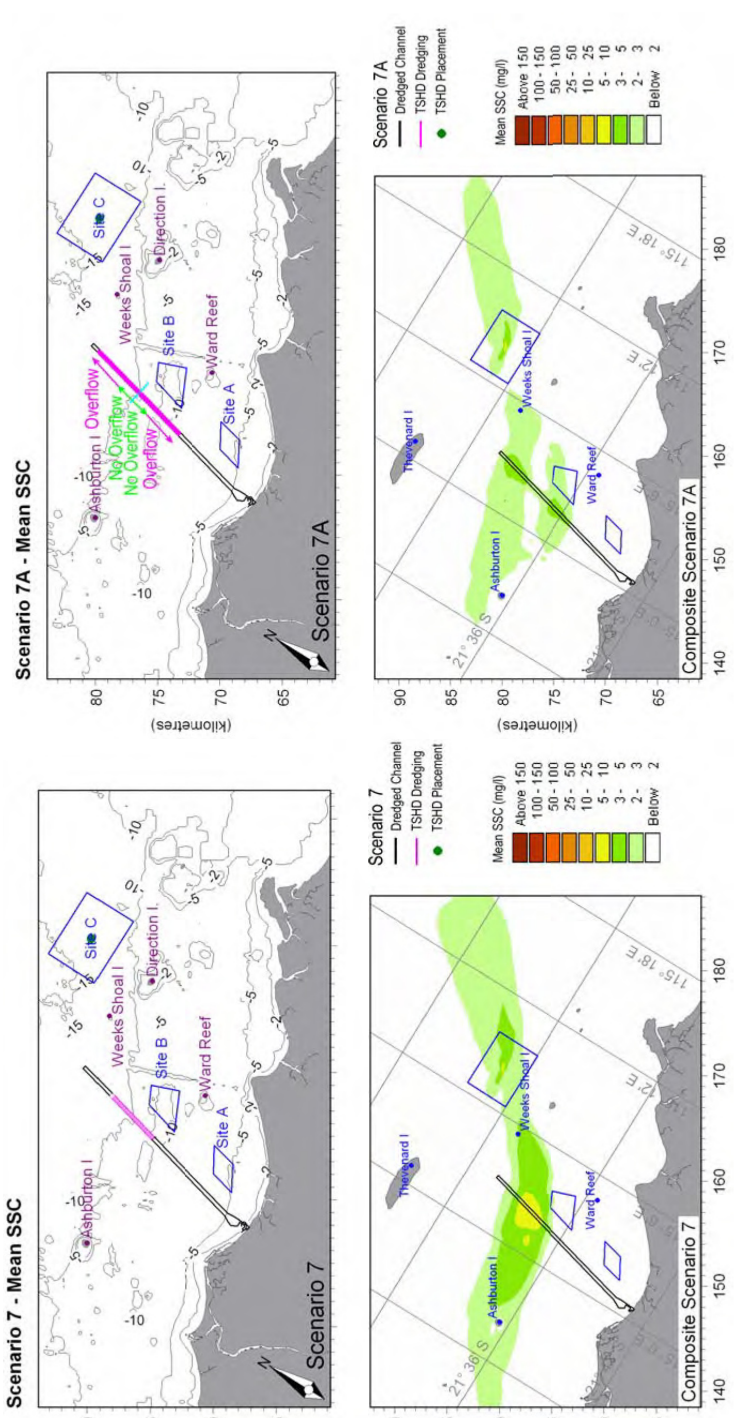

Figure 6.24 Mean SSC for Scenario 7 (left) and Scenario 7A (right) with low (realistic) spill rates. All climate scenarios combined.

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6.2.1.2 High (Worst-Case) Spill Rates

Results for the "Worst-case" spill rates are illustrated in terms of SSC for the eight dredge scenarios in Figure 6.25 to Figure 6.32. Only the spill rates are higher compared to the "realistic" spill rates, and the general trends for the plumes resulting from the "worst case" spill rates are similar to the plumes from the "realistic" spill rates. The concentrations are obviously much higher for the "worst case" spill rates, and the plumes corresponding to a given mean excess concentration stretches much further from the source.

No composite plots have been produced for the "worst case" spill rates as this is considered overly conservative. The "worst case" spill rates are best estimates for spill rates that only occur for limited periods of time during particularly unfavourable conditions. A composite plot for all the climatic conditions are thus considered overly conservative and potentially misleading if interpreted wrongly.

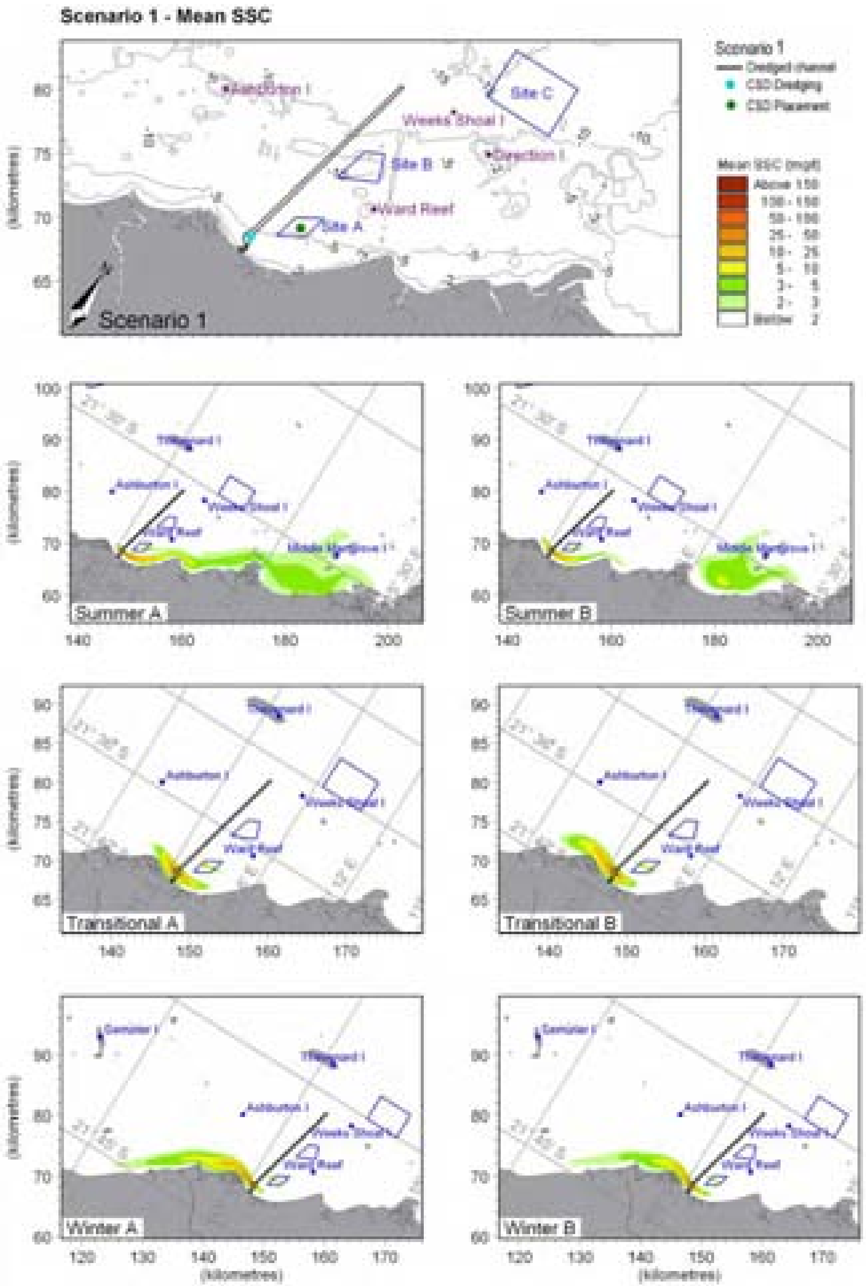

Figure 6.25 Mean SSC for Dredge Scenario 1 with high (worst-case) spill rates

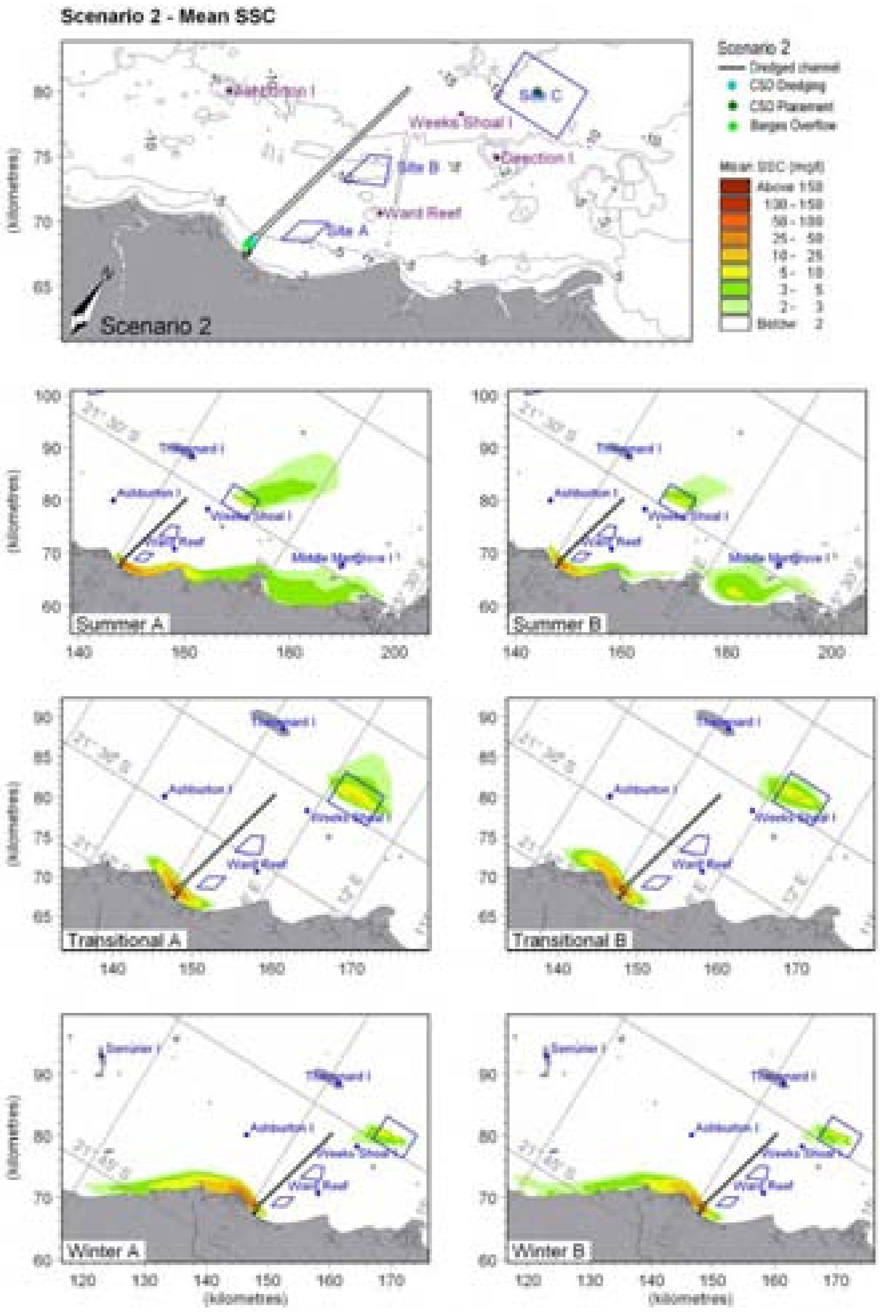

Figure 6.26 Mean SSC for Dredge Scenario 2 with high (worst-case) spill rates

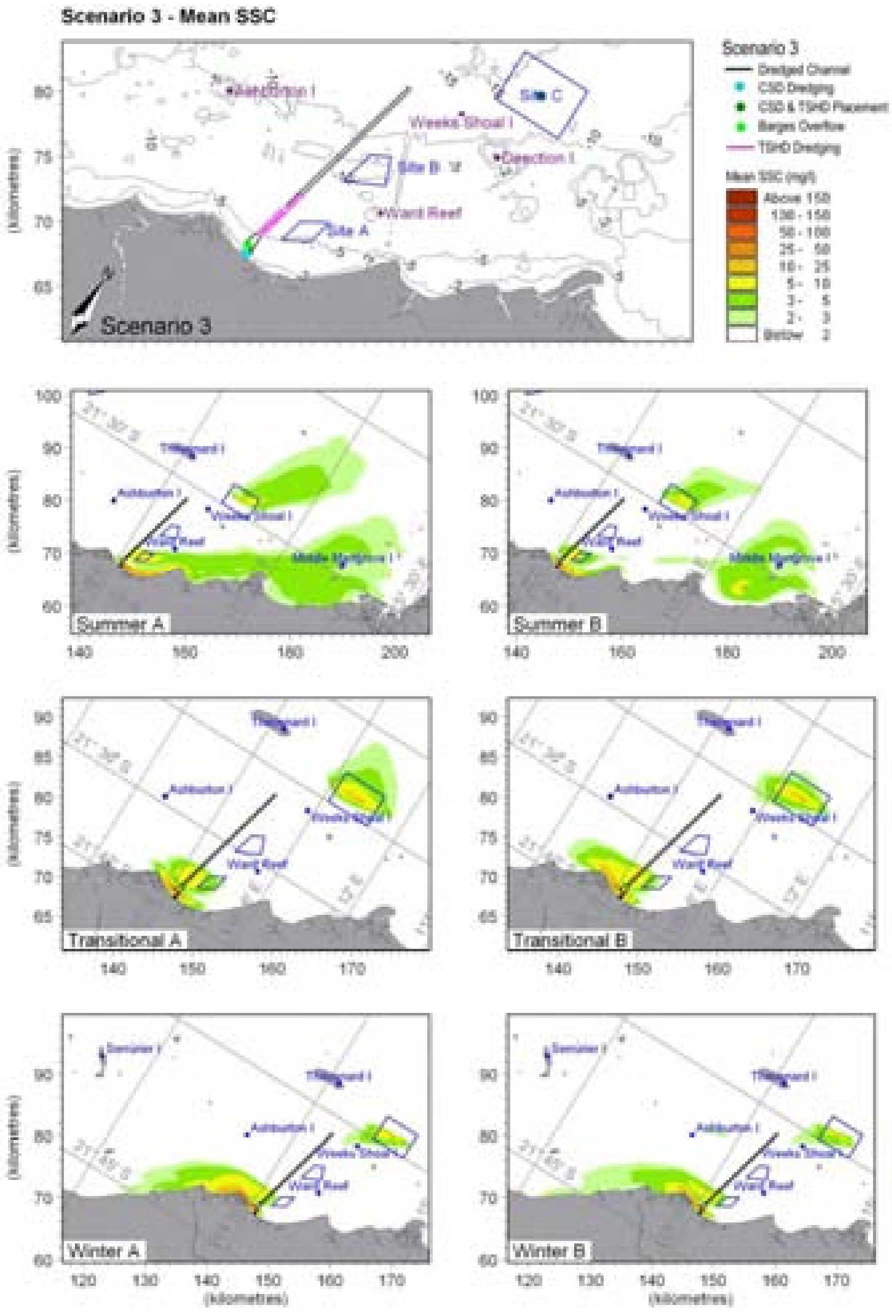

Figure 6.27 Mean SSC for Dredge Scenario 3 with high (worst-case) spill rates

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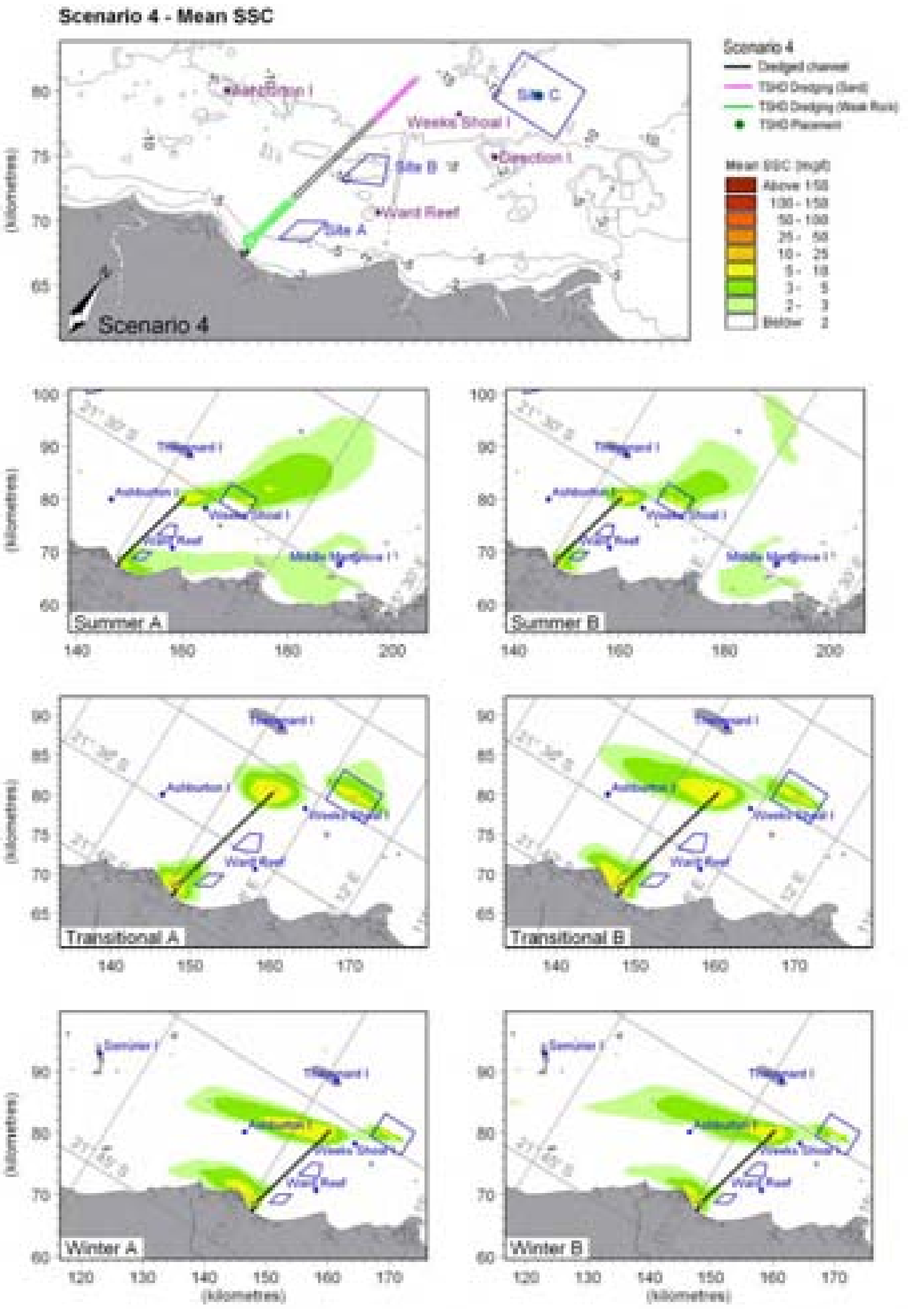

Figure 6.28 Mean SSC for Dredge Scenario 4 with high (worst-case) spill rates

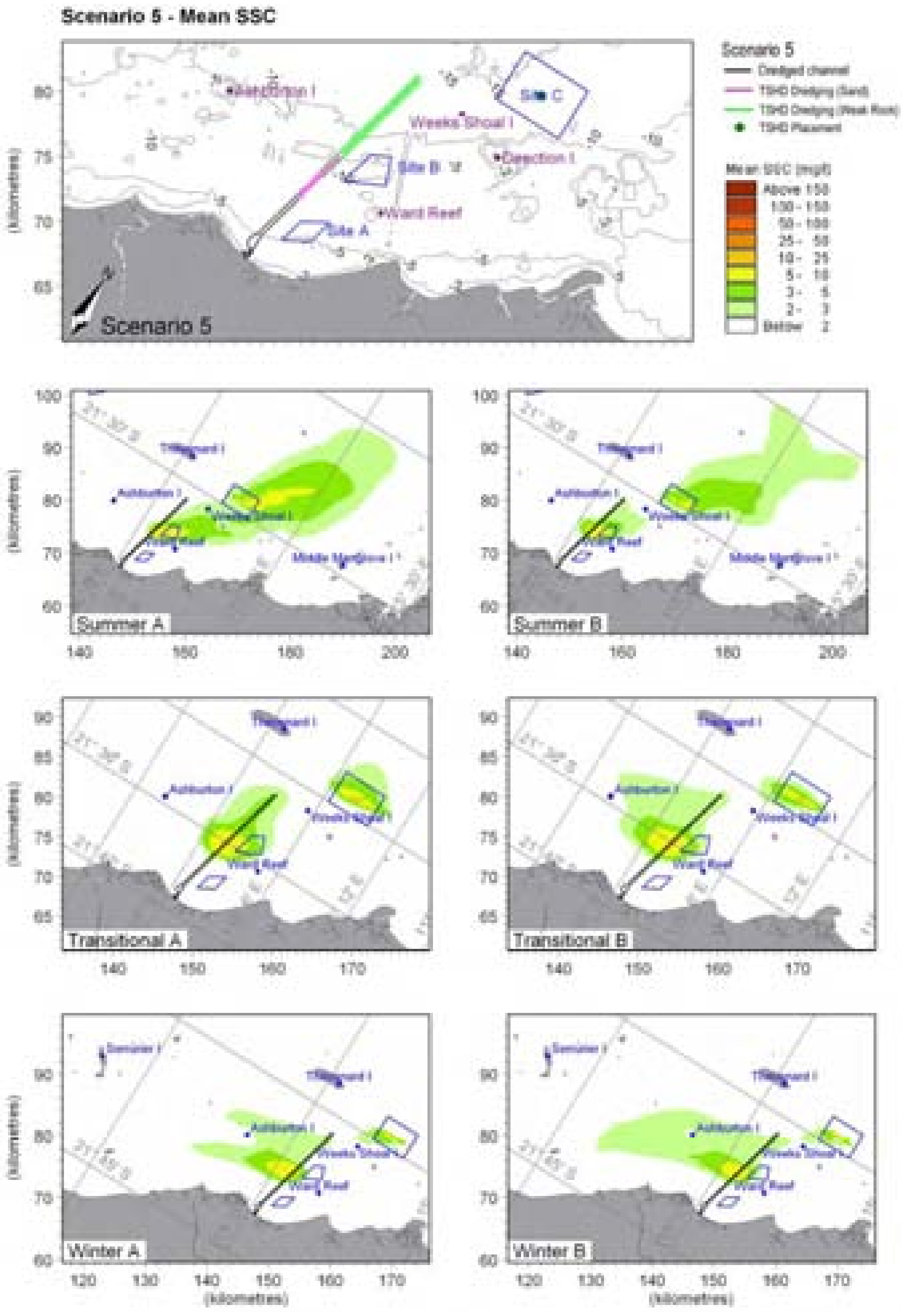

Figure 6.29 Mean SSC for Dredge Scenario 5 with high (worst-case) spill rates

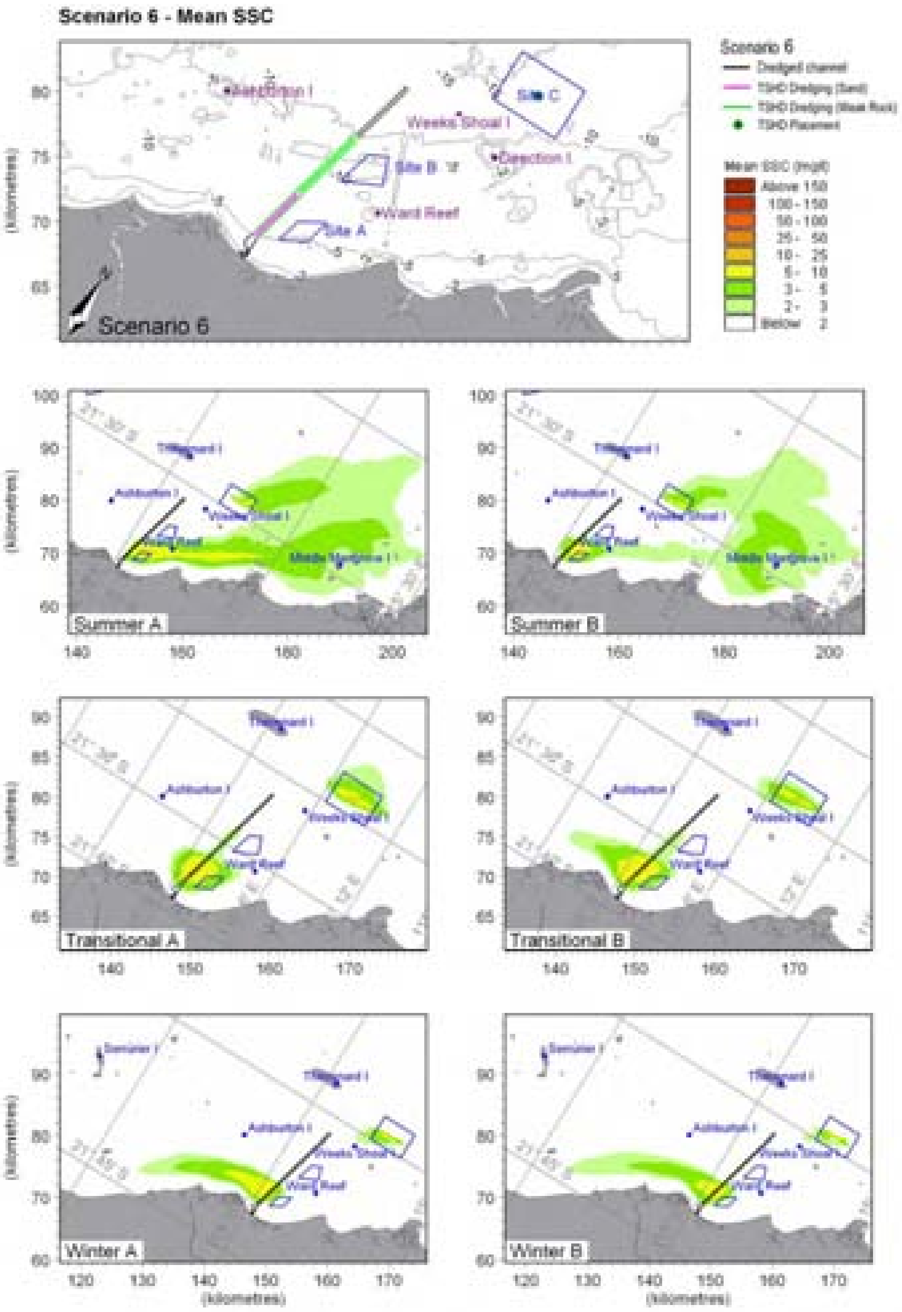

Figure 6.30 Mean SSC for Dredge Scenario 6 with high (worst-case) spill rates

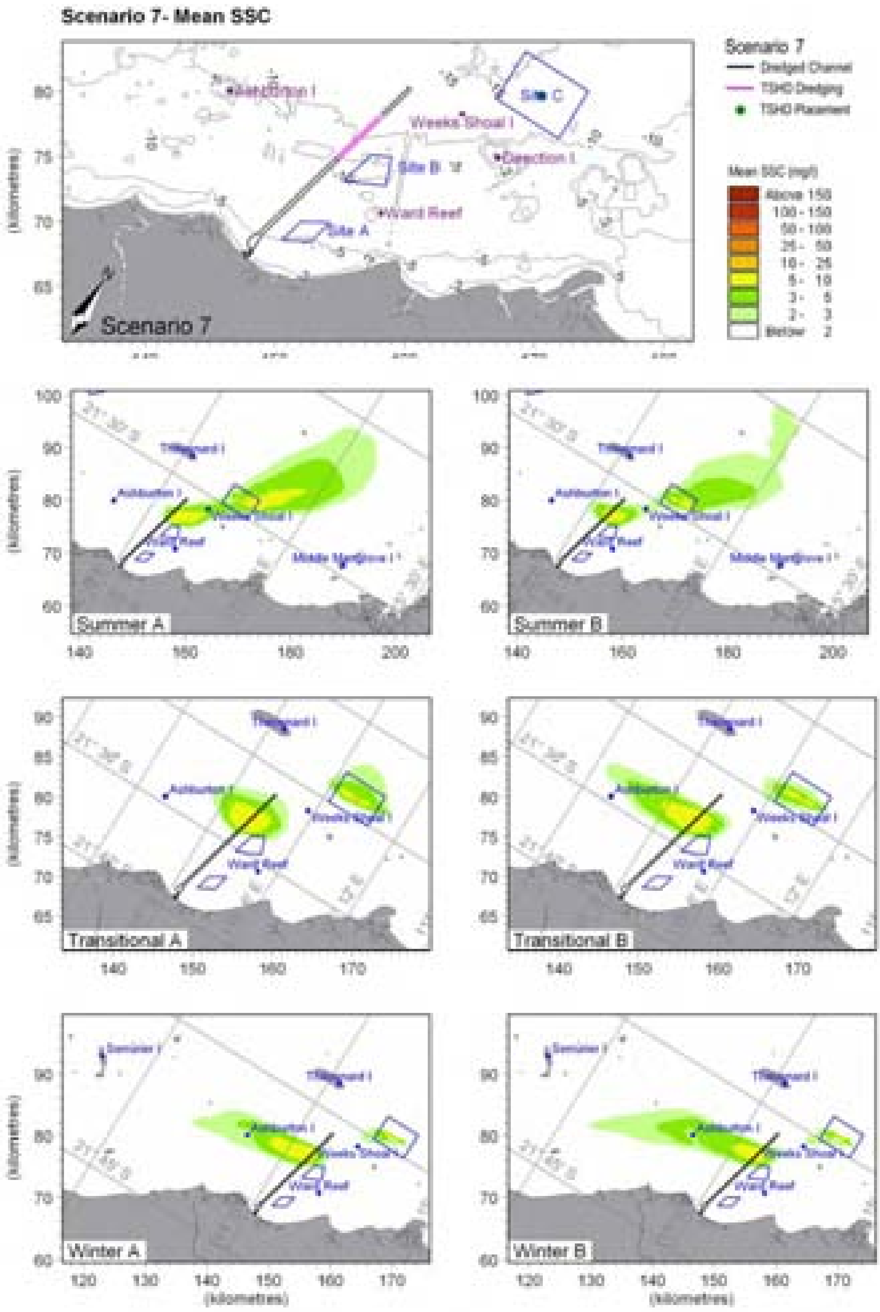

Figure 6.31 Mean SSC for Dredge Scenario 7 with high (worst-case) spill rates

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Scenario 7A - Mean SSC

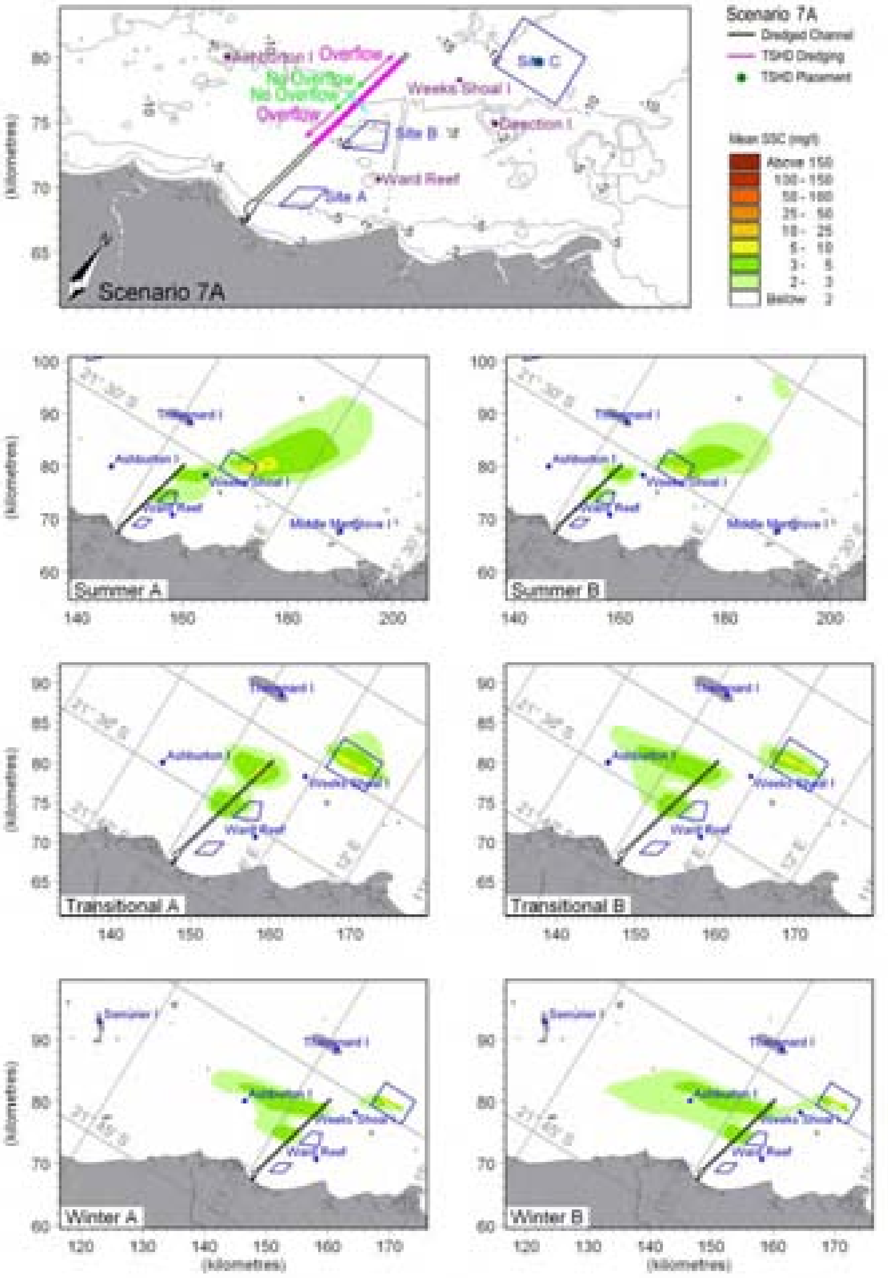

Figure 6.32 Mean SSC for Dredge Scenario 7A with high (worst-case) spill rates

6.2.2 Representation of the Full Dredge Period Program

As discussed in Section 3, one of the advantages of the scenario approach is the ability to assess the impact of dredging without either the need to know in advance the order that the dredge components will be implemented or the time of year during which these activities are undertaken.

As described in Appendix F, there are two principally different ways the scenario modelling results can be applied to represent the Full Dredge Period Program (FDPP).

1. All individual scenarios can be combined to produce an “envelope” of impact zones within which all individual footprints of the FDPP are expected to fall.
2. Individually scenarios can be “statistically” combined based on the FDPP dredge schedule to produce a likely footprint.

Noting that the dredge schedule at the moment defines the various activities well, but that the detailed schedule is almost certain to change, the envelope approach has been chosen for the Wheatstone project. The following results should therefore be viewed as “envelope” plots of impacts obtained by combining results from all combinations of individual climatic and dredge scenarios.

6.2.2.1 Low (Realistic) Spill Rates

Following the development of the dredge scenario climate composites (Section 6.2.1), the final step in developing a representation of worst-case impacts associated with the FDPP is to combine each of the climate composites for each of the seven dredge scenarios. The resultant plot of “envelope” means of the suspended sediment concentration (SSC) is presented in Figure 6.33. The top part of the figure shows the FDPP based on Dredge Scenario 7 and the bottom part of the figure shows the FDPP based on Dredge Scenario 7A (which incorporates restricted overflow zones in areas that may impact on sensitive receptor locations).

Comparing the two sets of results demonstrates the effectiveness of the overflow restrictions for the TSHD dredging in directing the plumes away from sensitive receptors. Operational optimisation is thus an important management tool to minimise potential environmental impacts.

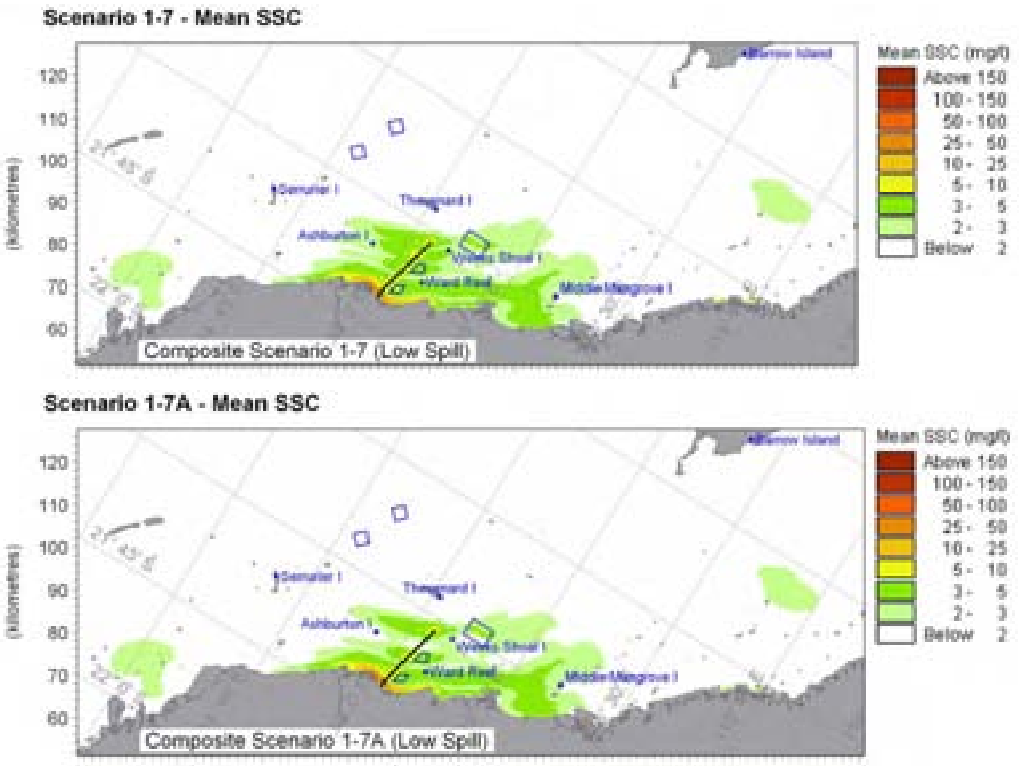

Figure 6.33 Mean excess concentration for the Full Dredge Log Program based on Dredge Scenario 7 (top) and Dredge Scenario 7A (bottom) with low (realistic) spill rates.

6.2.2.2 High (Worst Case) Spill Rates

As noted in Section 2.3, worst case spill rates were simulated in order to highlight the potential impacts associated with larger spill rates which may occur over a short duration. As these short term spill rates will not occur for the duration of the dredge program, composites of the dredge scenarios for the high spill rate scenarios have not been developed as a representation of the full dredge log program. The impacts of short-term spill events can be inferred from the results presented in Section 6.2.1.2.

6.3 Channel Sedimentation

The greater water depths in the dredged areas will lead to a reduction in sediment transport capacity and thus lead to sedimentation. Environmental concerns related to maintenance dredging necessitate an estimate of the sedimentation rates and related maintenance requirements.

The total sedimentation can be divided into a number of components:

- General mobilisation of the bottom sediments over the area of the dredged channel due to the combined effects of currents and waves.
- Littoral sediment transport bypassing the MOF breakwaters and settling in the entrance area to the MOF.

- Siltation of fine suspended sediments, either from background concentrations or originating from runoff during major flood events.
- Major mobilisation of the existing bottom during cyclonic conditions.

These components have been evaluated separately. Quantification of potential re-suspension and flushing of the sediments in the dredged channel caused by ship traffic has not been attempted.

6.3.1 Sediment Transport Model Setup

The model used to assess the potential for channel backfilling was a higher resolution model than the one used for the modelling of the transport and fate of sediment associated with dredging activities. Details of the model setup are presented in DHI (2010b).

6.3.2 Sedimentation from Bottom Mobilisation

An estimate of summer and winter sedimentation rates has been carried out based on the detailed current, wave and sediment transport modelling of representative summer and winter conditions over a neap-spring tidal period.

The surface sediments which can be mobilised and transported are variable throughout the area. Insufficient sediment data is available to produce a detailed sediment map for the modelling. To get a feel for the range of potential sedimentation rates, the assessment has been carried out for two sets of grain size distributions with representative mean grain size diameters of 0.1 mm and 0.2 mm.

To capture the variability in sedimentation rates along the dredged area, the channel and basins have been split into three main sections denoted MOF approach, PLF Basin and PLF approach – see Figure 6.34 (overview) and Figure 6.35 (details of MOF approach and PLF basin). Sedimentation within the MOF basin has been assumed to be small compared to the MOF approach channel.

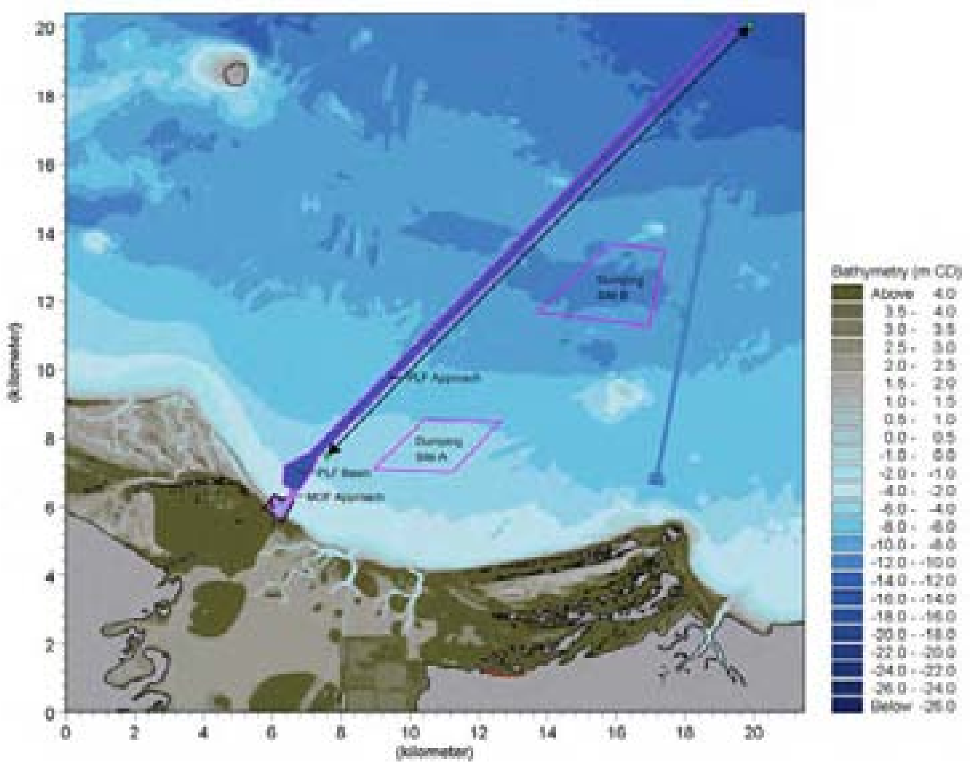

Figure 6.34 Overview of defined segments for sedimentation assessment.

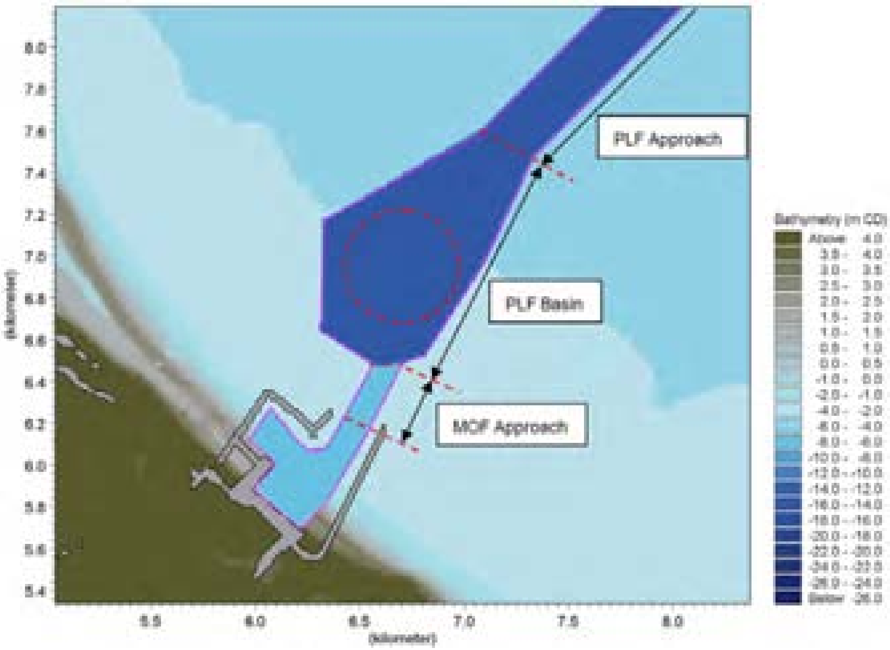

Figure 6.35 Details of defined channel segments for sedimentation assessment (MOF approach and PLF basin).

The MOF approach channel, dredged to app. -7.5 m CD including sedimentation and dredge tolerance allowance, is approximately 0.3 km long between the breakwater entrance and the PLF basin. The PLF basin and PLF approach channel are dredged from the -3m CD contour line to deep water (at the -14m CD contour including sedimentation allowance). The channel is aligned perpendicular to the main contours. The length of the PLF approach channel, from the turning basin to deep water, is approximately 16 km.

Profiles along the three defined channel segments of the simulated average sedimentation rates for summer and winter conditions are shown in Figure 6.36 and Figure 6.37. The rates are expressed in m^3/year/m channel length. Some general observations include:

- Sedimentation rates are generally higher during summer than during winter. This is caused by the stronger and more persistent winds and resulting higher net currents during summer as well as the slightly rougher wave conditions.
- The simulated beach profile in the vicinity of the MOF corresponds to an initial profile immediately after construction, and there is therefore minimal bypass and limited sedimentation in the MOF approach channel.
- Sedimentation rates for the sediment distribution with mean grain size of 0.1 mm are approximately twice as high as for 0.2 mm.
- The “spike” in sedimentation rates at chainage 11,000 per Figure 6.36 and Figure 6.37 for the PLF approach channel for summer conditions, is due to a shoal immediately to the west of the channel. The shallower water leads to the higher transport rates for the given grain sizes. In reality, the shoal will have rock/coral and the simulated transport capacities not be realised in this area.
- When summer and winter conditions are combined, the average sedimentation rates along the different channel segments are similar.

Annual sedimentation volumes and average sedimentation rates across the channel segments have been calculated for each of the three channel segments by weighing the summer and winter conditions together. The resulting rates are listed in Table 6.3 and Table 6.4 for D_{50}=0.1 mm and D_{50}=0.2 mm, respectively. Assumed channel width is also included in the table for the respective channel sections. It is noted that sedimentation will not be evenly distributed throughout the channel segments. However, the model was not set up at a detail to resolve the differences, and therefore only the average has been shown.

The 0.2 mm mean grain size is considered a more realistic estimate than the 0.1 mm grain size based on the limited information available on the grain size distribution in the area.

Due to the narrower channel, the highest sedimentation rates occur in the MOF approach channel. Total volumes are, however, small and manageable.

Table 6.3 Annual sedimentation rates along navigation channel within dedicated channel zones with mean grain size 0.1mm

Channel section	Channel Length (m)	Channel Width (m)	In-Channel build up (cm/yr)	Estimated Annual Qr (m^3/yr)
MOF Approach	225	120	20	6,000
PLF Basin	1,040	900	3	30,000
PLF Approach	16,000	260	12	520,000
Total				**556,000**

Table 6.4 Annual sedimentation rates along navigation channel within dedicated channel zones with mean grain size 0.2mm

Channel section	Channel Length (m)	Channel Width (m)	In-Channel build up (cm/yr)	Estimated Annual Qr (m^3/yr)
MOF Approach	225	120	10	3,000
PLF Basin	1,040	900	1	15,000
PLF Approach	16,000	260	5	220,000
Total				**238,000**

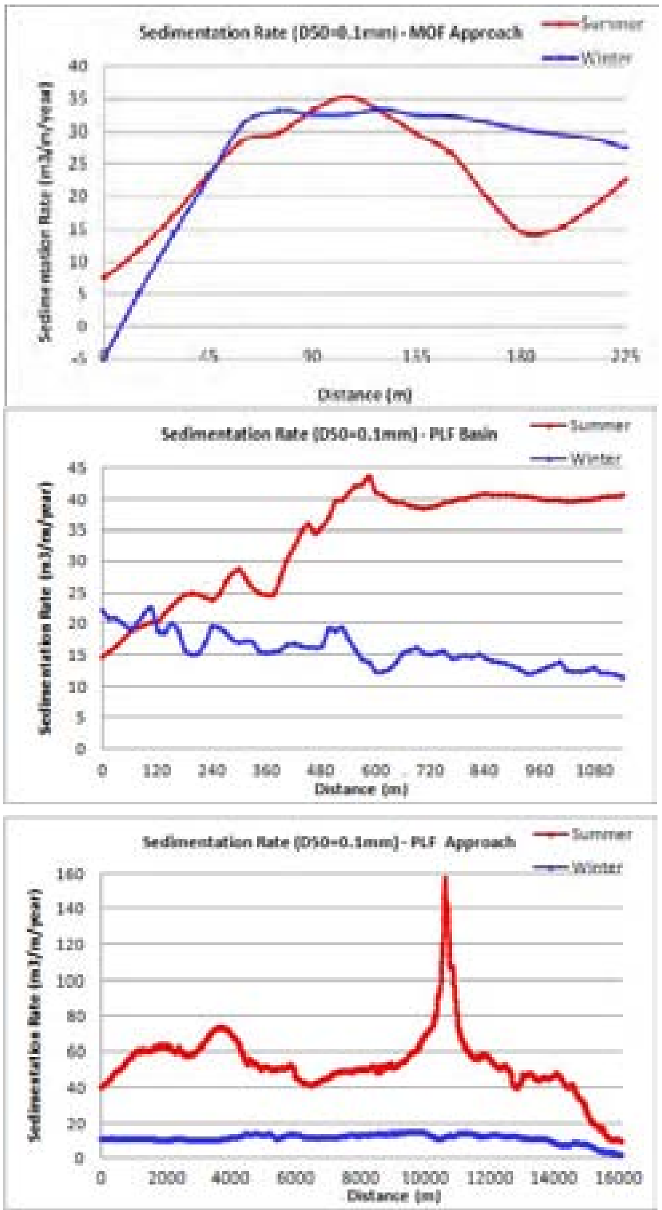

Figure 6.36 Simulated summer and winter sedimentation rates along MOF approach (top left), PLF basin (top right) and PLF approach (bottom) with D_{50}=0.1 mm

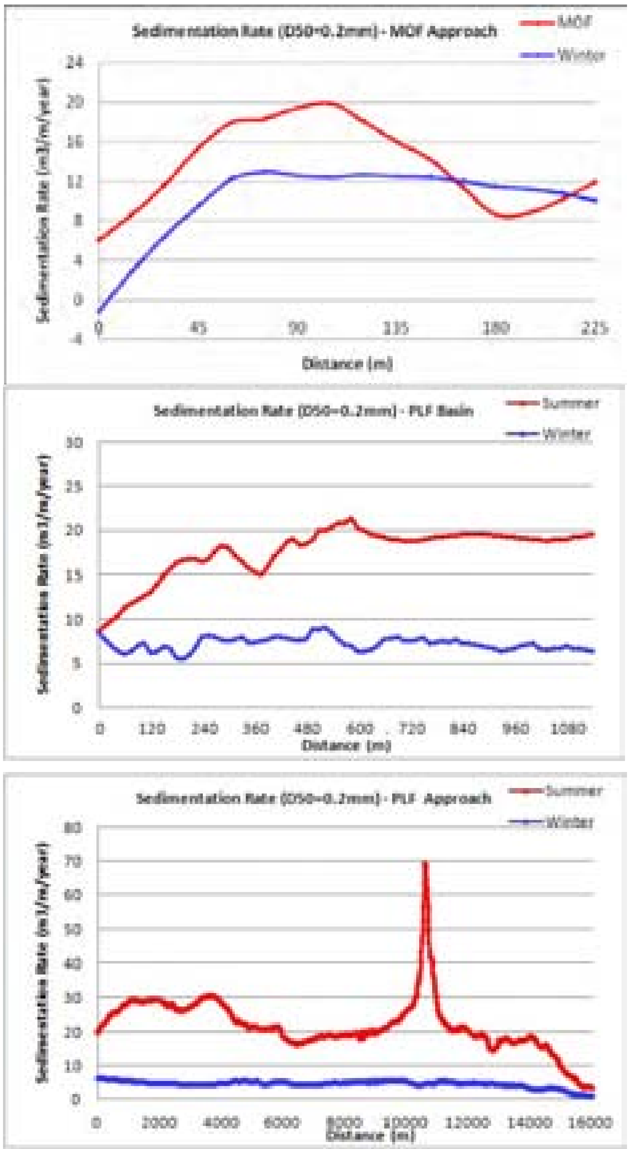

Figure 6.37 Simulated summer and winter sedimentation rates along MOF approach (top left), PLF basin (top right) and PLF approach (bottom) with D_{50}=0.2 mm

6.3.3 Littoral Infill of Channel

With the benign wave conditions during normal conditions (excluding major tropical storms and cyclonic events), the surf zone and littoral transport zone is restricted to relatively shallow water (DHI 2010b). The littoral transport is initially fully blocked by the MOF breakwaters, and the bypass and resulting infill into the MOF approach channel is limited (DHI 2010b).

If artificial bypassing or other management measures for the expected long-term sediment built-up against the western breakwater of the MOF is not in place, the bypass must be expected to gradually increase and lead to a higher sedimentation rate in the MOF approach channel.

6.3.4 Siltation of Fines

Siltation of fines can take place both under “normal” conditions and due to raised ambient concentrations following major rainfall and runoff events. A brief assessment of discharges from the Ashburton River following a cyclone showed that the plume does not directly impact the channel with high concentrations, although it cannot be ruled out that this could be the case for other events. The spreading of the plume very much depends on the winds and related net currents during and following the events. It is also possible that more local sources such as Hooley Creek and other smaller tidal outlets could discharge significant volumes of fines. This has, however, not been quantified and is not assessed here.

6.3.5 Cyclones

Simulations of Cyclone Vance demonstrated very high mobility of the sea bed throughout the area, and generally, sedimentation rates during a cyclone can be very large. The waves, currents and sediment transport will vary greatly depending on the track and speed of the cyclone.

A cyclone would not “fill in” the channel due to the limited duration of the severe conditions. However, depending on the water levels and wave approach angle, large littoral transport rates and infill could take place in areas like of the MOF approach channel. A survey of the channel would likely be required following a major cyclone.

6.3.6 Summary

Estimated sedimentation rates during “normal” climatic conditions are not negligible in terms of total volumes. An annual volume in the order of 500,000 m^3 or less is expected based on the limited simulations and a very rough estimate of siltation of fines.

The frequency of maintenance will depend on the distribution of the sedimentation. If significant build-up of sediments along the western MOF breakwater is allowed over time, then it is expected that sedimentation rates in the MOF approach channel and around the breakwater entrance area will increase.

Cyclonic conditions can lead to very high transport rates, but over limited time periods. This may trigger emergency maintenance requirements if critical channel sections such as the MOF approach channel and entrance to the MOF are blocked, or the PLF berthing areas are impacted.

7 TRUNKLINE DREDGING

A detailed description of the works anticipated for installation of the subsea trunkline in nearshore waters is presented in Section 2 of the Wheatstone Project EIA. In summary, the trunkline will be installed using either a conventional third generation moored laybarge or fourth generation dynamically positioned laybarge in deep waters, and a second generation flat-bottomed laybarge in shallow waters nearshore.

In waters deeper than -40 m CD, the trunkline will be laid directly onto the seafloor.

The currently preferred methods of trunkline installation in nearshore waters are:

- **Option 1**: Preferred methodology. In the nearest 8 km from the shoreline it is anticipated that trench excavation will be undertaken using a backhoe dredge over a period of approximately three months. Up to 700 000 m^3 of dredged sediments will be transported in small hopper barges and placed at site C from this operation. In waters between approximately 8 km and 34 km from shore, a mechanical trencher will be used for most of the length. The mechanical trencher deposits removed material directly to the adjacent seabed, so there is no transport and placement of dredged material at a remote site.
- **Option 2**: Contingency Plan. The pipelay is performed using larger dredging equipment, particularly if the geotechnical conditions do not favour the mechanical trenching methodology. In this case it is possible that a combination of CSD and TSHD dredging may be used to create a trench for the trunkline. This may be undertaken from a water depth of approximately -5 m CD, out to approximately -40 m CD which is a distance of approximately 33 km. The dredging volume could be up to 2.4 million m^3 removed over a period of approximately six months. Dredged material out to approximately -10m CD would be placed at site C, while material from approximately -10 m CD to -40 m CD would be placed at site D.

7.1 Trunkline Dredge Scenarios

In order to be conservative, dredge plume modelling has been undertaken based on the contingency plan (option 2), though it is noted that the actual impacts are expected to be much lower if the preferred methodology (option 1) is used.

The dredge plume modelling utilised the same methodology applied to the modelling of the channel. This involved defining short-term dredge scenarios and using the six climatic scenarios outlined in Section 5. The short-term trunkline dredge scenarios covered a 14-day segment of the trunkline dredge plan and were associated with sediment loading of 1,029 tonnes per day.

Two critical receptor locations were identified for detailed short-term scenario modelling:

- Ashburton Island – the proposed trunkline route passes approximately 1 km east of the reef around Ashburton Island, which has a high cover and diversity of hard corals. Dredging in this location may also impact sensitive coral areas at Paroo Shoal and Saladin Shoal. There is also a large seagrass meadow to the west of Ashburton Island.
- Bessieres Island – the proposed trunkline route also passes within 7 km of Bessieres Island, which has moderate cover and diversity of hard corals. A dredge location which carries the plume towards Bessieres Island as well as Brewis Reef and Thevenard Island has been chosen.

The two modelling dredge scenarios associated with the critical receptor locations are outlined in Figure 7.1.

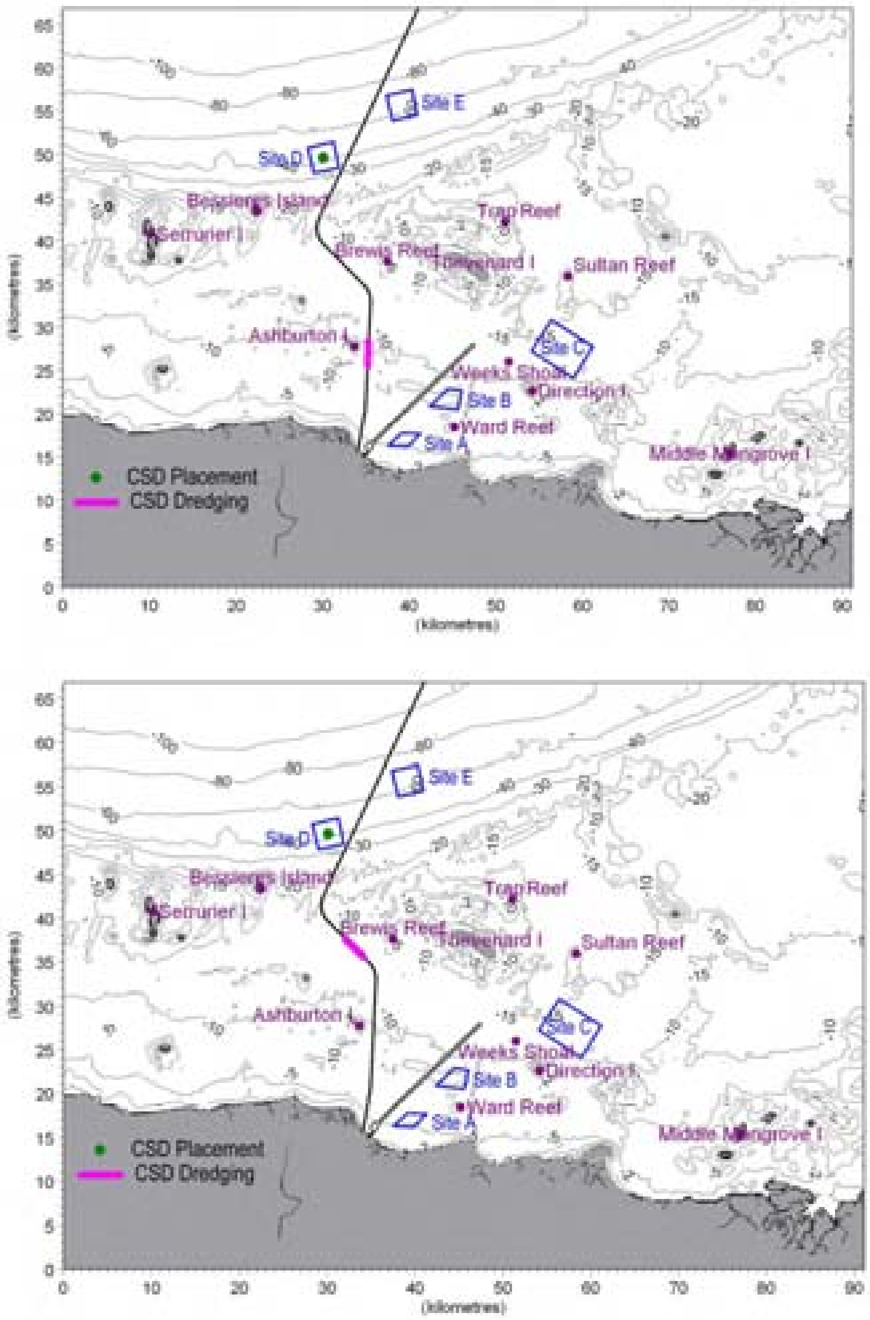

Figure 7.1 Locations for Trunkline Sediment Plume Modelling

7.2 Results of the Trunkline Dredge Scenarios

Figure 7.2 through Figure 7.5 show the results for the mean suspended sediment concentration from the sediment transport model for the two dredge trunkline scenarios. Note that these scenarios are based on option 2 (the contingency plan), and do not represent the preferred dredging option (option 1). Option 1 is associated with significantly lower spill rates that what has been presented here.

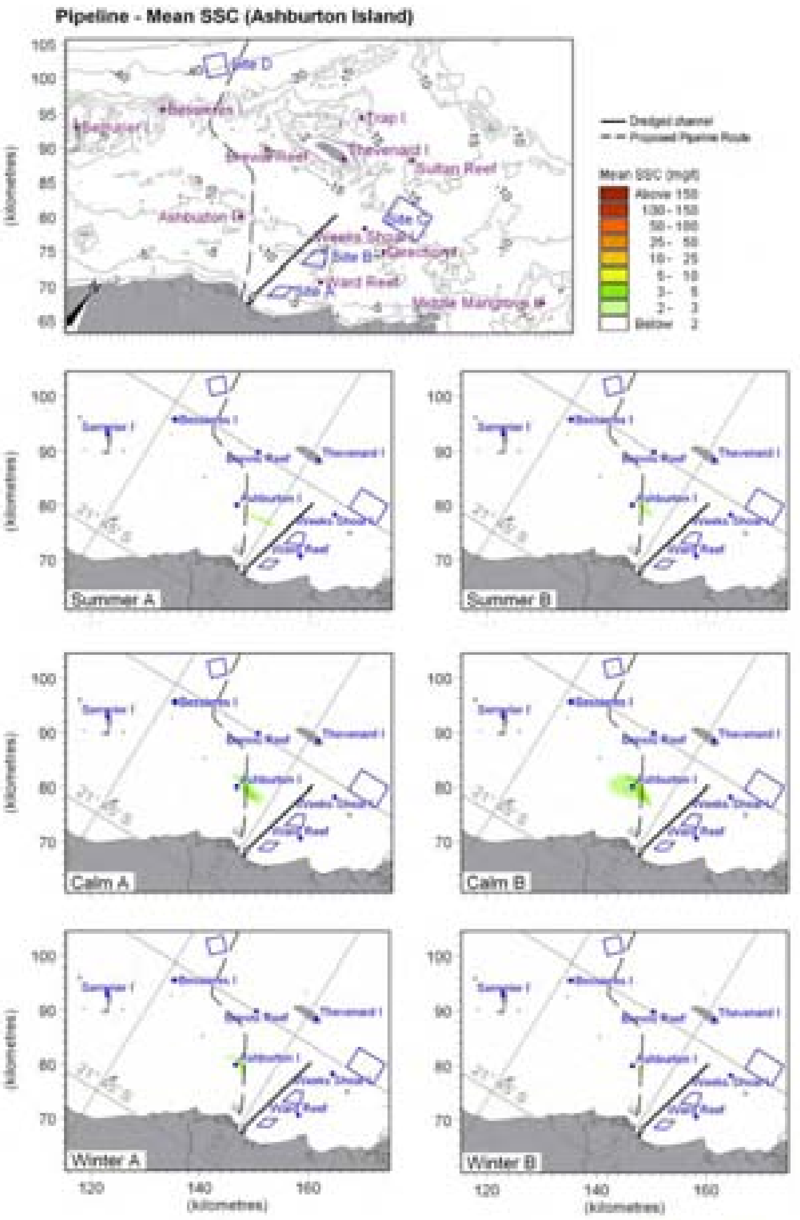

Figure 7.2 Mean SSC for Ashburton Island Trunkline Dredge Scenario based Contingency Plan spill rates

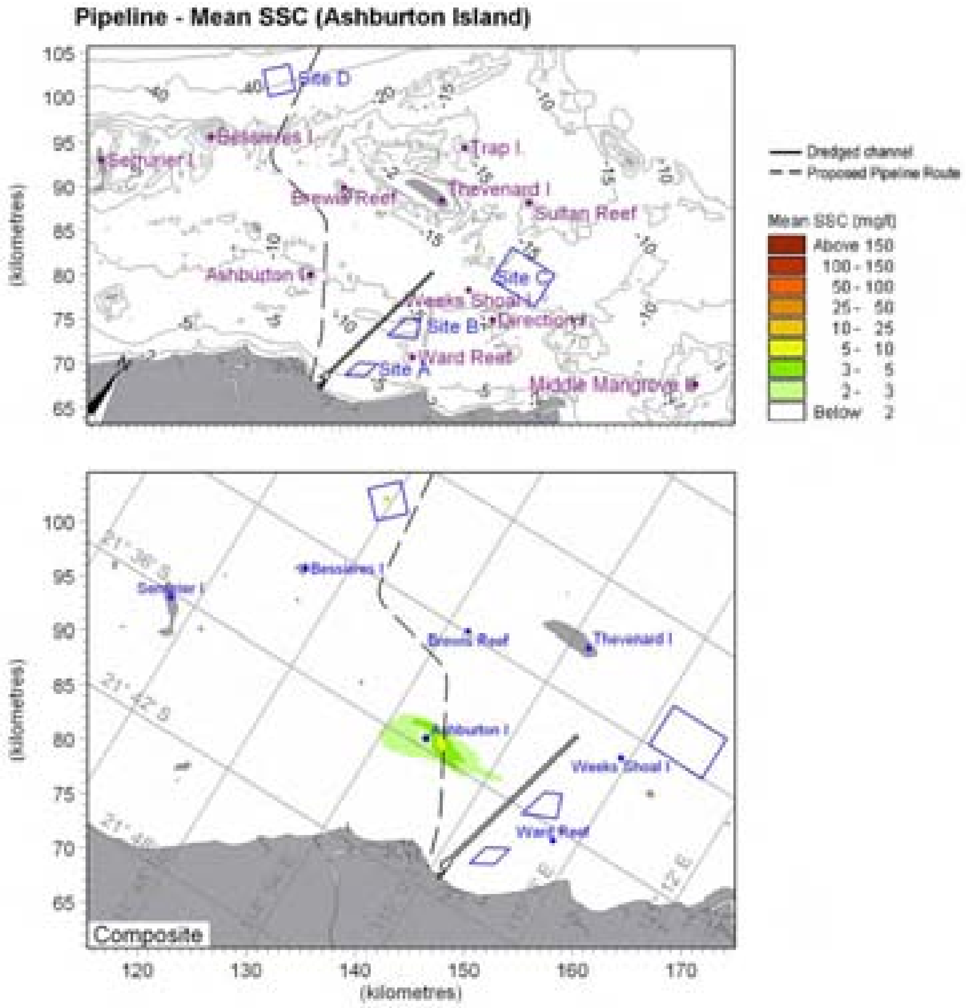

Figure 7.3 Mean SSC for Ashburton Island Trunkline Dredge Scenario based Contingency Plan spill rates – Climate Composite

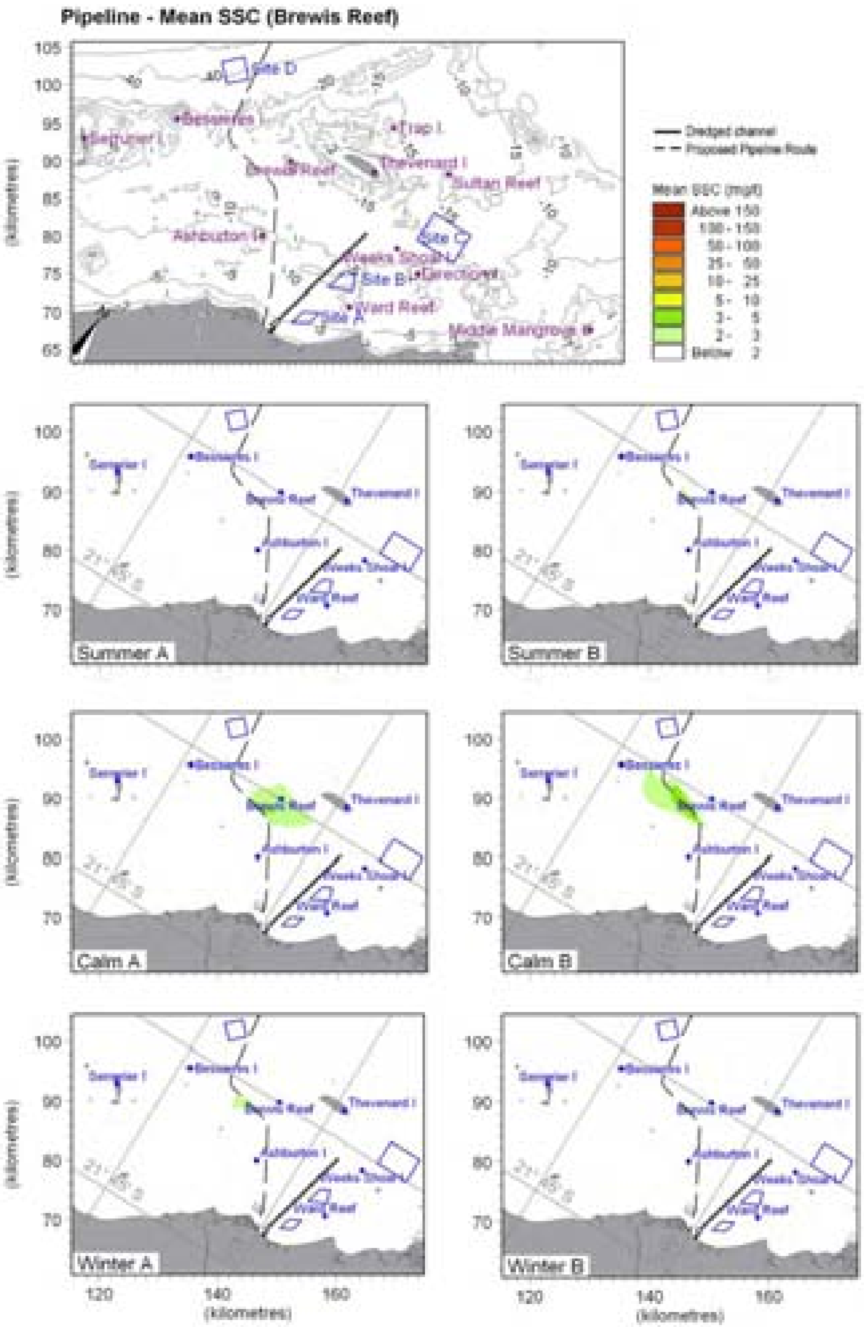

Figure 7.4 Mean SSC for Brewis Reef Trunkline Dredge Scenario based Contingency Plan spill rates

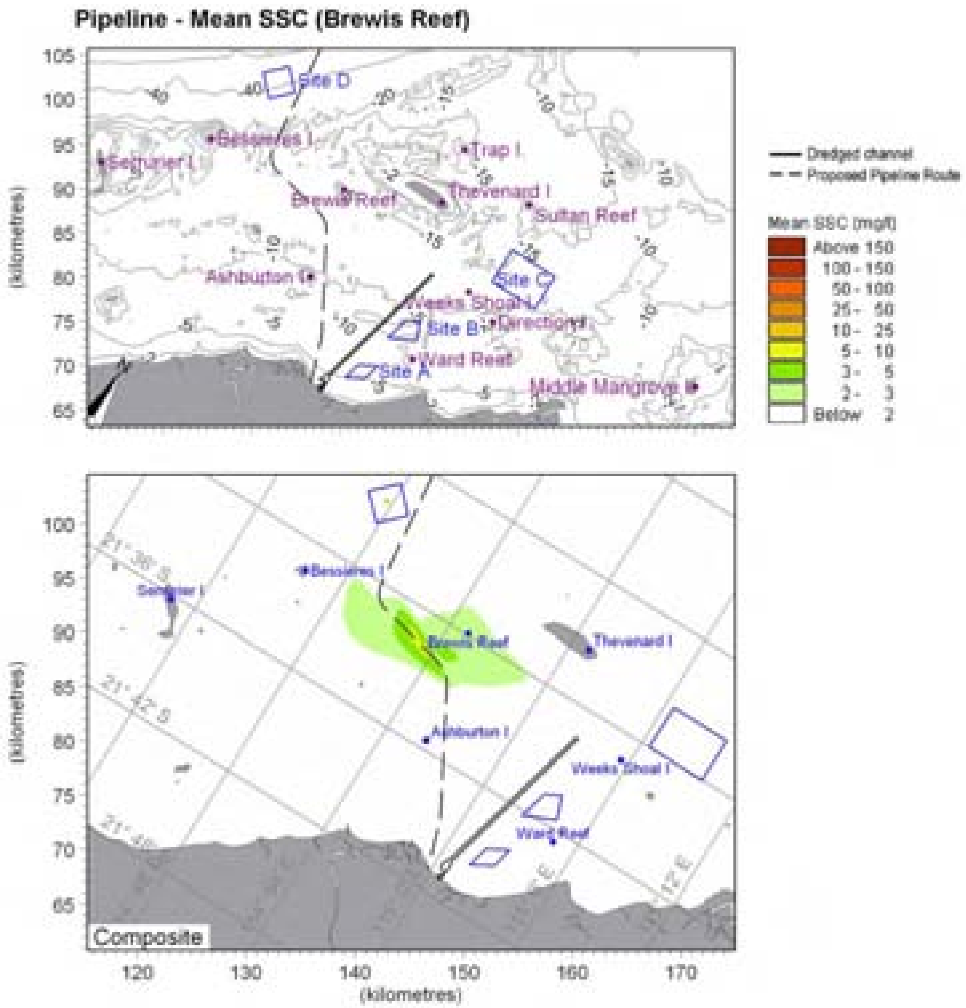

Figure 7.5 *Mean SSC for Brewis Reef Trunkline Dredge Scenario based Contingency Plan spill rates – Climate Composite*

8 DREDGE MATERIAL PLACEMENT AREA STABILITY

8.1 Background

As noted in Section 2.1, there are five proposed dredge material placement areas. Three of the dredge material sites (site A, site B and site C) are located in the nearshore in relatively shallow water to the east of the dredged channel. Two dredge material sites (site D and site E) are located in deeper offshore waters (Figure 8.1).

Site C is the main dredge material placement area, and site A is scheduled to be used in the initial dredging of a temporary access channel to the MOF. Site B is a contingency for dredging in the vicinity of Ward Reef. Sites D and E are intended for the disposal of fines from clean-up dredging only.

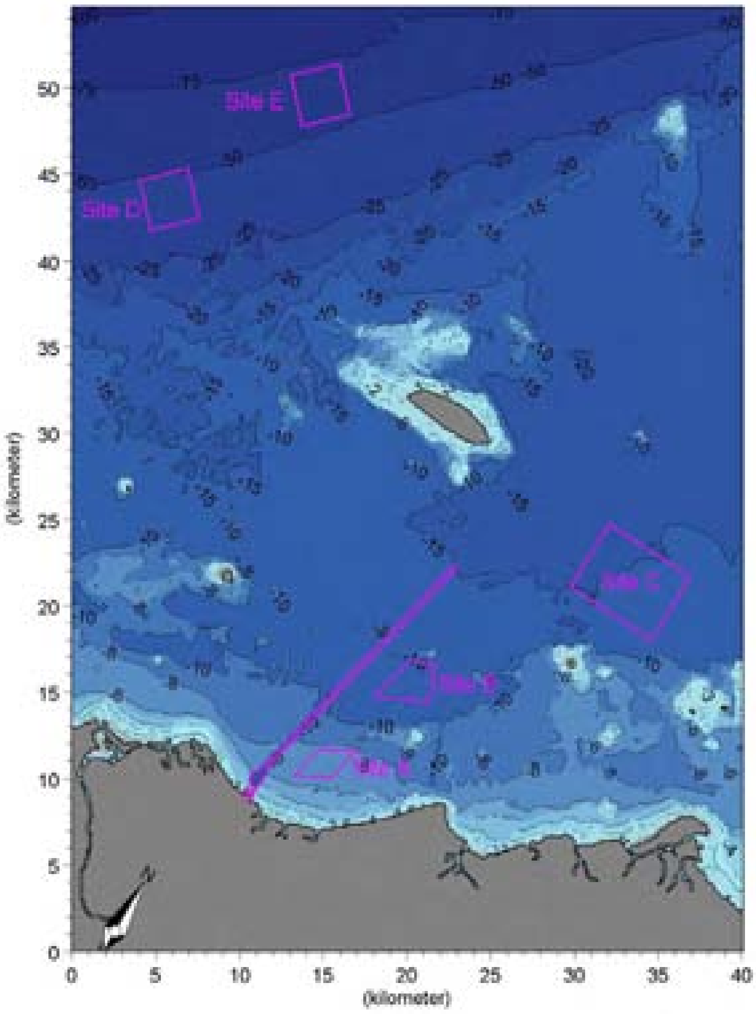

Figure 8.1 Local bathymetry with locations of the dredge material placement areas.

To address the environmental impacts of the dredge material placement areas, three points were considered:

1. The direct loss of habitats at the dredge material placement areas due to the operations – this may be of temporary or more permanent character depending on changes in the soil conditions and the potential for re-colonization.
2. The impacts to the surrounding areas from sediments emitted from the dredge material placement areas during the operations.
3. The impacts to the surrounding areas by sediments from the dredge material placement areas after completion of the project and placement activities.

Point 1 was addressed through the habitat assessment (URS 2010a), and point 2 through the sediment plume modeling and definition of impact zones (DHI 2010c). This section addresses point 3.

8.2 Dredge Material Placement Areas Stability Assessment

The stability of the dredge material placement areas depend on the sediment composition. As outlined in previous sections, only relatively coarse sediment is stable under its own weight and related friction forces at the proposed dredge material placement areas. For finer sediments, cohesive forces and consolidation is required to increase the stability both for the existing material and the expected composition of the material placed in the placement areas.

Normally, a criterion for stability at a placement site is that the new material should be similar to or coarser than the parent (surface) material at the placement site.

An overview of the dredge material placement areas' stability is provided here. Details of the assessment methodology and results are presented in Appendix EE - Spoil Ground Stability.

8.3 Summary of Findings

8.3.1 Stability of Material to be Placed at Placement Sites A, B and C

During the placement process, some of the fines in the dredged material will be released to the wider environment. The effects of this have been assessed through sediment plume modelling (Appendix EE - Spoil Ground Stability). Some of the fines however, along with coarser particles and clasts, will be placed at the site. This finest fraction of the placed material will, at times, be mobile at the placement sites under the prevailing flow and wave conditions. Sediment plume modelling has established that after placement of the material at the sites, the rates at which any fine sediment (< 75 µm) might be released from the sites is likely to be insignificant compared to the fines released during the placement operation.

Results of the modelling (Appendix EE - Spoil Ground Stability) indicates that the smallest grain which is likely to be at rest for 95% of the time, is estimated to be 200-300 µm at sites A and B and between 200-450 µm at site C. During cyclone conditions the mobility of the bed in general will be greatly increased.

Given the predicted mobility of the finer material placed on the seabed at any of the disposal sites there will be a degree of natural sorting of that material after placement.

This will commence at the time of placement, and may be influenced by subsequent placements at the site. This will result in some degree of loss of the finer fractions of material that are not well buried within the placed material. On completion of the placement activities in one area of a placement site, the surface of the placed material is likely to have an overlying veneer of fine material in patches. This fine material will, over time, be reworked by the action of waves and currents such that the fine material is winnowed out and, on average, the surface of the placed material will coarsen. The nature of material buried within the placement is not likely to change over time. The mixed nature of the material on the surface of the placement will act to stabilize the placed material compared to the situation if the placed material were homogenous fine sand. The coarsening of the placed material will also act to armour the bed over time. Where the placed material contains fines arising from the dredging of the very weak rock the coarser clasts will further help to stabilise the bed. Where the placed material has high fines content, then consolidation processes will take place over time further reducing the erodibility of the bed material.

In essence, over time the initial irregular form of the placed material will be smoothed. There will inevitably be some migration of placed material away from the placement site in the directions of dominant transport mixing into the natural transport pathways that already exist. For sites A and B, small amounts of fine sand placed at the sites would, at times, be transported towards the Onslow Salt Channel to the east and towards the Wheatstone navigation channel to the west. Rates of such transport are unlikely to be significantly greater than that presently occurring because of the distances involved and the presence of fine sand fractions on the seabed in these areas.

Placement at site A is scheduled to occur in the early stages of the dredging program. The main stabilisation and winnowing out of fines from sites A and B will gradually reduce with time after placement. By the end of the three year dredging period, the rate of reworking and change is expected to be low. The risk of significantly enhanced infill in the Onslow Salt Channel following completion of the works and as a result of migration from proposed disposal at sites A and B is considered small.

8.3.2 Stability of Existing Bed Material

Modelling results for sand transport by LWI (LWI 2009c) indicate that transport fluxes of 200 µm sand are weak in the study area and are not expected to give rise to significant infill in the existing Onslow Salt Channel or the future offshore dredged areas of the Wheatstone Project. This is consistent with the limited observational information available regarding infill in the Onslow Salt Channel.

LWI (LWI 2009c) have performed a brief analysis of infill of the Onslow Salt Channel to the east of the proposed Wheatstone navigation channel. The channel is about 9.5 km in length and 120 m in width and dredged to a reported depth of -10.8 m CD (LAT). It extends north westward from about 1 km offshore of Onslow. Information based on survey data has shown that over the seven and a half years period from July 1999 to December 2008, parts of the channel experienced up to 0.5 m of sediment deposition (and up to 1 m reported in the berth pocket). Between July 1999 and 2008 cyclones “Steve” (Cat 2, February 2000), “Monty” (Cat 3, February 2006) and “Glenda” (Cat 3, March 2006) made landfalls close to Onslow. Whilst none of these would be anticipated to have been as severe as cyclone Vance, the fact that the Onslow Salt Channel has had only a modest rate of infill is consistent with the findings of the LWI study (LWI 2009c).

9 SUMMARY AND DISCUSSION

DHI has conducted dredge material modelling in support of the Wheatstone Project EIA. The study involved the modelling of the dredging of the MOF, PLF, navigation channel, and the trunkline. Additionally, consideration has been given to assessing the stability of the dredge material placement sites and the eventuality of any channel backfilling.

Results from this study have been used to develop zones of impact within the study region. The impact assessment was outside the scope of the works presented here. The methodology and findings of the impact assessment are presented in DHI (2010c)

A summary of key points and/or findings of this study follows.

Methodology

The methodology adopted for this study was developed based on consideration of:

- The study objectives;
- The details of the dredge program; and
- The characteristics of the ambient environment.

It was concluded that a scenario approach using an Eulerian, coupled, sediment transport and two-dimensional depth averaged hydrodynamic model was appropriate for the modelling of the transport and fate of dredge sediment within the study region. The modelling methodology has incorporated a number of assumptions and/or components that contribute to the overall conservatism of the model results including:

- The use of two-dimensional depth averaged hydrodynamics for the purposes of representing the impacts associated with a 'line source' of sediment (i.e. the shipping channel);
- The initialisation of the sediment model with fines to support re-suspension within the modelling domain;
- The assessment of both high and low spill rates;
- The selection of an appropriate set of representative worst-case climate scenarios; and
- Determining the envelope of impacts for each dredge scenario under a range of worst case ambient conditions based on the climate scenarios.

A number of studies were undertaken in support of the adopted methodology. Results from these studies are reported in the appendices.

Channel Dredging

Based on the proposed Dredging and Disposal Plan (DDP), seven base-case Dredge Scenarios (1-7) were defined. An eighth Dredge Scenario (7A) that incorporates restricted overflow zones within the region covered by Dredge Scenario 7 was also modelled. The incorporation of restricted overflow zones in regions where dredging activities may potentially lead to adverse impacts at key sensitive receptor locations has been demonstrated to be an effective mitigation measure.

In total, 192 simulations were conducted for the purposes of assessing impacts from the dredging of the navigation channel. These simulations involved eight Dredge Scenarios, six climate scenarios, two spill rates, and two sets of hydrodynamics (one driven by Onslow wind-fields and one driven by MesoLAPS wind fields).

Outputs from the sediment transport modelling were used as inputs into the Dredge Plume Impact Assessment (DHI 2010c). Results of the impact assessment are reported in DHI (2010c).

Trunkline Dredging

The six climate scenarios were used in simulations involving two trunkline dredging scenarios. The trunkline scenarios were selected based on the proximity of dredging activities to key sensitive receptor locations, namely Ashburton Island and Bessieres Island. Spill rates for the trunkline dredge scenarios were based on the contingency plan as opposed to the preferred option and, therefore, results presented will be conservative.

Results of the sediment transport model were used as inputs into the Dredge Plume Impact Assessment (DHI 2010c). Results of the impact assessment are reported in DHI (2010c).

Dredge material Site Stability

An assessment of dredge material site stability suggests that there will inevitably be some migration of placed material away from the placement site. This will be in the directions of dominant transport mixing into the natural transport pathways that already exist. For dredge material site A and site B, small amounts of fine sand placed at the sites would, at times, be transported towards the Onslow Salt Channel to the east and towards the Wheatstone navigation channel to the west. Rates of such transport are unlikely to be significantly greater than that presently occurring because of the distances involved and the presence of fine sand fractions on the seabed in these areas.

Some emission of fine sediments will initially occur from the dredge material sites. This will gradually reduce to background levels as the fines are weaned out and the material consolidates. Sediment concentrations from re-suspension from the dredge material grounds are small compared to the sediment plumes due to spills from dredging and placement.

10 REFERENCES

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Wheatstone Project
Dredge Spoil Modelling

A P P E N D I X A :

Dredge Disposal Plan (DDP)

DHI Water & Environment

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FIGURES AND TABLES

A DREDGE DISPOSAL PLAN

Presented in this appendix is an overview of the dredging and disposal plan (DDP) (LWI Document No. EBR4454/0330/001: Wheatstone Project LNG Plant. Marine Facilities. *CUCA 3.2c Dredging and Disposal Plan*.). Due to modifications that have occurred since the release of the DDP, DHI have incorporated some additional comments and explanations. The details of the DDP as presented in this appendix represent the dredging programme at the time the sediment transport modelling was undertaken.

A.1 Dredge Disposal Plan with Elaborations by DHI

A slight expansion to the activity description provided in the Dredging and Disposal Plan (DDP) is provided below to form the framework for the non-optimised dredge scenario. The overall timing will follow the Outline dredge schedule for the base case provided in (LWI Document No. EBR4454/0330/001: Wheatstone Project LNG Plant. Marine Facilities. *CUCA 3.2c Dredging and Disposal Plan*.), refer also to Figure 2.3 of the main report.

The dredging philosophy outlined in the DDP is based on the use of 3 main dredge plants:

1. A CSD for the nearshore area too shallow for TSHD operations
2. A 5,000m^3 TSHD to deepen the PLF approach channel to allow access for larger TSHDs
3. 10,000m^3 TSHDs to deepen the PLF and PLF approach to the design depth.

A split of dredging activities on dredge plants along the dredged channel(s) and basins is reproduced from the DDP /1/ in Figure A.1.

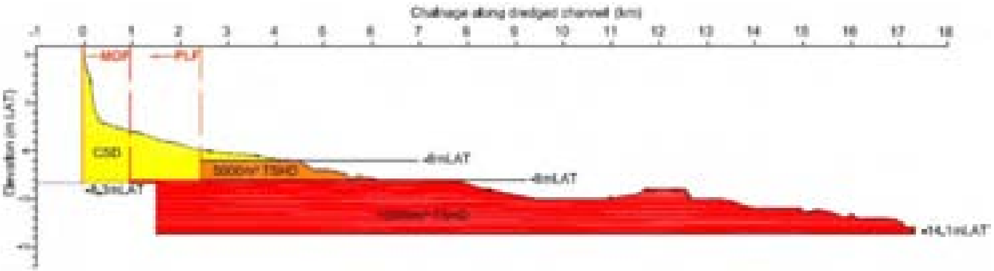

Figure A.1 Split of dredging activities by dredge plant (0 km chainage = MOF quay wall)

It is noted that the timeframes and volumes indicated below are indicative only as the dredging programme is still developing. It is, however, believed that the present programme represents a realistic scenario with some conservative (but not overly conservative) assumptions.

A.1.1 CSD Dredging

A.1.1.1 PLF Approach Channel Dredging for Barge access to -3m LAT Contour

To limit pumping distance and avoid impacts to Ward Reef from overflowing barges upstream of the reef, an access channel for barges is dredged to the -3m LAT contour (in the footprint of the PLF basin). The depth and width requirements of the channel and the associated volume will depend on the type and size of barges applied. A CSD will be used with initial placement to Site A through direct pumping. Assumed volumes required for access are outlined below:

Dimensions, volumes and timing assumed:

- Channel width: 100m
- Channel depth: to -7m LAT
- Volume: ~0.5 - 1 million m3
- Production rate: 250,000 m3/week in sand and 170,000 m3/week in weak rock
- Total time: 1.25 month

Dredging will start at the -7m LAT contour and move progressively to the -3m LAT contour on western side of MOF access channel within the PLF. Forward movement of the dredger will be progressively reduced to account for the change in bed level and dredge volumes.

A.1.1.2 Dredging for the Temporary MOF Access Channel

Dimensions, volumes and timing according to the DDP and dredge schedule:

- Channel width: 75m
- Channel depth: to -6m LAT
- Volume: 0.6 million m^3
- Production rate: 155,000 m^3/week
- Total time: 1.25 months

Dredging will continue from the turning basin within the PLF and progressively move towards the MOF with decreasing speed in shallower water. Material will be pumped to barges at the turning basin within the PLF basin close to the -3m LAT contour for transport to Placement Site C.

A.1.1.3 Dredging for the PLF Manoeuvring Area

After completing the temporary MOF approach channel, the CSD will continue to dredge the PLF down to -8m LAT to give access to the large TSHDs.

- Volume: ~ 2 million m^3
- Production rate: 250,000 m^3/week in sand and 170,000 m^3/week in weak rock
- Time: 2 months

Dredging will start at the nearshore limit at the entrance to MOF channel and progressively move offshore to the entrance from the PLF basin to the PLF approach channel. Material will be pumped to hopper barges / TSHDs for transport to Placement Site C. Overflow will occur at around the -3m LAT depth contour at the barge filling station.

According to the geotechnical information available, this component consists predominantly of loose material, and the corresponding production and spill rates for sand have been applied.

A.1.1.4 Dredging for the MOF and MOF Approach Channel

Dimensions, volumes and timing according to the DDP:

- Channel width: 120m
- Channel depth: -8.3m LAT inclusive of sedimentation and dredge allowances

- MOF: Dredge layout and volumes per latest drawing
- Production rate: 250,000 m^3/week in sand and 170,000 m^3/week in weak rock
- Total Time: 1.75 months

Starting with dredging of the MOF and progressively moving offshore to dredge the MOF channel to its final dimensions. Material will be pumped to hopper barges with overflow around the -3m LAT contour at the barge filling station within the PLF basin.

According to the soil investigation, the nearshore area consists of a mixture of loose and more consolidated soils. Average production and spill rates have therefore been applied.

A.1.2 5,000 m^3 TSHD dredging

A.1.2.1 Clean-up of MOF and MOF Approach

A 5,000m^3 TSHD is mobilised to initially perform a clean-up dredge of the MOF and MOF channel to remove residual fines accumulated in the dredged areas. The dredging will be carried out with no overflow, so only the source term for draghead and propeller disturbance is included while dredging.

The material will be disposed off at Site D. Assumed grain size distribution and spill rates for this are included in the DDP. Cycle time for this operation will be 380 minutes in total with 60 minutes dredging with no overflow.

- Production rate: 55,000 m^3/week
- Total Time: 1 month

A.1.2.2 PLF Approach Channel to – 8 m LAT

A 5,000 m^3 TSHD is used to expand the approach channel to the -8 m LAT contour to provide access for a 10,000 m^3 TSHD. The dredging in the model is established according to the cycle times in the DDP with a total cycle time of 230 minutes, dredging with no overflow of 28 minutes and overflow of 86 minutes. The total dredge time of 114 minutes corresponds to a distance of approx. 6.8 km in total, assuming a dredge speed of about 2 knots. It is assumed that the dredger initially starts around the -8m LAT contour and runs to the PLF channel to turn around and dredge back to the -8m LAT contour.

- Volume: ~ 1 million m^3
- Production rate: 180,000 m^3/week
- Total Time: 2 months

A.1.3 10,000m^3 TSHD Dredging

Two 10,000 m^3 TSHDs will be used to dredge the PLF basin and the PLF approach channel to the full depth.

A.1.3.1 Clean-up Dredge of PLF

The CSD dredging and the barge overflow within the PLF may leave a layer of fines within the PLF, which could potentially lead to higher spill rates at the start of the dredging. To mitigate this, a "clean-up" dredge of the PLF is carried out with the 10,000m^3 TSHD immediately after the CSD has completed works.

The clean-up dredge will be carried out with no overflow and will therefore only entail minimal spill within the PLF. Material from the clean-up dredge will be transported to Offshore placement site D. Two months are allocated in the schedule for the clean-up dredge. Filling time for the hopper performing clean-up dredging is in the order of 45 minutes, and total cycle time for transport to Site D is given to 255 minutes.

A.1.3.2 Dredging for the PLF

The 10,000m^3 TSHD will be used to dredge the PLF from -9.4 to -14.9 AHD. To maintain conservatism, dredging and spill rates corresponding to lose material are applied initially for the 10,000 m^3 operation, although the top layer has already been removed by the CSD. Lower production and spill rates are applied towards the bottom of the PLF. For the initial sand phase for the top layers, the cycle time specified in the DDP and an assumed dredge speed of 1m/s corresponds to dredging along an approximately 4.5km section of channel to fill the dredger. The dredge footprint for this operation is set up following a track around the PLF corresponding to this distance.

Bearing in mind that the impact criteria are set up based on statistical parameters for a 14 day period, the dredging over a given 4.5km stretch of channel is maintained for at least 14 days.

- Production rates: 385,000 m^3/week in sand and 70,000 m^3/week in weak rock
- Total Time: 6.25 months

A.1.3.3 Dredging for the PLF Approach Channel

Dimensions, volumes and timing according to the DDP:

- Channel width: 260m
- Channel depth: -14.1m LAT inclusive of sedimentation and dredge allowances
- Volume: ~19 million m^3 (exclusive of volumes dredged for barge access to loading area at -3m contour and by 5,000m^3 TSHD)
- Production rates: 385,000 m^3/week in sand and 70,000 m^3/week in weak rock
- Total Time: 36 months

The PLF Approach Channel is largely dredged by TSHD dredgers with only a minor component expected to be too consolidated for removal by TSHD. This will be removed by backhoe dredger (BHD).

To maintain conservatism, dredging and spill rates corresponding to lose material is applied for the top layer along the entire channel, with lower production and spill rates towards the bottom of the channel. For the initial sand phase for the top layers, the cycle time specified in the DDP and an assumed dredge speed of 1 m/s corresponds to dredging along an approximately 4.5km section of channel to fill the dredger.

Bearing in mind that the impact criteria are set up based on statistical parameters for a 14 day period, the dredging over a given 4.5km stretch of channel is maintained for at least 14 days. Not accounting for channel slopes, a weekly dredge rate of 385,000m^3 corresponds to a dredge depth of about 66 cm for a 260m wide and 4.5km long channel.

Depending on the travel route, the distance to placement site C varies between about 8km at the outer end of the channel to about 20km at the inner dredging part. Assuming an average transit speed (loaded and unloaded) of 12knots, this corresponds to transit times ranging from about 45 to 111 minutes. A shorter total cycle time (and corresponding higher daily production rate) has thus been applied at the outer section of the channel, with transit times progressively increasing shoreward along the channel.

It is noted that drainage of sediment laden water from the hopper can continue for a period of time after dredging has ceased. To avoid discharge taking place closer to sensitive habitats, it is assumed that the dredger will follow a route over the dredge corridor until spillage has ceased.

A.1.4 Backhoe Dredging of Rocks

An allowance has been made in the DDP for removal of rock patches too consolidated for the TSHD with a Backhoe Dredger (BHD).

Volumes, rates and timing according to the DDP:

- Volume: 70,000m^3 in PLF and 160,000m^3 in PLF approach channel.
- Production Rate: 28,000 m^3/week
- Total Time: 2.25 months

The production and spill rates from the BHD are small compared to the TSHDs. Dredging at the PLF and at 2 locations along the PLF approach channel are assumed.

Material from the BHD dredging will be transported to Placement Site C with barges.

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Wheatstone Project
Dredge Spoil Modelling

A P P E N D I X B :

LWI and DHI Spill Rate Assessments

DHI Water & Environment

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B SPILL RATE ASSESSMENTS

B.1 LWI Spill Classification

Downstream Contractor LWI have used their in-house Dredger Simulation Models to predict production rates, spill rates and associated particle size distribution (psd) of spill. The following sections were provided by LWI to Chevron through RFI No WS0-0000-INT-RIM-WTS-WDS-00189 0R and provide brief details of the modelling approaches and associated references. Further summary information on these models is included in Section B.3 of this appendix.

B.1.1 Trailing Suction Hopper Dredger

The LWI Dredger Simulation Models have been developed over many years by Dredging Research Limited (DRL) a specialist dredging consultancy company which has been wholly owned by HR Wallingford since October 2007. The TSHD model takes input on environmental parameters, soil conditions and specification of a TSHD as a starting point. Production rates are defined primarily on the basis of density and velocity of the mixture in the dredge pipe, the in-situ particle size distribution of the material being dredged and the settling specifications of the hopper. Processes within the hopper are based upon the concept of an ideal settling tank (Camp T R, 1946, *Sedimentation and the design of settling tanks,* ASCE Trans., p895.) with a few modifications to take account of hindered settling, scouring as the load increases and the effects of the Constant Tonnage Loading System modified Camp model as described in Vlasblom and Miedema (Vlasblom, W.J. and Miedema, S A, 1995, *A theory for determining sedimentation and overflow losses in hoppers*. Proceedings of the 14th World Dredging Congress (WODCON XIV), Amsterdam, November.). The model thus calculates in-situ production rate, spill rates and particle size distributions for the material in the hopper and material discharged from the dredger (the spill).

It is known that a large proportion of the material discharged from TSHDs (the spill) falls to the seabed as a density current and remains close to the footprint of the dredging, though subsequently this material may be remobilised. For the purposes of modelling it is necessary to represent both a source in the water column and a source on the seabed in the footprint of the dredging works.

Measurements carried out in the vicinity of a working sand dredger (8,225 m^3 capacity trailing suction hopper dredger) in Hong Kong (Whiteside, P.G.D. Ooms, K. Postma, G. M. *Generation and decay of sediment plumes from sand dredging overflow*. Proceedings World Dredging Congress, Amsterdam, November 1995, p 877-892.) indicated that, after taking account of background suspended sediment levels and residence times, an average of around 15% of the total fines discharged through overflow remained to form the residual passive plume. The measurements were made at two different dredger sailing speeds with similar results. The “high” release rates agreed by LWI and DHI are based on this assumption. The “low” or “realistic” rates are based on the assumption of the use of the green valve which restricts entrainment of air into the overflow and thereby increases the mass of the fines that descend initially to the sea bed. A conservative estimate of about 7% of the total release rate of fines has been used for this spill rate.

LWI have participated in a confidential Research Programme with the Dutch Dredging Contractors since the mid 2000’s. The results of this programme relating to source terms from TSHDs will begin to be disseminated to the wider audience this year. Papers are proposed at WODCON 2010 and for publication in Terra et Aqua.

In addition to the source from overflow of the TSHD the agitation and suspension caused by the action of the drag head and propeller wash over the seabed also generates a source of fine material if fine material is present on the seabed. It is generally accepted that this source is approximately an order of magnitude smaller than the total losses should the vessel be overflowing; here it is assumed that re-suspension of the seabed material at the drag head and propeller wash is equivalent to one third of the residual loss (or 5% of the total fines that would be overflowed without the green valve operating) noting that this will occur throughout the total loading cycle.

When considering losses from bottom dumping of material from the TSHD the assumption is made for the “high” release rate that the available fines in 25% of the mass in the hopper are released. Thus if the hopper had on average 20% fines content the loss of fines on bottom dumping would be 5% of the total hopper mass. This “high” estimate is proposed by DHI. The “low” or “realistic” release rate assumes that the available fines in 5% of the mass in the hopper are released. This “realistic” rate is consistent with the findings of Dredging Research Limited in Hong Kong (Land, J. M., and Bray, R. N., 1998. *Acoustic measurement of suspended solids for measurements for monitoring of dredging and dredged material disposal*. WODCON, Las Vegas.)

B.1.2 Cutter Suction Dredger (CSD)

LWI also use a CSD simulation model developed by DRL. The model takes input in the form of rock strength, plant specification and assumptions about the dredge cut width and depth and rate of swing of the cutter head. Power on the cutter head and on the pump influence production rates and the distance that material can be pumped. Assumptions have to be made about the way in which rock breaks up on dredging and abrades on pumping. Laboratory tests are used to explore the generation of fines when using CSD in soft rocks.

Few detailed measurements have been made in the field around CSD dredging operations. A CIRIA report on plumes from dredging activity indicates very low release rates from CSD operations (John, S.A., Challinor, S.L. Simpson, M.But, T.N. and Simpson J (2000) Plumes from dredging, CIRIA publication C547) but this can be attributed to the particular circumstances of the dredging operations referred to and should not be generally applied. A key reference for the spill rates from CSD is the work of Vlasblom at the Technical University of Delft which is based on laboratory tests of scale models of CSD (Vlasblom, W. J., 2005. *Lecture notes on Cutter Suction Dredgers*.). This work demonstrates that about 30% of the material cut on a single pass of the cutter head across the dredge cut is left behind as spill in the cut. The worst case release rate of fines from a CSD operation is thus the available fines in 30% of the cut material. However, in most circumstances the CSD operation results in a cut area of some depth so several passes of the CSD head are substantially below the ambient bed level and a proportion of the fines released will be contained within the cut area and settle out to be redredged rather than released as a near bed plume. Our “high” release rate is 50% of the available fines in 30% of the cut material. The “low” release rate is 25% of the available fines in 30% of the cut material. This assumes that more of the fines are retained in the cut.

A key factor in considering the release rate of fines from CSD operations is evidence about how the material being cut behaves under the action of the cutter head and the associated zone of high turbulence in the vicinity of the cutter head. Laboratory tests generally indicate that the fracturing action of the cutter head generates very low percentages of fines but that in soft rocks significant proportions of fines can be generated very quickly in a turbulent flow field. The pumping process can further abrade clasts of rock derived at the cutter head generating fine and sands sized materials during transport.

Loading barges with material arising from CSD operations needs to consider the likely size distribution of material generated by the CSD and pumping operations – in particular the fines content as much of these fines will be released during the overflow of a barge. The TSHD model can be used to simulate losses (and productivity) associated with loading barges in this mode.

B.1.3 Back Hoe Dredgers (BHD)

Very few measurements of re-suspension around backhoes have been made. Kirby and Land (1991), suggest a general "S" factor of 12kg per cubic metre dredged for the larger backhoes /12/. Detailed measurements made around grab dredging that was undertaken in the River Tees, in the UK in May, 2000 (Burt, N., Land, J., and Otten, H., 2000. *Measurement of Sediment Release from a Grab Dredge in the River Tees, UK*. For the calibration of Turbidity Prediction Software. Proc. World Dredging Congress XVIII WODCON: Global Dredging), in an area of strong currents indicated a loss rate of some 3.35% of the total. Taking account that the grab dredger on the Tees was smaller than most that might be utilised in a large capital dredge and the fact that either a backhoe or grab might be used, a loss of 3% is considered to be a conservative release rate.

For disposal of material from barges filled by BHD the assumptions regarding losses are revisited compared to those with the TSHD. This is because much of the material dredged will retain near in-situ properties and consequently will arise on the seabed in this form. The assumptions regarding losses are based on all the fines in 10% ("high") or 5% ("low") of the barge load by volume. The volume in the barge is assumed to comprise largely material at in-situ density and a small proportion at a slurry density of 0.1T/m^3.

B.1.4 Use of DRL production models

The DRL production models have been applied on various dredging projects throughout the world and planning, design, contract and post contract stages. The models have been widely applied in Australia.

The models have been compared with Contractor's own estimates of productivity, loss rates and psd of dredged material on numerous occasions and accepted by Contractors. The models have been used to explore issues associated with post construction claims. The models have gained a wide acceptance in the industry. Inevitably it is necessary to make certain assumptions about dredging plant and performance at the planning and design stage. Where possible the models are applied based on experience from similar applications informed by information derived from on-site soils conditions. Recently the behaviour of soft rocks under the action of CSD has been investigated further using laboratory test procedures.

B.2 DHI Spill Rate Assessment

It is valuable to benchmark the spill ranges put forward by LWI in the previous sections against spill monitoring data from similar sediment types. DHI has an extensive data base of spill monitoring covering most forms of dredging and placement activities as a result of strict environmental management practices for marine construction in Singapore implemented from 2004. The data, as is the case for the vast majority of spill measurements worldwide, is proprietary and cannot be used directly in the context of the present document. It is, however, possible to put forward data to validate certain items of the spill source terms. On the basis of the documented suitability of these items, other items in the spill source terms must be taken on face value as being suitable based on the combined experience of DHI and LWI.

B.2.1 TSHD Overflow Measurements

Figure B.1 provides an extract of measured overflow of fines from dredging in silty sand for a large 20,000m^3 TSHD. The 84 trips represent 1 month of production in the same dredging area in nominally the same material type (silty sand) as present in the majority of the Wheatstone dredging area. It is clear that the inter-trip variability is high, with a mean of 623T per trip and StDev of 411T per trip. Figure B.2 provides similar information for a smaller, 9,000m^3 TSHD, which demonstrates an average spill of 326T per trip and StDev of 200T per trip.

Assuming a linear scaling based on hopper volume would give a mean overflow spill range of between 311T per trip (scaled down from the 20,000m^3 TSHD) and 326T per trip (scaled up from the 9000m^3 TSHD) for a 10,000m^3 TSHD. The fact that the smaller TSHD provides a slightly higher spill per unit volume is consistent with the relative retention time of the hoppers. Given the high inter trip variability it is elected to average the two estimates for the spill per trip for a 10,000m^3 hopper; giving 318.5T per trip or a spill rate of 106kg/s in modelling terms. The LWI proposed “low” estimate of 87kg/s (which they state is based on use of a green valve) is therefore actually a “realistic” spill estimate for non-green valve TSHD dredging, given the nature of the silty sand material present at the site. LWI’s “high” estimate is actually found to be approximately the 90th percentile of the scaled (by hopper volume) measured data, and is regarded by DHI as a “worst case” estimate.

Similarly for the 5,000m^3 TSHD, scaling the measured data from the 9,000m^3 TSHD measurements down to represent a 5,000m^3 TSHD indicates an average spill of 181T per trip or 35kg/s in modelling terms. The LWI proposed “low” estimate of 33kg/s (which they state is based on use of a green valve) is therefore actually a “realistic” spill estimate given the nature of the silty sand material present at the site. LWI’s “high” estimate is again found to be approximately the 90th percentile of the scaled (by hopper volume) measured data, and is regarded by DHI as a “worst case” estimate.

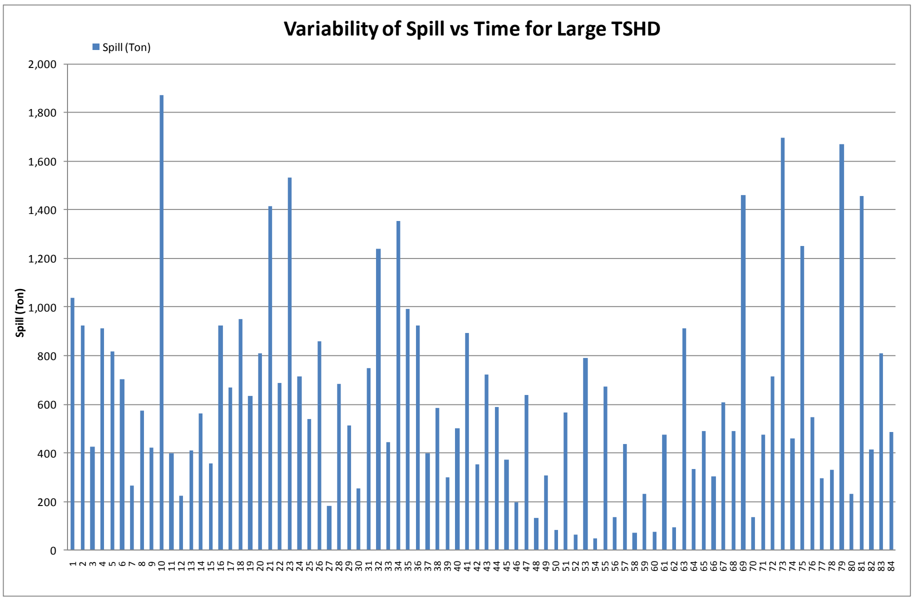

Figure B.1 *Measured spill of fines in overflow from 84 TSHD trips dredging in a single designated dredging block. Vessel size 20,000m³ and seabed material is silty sand*

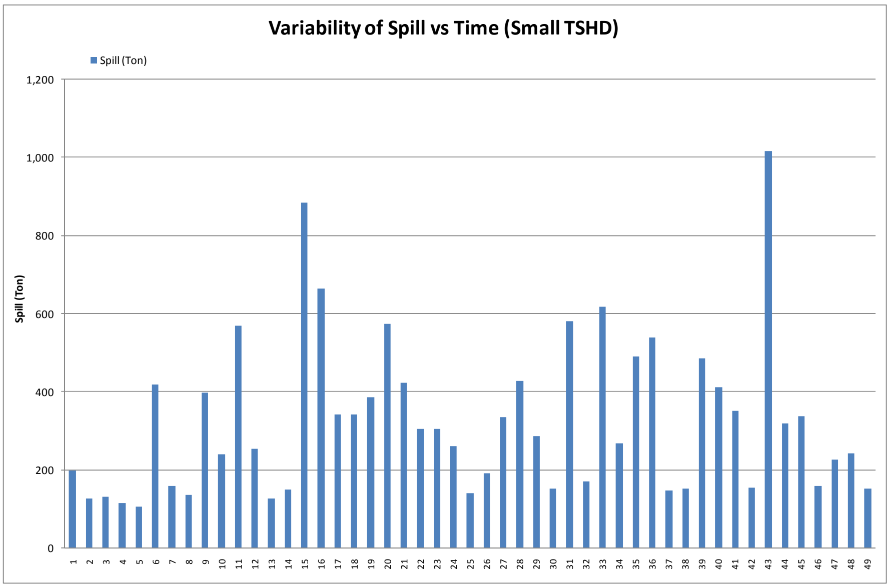

Figure B.2 *Measured spill of fines in overflow from 49 TSHD trips dredging in a single designated dredging block. Vessel size 9,000m³ and seabed material is silty sand*

B.2.2 Spoil Ground Placement

Indirect measurement of spill using ADCP sediment flux measurements (Figure B.3) is the standard methodology for quantification of spill from the other sources related to TSHD dredging and disposal, and although it is recognised that a considerable degree of uncertainty exists, such measurements have, given suitable calibration, been found to give a credible quantification of the spill escaping the immediate dredging or placement area.

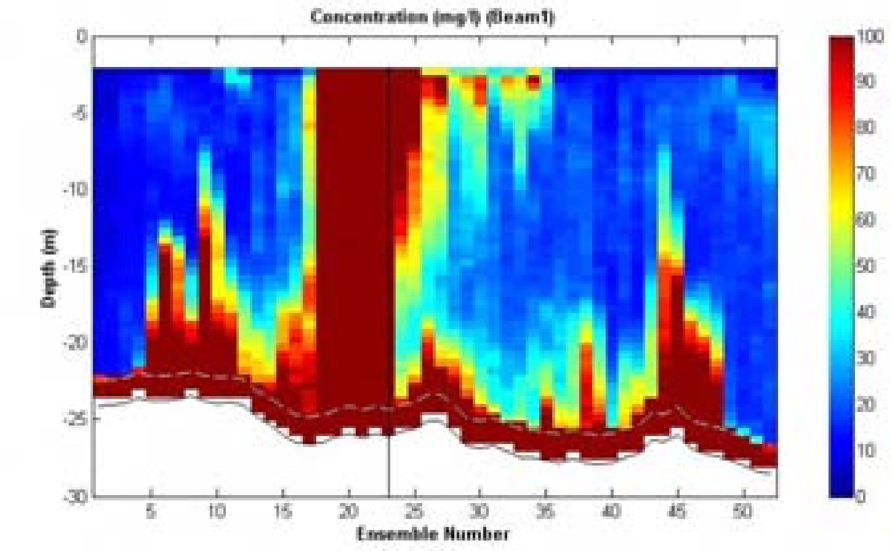

Figure B.3 Example ADCP Sediment flux transect though a material placement operation. The density driven current phase of the placement running along the seabed is clearly visible. Total spill leaving the immediate placement area is found to be (on average) 25% of the fine material in the hopper

For material placement the spill rate will depend upon many factors not least the prevailing water depth and current conditions. Averaging across available measurement data sets of TSHD placement operations with hopper load derived from silty sand seabed indicates that approximately 10% (relatively shallow waters and low prevailing current) to 25% (relatively large water depths and high prevailing current) of the residual fines (for material derived from silty sand) in the hopper will escape the immediate material placement area. Figure B.4 demonstrates that for normal TSHD operation the percentage of residual fines in the hopper (for dredging in silty sand) is a weak function of the fines on the seabed. For the material anticipated on site, with a bed fines in the order of 30%, Figure B.4 indicates a likely hopper fines in the order of 4% to 8% (depending on the best fit methodology adopted).

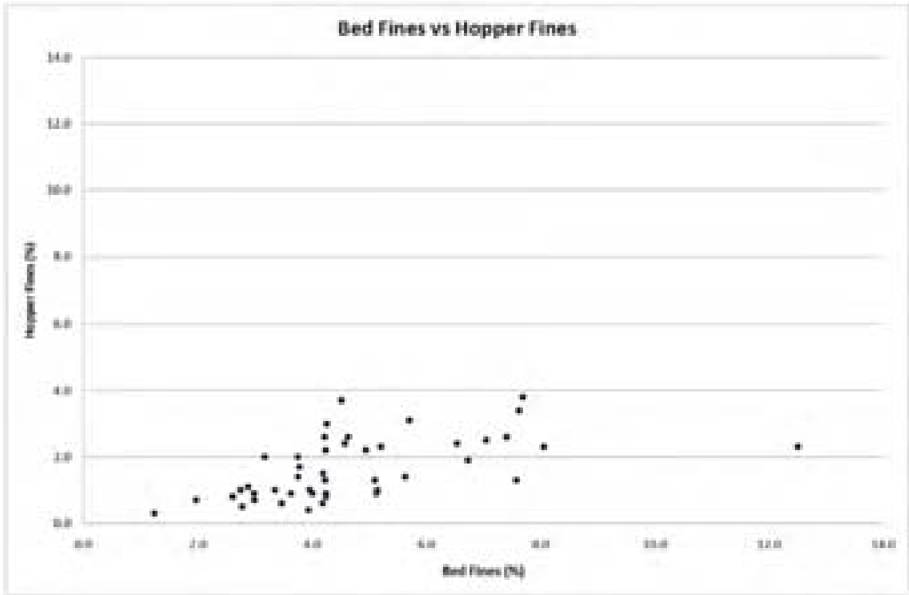

Figure B.4 Residual fines in hopper as a function of bed fines (back calculated from overflow fines plus residual fines)

Given the relatively shallow nature of the material placement areas (less than 15m depth) and low prevailing currents (0.3 to 0.5m/s) it is DHI's opinion that the spill will fall towards the lower bound of the available data, i.e. 10% of fines. This indicates a spill for material placement from a 10,000m^3 TSHD of between 72T and 144T (average of 360kg/s over 5 minutes in modelling terms), whilst a 5,000m^3 TSHD would yield between 36T and 72T (average of 180kg/s for 5 minutes in modelling terms). This indicates that the LWI proposed "low" spill rates of 376kg/s for a 10,000m^3 TSHD and 161kg/s for a 5,000m^3 TSHD over 5 minutes are actually "realistic" estimates based on DHI monitoring data. The "high" spill rates put forward by LWI equate to a spill rate of approximately 25% with a residual fines content of 12%. This is outside the upper bound of measurements available to DHI. Nevertheless, the % fines in the hopper will depend heavily on the method of TSHD operation and 12% residual fines is therefore not unrealistic as a "worst case" high estimate.

B.2.3 TSHD Drag-head and Propeller Wash

Spill from the drag head and propeller wash during dredging operations is difficult to isolate in ADCP sediment flux measurements primarily due to safety concerns in terms of the proximity of the survey vessel to the TSHD during dredging operations. DHI has, however, undertaken extensive measurements of propeller wash suspension in isolation (Figure B.5 and Figure B.6). This is clearly dependent on, amongst other issues, the under keel clearance of the TSHD. A 10,000m^3 TSHD is likely to have a fully loaded draft between 4m (empty) and 9m (loaded) such that it is likely that for most of the operation it will be dredging with an under keel clearance in the order of 2 to 8m depending on progress and tide level. Measurements of propeller wash induced suspension over soft material (which is likely to be the situation in the dredge channel, which will tend to capture finer material from earlier passes) indicate a range of propeller wash suspension in the order of 27.5kg/s (2 - 4m under keel) and 10.8kg/s (4 - 8m under keel). DHI cannot put forward any data to validate the contribution from the drag head. Our normal practice is to allow approximately 0.5% of the bed fines (9kg/s for 30% bed fines).

Adopting 9kg/s for the drag head and averaging between the two under keel data sets available (which is considered appropriate given the range of under keel clearances anticipated at Wheatstone) gives an estimate of 28kg/s for the drag head and propeller wash contribution. Overall, DHI is therefore of the opinion that the "low" estimate of 29kg/s put forward by LWI is actually "realistic" based on available data.

The source term from the drag head and propeller disturbance is considered very uncertain, but it is generally recognised that the term will be small compared to the overflow term. Based on this, a single rate has been adopted for this source.

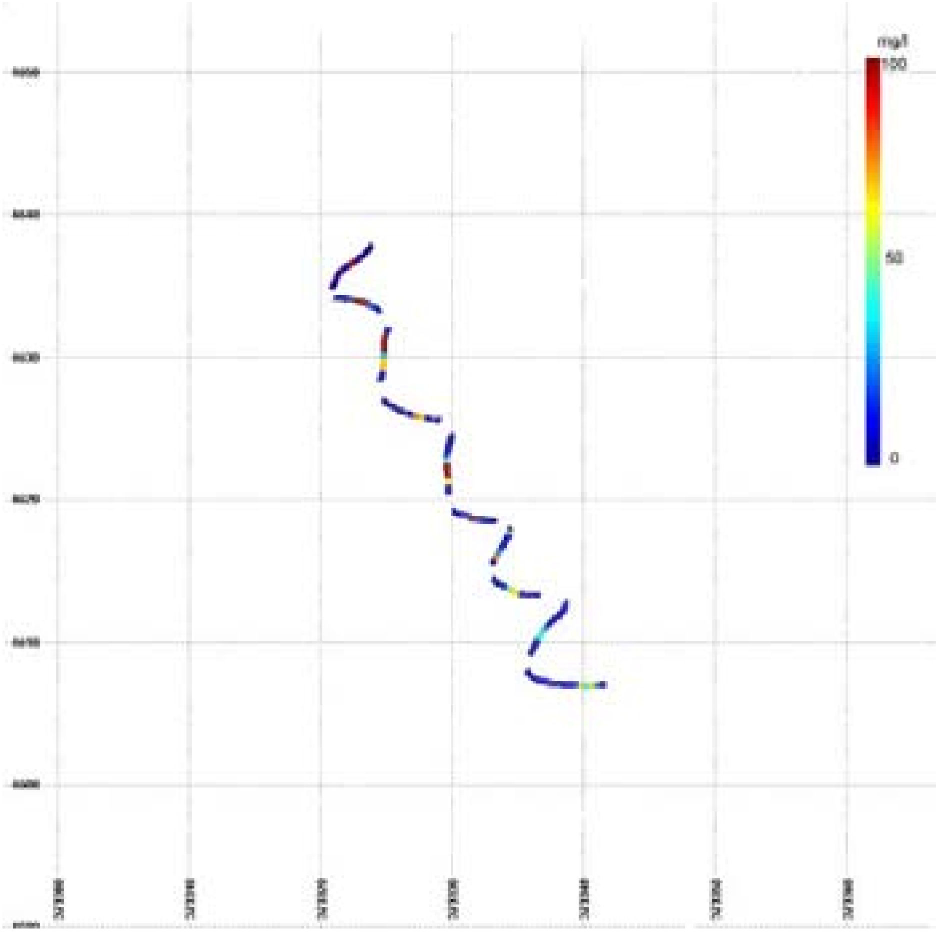

Figure B.5 *Example sediment flux transects behind a vessel with 2 – 4 m under keel clearance transiting over soft bottom resulting in an average suspension rate of 27.5kg/s. Material is well distributed through the water column as indicated in Figure B.6.*

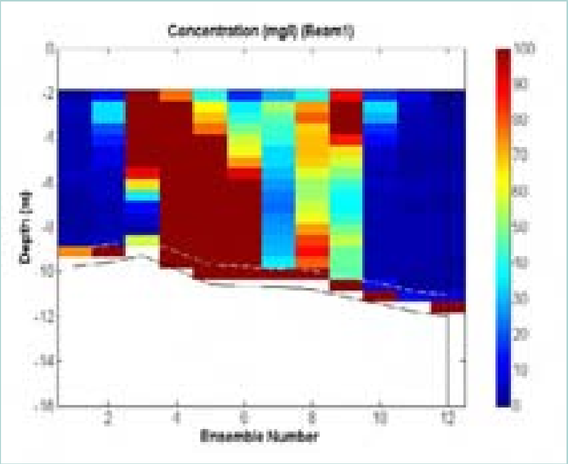

Figure B.6 Propeller wash suspension (2 – 4m under keel clearance)

B.3 Additional Information from the LWI Spill Rate Assessment

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Dredging Research dredger simulation models

Photograph courtesy of Van Oord

The Dredging Research dredger simulation models cover a wide range of commonly used dredger types. Each model replicates the operations of the dredger in question in the particular site conditions to be encountered, for the soils or rocks to be dredged and for the specific project being examined.

For the more sophisticated models, such as the cutter suction and trailing suction hopper dredgers, each model has the ability to deal with:

- varying sets of ground conditions;
- operator controlled usage of the dredger in different modes; and
- alternative dredging methodologies and strategies.

For each specified scenario, the model outputs the instantaneous production rate, the average weekly production rate and relevant environmental data, such as overflow rates for fine materials, loading times, cycle times and the like. In addition, the models output weekly operating costs, standing time rates and unit rates, using the CIRIA Cost Standards as a starting point.

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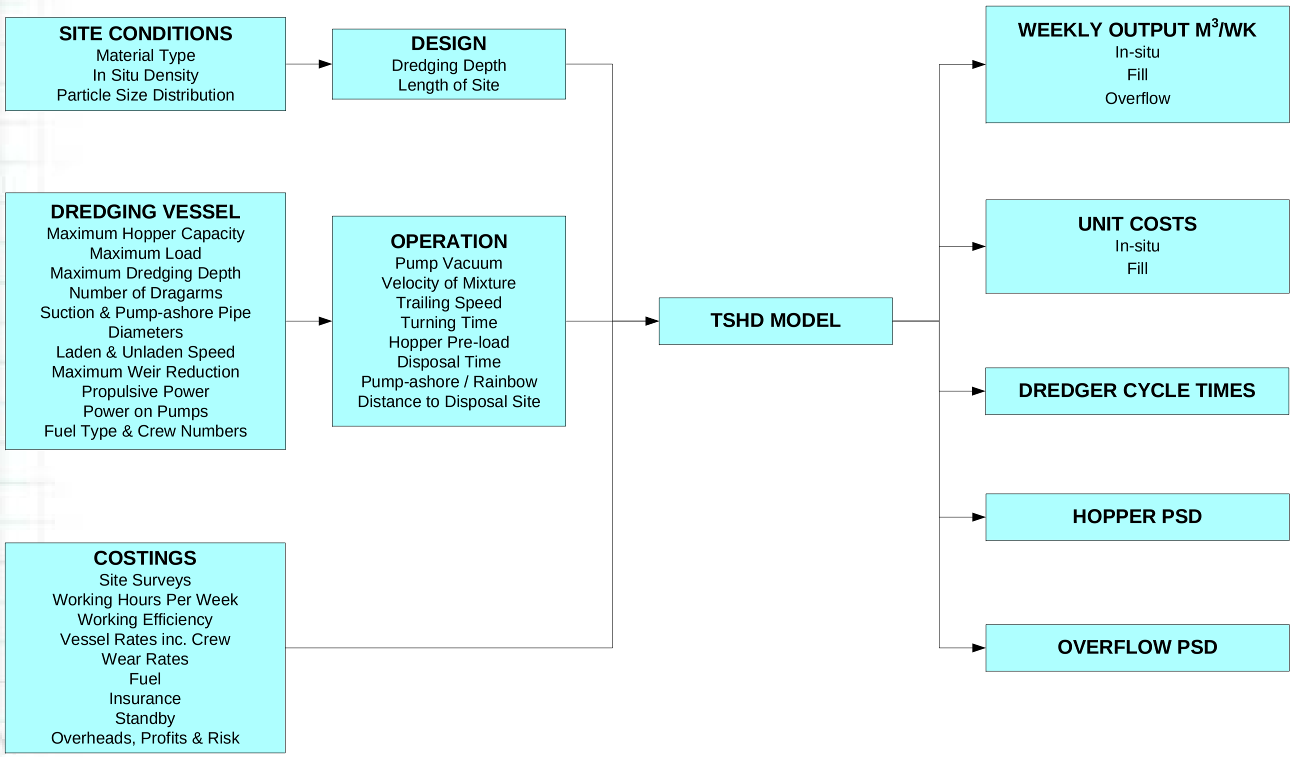
Dredging Research

TSHD Model Overview



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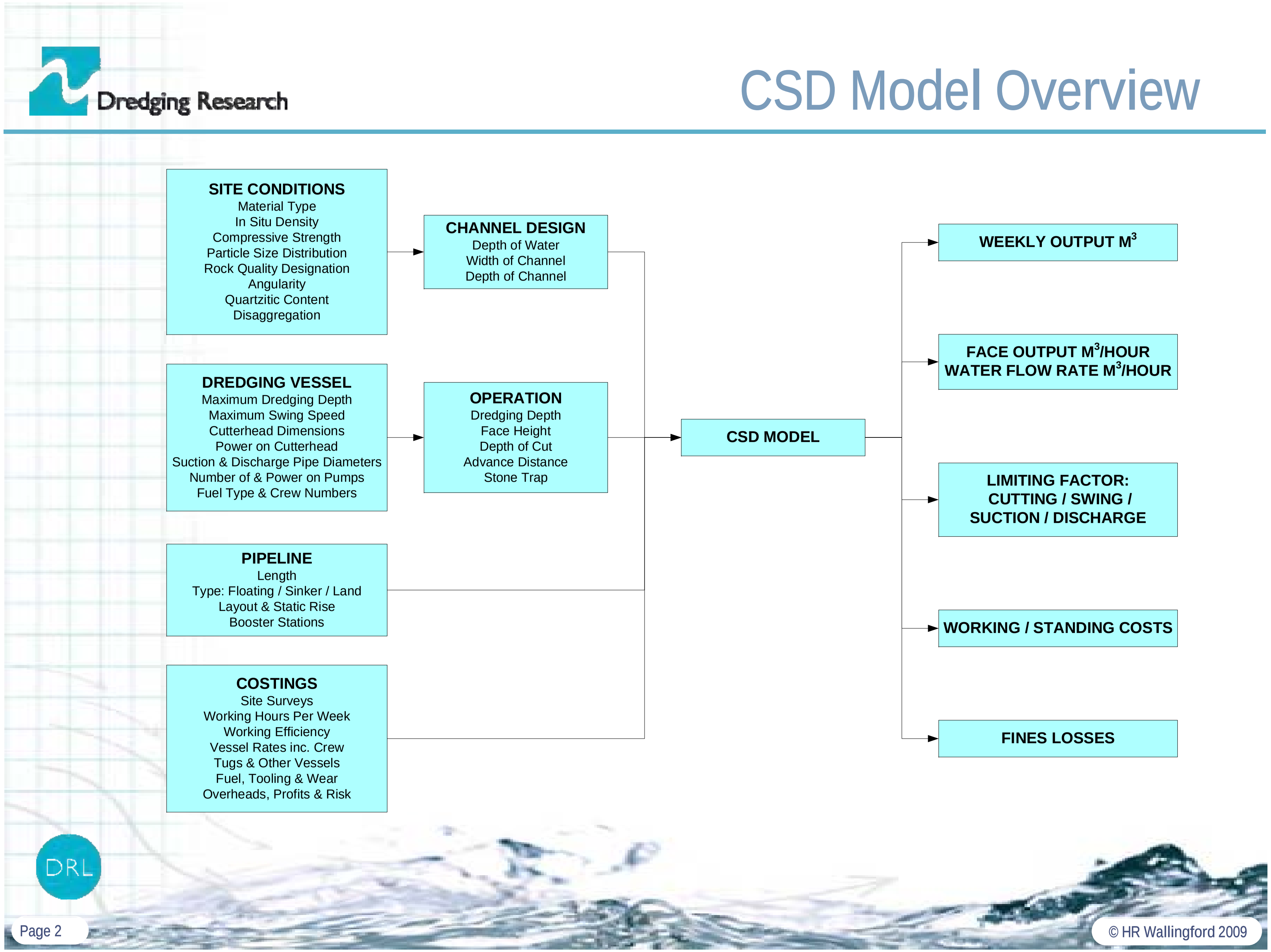
Dredging Research
CSD Model Overview
SITE CONDITIONS
Material Type
In Situ Density
Compressive Strength
Particle Size Distribution
Rock Quality Designation
Angularity
Quartzitic Content
Disaggregation
DREDGING VESSEL
Maximum Dredging Depth
Maximum Swing Speed
Cutterhead Dimensions
Power on Cutterhead
Suction & Discharge Pipe Diameters
Number of & Power on Pumps
Fuel Type & Crew Numbers
PIPELINE
Length
Type: Floating / Sinker / Land
Layout & Static Rise
Booster Stations
COSTINGS
Site Surveys
Working Hours Per Week
Working Efficiency
Vessel Rates inc. Crew
Tugs & Other Vessels
Fuel, Tooling & Wear
Overheads, Profits & Risk
CHANNEL DESIGN
Depth of Water
Width of Channel
Depth of Channel
OPERATION
Dredging Depth
Face Height
Depth of Cut
Advance Distance
Stone Trap
CSD MODEL
WEEKLY OUTPUT M3
FACE OUTPUT M3/HOUR
WATER FLOW RATE M3/HOUR
LIMITING FACTOR:
CUTTING / SWING /
SUCTION / DISCHARGE
WORKING / STANDING COSTS
FINES LOSSES
DRL
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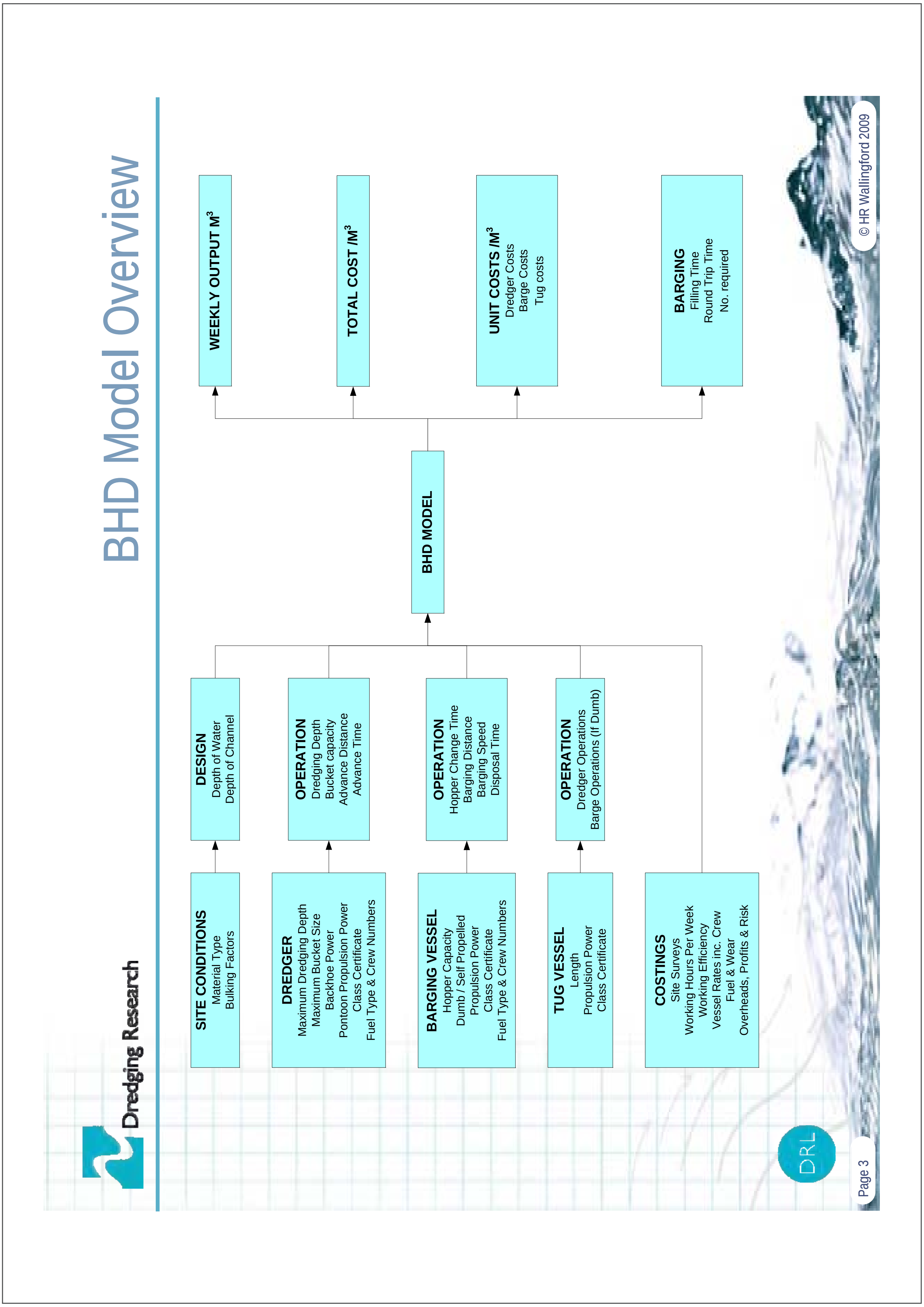
BHD Model Overview
Dredging Research
SITE CONDITIONS
Material Type
Bulking Factors
DREDGER
Maximum Dredging Depth
Maximum Bucket Size
Backhoe Power
Pontoon Propulsion Power
Class Certificate
Fuel Type & Crew Numbers
BARGING VESSEL
Hopper Capacity
Dumb / Self Propelled
Propulsion Power
Class Certificate
Fuel Type & Crew Numbers
TUG VESSEL
Length
Propulsion Power
Class Certificate
COSTINGS
Site Surveys
Working Hours Per Week
Working Efficiency
Vessel Rates inc. Crew
Fuel & Wear
Overheads, Profits & Risk
DESIGN
Depth of Water
Depth of Channel
OPERATION
Dredging Depth
Bucket capacity
Advance Distance
Advance Time
OPERATION
Hopper Change Time
Barging Distance
Barging Speed
Disposal Time
OPERATION
Dredger Operations
Barge Operations (If Dumb)
BHD MODEL
WEEKLY OUTPUT M³
TOTAL COST /M³
UNIT COSTS /M³
Dredger Costs
Barge Costs
Tug costs
BARGING
Filling Time
Round Trip Time
No. required
DRL
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Wheatstone Project
Dredge Spoil Modelling

A P P E N D I X   C :

NUMERICAL MODELLING METHODOLOGY OPTIONS

DHI Water & Environment

CONTENTS

C NUMERICAL MODELLING METHODOLOGY OPTIONS

This appendix presents some supporting discussion associated with the modelling methodology presented in Section 3 of the main report. The reader may find it helpful to review the general discussions relating to the objectives, and overall study strategy presented in Section 3 of the report in conjunction with the discussions presented here.

In particular, this appendix focuses on the following within the context of sediment transport modelling for the Wheatstone Project:

- Eulerian models versus Lagrangian models
- Coupled models versus decoupled models

An in depth discussion relating to the pros and cons of sediment transport modelling driven by two-dimensional versus three-dimensional hydrodynamics including results from a case study is presented in Appendix E *Sediment Transport Modelling Using 2D versus 3D Hydrodynamics*.

C.1 Eulerian Models versus Lagrangian Models

DHI has a range of models comprising both Eulerian and Lagrangian type models for sediment transport modelling. Each model type has its strengths and weaknesses, and the choice of model depends on the problem under consideration.

For an Eulerian model, the sediment dispersion is grid dependent. Resolving high concentration gradients requires a very fine grid spacing, and is computationally demanding. Simulations of density-driven currents in the vicinity of a dredger (results not presented here) indicated that grid spacing in the order of 1m was required in order to adequately resolve the concentrations and density-driven currents associated with the release of overflow within the region that is in close proximity to the dredger.

The theoretical formulation of a Lagrangian model differs from that of an Eulerian model in that the dispersion is not directly linked to the grid spacing (although there is an indirect link as the resolution of the current field depends on the applied grid spacing and the sediment dispersion is linked to the current field). A Lagrangian model is therefore well suited to simulate conditions where near-field dispersion and/or dilution is important and when the use of an Eulerian approach would be computationally prohibitive.

To properly resolve the dispersion of a concentration field in a Lagrangian model, a large number of particles are required for each fraction of fines. This is generally not a major issue for plumes that are limited temporally and/or spatially. However, for continuous discharges over long periods of time of substances with no or limited decay, the number of particles required to simulate the total plume grows linearly with time, and quickly becomes a major factor in terms of computational and computer storage requirements. There are numerical means of reducing the number of particles (e.g. the cloud-and-cell method), but this introduces numerical errors in the calculated concentration fields which in particular for the lower concentrations can become significant or even dominant. For longer simulations with continuous discharges and re-suspension events where material spread over a large area, and where the smaller concentrations cannot be ignored, the number of particles that must be tracked can easily surpass billions to achieve the same accuracy as that of the Eulerian method. The Eulerian scheme is generally a more effective tool under such conditions.

Dredge spoil modelling normally has continuous and/or intermittent discharges over an extended period of time and the possibility of re-suspension needs to be considered. Details of the concentration fields in the immediate vicinity of the sources, which are normally within areas where "total loss" of habitats is expected, are generally not required. It is however, crucial to be able to simulate the fate of the plume throughout the spatial and time domains for potential impacts and at low concentration levels. For these conditions, DHI generally prefers the Eulerian model as it provides a more efficient tool for mid to far-field simulations and provides considerably more accurate results in areas of relatively low concentrations.

For the Wheatstone Project, all sediment plume modelling has been carried out using an Eulerian model.

C.2 Decoupled Models versus Coupled Models

The sediment plume models can be run coupled or de-coupled to the hydrodynamic. De-coupling of the models can be used to speed up the simulations if e.g. multiple spill scenarios have to be run for a given hydrodynamic scenario. Assuming that there is no or negligible feedback from sediment transport on the hydrodynamics (for example for conditions in which density driven currents can be neglected), the hydrodynamics can be developed and then used to drive the sediment transport model(s).

The decoupling of the hydrodynamics from the sediment transport modelling has to be used with caution as there are a number of significant assumptions that are inherent in a de-coupled approach including:

- There is no feedback from plume modelling to the hydrodynamics including the potential influence of dredging methodologies
- The flow patterns are only resolved at the temporal resolution provided in the timescale of the hydrodynamic output. For simulations covering large areas and/or long periods of time, a fine temporal resolution in the hydrodynamic output is required. However, storage of hydrodynamics at these time and/or spatial scales is generally not practicable
- If there are rapid variations in the current field (e.g. from large scale eddies) this will generally not be well captured in the output hydrodynamics, and thus not reflected in the sediment plume modelling

In coupled mode, the transport equations are solved at each time step, and the full hydrodynamic resolution is utilised.

For Wheatstone, simulations have been conducted using fully coupled sediment transport and hydrodynamic models.

Wheatstone Project
Dredge Spoil Modelling

A P P E N D I X   D :

HYDRODYNAMIC MODEL CALIBRATION AND VALIDATION

DHI Water & Environment

CONTENTS

FIGURES AND TABLES

D HYDRODYNAMIC MODEL CALIBRATION AND VALIDATION

This appendix presents the details of work undertaken in relation to the calibration and validation of the two-dimensional hydrodynamic model. The reader is directed to the following sections of the main report and supporting appendices for additional information:

- Section 4.1
- Appendix C: Numerical Modelling Methodology Options
- Appendix I: Hydrodynamic Module, Scientific Documentation
- Appendix J: Development of Bathymetric Data Set
- Appendix K: KMS Model Tidal Components
- Appendix M: Comparison of MesoLAPS wind fields with monitoring data
- URS (2010) *Characterisation of the Ambient Environment Report*

D.1 Introduction

To ensure that the hydrodynamic model produces reliable results it is important that the model is calibrated and that the validity of the model predictions is verified. Calibration is the process by which model parameters are adjusted within reasonable limits so that model predictions match measurements or theoretical predictions.

D.2 Calibration Parameters

In addition to the crucial aspects of a well resolved bathymetry, good boundary conditions and wind data to drive the model, there are a number of parameters in the model setup that can be varied within physical limits. These include the bottom friction, turbulence exchange and wind friction factors as some of the main parameters.

For the shallow water modelling in this project the bed friction is an essential parameter, and therefore applied friction is discussed briefly in the following. In Mike 21, the friction parameter is expressed as:

$$k = \frac{g}{M^2 h^{1/3}}$$

where M ($m^{1/3}/s$) is the Manning number (the Manning number is also seen in the literature as n=1/M). The Manning number is well known in both traditional as well as numerical hydraulics. Values in the range 20-40 $m^{1/3}/s$ are normally used.

In most 2D hydrodynamic models the turbulence closure problem, resulting from the Reynolds-averaging of the Navier-Stokes equations over the water column to yield the depth-integrated equations St Vernaint equations presented above, is solved through the Boussinesq eddy viscosity concept relating the Reynolds' stresses to the mean velocity field. In this manner the problems of describing the turbulent fluctuations are transformed into a description of an eddy viscosity. The eddy viscosity may be modelled using various techniques ranging from a simple relation to two-equation models such as the k-ε model.

It is essential to understand that in a numerical model classical turbulence is only one of several processes with similar behaviour and characteristics. In the discrete world, processes that are not resolved by the adopted grid are typically called sub-grid scale processes. A similar analogy for the turbulent fluctuations leads to terms similar to the eddy viscosity. Often all these terms are lumped together into one (eddy) formulation. Which of the physical processes are significant depends on the adopted grid resolution and time scales.

For the present model set-up the Reynolds' stresses are calculated on the basis of the Smagorinsky formulation. The constant used in the Smagorinsky formulation are set to a "standard" value of C_S=0.5. This value has been obtained on basis of calibrations carried out in previous hydraulic modelling studies carried out by DHI.

A large number of calibration runs have been carried out to achieve the "best" calibration. It is beyond the scope of the present report to document the 100 odd tests carried out for calibration. Only the performance of the calibrated model, which is the key in the model application and results, will be documented here.

D.3 Calibration of Regional Model to (Predicted) Water Levels at Tidal Stations

For calibration of the regional hydrodynamic model, comparison of water levels has been performed using predicted water levels at the 16 primary tidal stations located within the model domain; locations are listed in Table D.1 and shown in Figure D.1. The model has been set up without wind to reproduce the pure tidal signals obtained from predictions based on tidal constituents (source: Admiralty Tide Tables. Pacific Ocean. Volume 4, 2004).

This is the initial phase to ensure the basic boundary conditions of the model domain are sound and performing well. Figure D.2 to Figure D.4 show comparisons between simulated and predicted water levels (based on constituents) at the various stations. The model generally performs very well throughout the area with only very minor differences in amplitude. This shows that the basic tidal boundaries derived from the KMS model (Appendix K) provide a good representation of the dominant tidal constituents, and that the model can resolve the progression of the tidal wave throughout the model domain. It is noted that there are significant changes in tidal amplitude within the model domain, and these variations are reproduced accurately by the model.

Table D.1 Locations of the tidal stations in the regional model

Tidal Station Name	Longitude	Latitude
TANTABIDDI	113.9833	-21.9167
POINT MURAT	114.1833	-21.8167
EXMOUTH	114.15	-21.9333
SERRURIER (LONG) I	114.6833	-21.6
THEVENARD I	115.0167	-21.4667
ONSLOW, BEADON POINT	115.1	-21.6333
LARGE ISLET	115.5	-21.3
TANKER MOORING	115.55	-20.8167
WAPET LANDING	115.4667	-20.7167
NORTH WEST I	115.5167	-20.3667
TRIMOUILLE I	115.55	-20.3833
DAMPIER (HAMPTON HARBOUR)	116.7167	-20.65
CAPE LEGENDRE	116.8333	-20.35
HAUY ISLET	116.9667	-20.4167
PORT WALCOTT	117.1833	-20.5833
PORT HEDLAND	118.5833	-20.3

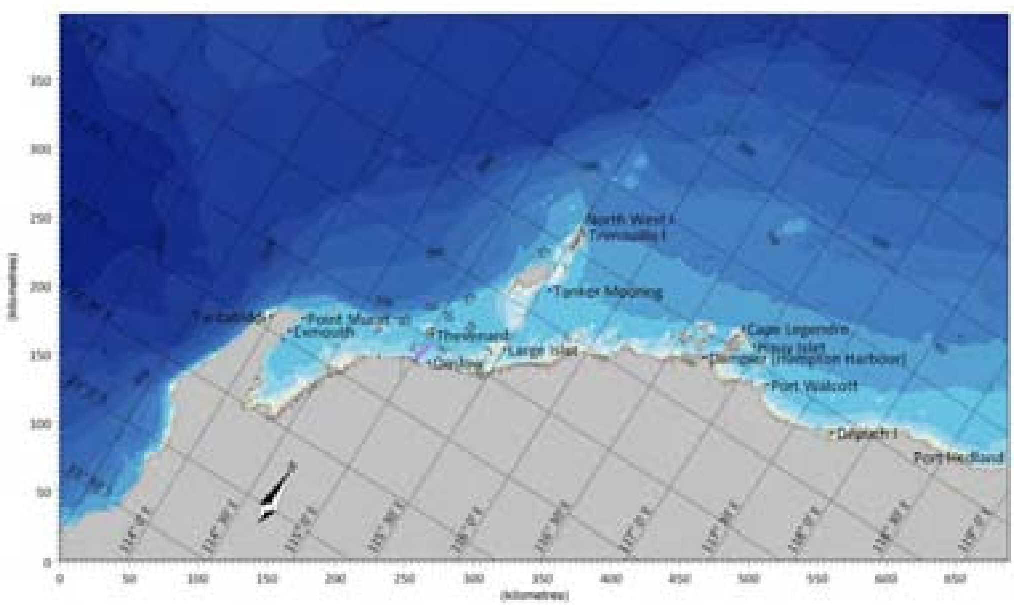

Figure D.1 Locations of tidal stations used for model calibration and validation.

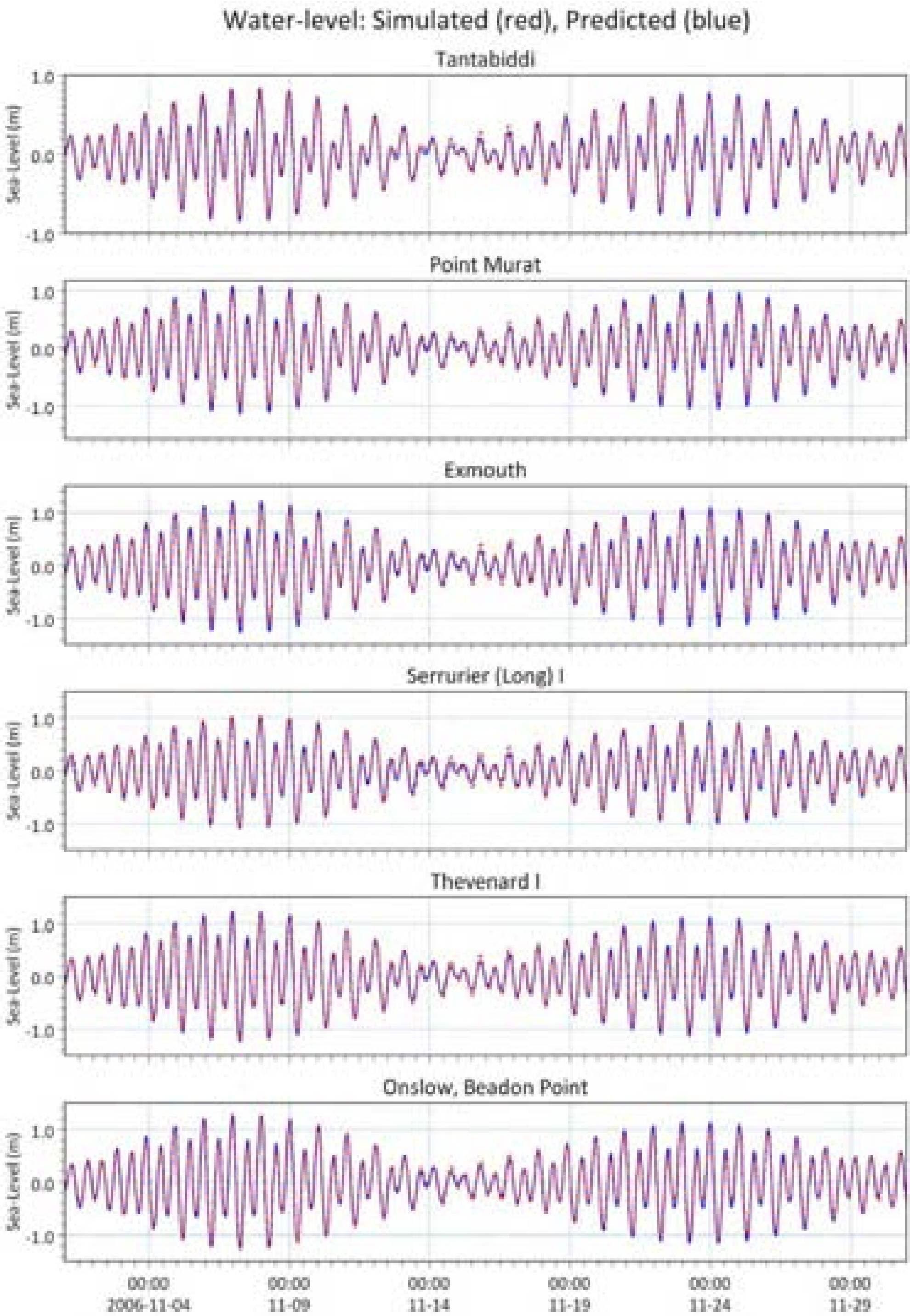

Figure D.2 *Comparison of simulated and predicted water levels at selected tidal stations during a typical period in November 2006. Simulated elevations in red and predicted elevations in blue.*

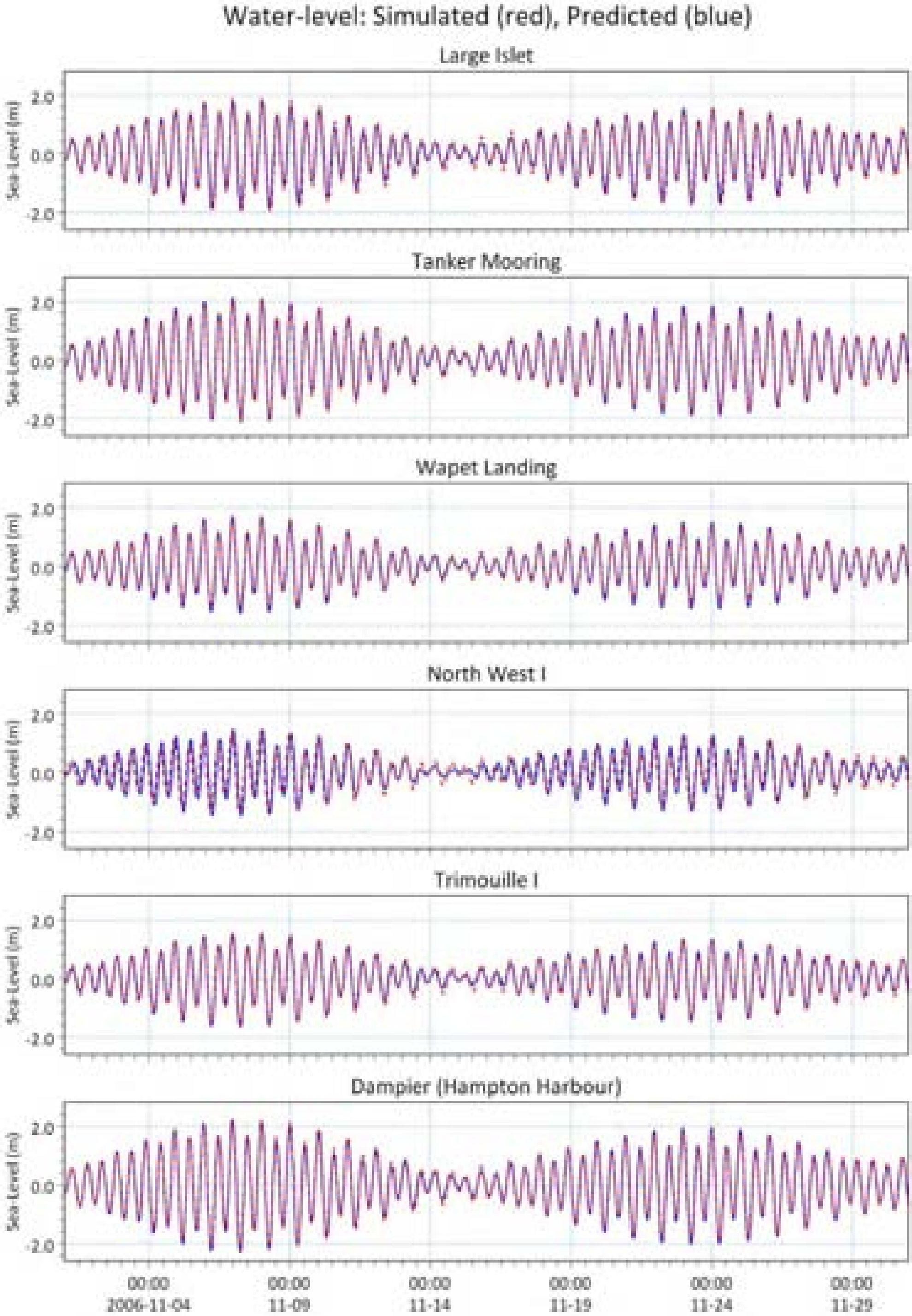

Figure D.3 Comparison of simulated and predicted water levels at selected tidal stations during a typical period in November 2006 (continued). Simulated elevations in red and predicted elevations in blue.

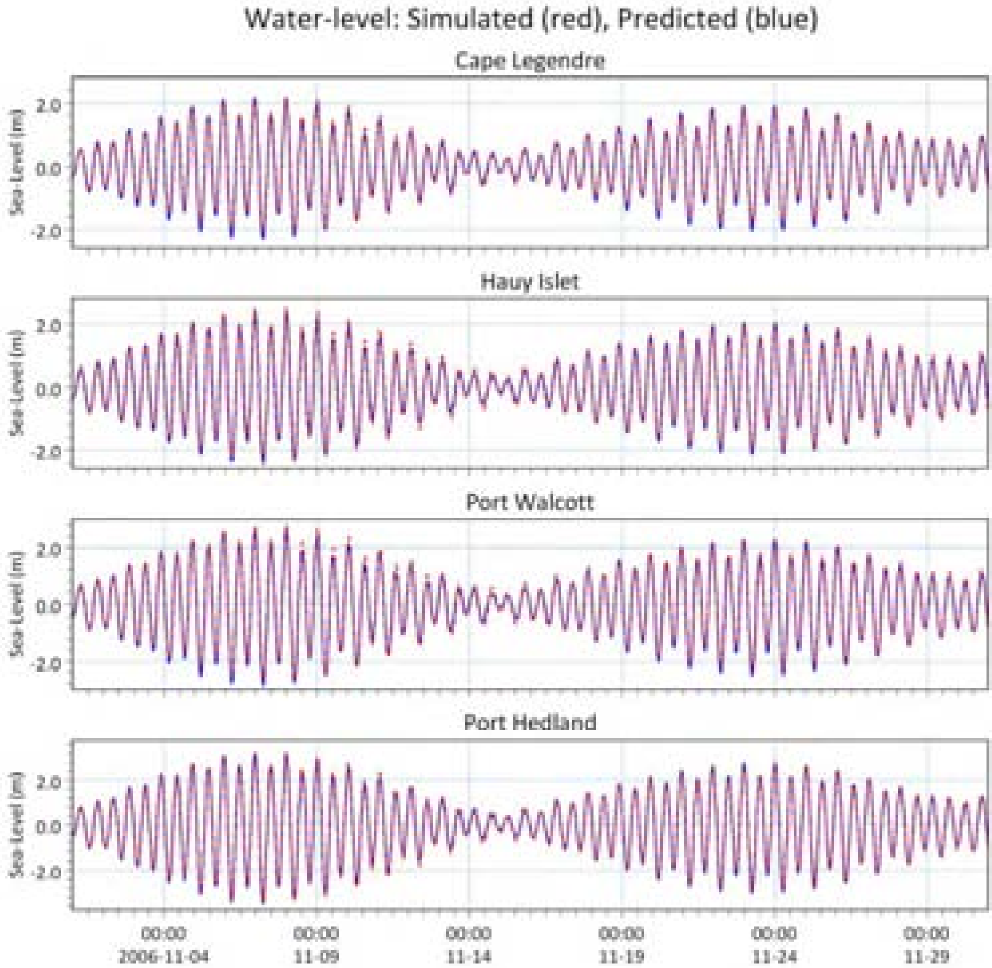

Figure D.4 *Comparison of simulated and predicted water levels at selected tidal stations during a typical period in November 2006 (continued). Simulated elevations in red and predicted elevations in blue.*

D.4 Calibration to 2006/07 Current Speeds and Directions

Good calibration to tidal elevations is a pre-requisite, but does not necessarily guarantee a good calibration against currents. The model has been extensively calibrated and verified against current data available in the vicinity of the site. The model was initially calibrated and validated against current data from 2006/07 available early in the project, and has subsequently been further validated against current data from 2009 from the ongoing field campaign for the project.

The locations of the current stations are listed in Table D.2 and shown in Figure D.5. It is noted that a comprehensive field campaign is ongoing at the time of reporting, and the current data base is continuously expanding. The model will be further validated against the new data, but it is the opinion of the hydraulic consultants that the current measurements that have been available during the study period, including both older data from 2006/07 and data from 2009 from the ongoing field campaign, is adequate to ensure a good calibration, and additional data is not anticipated to lead to changes of the model setup that will change the impact assessment.

Table D.2 Overview of available current measurements.

No.	Location	Id	Period	Water Depth	Longitude (E)			Latitude (S)		
					deg	min	sec	deg	min	sec
1	Basin ADCP	P3	25-01-2006 to 25-02-2006	9.5	115	3	0	-21	38	31.5
2	Bank ADCP	P4	25-01-2006 to 25-02-2006	13.5	115	5	19.8	-21	31	12.9
3	Basin CM04P	P6	25-01-2006 to 25-02-2006	9.5	115	3	27.4	-21	38	14.3
4	Jetty CM04P	P7	25-01-2006 to 25-02-2006	4.5	115	3	50.4	-21	39	37.1
5	Basin CM04p #2	P8-1	26-02-2006 to 22-04-2006	11	115	3	25.6	-21	38	40.3
		P8-2	14-05-2006 to 07-06-2006							
6	Basin CM04p	P9	26-02-2006 to 07-06-2006	11	115	3	25.2	-21	38	17.5
7	Basin CM04p #2	P10	08-06-2006 to 20-09-2006	8	115	3	28.1	-21	38	43.3
8	Basin CM04p #2	P11	21-09-2006 to 01-02-2007	8	115	3	32.0	-21	38	38.8
9	Jet015	Jetty	11-01-2009 to 16-04-2009	8.2	115	0	42.5	-21	39	17.7
	Jet051	Jetty	17-04-2009 to 13-06-09							
	Jet052	Jetty	26-07-2009 to 10-09-2009							
10	Spoil Ground		10-01-2009 to 16-04-2009	51	114	51	6.8	-21	21	51.5
11	Channel		24-07-2009 to 12-09-2009	15	115	2	56.4	-21	30	6.18

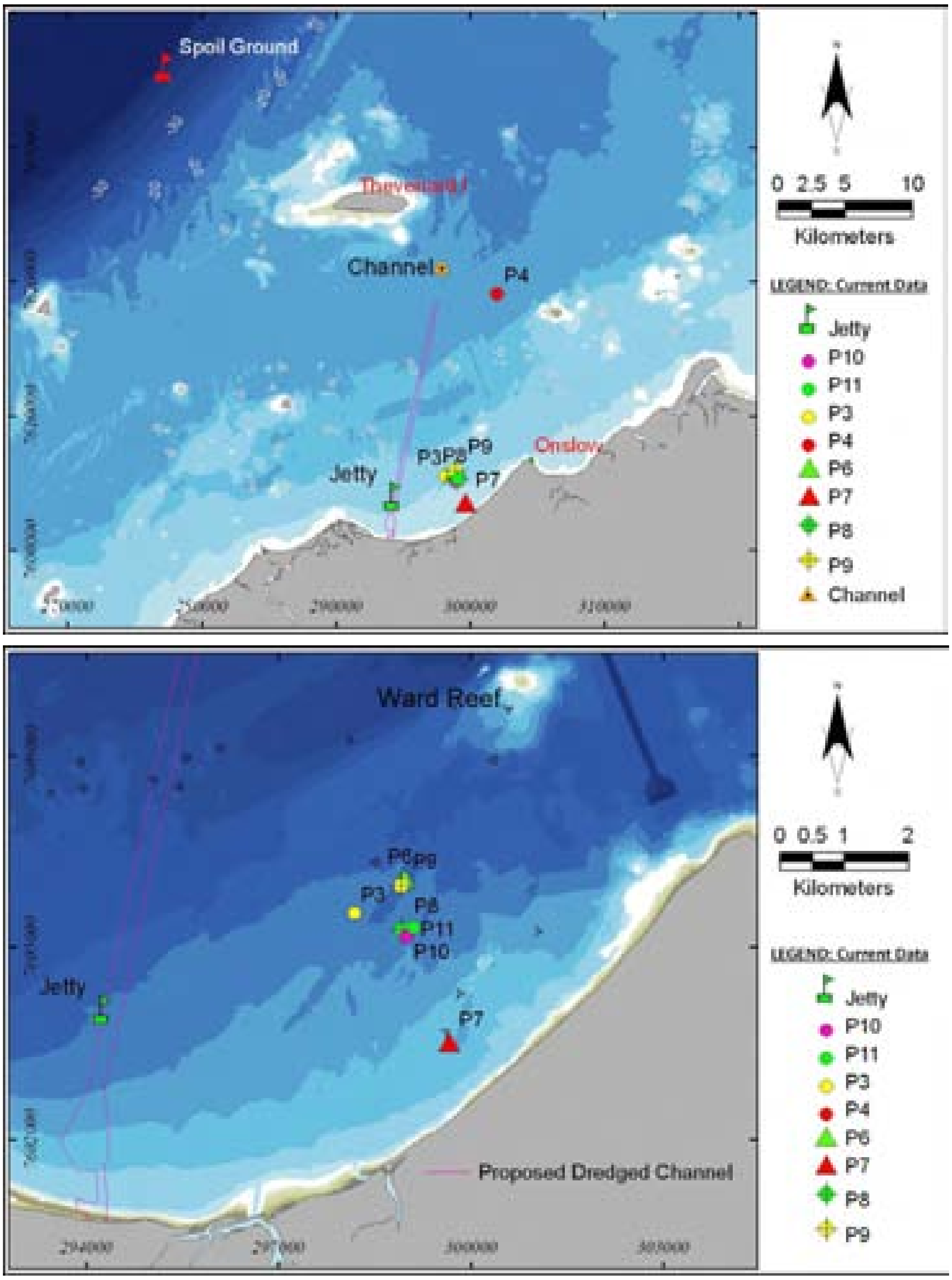

Figure D.5 Locations of current measurements that have been available for the study for model calibration and validation. See Table D.2 for details of measurements.

D.4.1 Wind Effects and Choice of Wind Fields

The currents in the area of interest are primarily driven by tides and winds with regional pressure fields playing a secondary role except perhaps during stronger cyclonic conditions. Regional Ocean currents, although very important in deep water off the shelf, do generally not impact the nearshore area of interest. The wind data, in addition to the KMS tidal boundaries, is therefore crucial for the calibration/verification process.

An initial assessment investigated the model performance for a range of available wind sources, including point measurements from Met-stations (Onslow Met-station, Onslow Airport, Thevenard Island, Barrow Island, Varanus Island) and 2D wind field from prediction models (GFS model, MesoLAPS 6-hourly and MesoLAPS 1-hourly).

A sample comparison is shown in Figure D.6 at P4 (see Figure D.5 for location). It is clear that including winds in the simulations is crucial (comparing to the pure tidal simulation which cannot reproduce the net current flows). All the wind records lead to similar overall patterns, but with some significant differences throughout the model area and with seasons which are briefly discussed below.

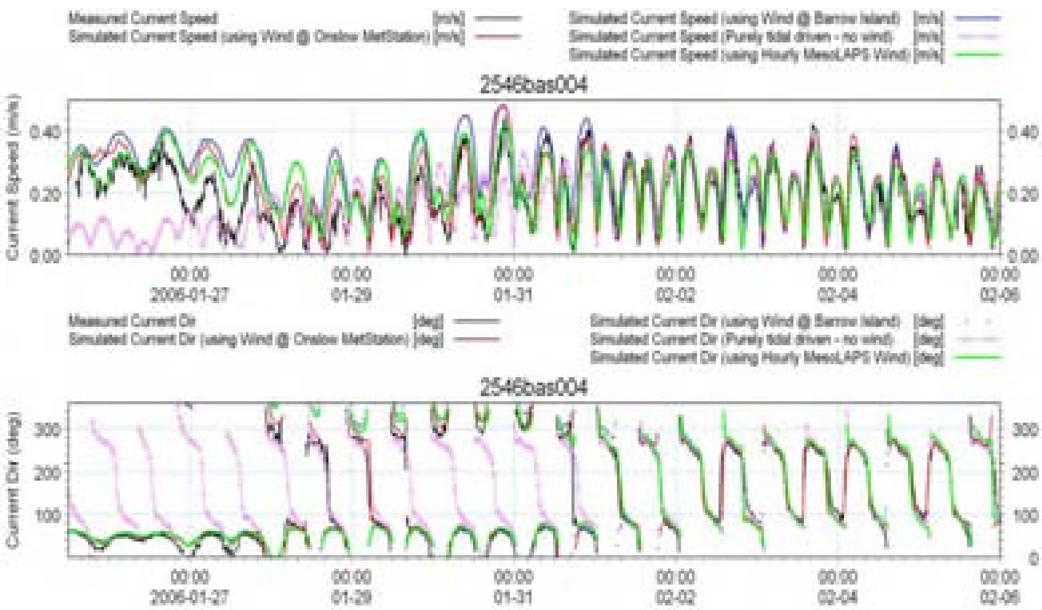

Figure D.6 Time series comparison of measured current at P4 against simulated currents from purely tidal driven model as well as models with different wind sources (Onslow Met Station and hourly MesoLAPS record).

A discussion of the wind fields is provided in:

- URS (2010) *Characterisation of the Ambient Environment Report*
- Section 4.1.3.2 of the main report and
- Appendix M: Comparison of MesoLAPS Wind Fields with Monitoring Data

In brief, it is normally preferable to use wind maps rather than single point measurements. The wind maps may include spatial variability in the wind fields which are obviously not captured by single point measurements. Ideally, the wind maps should be of sufficiently high spatial and temporal resolution to capture e.g. land/sea breezes if these are important for the site and the model application, and they should assimilate available data to ensure as accurate and realistic information as possible (the wind maps are based on model predictions, and therefore need to be verified for the area of interest).

An assessment of the model performance for the various wind sources has led to the conclusion that:

- The net currents in the coastal area are largely driven by local wind effects rather than regional wind and pressure fields (exception to this will be during strong cyclonic conditions).
- The best wind maps presently available from the site to the study team are the 1-hour MesoLAPS data. The GFS winds fields are spatially much too coarse to resolve the important land/sea interface.
- The MesoLAPS wind maps tend to under predict the wind speeds, in particular the land/sea breeze effects in the nearshore areas are not well resolved during summer.
- The Onslow Met-station and Onslow Airport winds lead to significantly higher net easterly currents in the nearshore area during summer
- The Onslow winds under-estimate the easterly winds during winter, which likely leads to an under-prediction of net westerly currents during winter if the Onslow winds are applied.
- The Thevenard Island wind record is well placed in terms of representing winds over the key area of interest. The consultants are cautious in using the Thevenard record due to periods with inconsistent wind directions in the record.

From an impact point of view, the plume modelling has demonstrated that the use of MesoLAPS winds severely under-predicts the easterly nearshore plume dispersion during summer compared to the modelling with Onslow winds. Similarly, using Onslow winds severely under-predicts the westerly plume dispersion during winter compared to the simulations with the MesoLAPS wind and pressure maps. The key for these simulations is whether the threshold on current speeds for sediment re-suspension is exceeded. The modelled areas of plume dispersion during summer and winter conditions correlate well with MODIS satellite images showing high turbidity in these areas, indicating that there is re-suspension of material taking place. To avoid non-conservatism in the impact assessment, it has therefore been chosen to carry out the impact assessment as a composite between results based on the models driven by MesoLAPS and Onslow wind data. This captures the worst case scenarios from the net easterly flows driven by Onslow winds during summer and the net easterly flows driven by the MesoLAPS winds during winter.

The calibration/validation of the hydrodynamic model has thus been demonstrated for both MesoLAPS and Onslow winds with some comparison included. It is noted that in the initial phases of the study, the MesoLAPS wind fields were only available to the study group at 6-hourly intervals, but it has more recently become available at 1-hourly intervals. All the modelling for the impact assessment using MesoLAPS winds has been carried out using the 1-hourly records. For Onslow, the met-station data covers a limited period. The met-station data correlates well with the Onslow Airport data, and where required, the Onslow met-station data has been supplemented with data from Onslow Airport.

D.4.2 Onslow Winds – Qualitative Time Series Comparisons

The model has been extensively validated against the available measurements at the various current meter stations, see locations in Figure D.5. Visual comparisons of the modelled and simulated current speeds and directions have been shown for the model driven by winds from Onslow Met Station in Figure D.7 to Figure D.15. Validation against derived net currents is shown in Section D.4.4, while a quantification of RMS errors and comparison to a relevant standard is included in Section D.6.

Based on the visual comparisons, there are times and areas with some discrepancies between simulated and measured current speeds and directions, but considering the complexity of the mixed tidal and wind generated current fields, the model performs very well and the calibration is considered fully adequate for the intended applications.

Keeping the overall application of the model in mind, it is not essential that every single peak or spike is reproduced, but important that the model reproduces the overall amplitudes of both tidal and wind driven currents, and that the model is capable of capturing the seasonal variability of net currents. This will ensure a sound base hydrodynamic model for simulating the spreading of the sediment plumes.

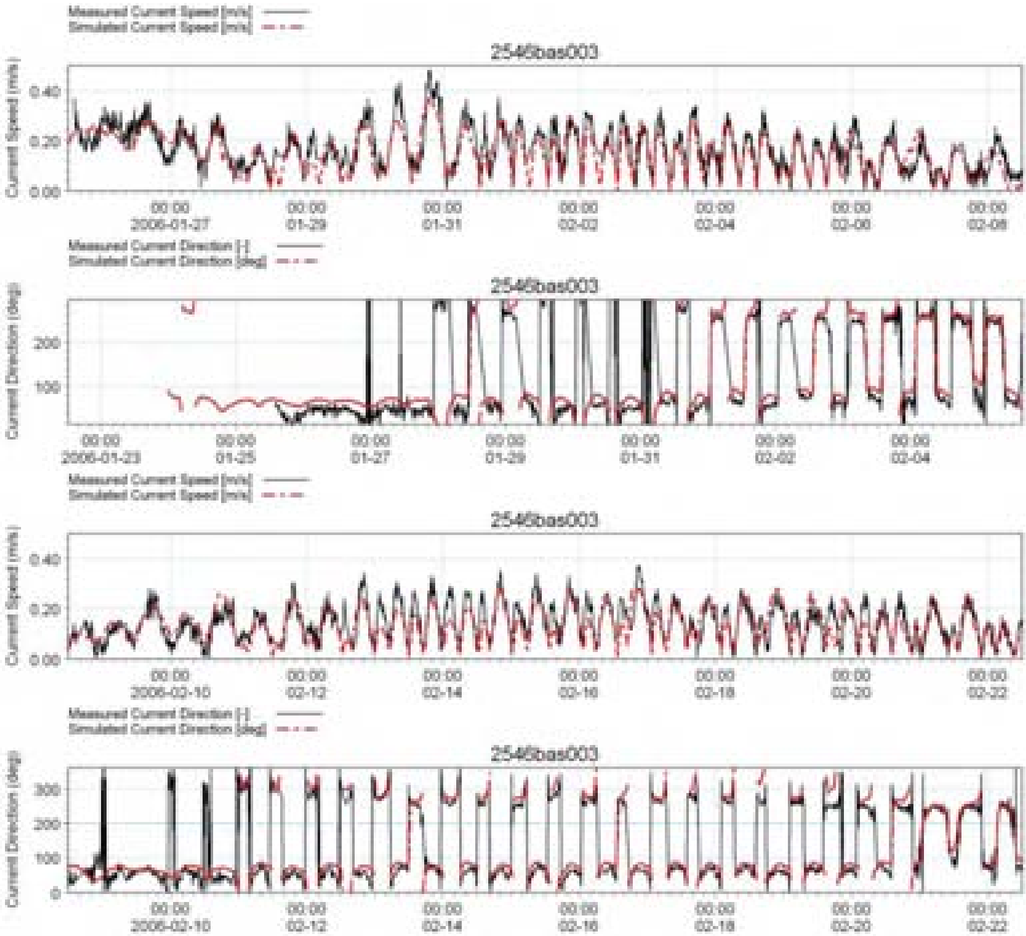

Figure D.7 Time series of measured and simulated current speeds and directions at P3 using Onslow winds.

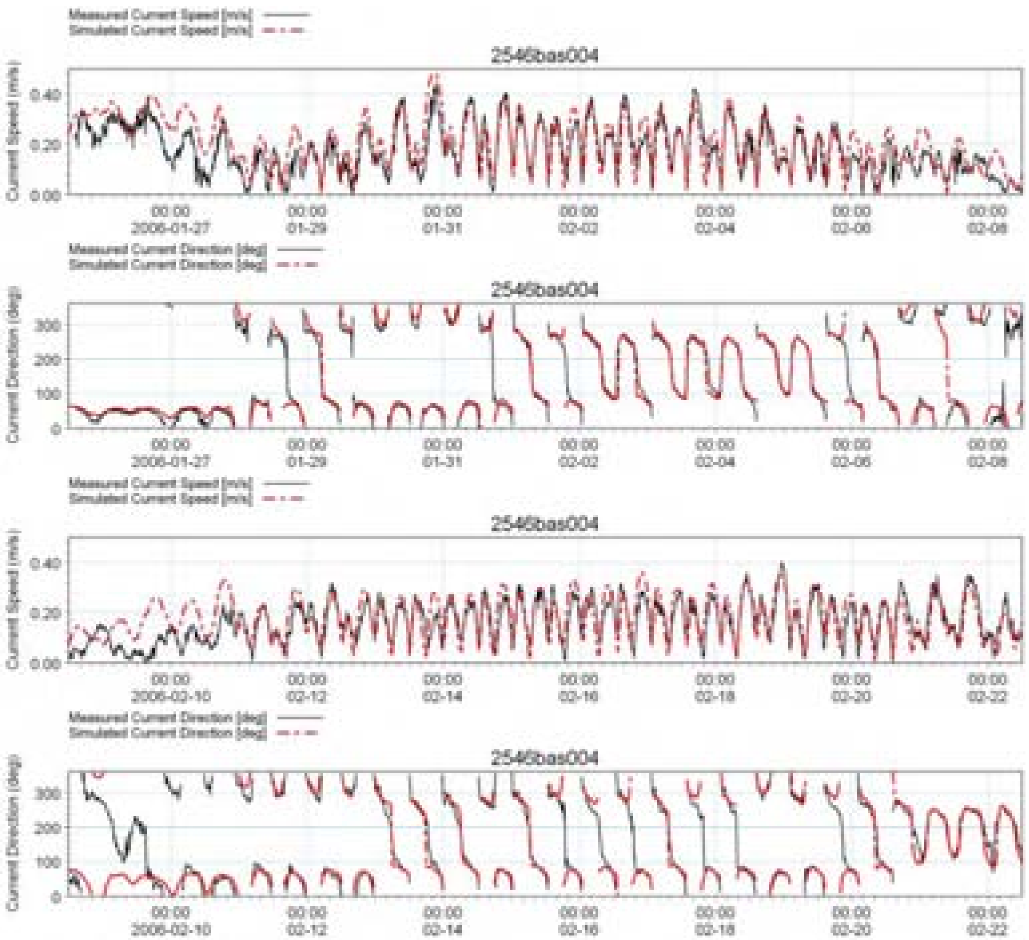

Figure D.8 Time series of measured and simulated current speeds and directions at P4 using Onslow winds.

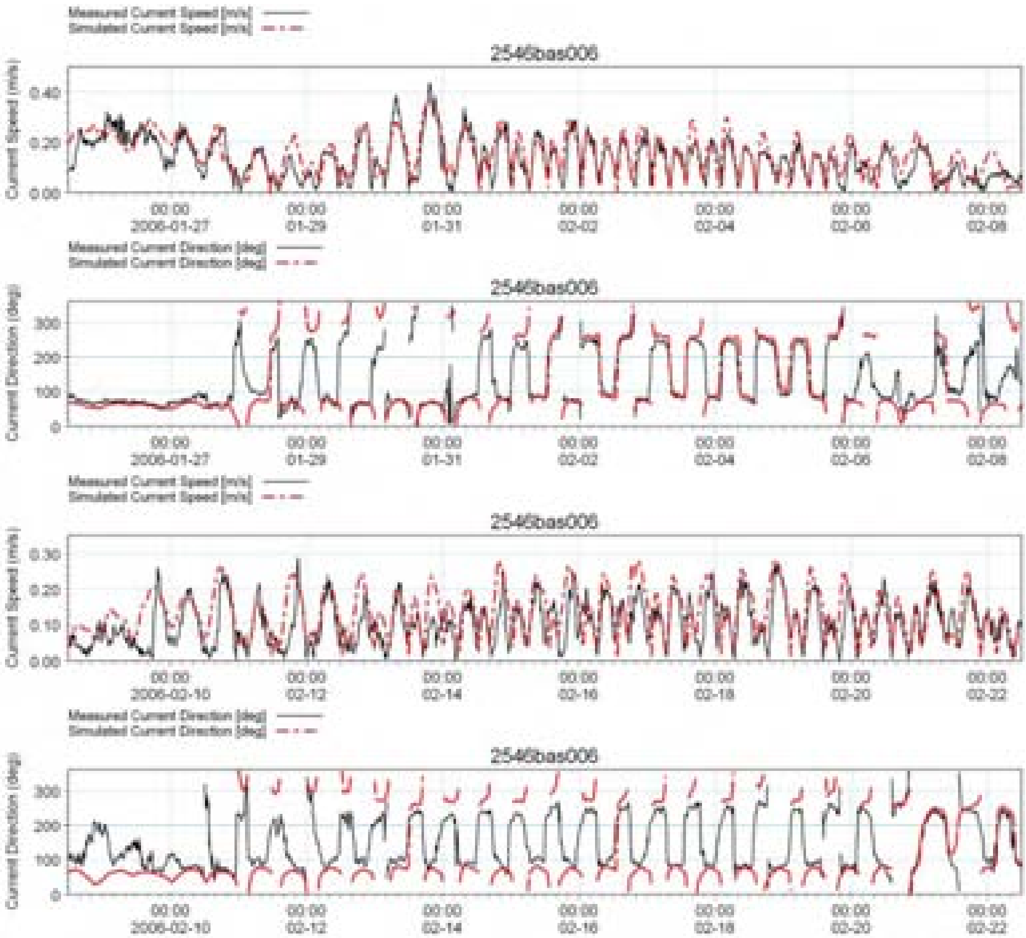

Figure D.9 Time series of measured and simulated current speeds and directions at P6 using Onslow winds.

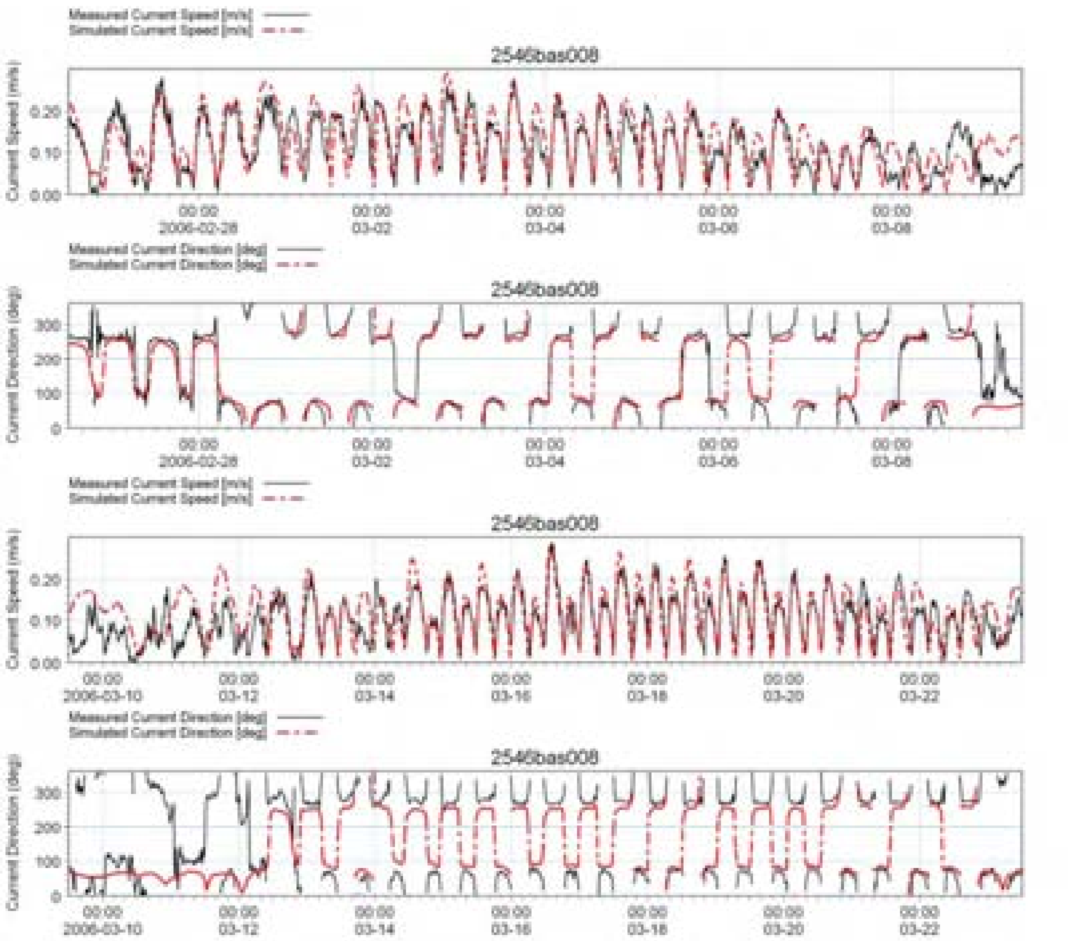

Figure D.10 Time series of measured and simulated current speeds and directions at P8 using Onslow winds.

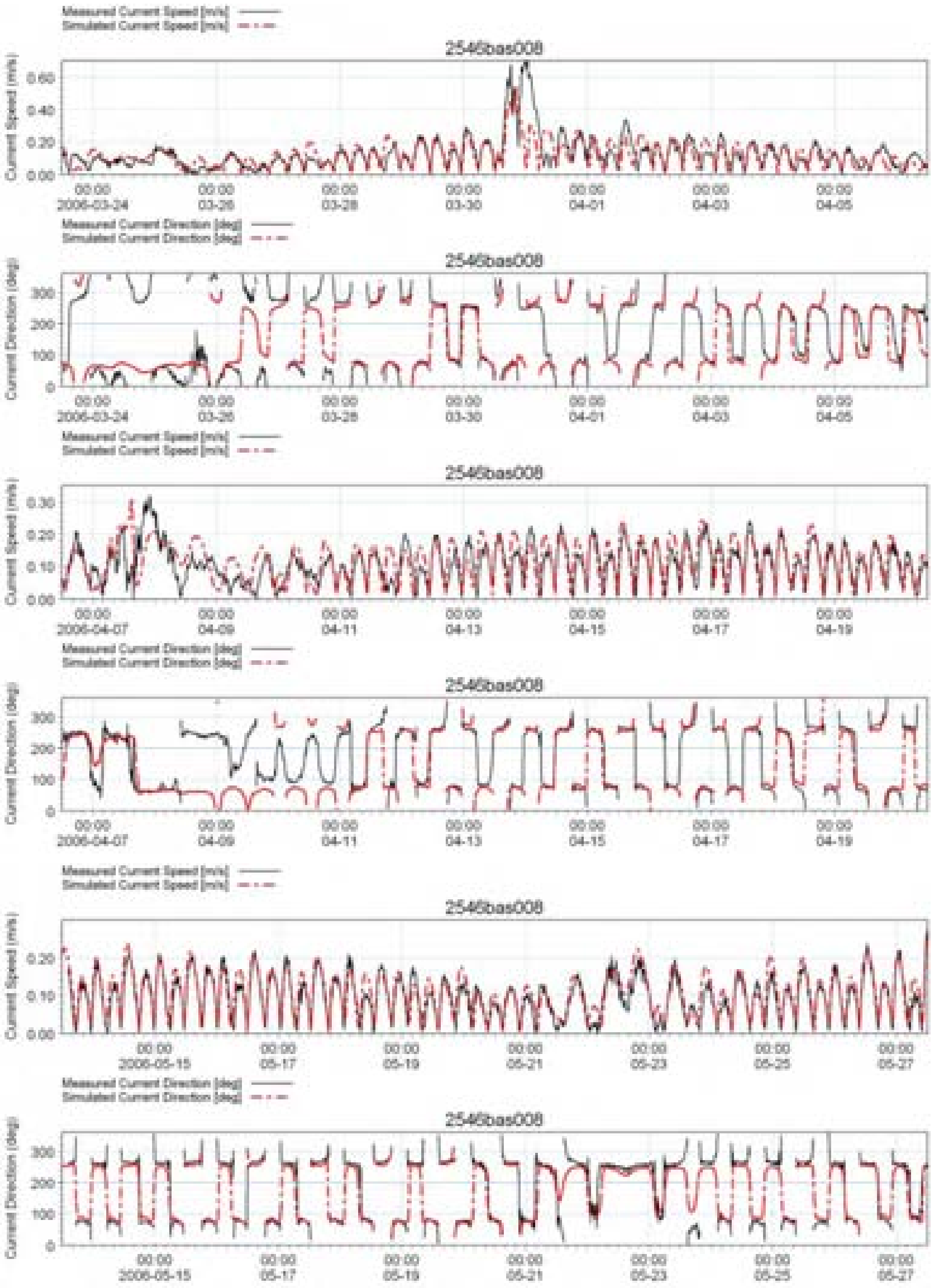

Figure D.11 Time series of measured and simulated current speeds and directions at P8 using Onslow winds, (continued).

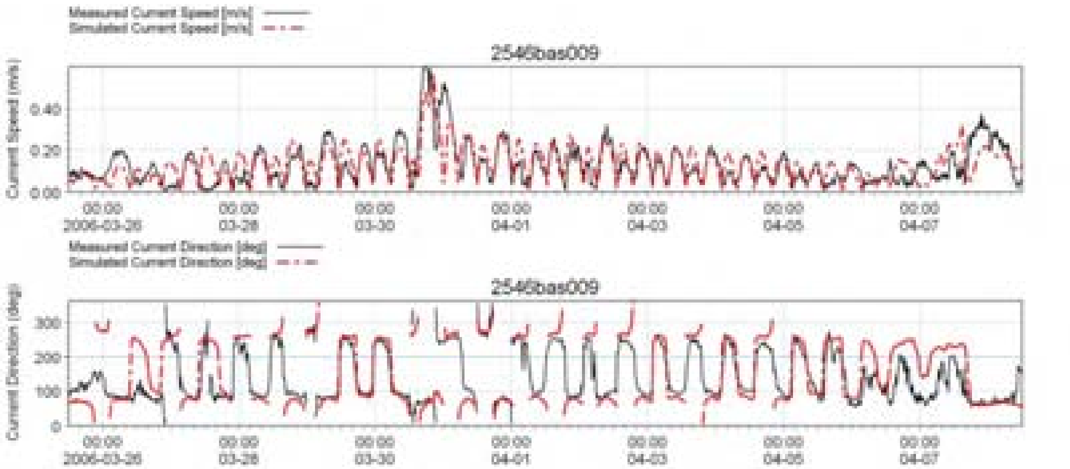

Figure D.12 Time series of measured and simulated current speeds and directions at P9, Onslow winds.

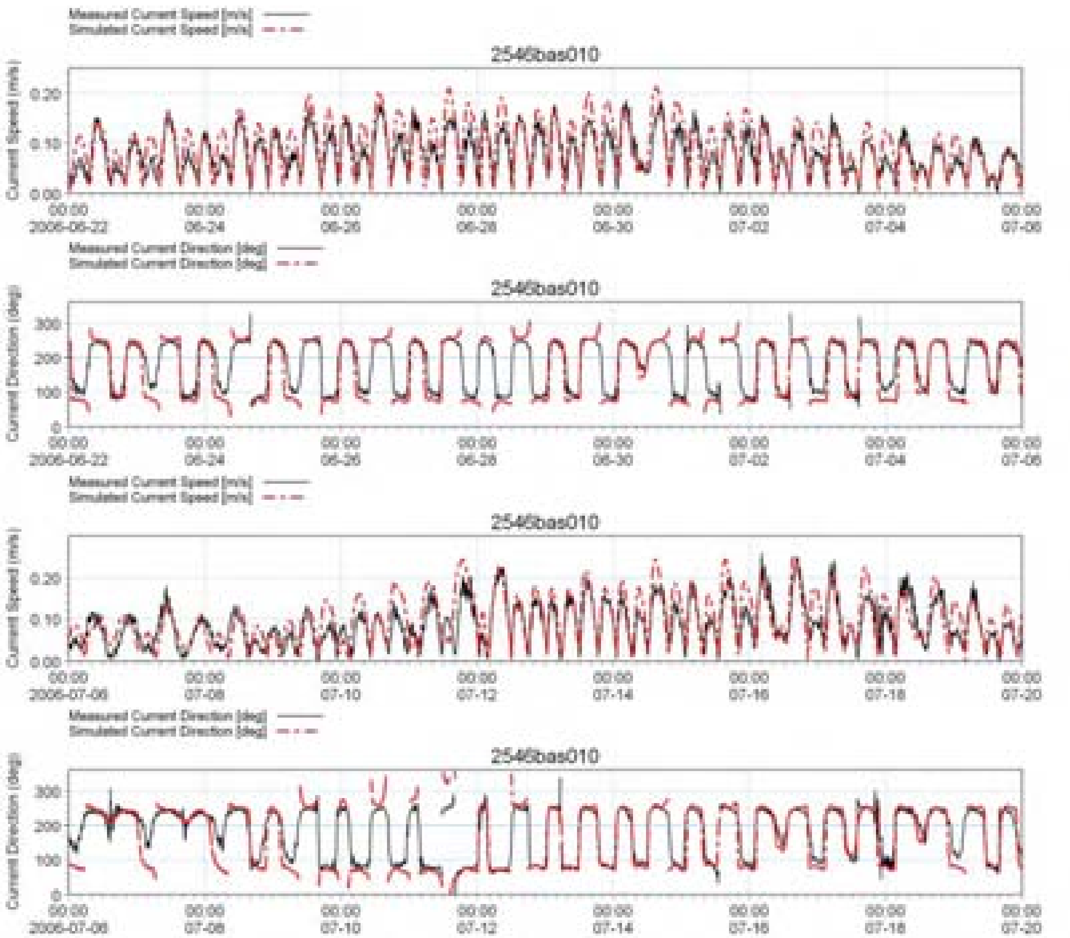

Figure D.13 Time series of measured and simulated current speeds and directions at P10, Onslow winds.

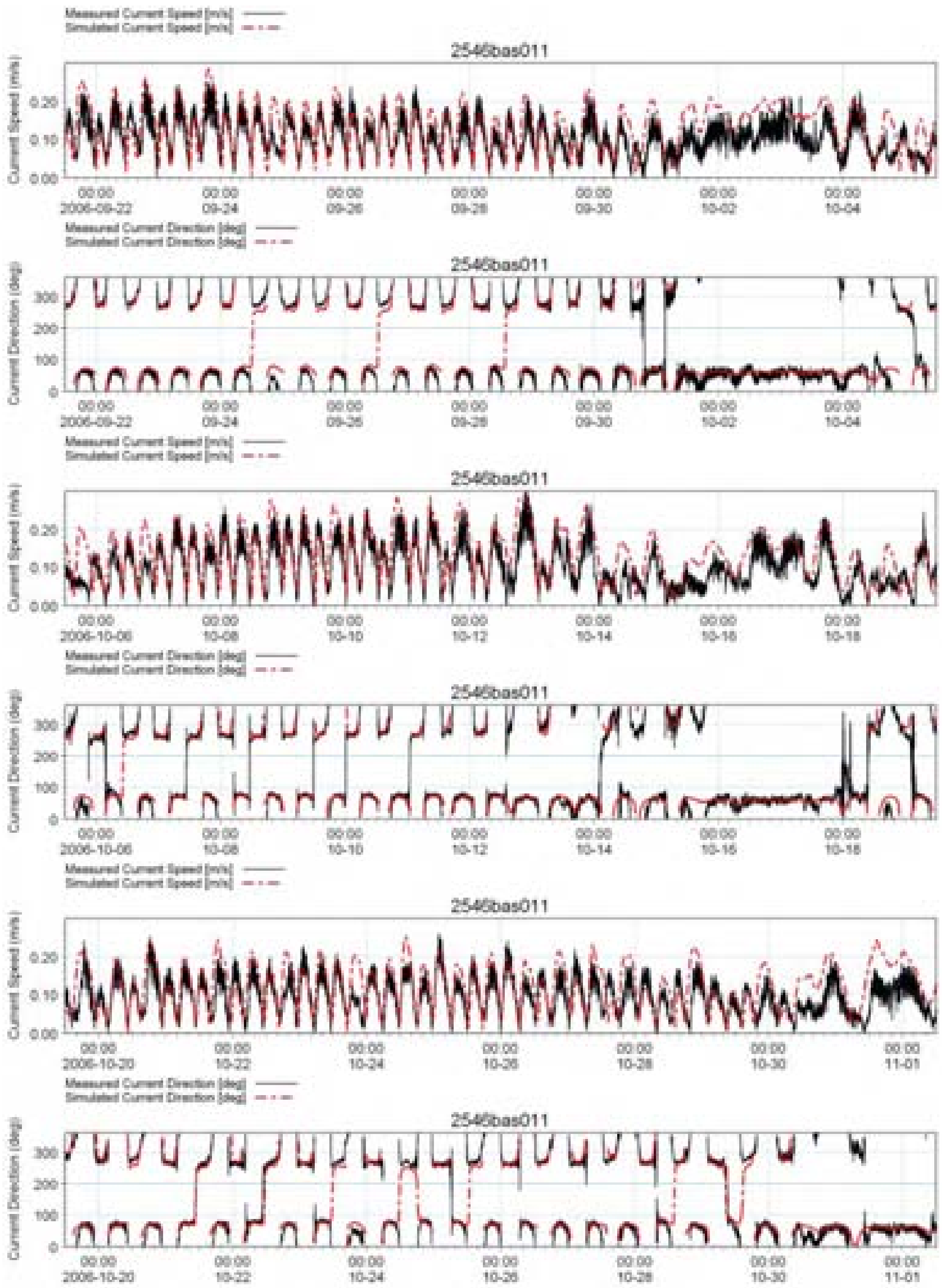

Figure D.14 Time series of measured and simulated current speeds and directions at P11, Onslow winds.

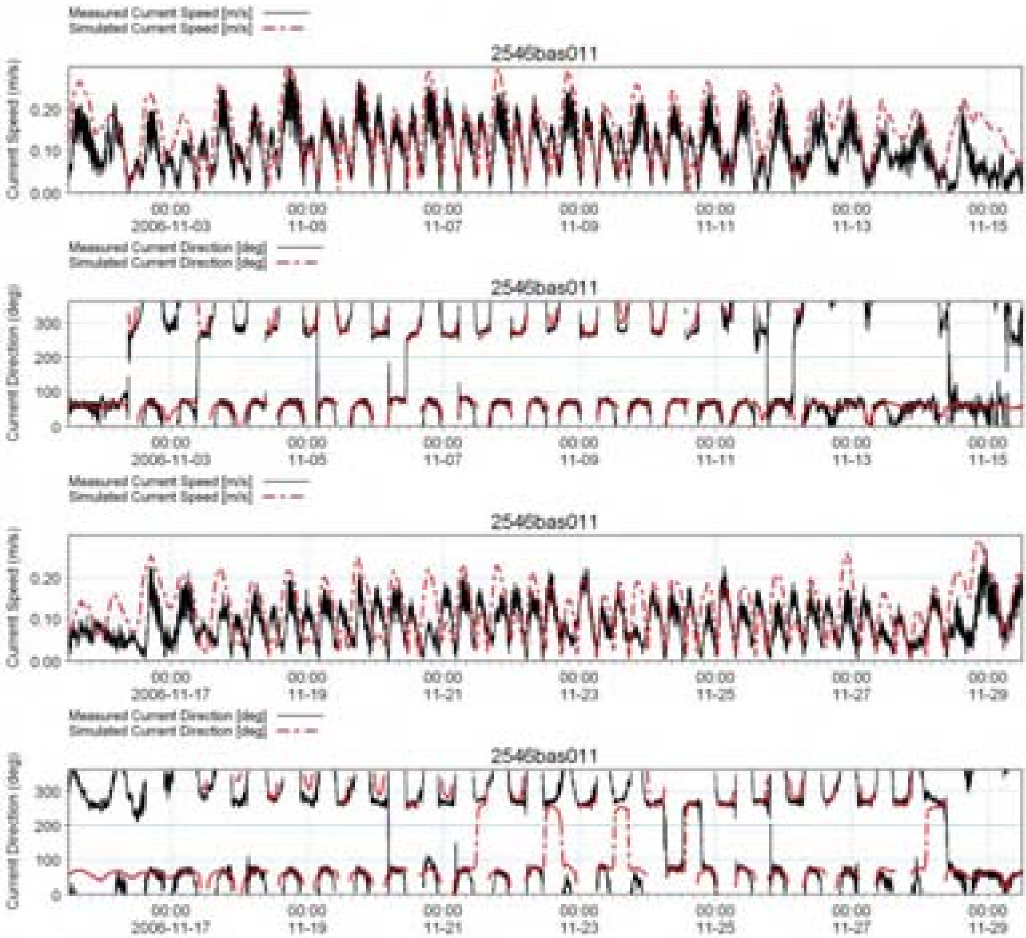

Figure D.15 Time series of measured and simulated current speeds and directions at P11, Onslow winds (continued)

D.4.3 MesoLAPS Winds – Qualitative Time Series Comparisons

Similarly to the assessment based on the model driven by Onslow Winds, the 1-hour MesoLAPS wind fields have been tested and comparisons have been made for the extracted time series of current speeds and directions at the measured locations. The findings lead to similar overall patterns as the Onslow Met Station winds but with slightly lower current speeds during the summer period. Due to data gaps in the 1-hour MesoLAPS wind record (which only covers the first half of year 2006), only a month of current validation has been carried out for the winter period (June 2006). For this period at P10, the 1 hour MesoLAPS winds lead to slightly higher current speeds and a better comparison with the measured data than the Onslow data.

These observations support the notion that MesoLAPS winds underestimate the near-shore currents during summer, while the Onslow winds under-estimate the westerly net drift during winter.

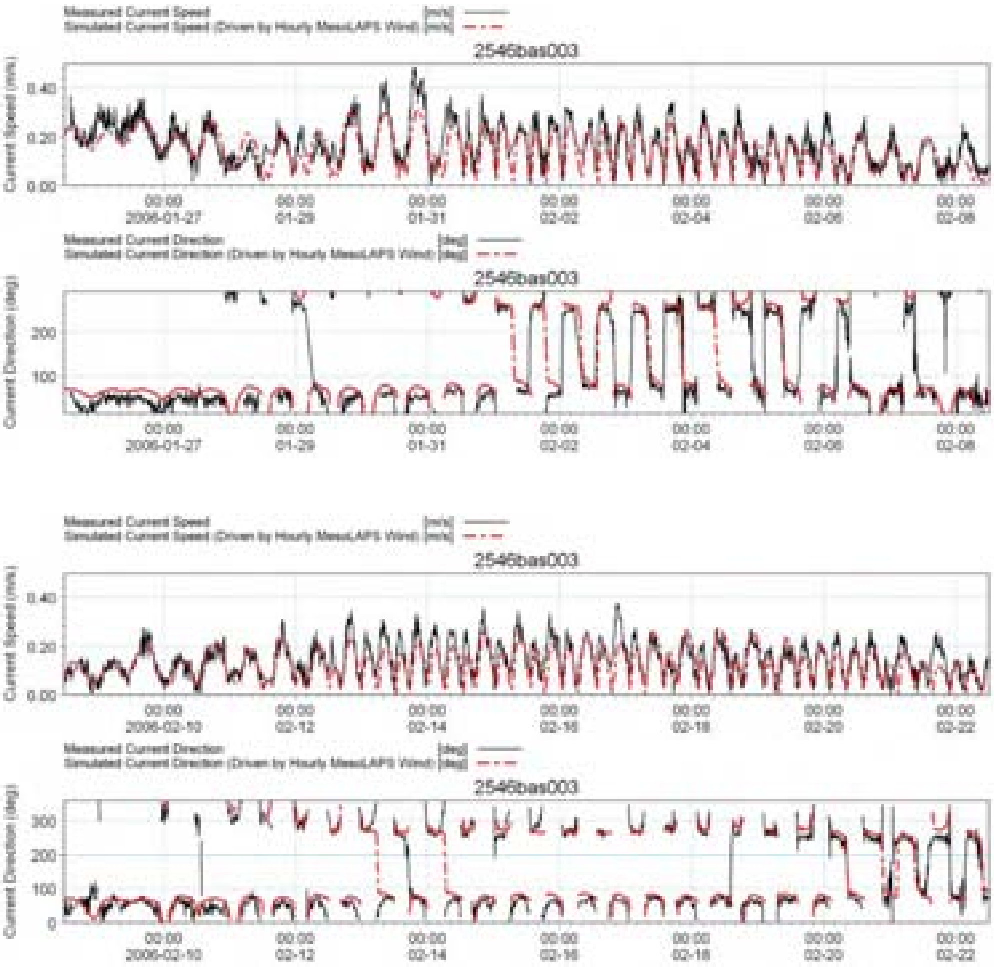

Figure D.16 Time series of measured and simulated current speeds and directions at P3, MesoLAPS winds.

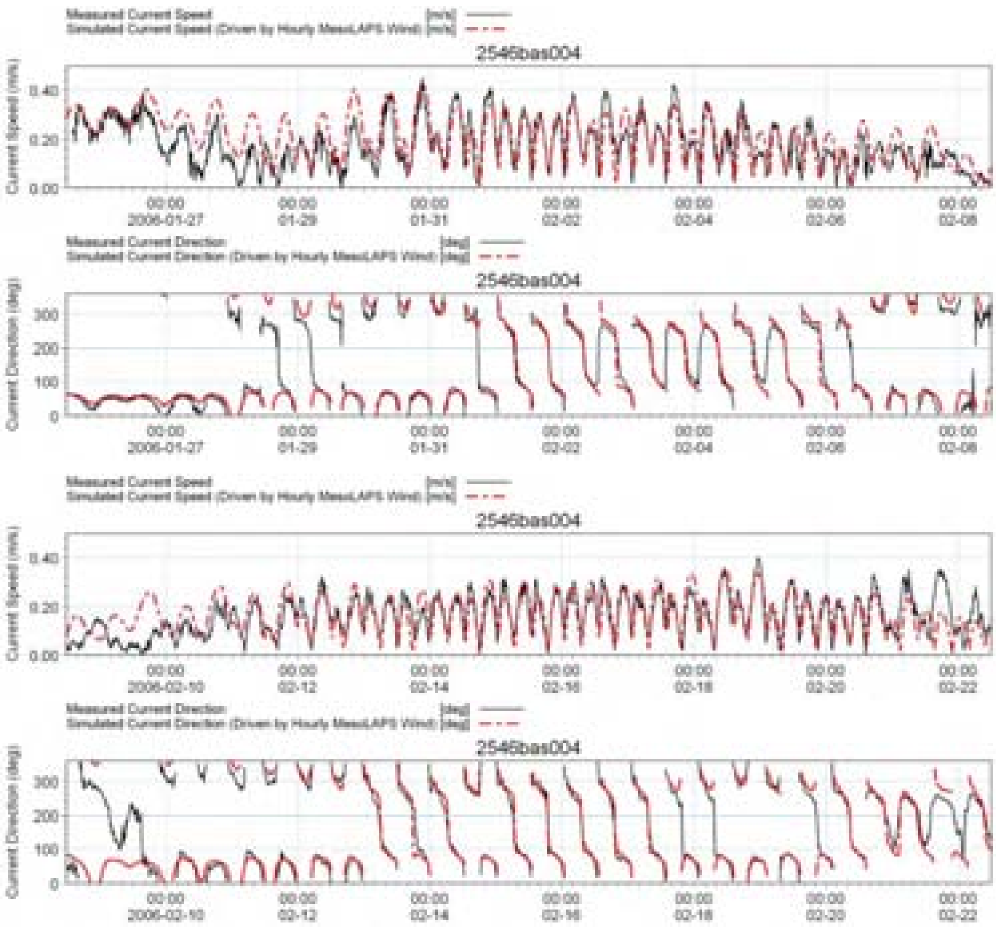

Figure D.17 Time series of measured and simulated current speeds and directions at P4, MesoLAPS winds.

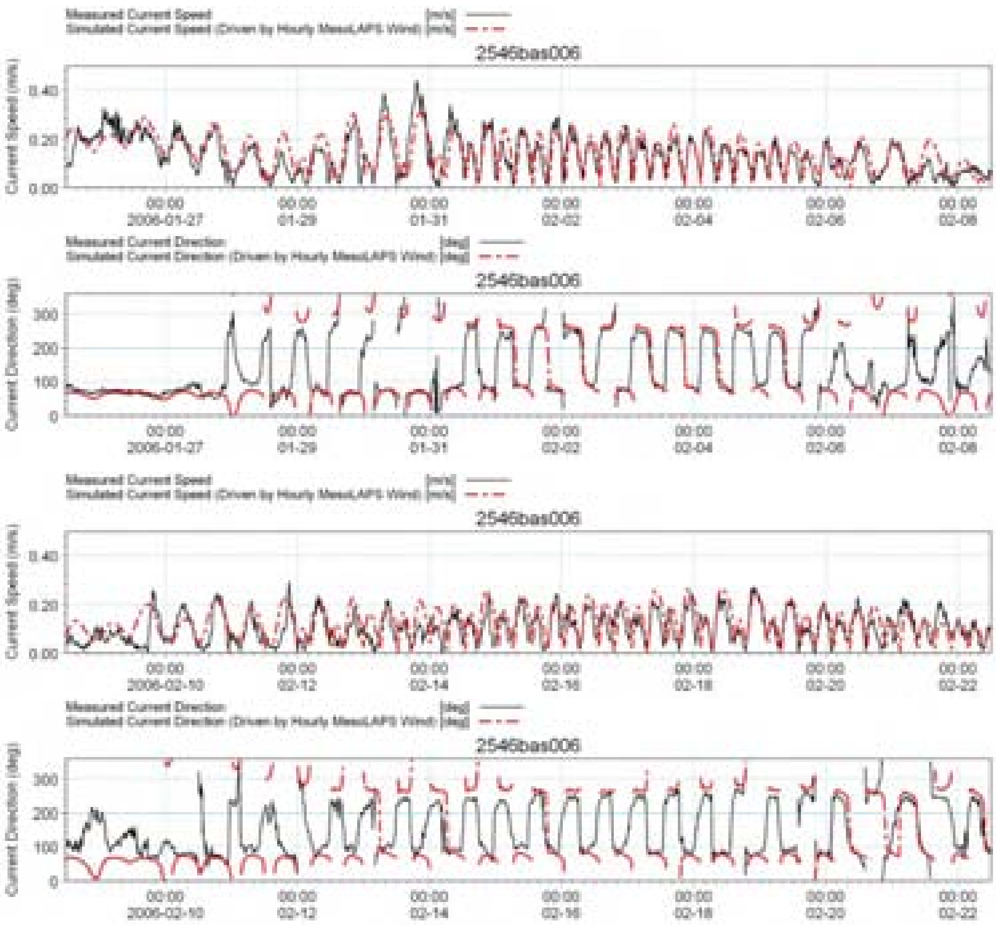

Figure D.18 Time series of measured and simulated current speeds and directions at P6, MesoLAPS winds.

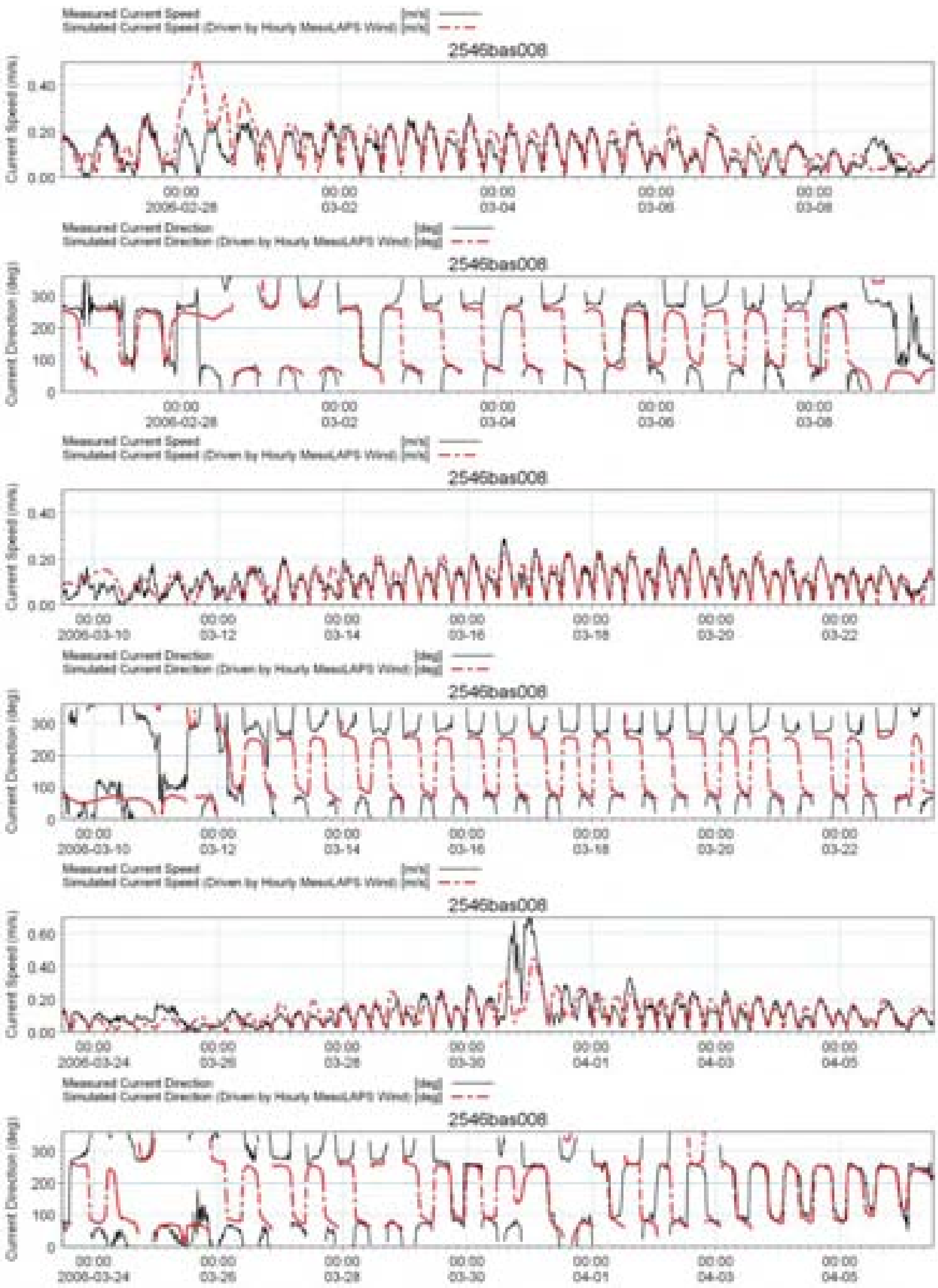

Figure D.19 Time series of measured and simulated current speeds and directions at P8, MesoLAPS winds.

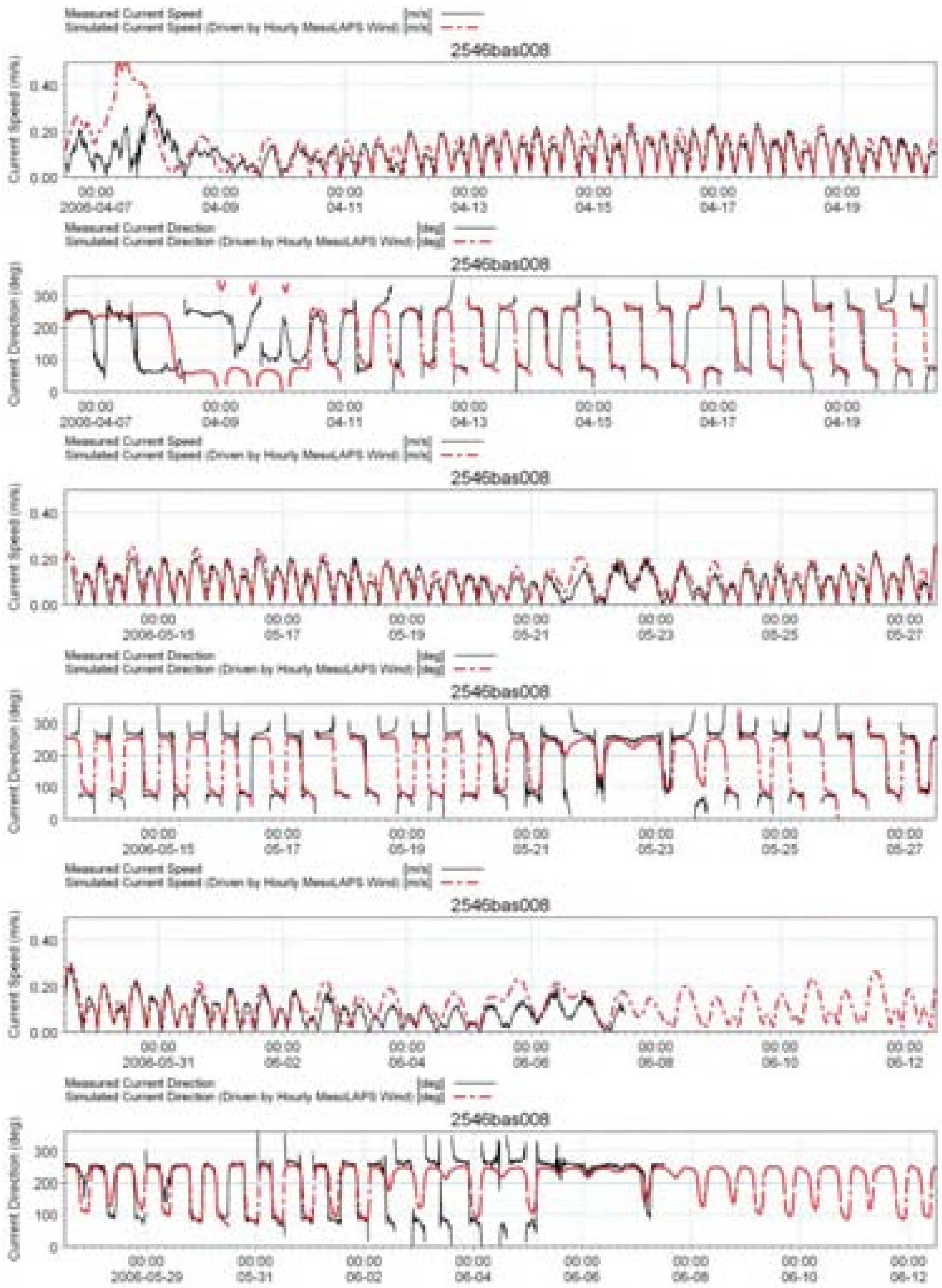

Figure D.20 Time series of measured and simulated current speeds and directions at P8, MesoLAPS winds (continued).

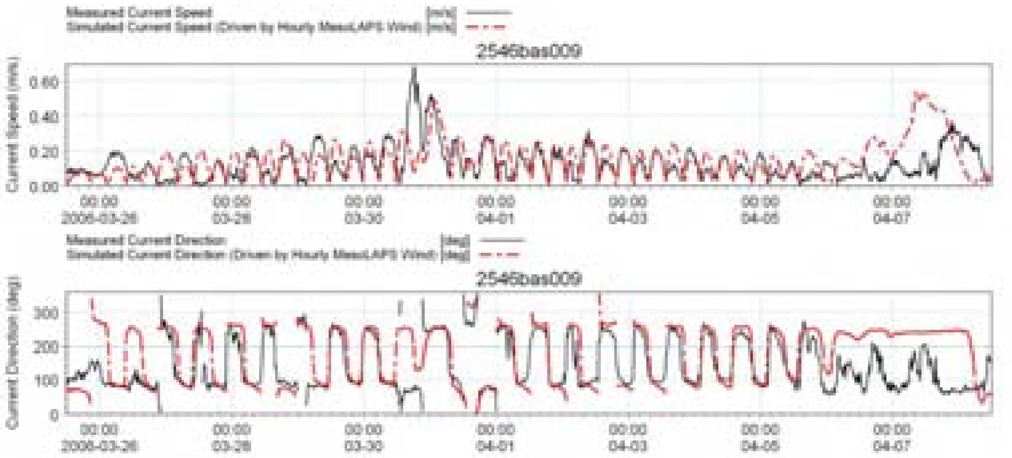

Figure D.21 Time series of measured and simulated current speeds and directions at P9, MesoLAPS winds.

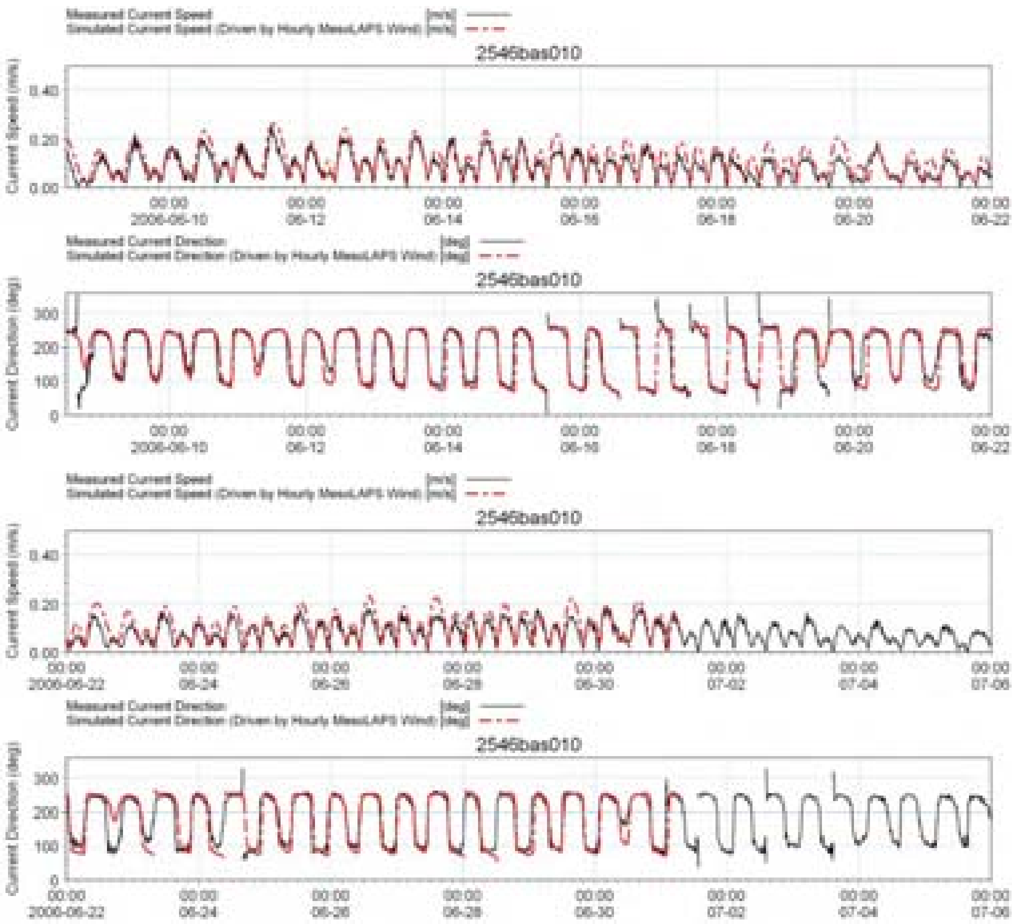

Figure D.22 Time series of measured and simulated current speeds and directions at P10, MesoLAPS winds

D.4.4 Validation of Net Currents for Onslow and MesoLAPS winds

The model ability to simulate net current has been further investigated by deriving the net currents from the data and model output through running averaging over a tidal cycle. This is presented in Figure D.23 to Figure D.26 based with comparisons for model results driven by both Onslow and MesoLAPS winds. Due to data gaps in the wind fields as well as the data fields, there is not complete coverage for all components.

Considering the uncertainties in deriving these residuals from the data, the model performance is considered excellent. It is noted that the model exaggerates the residuals at some stations, e.g. P6 and P11. The model calibration was tailored to ensure that the wind effects were not under estimated, which has led to the slightly high values at some stations. From a plume dispersion and impact point of view, this is considered conservative.

Very generalised, the data and models show the strongest and most persistent net easterly directed currents during summer, although periods of net westerly flow also occurs during late summer. During the transitional period (March – May), net currents are generally weaker and variable in direction. During winter (June July), the net currents are predominantly westerly, but weaker and less persistent than during summer at the available locations (primarily point 10).

Comparing the performance of the models driven by Onslow and MesoLAPS winds, the resulting net currents are fairly similar with the Onslow data providing a slightly better validation at some stations and times, and the MesoLAPS a slightly better validation at other times and stations. Limited MesoLAPS data is available for the 2006 winter period, but the limited data available tends to indicate slightly higher net currents at P10 than for the Onslow winds, which is in line with expectations.

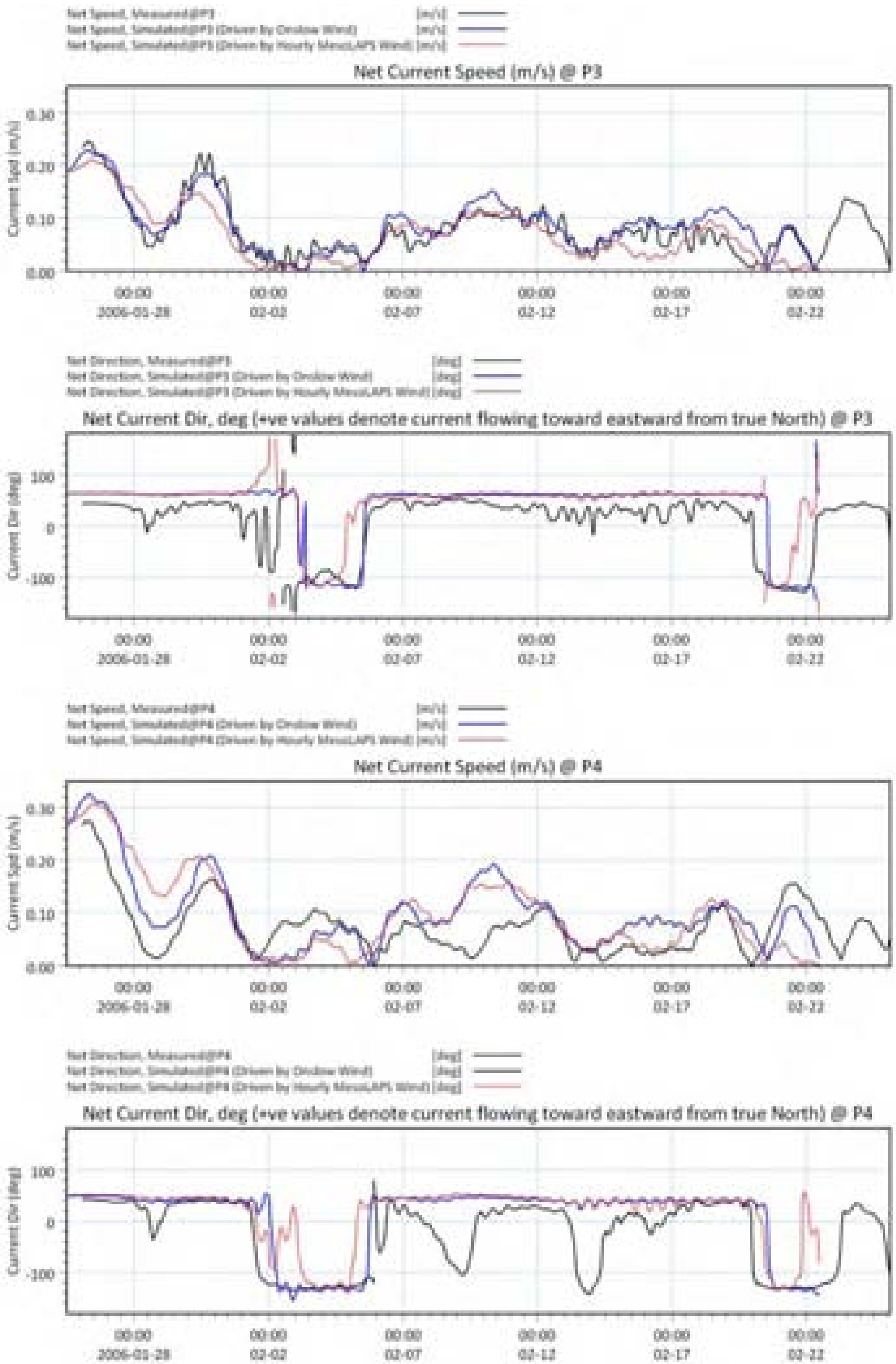

Figure D.23 Time series of net currents (averaged over a tidal cycle) derived from the data and model simulations for P3 and P4 for Onslow winds (blue) and 1-hour MesoLAPS winds (red).

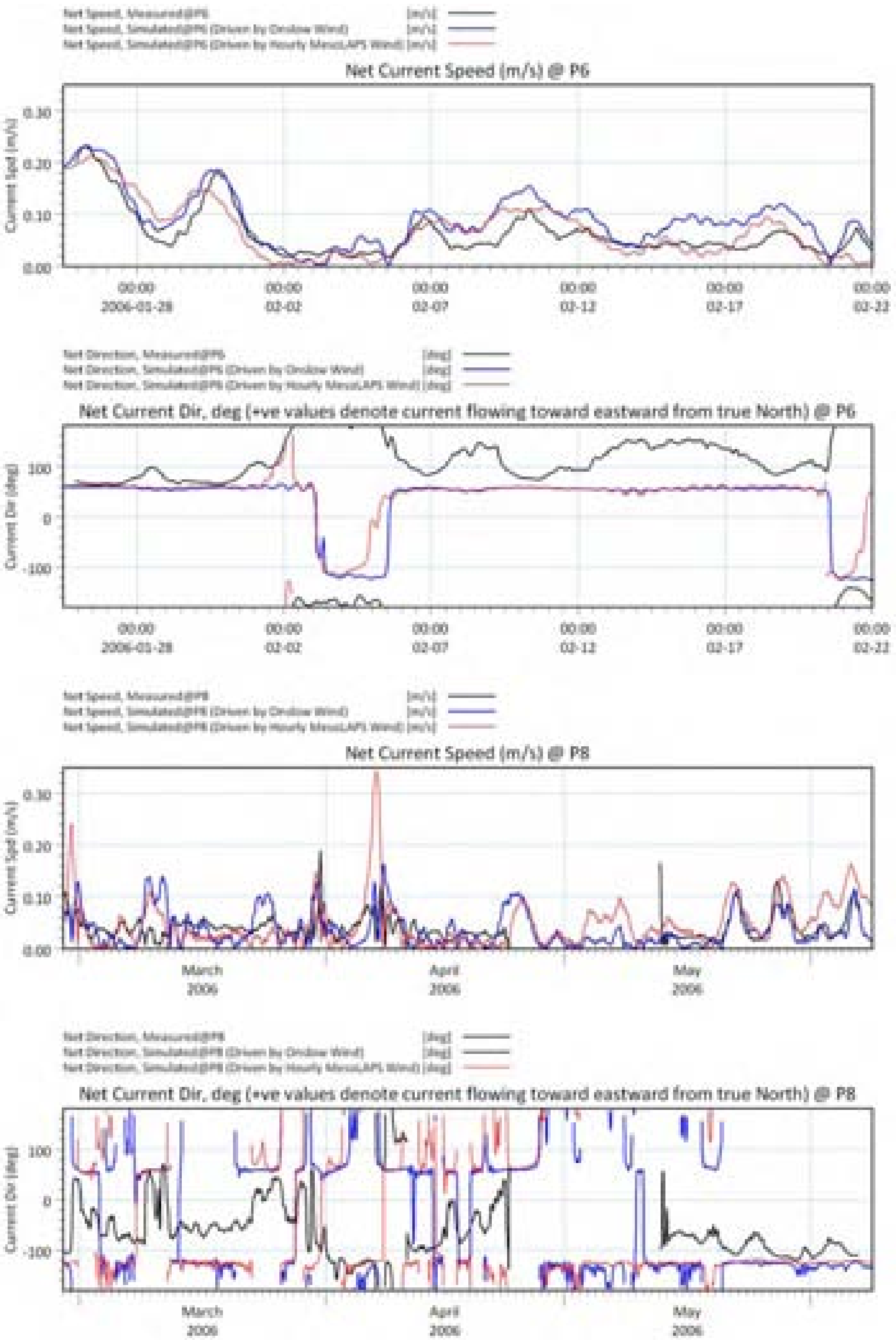

Figure D.24 Time series of net currents (averaged over a tidal cycle) derived from the data and model simulations for P6 and P8 for Onslow winds (blue) and 1-hour MesoLAPS winds (red).

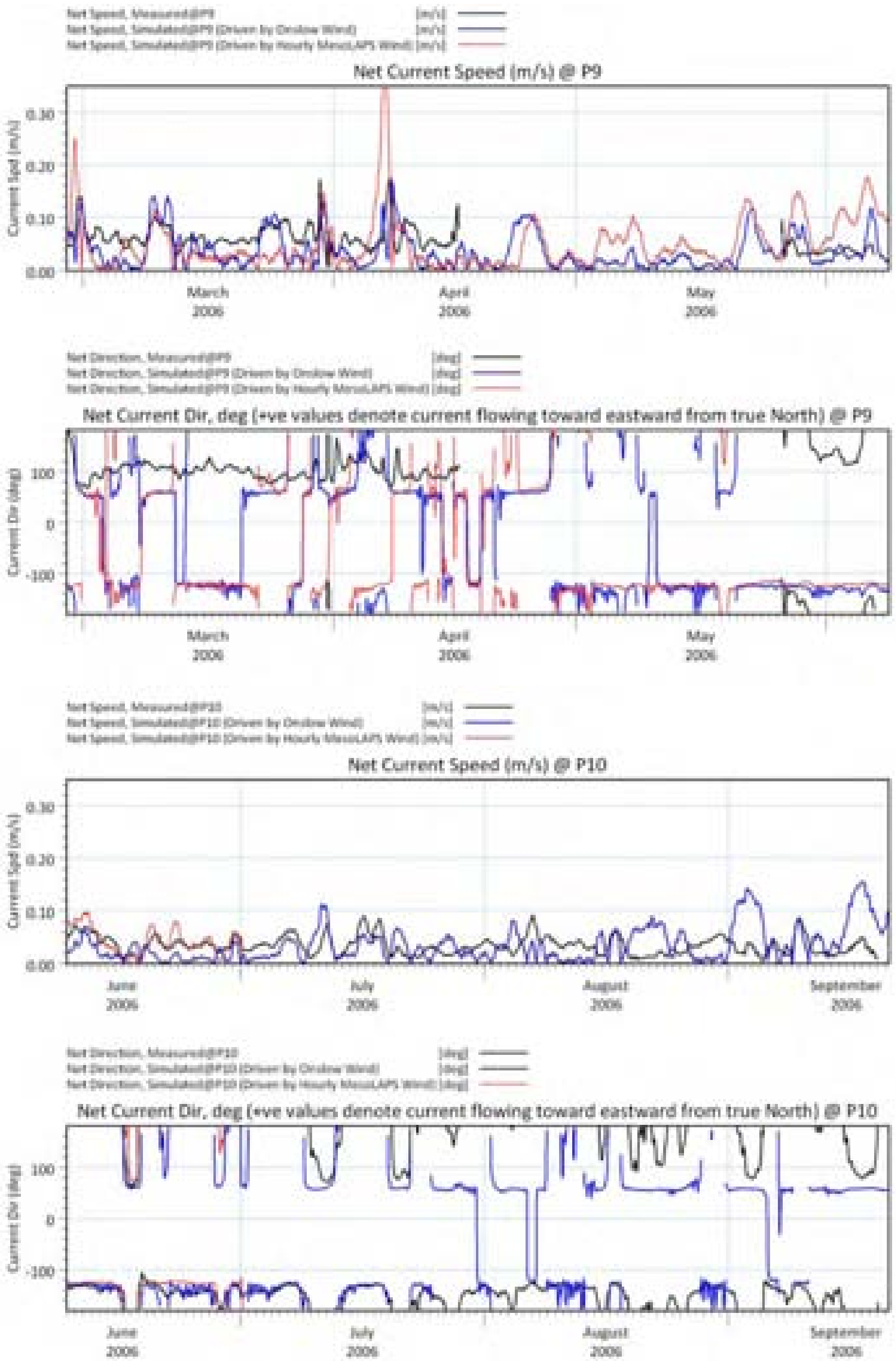

Figure D.25 Time series of net currents (averaged over a tidal cycle) derived from the data and model simulations for P9 and P10 for Onslow winds (blue) and 1-hour MesoLAPS winds (red).

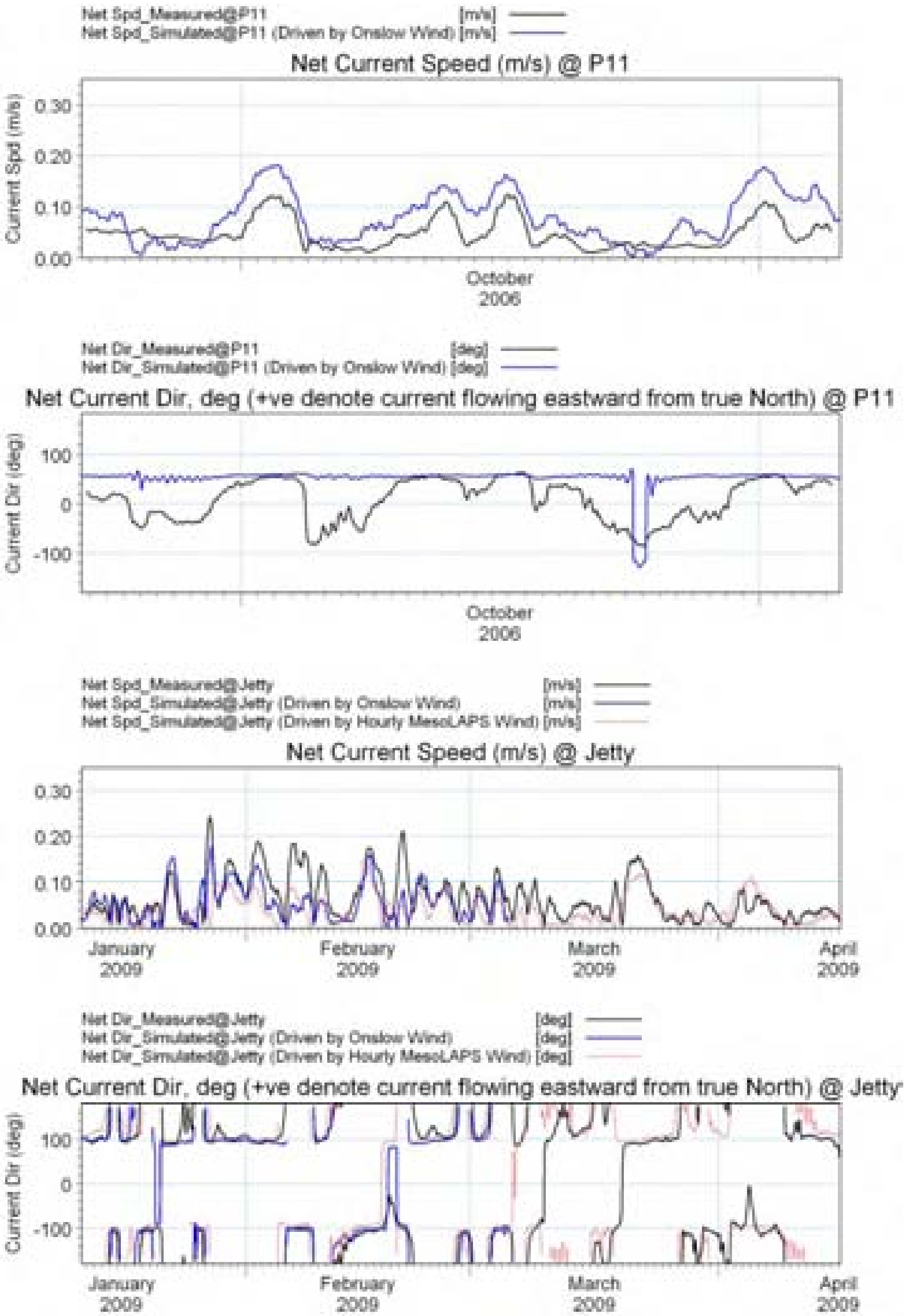

Figure D.26 Time series of net currents (averaged over a tidal cycle) derived from the data and model simulations for P11 and jetty for Onslow winds (blue) and 1-hour MesoLAPS winds (red).

D.5 Validation to 2009 Data

The model performance has further been validated against current measurements obtained from the ongoing field campaigns carried out by RPS. This validation is work in progress and continuously updated as more data becomes available from the field campaign. The model performance has been tested for both the Onslow and 1-hour MesoLAPS winds, and both are shown in the time series plots for comparison.

Overview of the current data locations from the 2009 (and ongoing) field campaign is provided in Figure D.27. It is noted that the names “Jetty”, “Channel” and “Spoil Ground” were assigned in the early stages of the project planning and do not reflect the exact locations of these components in the optimised layout. “Jetty” is at a nearshore location of the channel, “Channel” is close to the outer limit of the proposed dredged channel, and “Spoil Ground” is in deep water in the vicinity of the proposed off-shore spoil ground Site E.

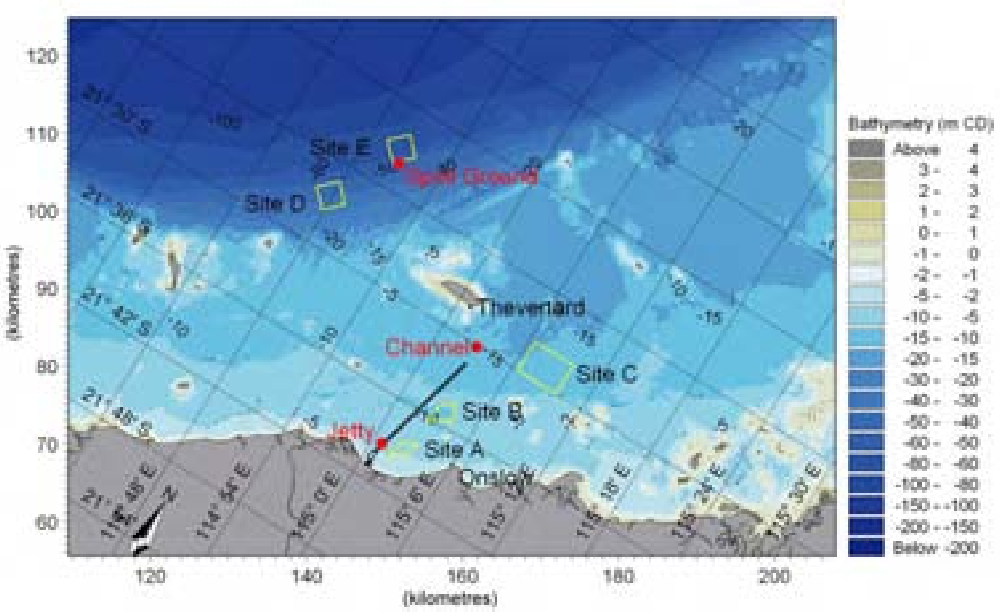

Figure D.27 Overview of locations of available current measurements from ongoing field campaign

D.5.1 Nearshore “Jetty” Location

Comparisons of depth-averaged currents are shown in Figure D.28 to Figure D.35 for the nearshore jetty location. Onslow winds have only been available up till March, and the rest of the period is only shown for MesoLAPS wind driven model output. For the period with overlap between the model output driven by Onslow winds and MesoLAPS winds, it is evident that the Onslow winds perform better for this near-shore location during the summer period. Both general speeds and individual peaks are generally captured better by the model driven by Onslow winds.

The model generally reproduces the tidal amplitudes well, and generally also captures the net driven currents as illustrated in Figure D.36, which shows derived net currents from the measurements compared to the corresponding net currents from simulations driven by Onslow and MesoLAPS winds. There are, however, periods for both the Onslow and

MesoLAPS winds where net flows are not captured in full strength. This is in particular evident for February which has two peaks of net currents during neap tide that are not well captured by either wind field. This stresses the importance of selecting periods for the climatic scenarios which have sufficiently strong and/or persistent net currents to capture the potential environmental impacts of this climatic scenario.

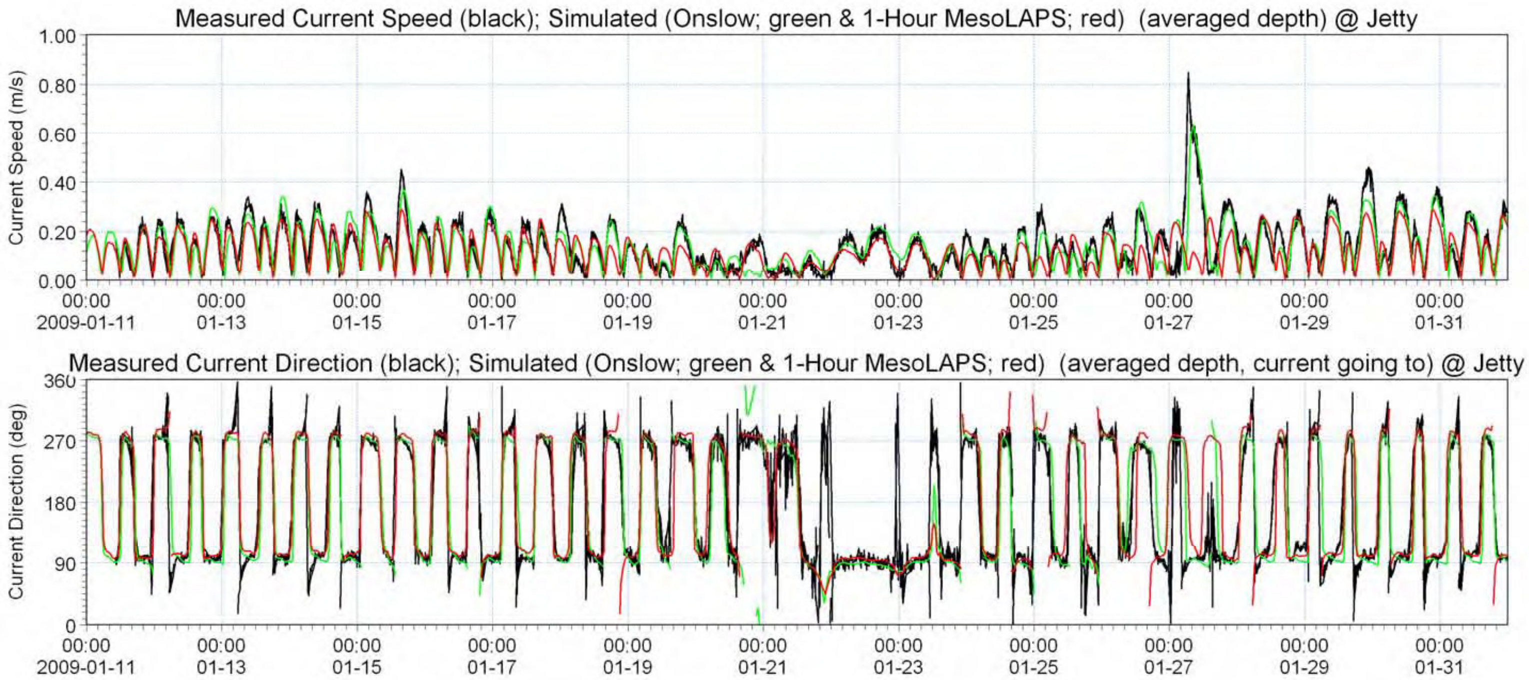

Figure D.28 Time series comparison of measured (black) and simulated driven by Onslow wind (red) and 1-hourly MesoLAPS winds (green) current speeds and directions at "Jetty" location for January 2009.

D-34

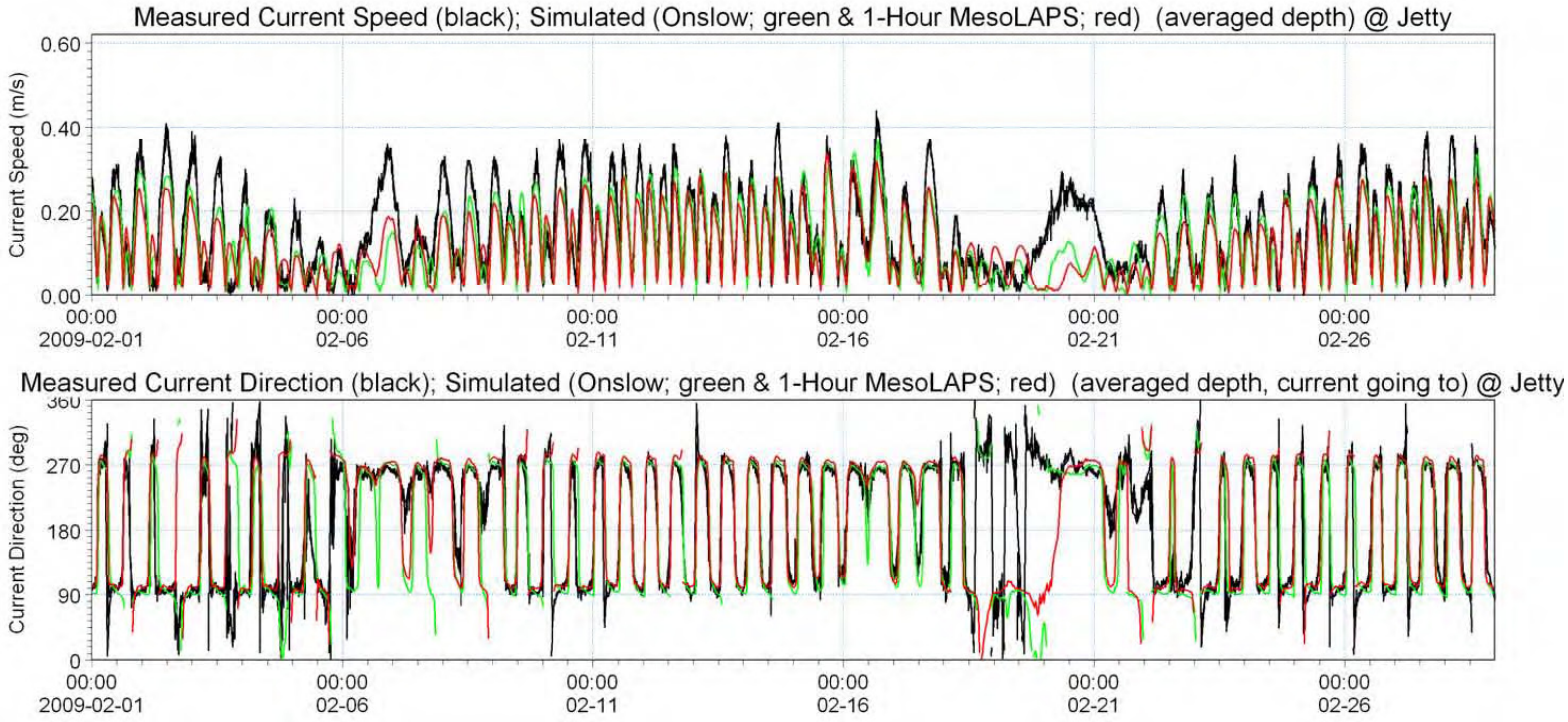

Figure D.29 Time series comparison of measured (black) and simulated driven by Onslow wind (red) and 1-hourly MesoLAPS winds (green) current speeds and directions at "Jetty" location for February 2009.

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D-35

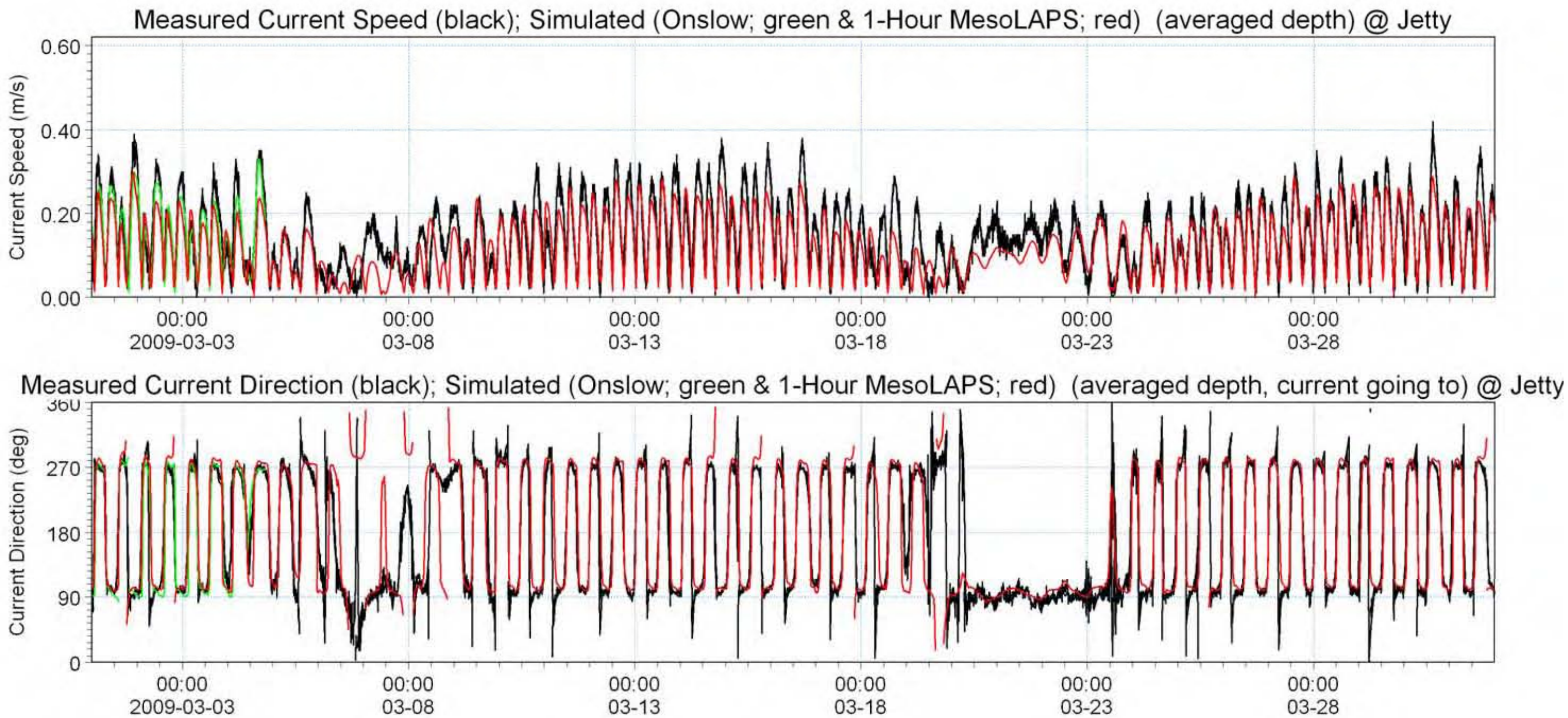

Figure D.30 Time series comparison of measured (black) and simulated driven by Onslow wind (red) and 1-hourly MesoLAPS winds (green) current speeds and directions at "Jetty" location for March 2009.

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D-36

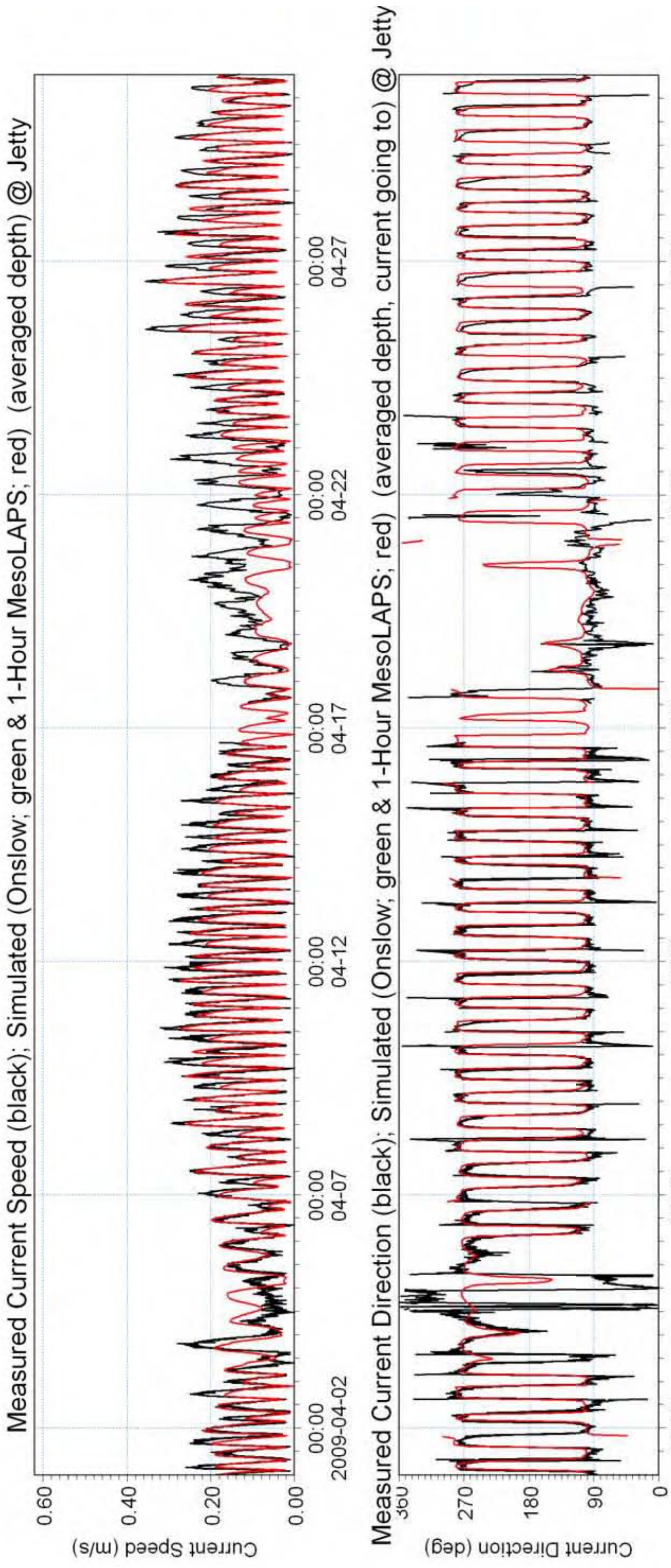

Figure D.31 Time series comparison of measured (black) and simulated driven by Onslow wind (red) and 1-hourly MesoLAPS winds (green) current speeds and directions at "Jetty" location for April 2009.

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D-37

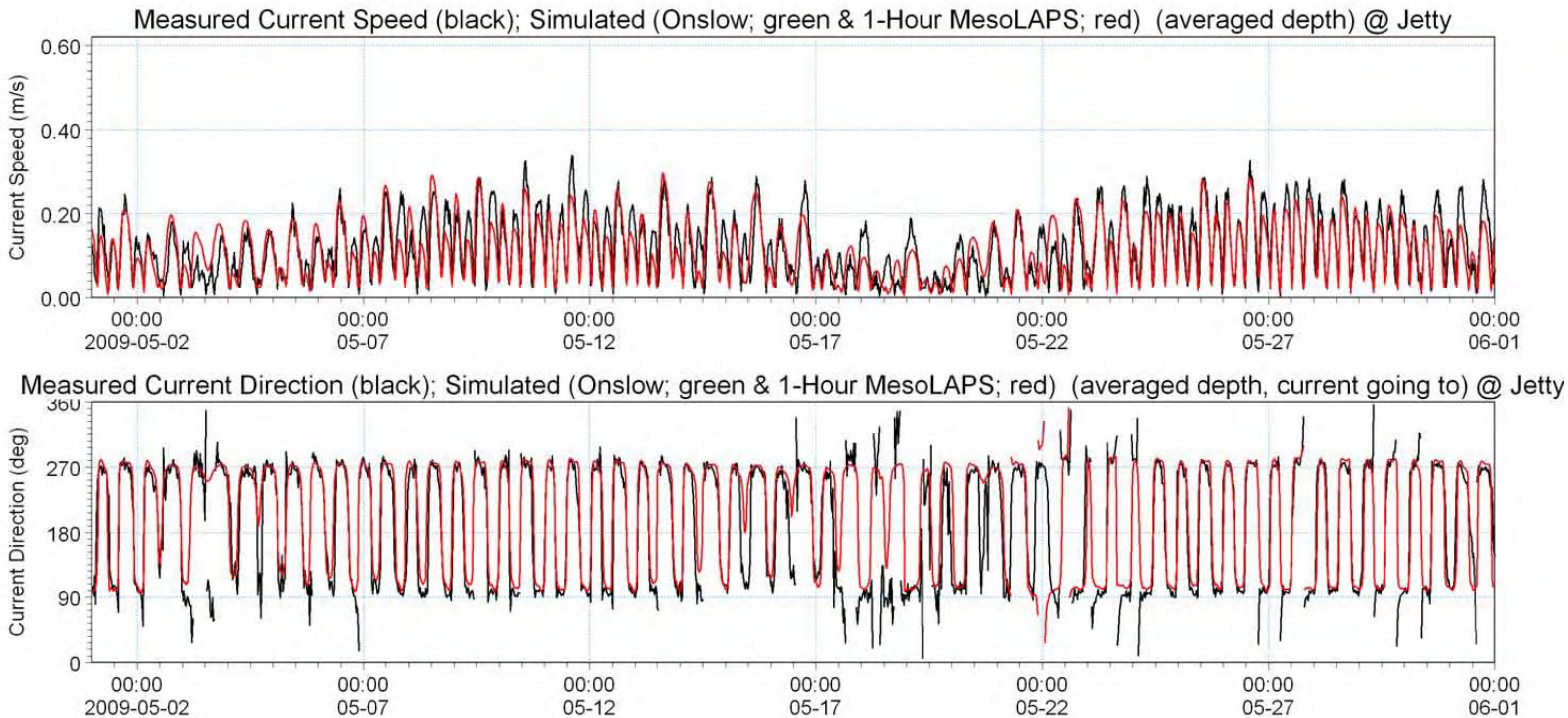

Figure D.32 Time series comparison of measured (black) and simulated driven by 1-hourly MesoLAPS winds (green) current speeds and directions at "Jetty" location for May 2009.

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D-38

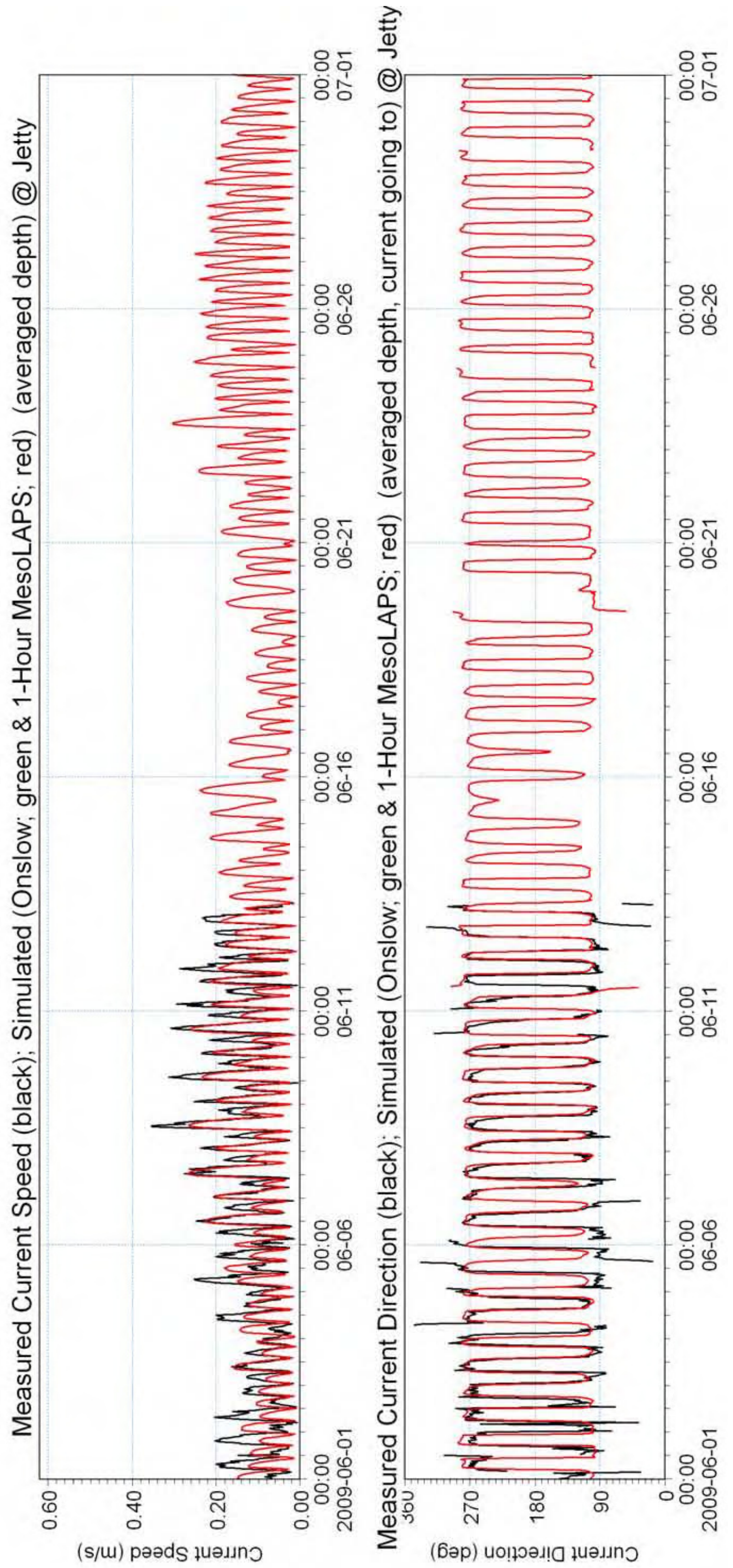

Figure D.33 Time series comparison of measured (black) and simulated driven by 1-hourly MesoLAPS winds (green) current speeds and directions at "Jetty" location for June 2009.

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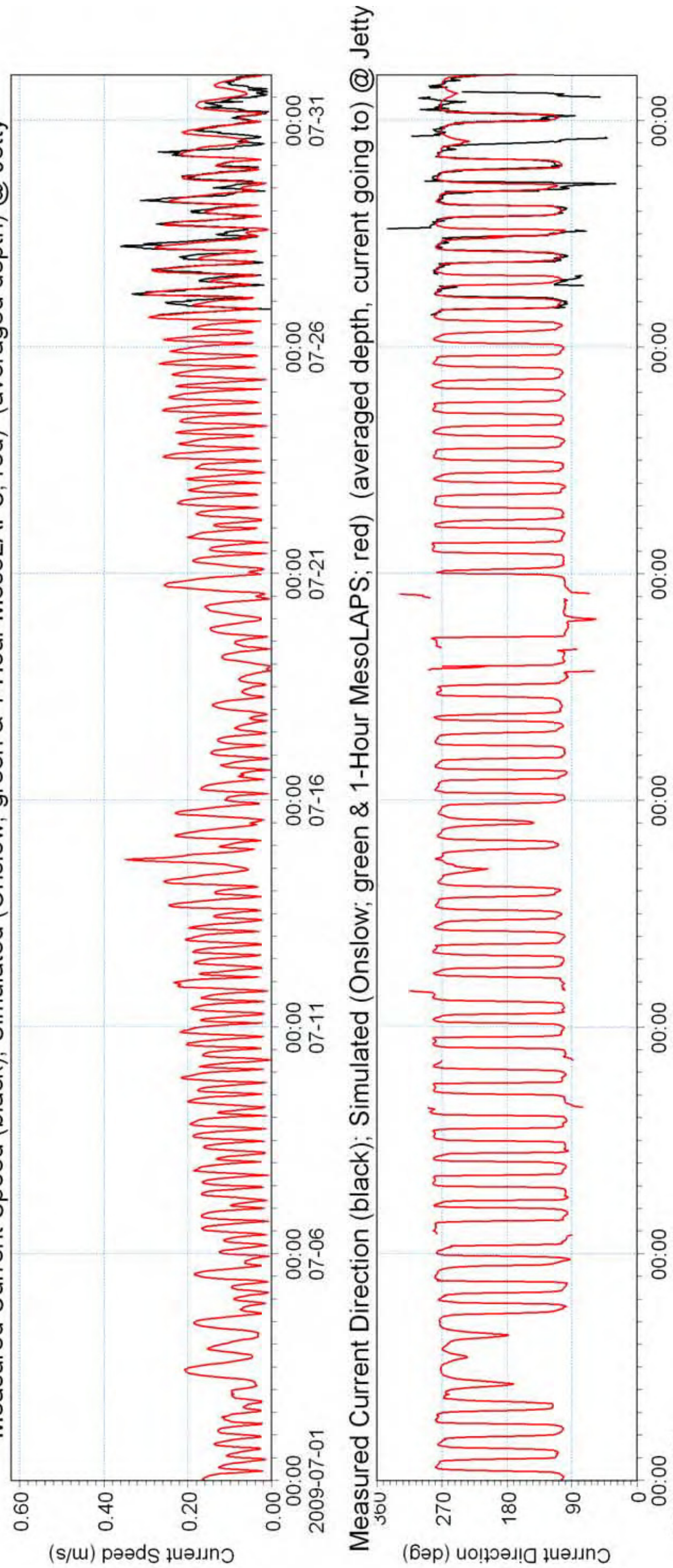

Figure D.34 Time series comparison of measured (black) and simulated driven by 1-hourly MesoLAPS winds (green) current speeds and directions at "Jetty" location for July 2009.

D-40

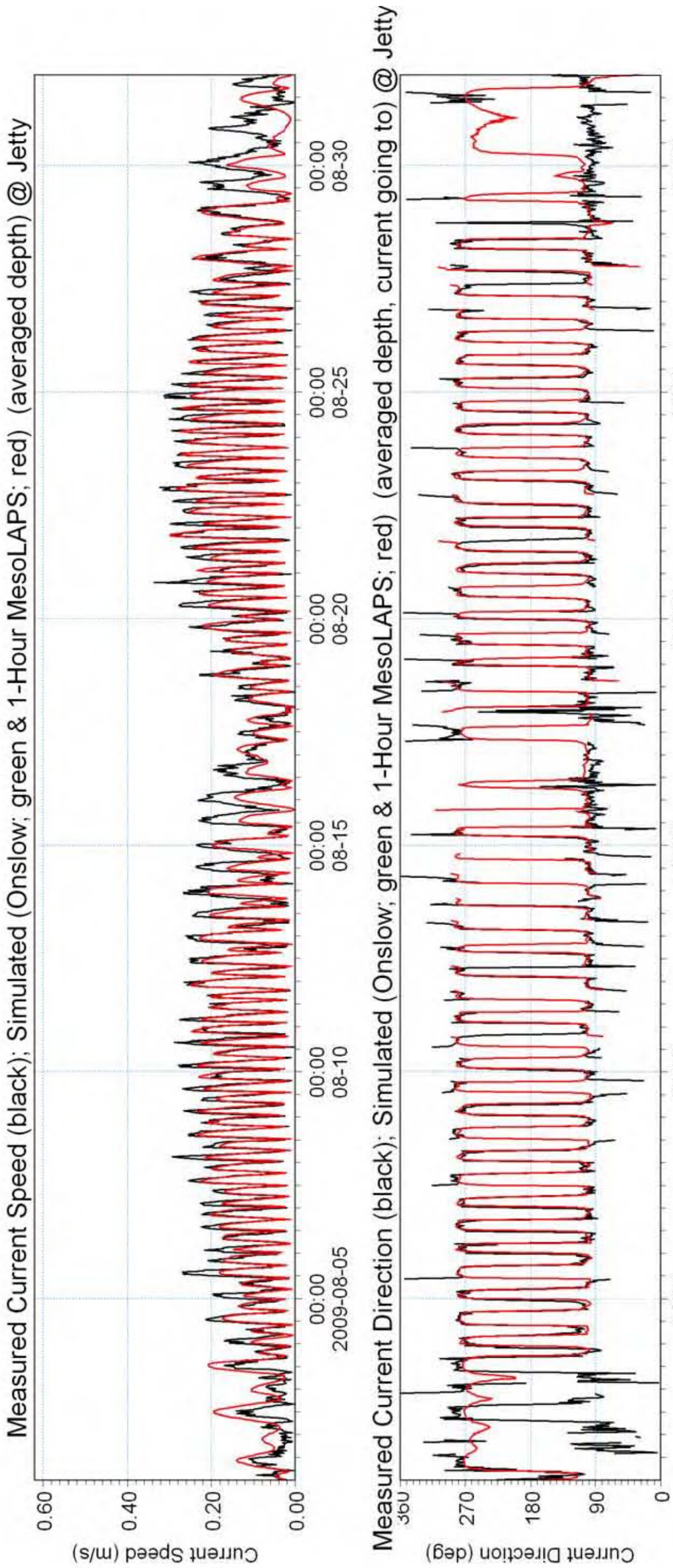

Figure D.35 Time series comparison of measured (black) and simulated driven by 1-hourly MesoLAPS winds (green) current speeds and directions at "Jetty" location for August 2009.

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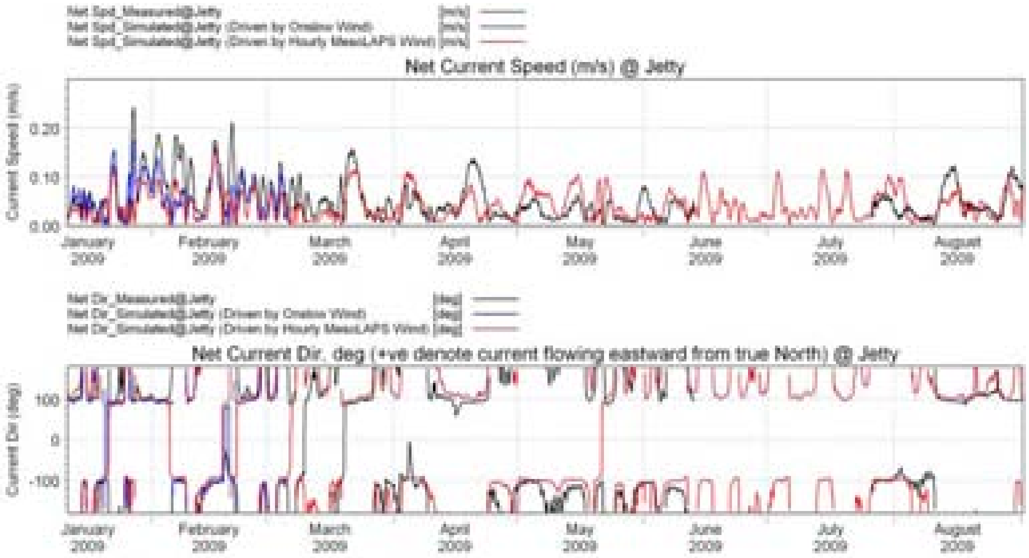

Figure D.36 Time series of net currents (averaged over a tidal cycle) at the "Jetty" location derived from the data (black) and compared to model simulations driven by Onslow Wind (blue) and 1-hour MesoLAPS wind (red).

D.5.2 "Channel" Measurements

Only a relatively short record is available from the "Channel" location at the time of writing. Comparison of measured and simulated current speeds and directions are illustrated in Figure D.37 together with simultaneous wind speeds and directions extracted from the MesoLAPS data at Thevenard Island. Only MesoLAPS winds are currently available for this period, and only the MesoLAPS driven model has been run. Net currents from data and model are compared in Figure D.38.

Current amplitudes are generally well captured, and net currents, both easterly and westerly, are also well captured. It is noted that the net currents change between being easterly and westerly directed.

As additional data becomes available, further validation will be carried out.

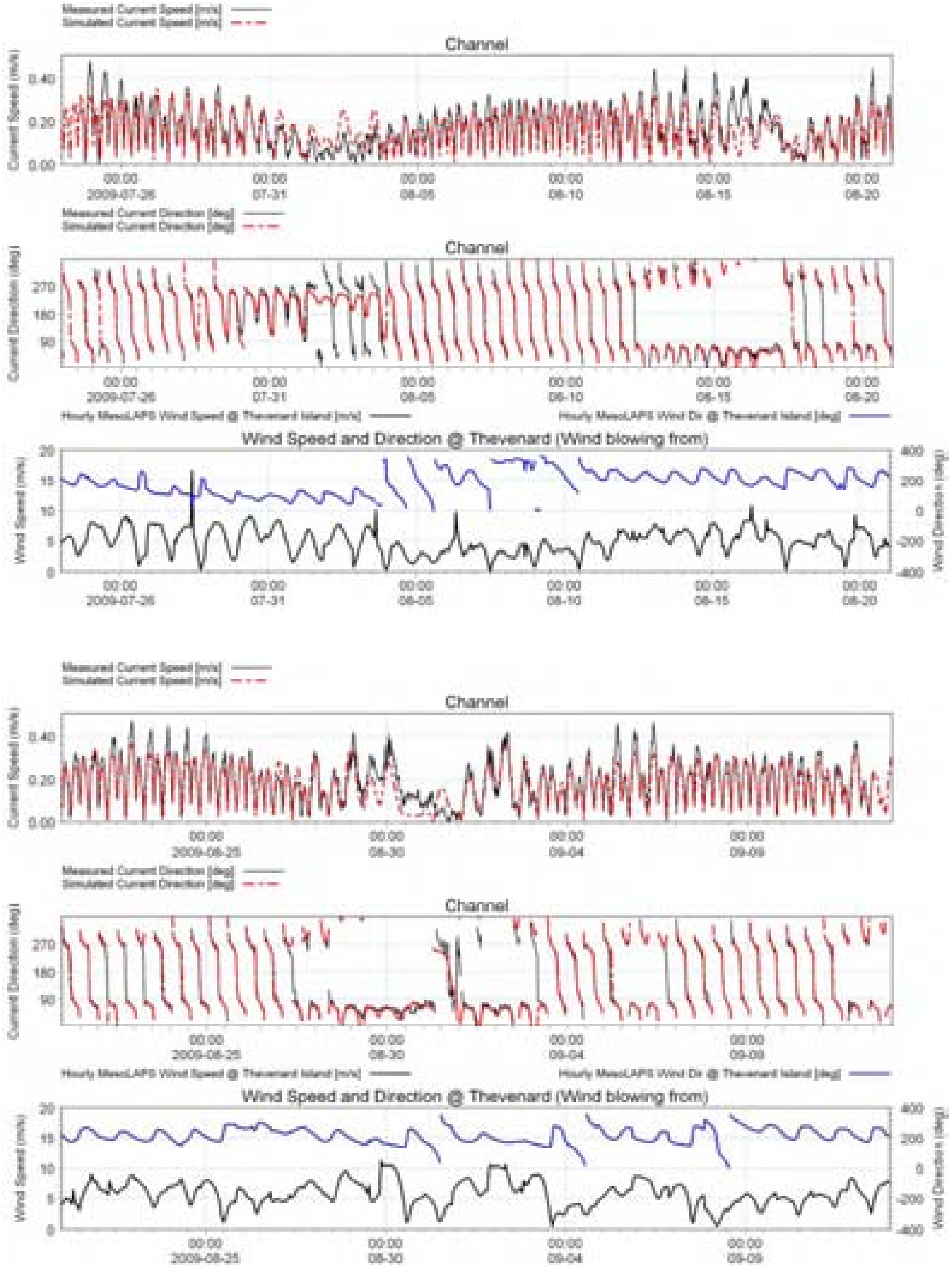

Figure D.37 Time series of net currents (averaged over a tidal cycle) at the "Channel" location derived from the data (black) and compared to model simulations driven by 1-hour MesoLAPS wind (red).

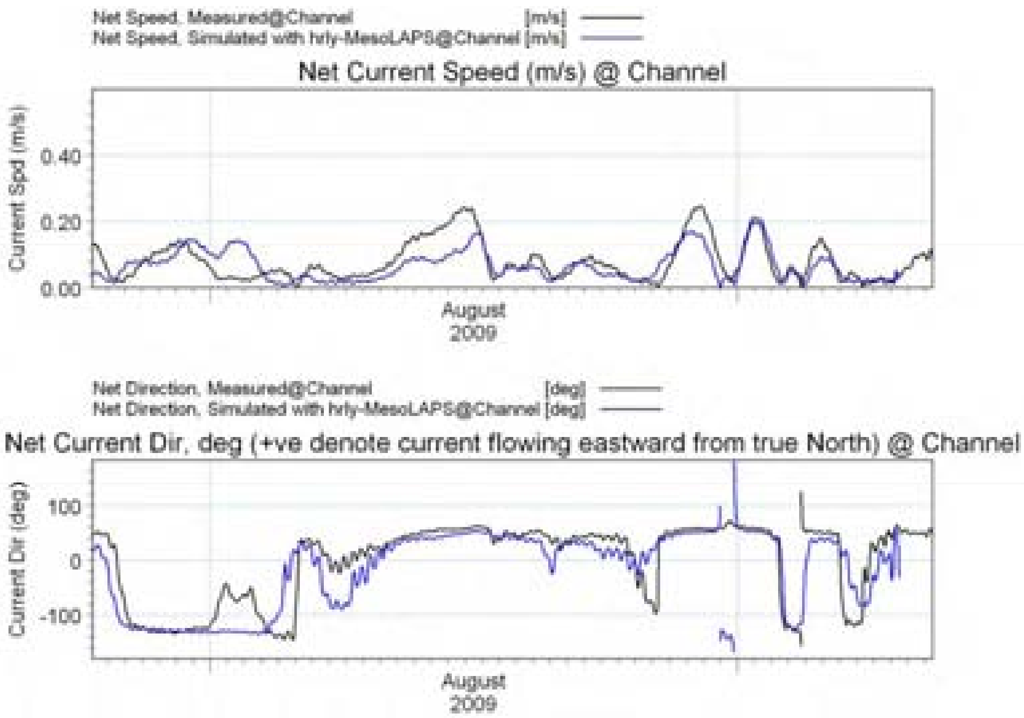

Figure D.38 Time series of net currents (averaged over a tidal cycle) derived from the data and model simulations for the "Channel" location. Simulations are driven by 1-hour MesoLAPS winds.

D.5.3 "Spoil Ground" Measurements

Validating the 2D model against the "spoil ground" measurements in deep water is less relevant as there are clearly wind-driven current profiles over the larger water depths in this area, and the 2D model complex is not applied for simulations in the deeper water. Performance of the 3D modelling complex is reported separately in Appendix E. However, for completeness, a comparison to the measured data has been carried out for models run with Onslow, Barrow Island and 1-hour MesoLAPS winds.

Comparisons of depth-averaged currents are shown in Figure D.39 to Figure D.47 for the three wind sources. Model discrepancies at this location are larger than in the shallower areas as expected. Tidal currents are weaker, and the wind driven currents dominate a larger portion of the time, which is clearly seen through extended periods with no current reversal. Whereas using the Barrow Island winds clearly helps compared to the simulations based on the Onslow Met Station winds in some periods – see e.g. the period 14-17/2, this is not always the case. 1-hour MesoLaps winds similarly also improve the model performance over the Onslow winds at some times, but not throughout the period.

It is noted that very limited dumping is presently planned at the off-shore dump site. Furthermore, this area is remote from any sensitive habitats. It is noted that wind driven current profiles are more pronounced in the deeper water, and 3D modelling is therefore applied. As the 2D model is capable of reproducing tidal amplitudes and net current patterns, the 3D model will similarly reproduce this and further improve the distribution over depth. Net currents from data and model are compared in Figure D.48, showing a fairly good agreement for the depth-averaged net currents.

D-44

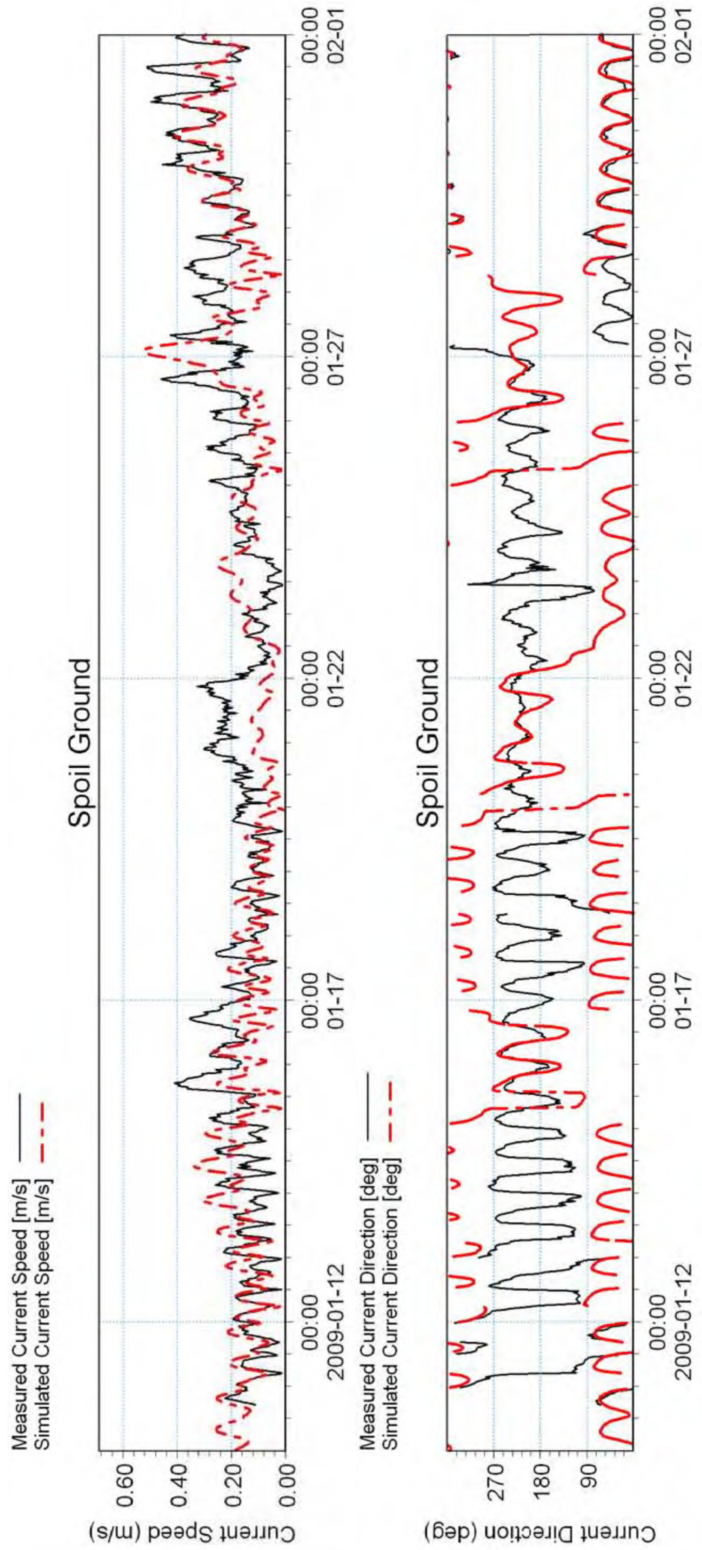

Figure D.39 Time series comparison of measured and simulated current speeds and directions at "spoil ground" location. Model driven by Barrow Island winds.

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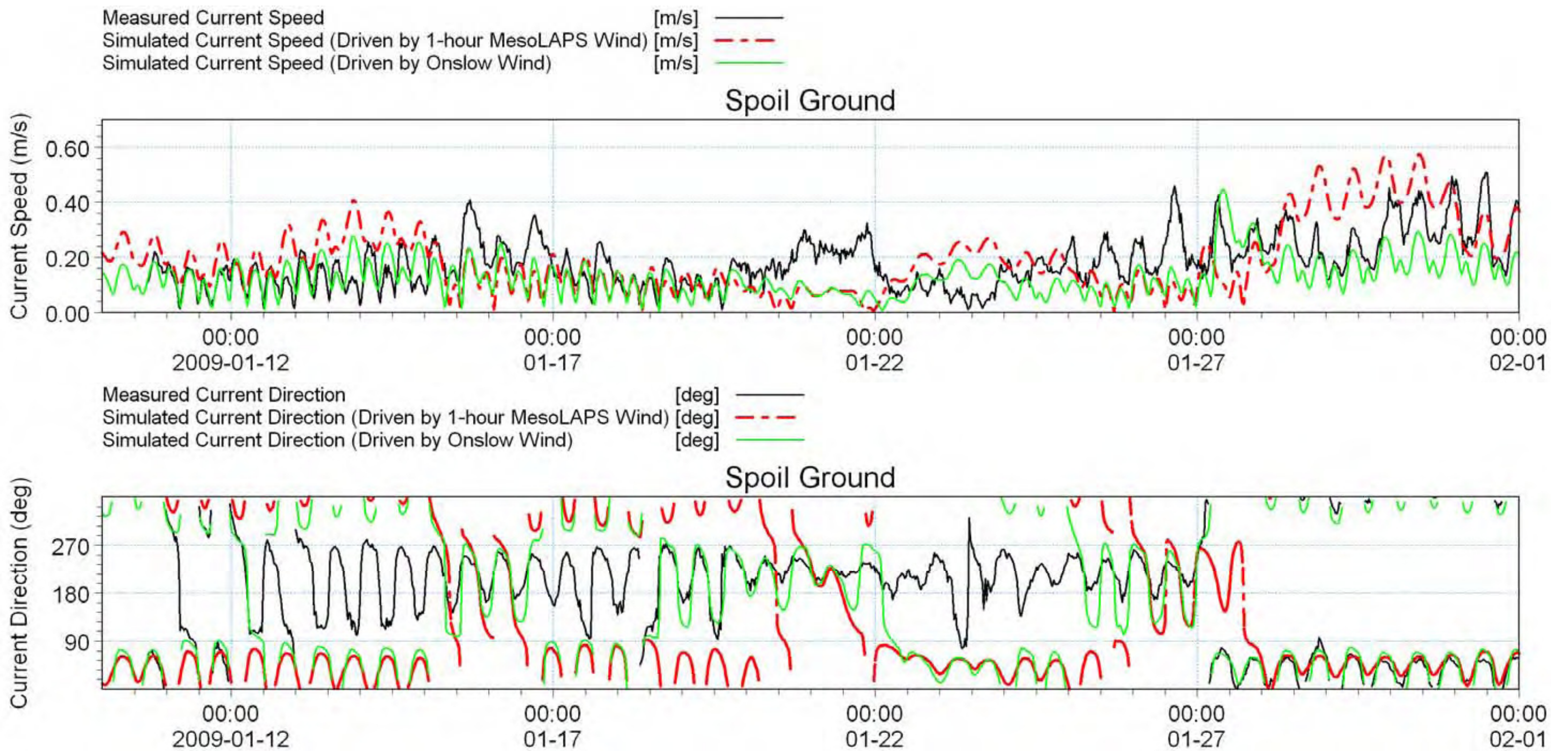

Figure D.40 Time series comparison of measured and simulated current speeds and directions at "spoil ground" location. Model driven by Onslow winds (red) and 1-hour MesoLAPS winds (green).

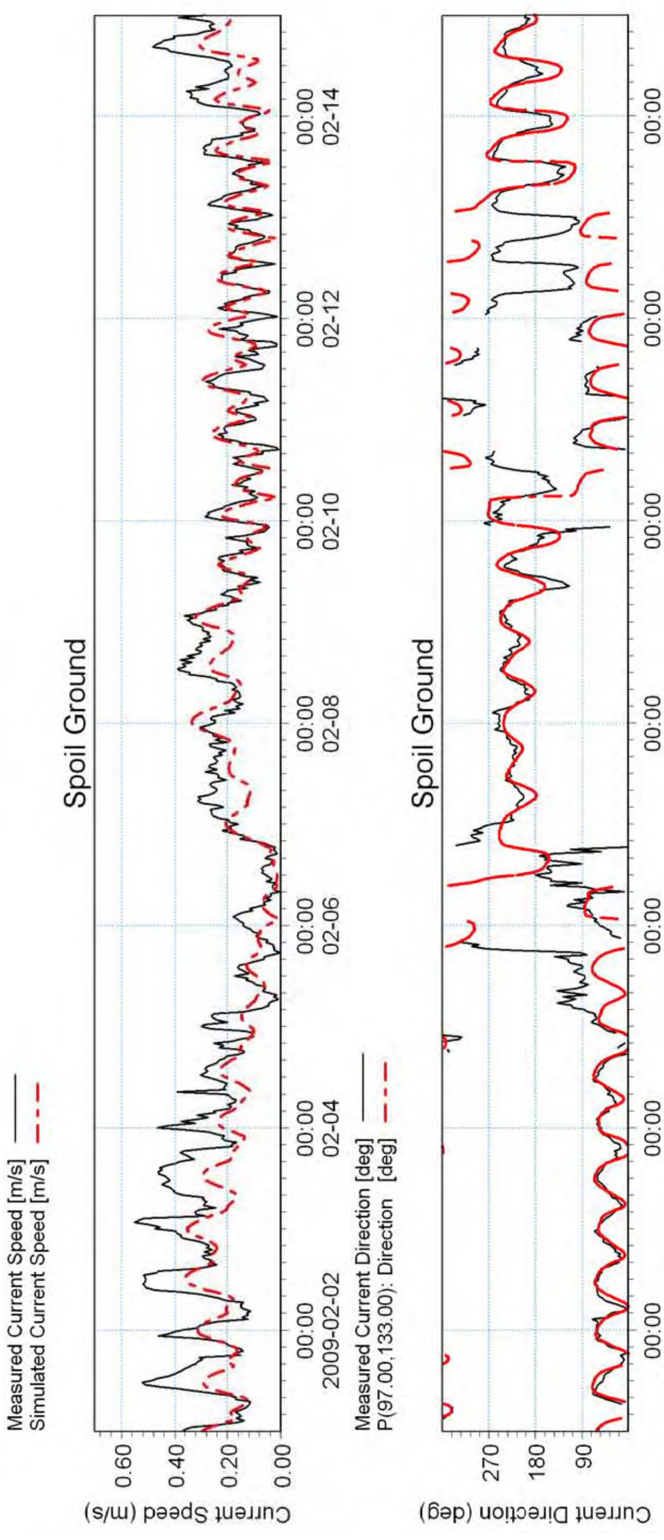

Figure D.41 Time series comparison of measured and simulated current speeds and directions at "spoil ground" location. Model driven by Barrow Island winds.

D-47

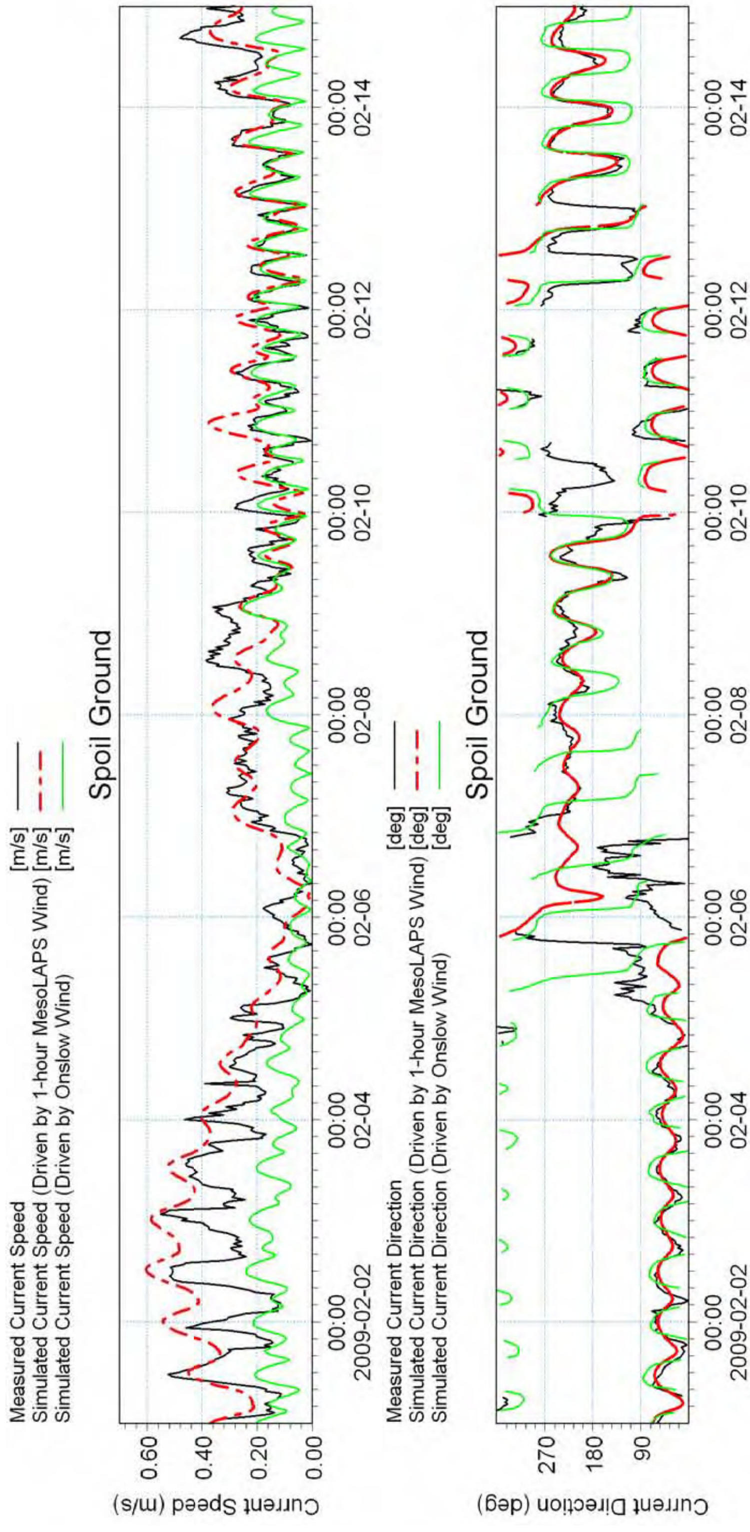

Figure D.42 Time series comparison of measured and simulated current speeds and directions at "spoil ground" location. Model driven by Onslow winds (red) and 1-hour MesoLAPS winds (green).

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D-48

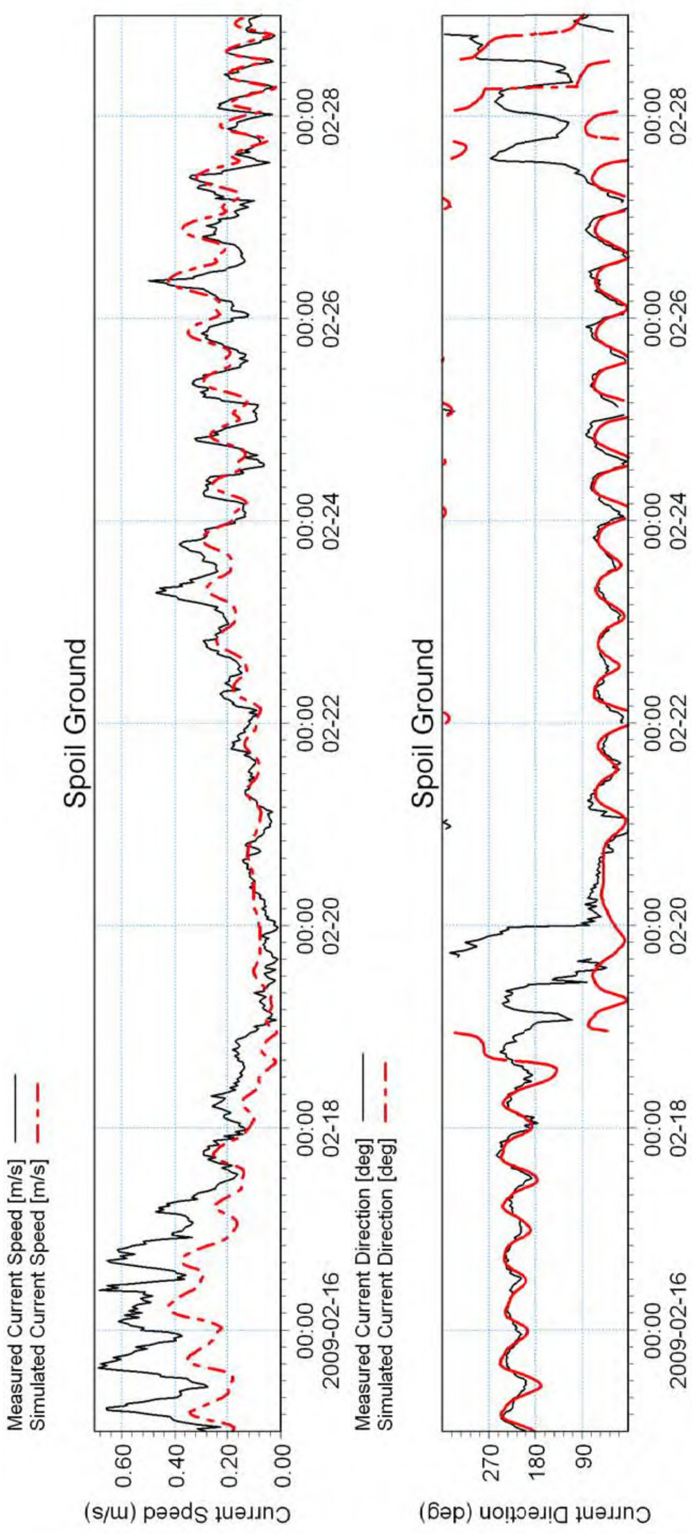

Figure D.43 Time series comparison of measured and simulated current speeds and directions at "spoil ground" location. Model driven by Barrow Island winds.

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D-49

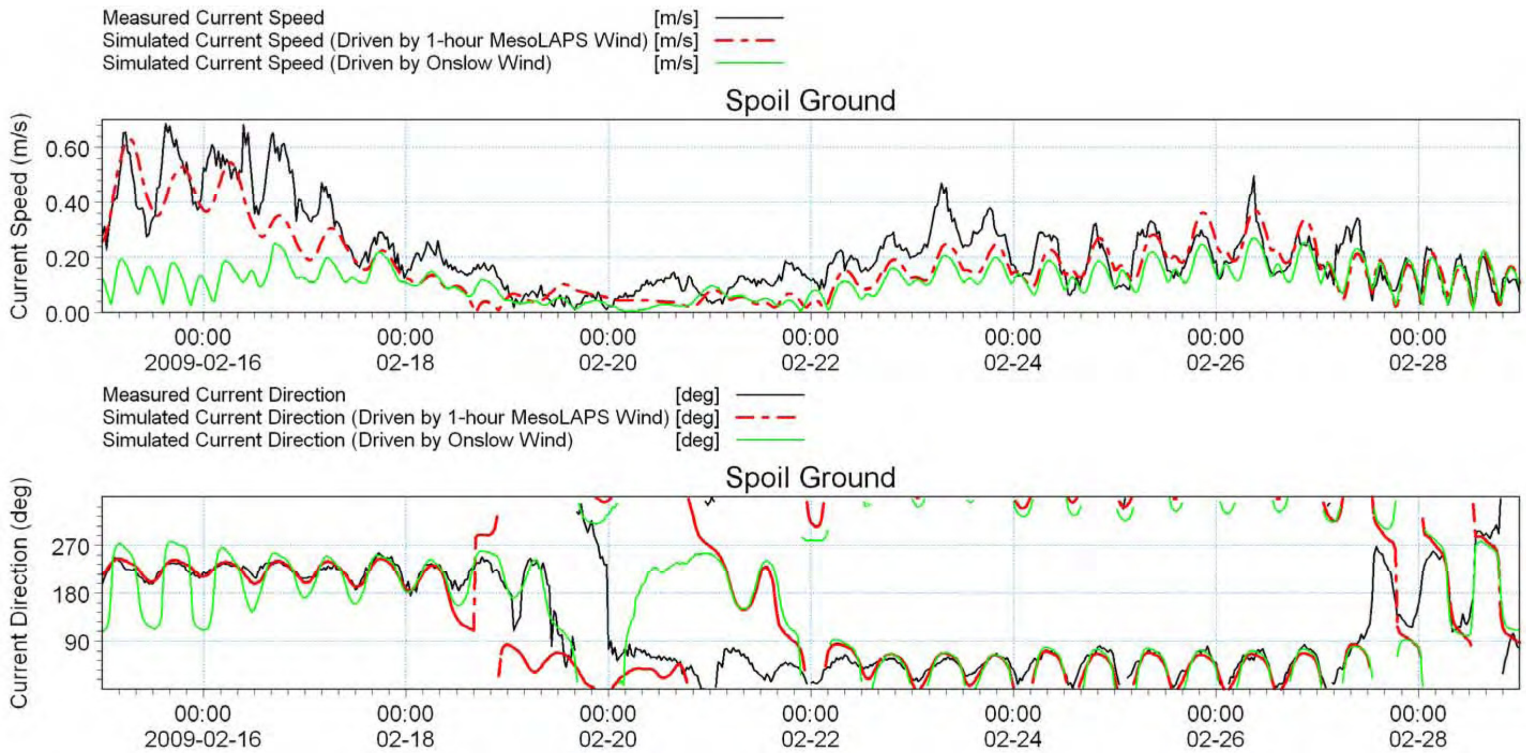

Figure D.44 Time series comparison of measured and simulated current speeds and directions at "spoil ground" location. Model driven by Onslow winds (red) and 1-hour MesoLAPS winds (green).

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D-50

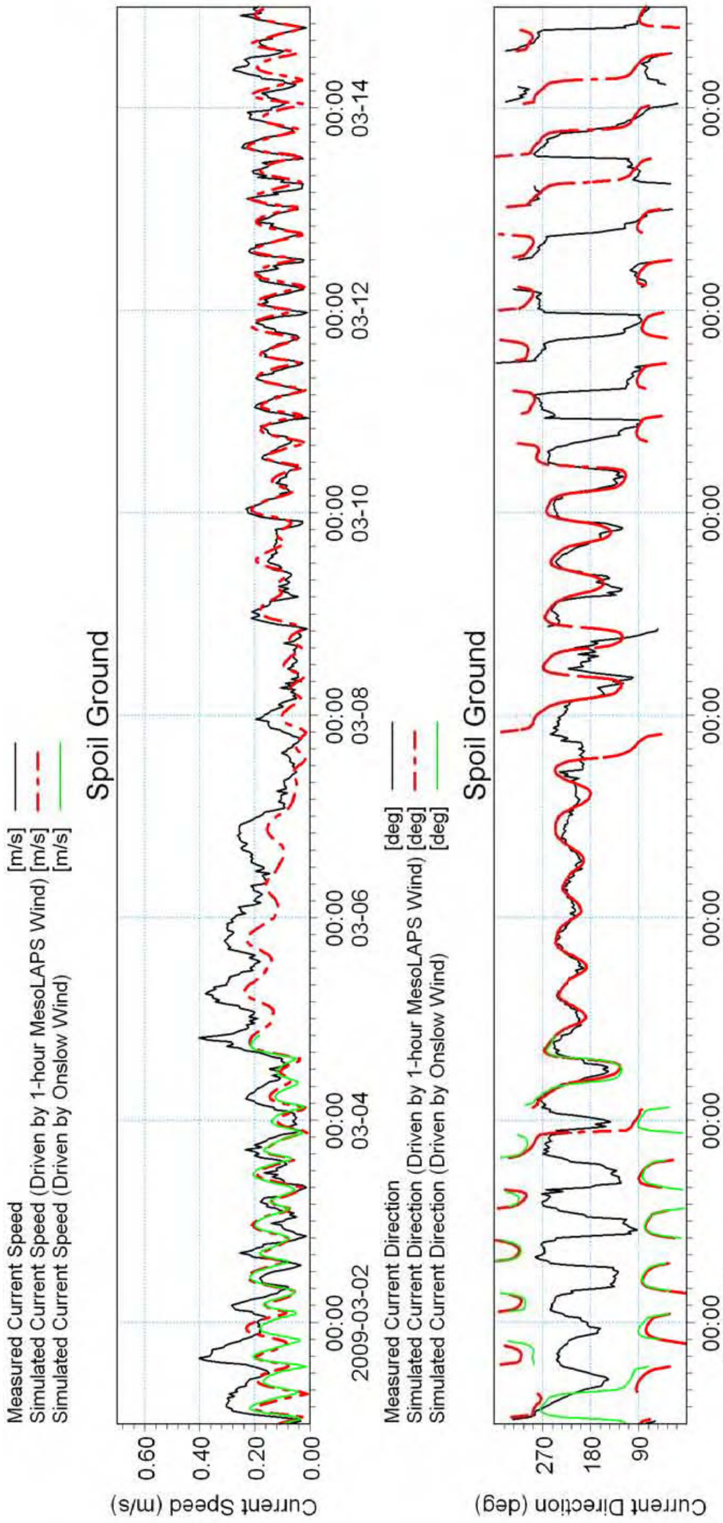

Figure D.45 Time series comparison of measured and simulated current speeds and directions at "spoil ground" location. Model driven by 1-hour MesoLAPS winds (red).

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D-51

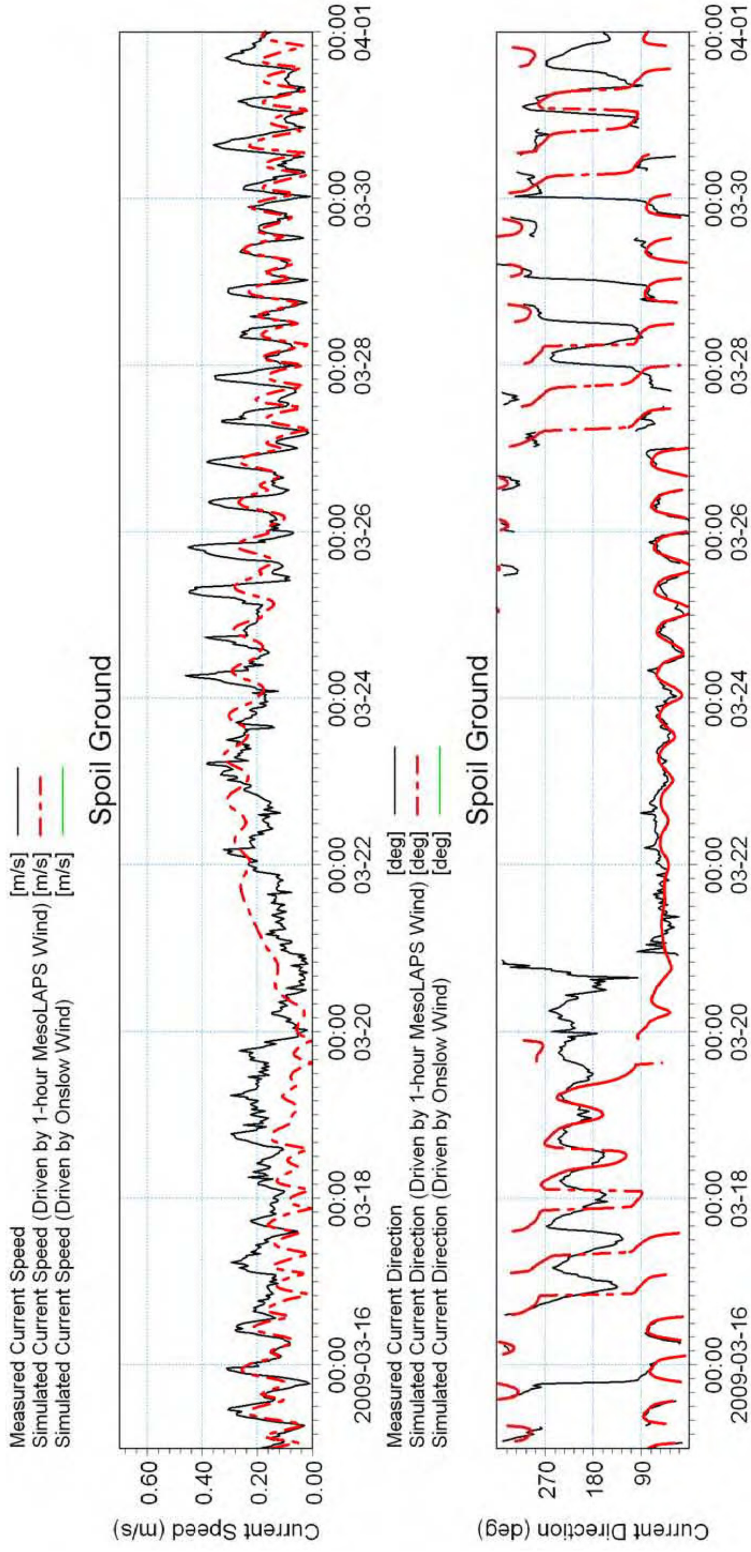

Figure D.46 Time series comparison of measured and simulated current speeds and directions at "spoil ground" location. Model driven by 1-hour MesoLAPS winds (red).

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D-52

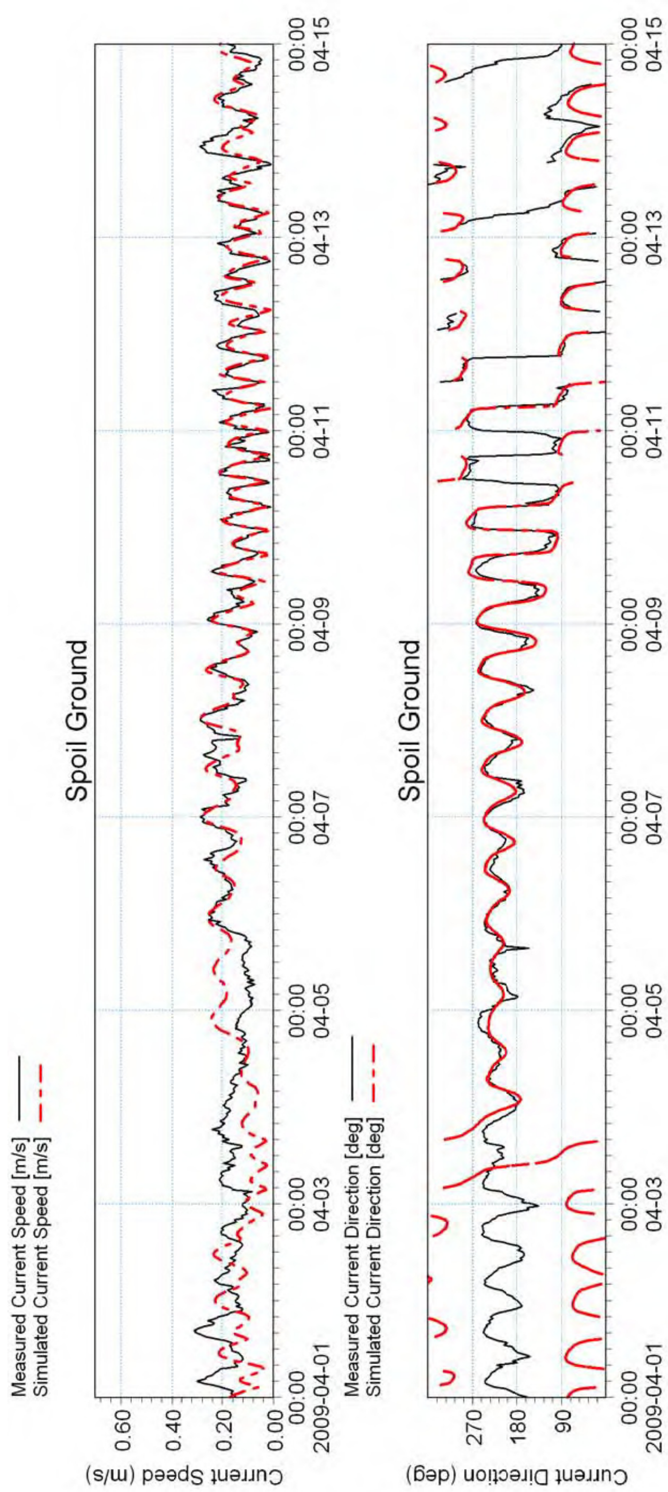

Figure D.47 Time series comparison of measured and simulated current speeds and directions at "spoil ground" location. Model driven by 1-hour MesoLAPS winds (red).

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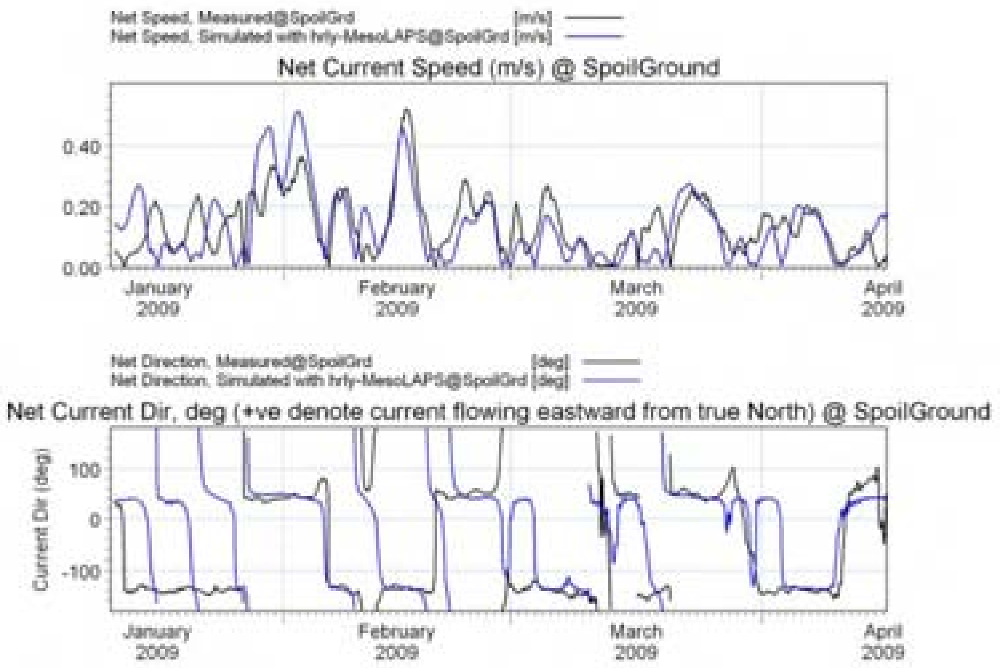

Figure D.48 Time series of depth-averaged net currents (averaged over a tidal cycle) derived from the data and model simulations driven by 1-hour MesoLAPS winds for Spoil ground.

D.6 Quantification of Model Performance

The comparison between measured and modelled flow properties was presented above and from a qualitative visual inspection the models seem to perform well. A more quantitative measure of model performance is provided in the following by using statistical analysis of the differences in modelled and measured flow properties.

The values of such statistical analysis are trialled against the intervals of confidence as outlined per international standards in the UK Foundation for Water Research (FWR) publication on hydraulic model calibration works (UK Foundation for Water Research (FWR) (1993): Publication Ref FR0374 - *A framework for marine and estuarine model specification in the UK*, March 1993).

D.6.1 Performance Criteria

The evaluation of whether an established model provides a sufficiently accurate description of measurable flow properties depends in general on the specific objective of the model. In practice, achievable quality depends on several factors, such as:

- The basics of the numerical model, such as processes included and their formulations.
- The quality of the available forcing conditions, initial conditions and bathymetric information for the model domain.
- The quality of the calibration and validation data for comparison with model results. It should be noted that there is also uncertainties related to the measurements, and performance criteria only can be expected fulfilled for high quality monitoring data without dubious signals and for periods where the forcing data are of general high quality.
- The complexity of the area and processes being simulated

An appropriate internationally accepted standard for the validation of hydrodynamic model performance can be found in the UK Foundation for Water Research (FWR, 1993) publication on hydraulic model calibration works. The standard within coastal areas defines the following intervals of confidence (performance limits):

- Tidal elevation error: RMS(error) < 0.1m;
- Current speed deviation RMS(error) < 0.1m/s;
- Current direction error RMS(error) < 10-20 deg

Where RMS = Root Mean Square. According to /8/ the criteria outlined above will be too testing at all times and for all regions of a model area, and a less stringent expectation is therefore normally accepted. This normally involves that intervals of confidence are to be fulfilled for 90% of time/locations.

Note that the intervals given above for coastal areas are the most strict of the standards given in FWR (1993) as standards applied to e.g. estuarine areas are more relaxed. The morphological setting for this project is recognized as being complex with numerous islands, fringing reefs and with intricate systems of large scale bed forms and channels scoured around the islands and reefs. Consequently; above standards are considered to be very strict for the area.

D.6.2 Tidal Elevations & Water Levels

In Table D.3, the match between predicted and modelled tidal elevations at various tidal stations is presented using RMS as well as the BIAS parameter. The BIAS parameter gives an indication of whether the model have a tendency for over-predicting (positive value) or under-predicting (negative value) the tidal levels. Referring to the performance criteria listed above the RMS (Root Mean Square) error for tidal elevations should preferably be less than 0.10 m. This is fulfilled for all stations at all locations. With all BIAS-values being only a few cm the modelled tidal elevations are considered to be acceptable, and well within the performance criteria. It is noted that the RMS and BIAS values are derived from the full time-series.

Table D.3 Model RMS errors on tidal elevations comparing to a number of tidal stations in the area.

Tidal Station	Period	BIAS [m]	RMS [m]
Exmouth	2006	0	0.06
Onslow	2006	0.01	0.08
Serrurier	2006	0.01	0.06
Tantabiddi	2006	0	0.04
Thevenard	2006	0.01	0.06
Wapet_Landing	2006	0.03	0.09

The comparison to tidal stations (predicted tidal elevations based on tidal constituents) in Table D.3 demonstrates the capability to simulate the tidal elevations (which have a large gradient in amplitude going along the coast as demonstrated in the data section). Measured water levels further comprise setup generated by wind and pressure fields. A comparison of water levels, with the wind included in the model, has been carried out for the available records at site. Table D.4 and Table D.5 show the match between measured and modelled water levels at available stations using RMS as well as the BIAS parameter. The first table below provides values from the 2006 campaign whereas the second table provide values for the 2009 campaign. Again, the overall performance of the model is good and values are seen to fall within intervals of confidence as per outlined in /8/ for coastal areas.

Table D.4 Model RMS errors on water levels comparing to available records from the 2006 data, see Figure D.5 for locations.

Location	BIAS	RMS
P6	-0.02	0.12
P8	-0.01	0.08
P9	0	0.09
P10	-0.01	0.09
P11	-0.03	0.09

Table D.5 Model RMS errors on water levels comparing to available records from the 2009 data, see Figure D.5 for locations.

Location	BIAS	RMS
Channel	0	0.09
Jetty015	-0.01	0.06
Jetty051	0	0.08
Jetty052	0.01	0.09

D.6.3 Current Speeds & Directions

Table D.6 shows the match between modelled and measured depth-averaged current speeds at locations 3 through 11 (see Figure D.5 for sketch of locations). The modelled currents are obtained with the Onslow winds as well as the MesoLAPS winds. Directions for very low current velocities are poorly defined and associated with a large uncertainty in the measurements. Currents with speeds less than 5 cm/s, which is the expected order of magnitude of uncertainty on field measurements, have been ignored in the calculation of the RMS.

Referring to the performance criteria listed above, the RMS error for speed in coastal areas should preferably be less than 0.10 m/s. This is fulfilled for all stations at all locations.

The current directions fall within the performance criteria for coastal waters for 90% of the time. There are RMS values that are close to the limit, e.g. P3, P6 and P9. A detailed plot of the local bathymetry, see Figure D.49, shows that the local bottom is not flat, and the three stations are placed along a channel/ridge formation which will affect local current patterns and may well affect the measured current directions. The simulated values are derived from a relatively coarse grid model, and it is thus not surprising that some discrepancies between measured and simulated directions occur.

The quantitative performance of the models driven by Onslow and MesoLAPS winds is fairly similar on a broader scale with some smaller differences at individual stations.

Table D.6 Model RMS errors on current speeds and directions driven by Onslow winds and hourly MesoLAPS winds comparing to available records from the 2009 data, see Figure D.5 for locations.

Location	Onslow Winds		MesoLAPS Winds	
	RMS [m/s]	RMS [Deg.]	RMS [m/s]	RMS [Deg.]
P3	0.052	19.8	0.056	19.8
P4	0.056	16.4	0.064	16.6
P6	0.063	19.7	0.054	18.9
P7	0.092	12.5	0.062	11.5
P8 - 1	0.053	17.1	0.061	17.8
P8 - 2	0.034	12.7	0.043	13.5
P9	0.071	18.1	0.079	17.1
P10	0.059	14.9	0.042	10.6
P11	0.081	15.7	-	-
Jetty015	0.081	16.5	0.057	13.5
Jetty051	0.054	12.5	0.070	12.6
Jetty052	0.039	12.0	0.054	12.9
Channel	0.061	10.2	0.044	10.4
Spoil Ground	0.108	19.7	0.096	18.6

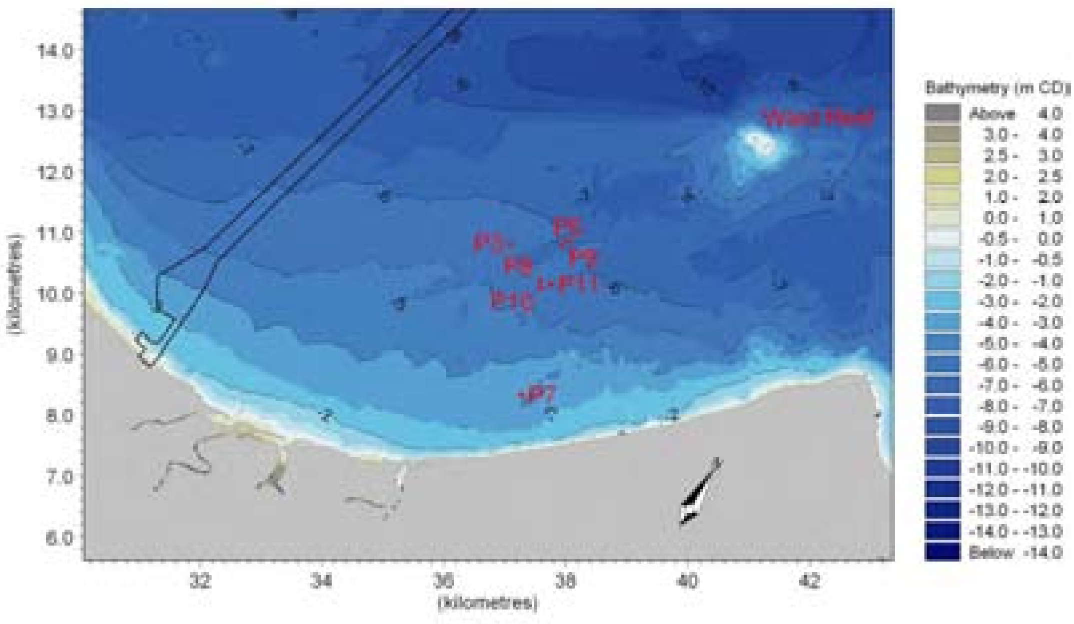

Figure D.49 Details of bathymetry at the 2006 measuring stations for currents.

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Wheatstone Project
Dredge Spoil Modelling

APPENDIX E:

Sediment Transport Modelling Using 2D vs 3D Hydrodynamics

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CONTENTS

FIGURES AND TABLES

E SEDIMENT TRANSPORT MODELLING USING TWO-DIMENSIONAL VS THREE-DIMENSIONAL HYDRODYNAMICS

This appendix presents a detailed discussion of the pros and cons of conducting sediment transport modelling driven by either two-dimensional or three-dimensional hydrodynamics. These discussions are presented both in general, and with reference to the project-specific conditions associated with the Wheatstone Project.

Additional information relevant to the material presented in this appendix may be found in the following sections of the main report and supporting appendices:

- Section 4.1 *Development of Local and Regional Hydrodynamics*
- Section 4.3 *Development of the Sediment Transport Model*
- Section 6.1.1 *Dredge Scenarios*
- Appendix D *Hydrodynamic Model Validation and Calibration*
- Appendix H *3D Hydrodynamic Model Setup and Calibration*

E.1 Introduction

An important component of the methodology defining stage for dredge plume modelling is to determine whether there are three-dimensional processes that need to be resolved. The selected model should reflect the degree of three-dimensionality and temporal variability inherent in the problem under consideration. If the problem is governed by three-dimensional processes then a three-dimensional model is required. However, often the degree of three-dimensionality is not significant and is of a complexity which can be adequately represented by a two-dimensional depth-averaged model.

For problems with a high degree of three-dimensionality state-of-the-art, high resolution computational fluid dynamics (CFD) models may be required. However, for the purposes of conducting assessments in support of EIAs engineering (oceanographic) three-dimensional models are typically sufficient to resolve the critical three-dimensional processes.

There is a wide range of available tools for modelling sediment plumes and the choice of an appropriate model and modelling methodology needs to be guided by the the objectives of the study and the degree of complexity of the system under consideration.

DHI’s two-dimensional depth-averaged models make use of sub-models for various three-dimensional phenomena such as helical flow, logarithmic velocity profile, vertical profile of concentration etc and are perhaps better described as being semi-three-dimensional models as opposed to two-dimensional.

Thus, choosing an appropriate plume model for the given study requires:

- An understanding of the scope and the complexity of the problem
- A model that can resolve governing processes to required level of detail.

As noted above, problems dominated by processes that are not three-dimensional, or have moderate three-dimensionality can often be handled by a depth-averaged (two-dimensional) model. Using a two-dimensional model in preference to a three-dimensional model brings along certain modelling benefits which must be carefully considered and weighed against the overall objectives of the study. When compared with three-dimensional modelling, the increase in computational efficiency of two-dimensional models may be utilised by increasing grid resolution or the size of the study region. Additionally, the differences in the computational requirements of two-dimensional and three-dimensional models mean that more two-dimensional simulations can be completed within a shorter timeframe than using a three-dimensional model. This turn-around time becomes important when feedback from model results is required as input into project-related decisions.

Three-dimensional processes typically increase the dispersion of a sediment plume, e.g. through a stretched velocity profile over the depth with the sediments at the surface moving faster away from the source than the sediments lower in the water column, or by differences in direction over the depth which will also lead to a “transverse” dispersion. For a point source, it may be critical to include three-dimensional processes to capture the full impact area.

The increased dispersion due to three-dimensional processes may partly be included in a two-dimensional model. If the dispersion is maintained relatively low in the two-dimensional model, the lower dispersion compared to the three-dimensional situation may lead to higher concentrations further away from the source, and the resulting impact zone likely stretching further away from the source in the main transport direction.

If a two-dimensional model is combined with a scenario modelling approach (see Appendix F), it may well lead to larger impact zones than a three-dimensional modelling approach. The differences are illustrated in Figure E.1. The left side illustrates a single full dredge period simulation for a channel dredged progressively over a period of 2.5 years with assumed net westerly currents during winter and net easterly currents during summer (similar to the hydraulic conditions at Wheatstone). This leads to impacts predominantly to the west of the channel for the stretches dredged during winter and predominantly to the east of the channel for the sections dredged during summer. This footprint will be accurately delineated only if the climatic conditions over the 2.5 years are correctly predicted and the timing and dredging is in continuous accordance with the schedule of the dredge programme.

At the EIA stage, changes in the schedule and/or dredge methodology are almost inevitable, and a preferred approach is therefore to use combinations of dredging and climatic scenarios to cover a full spectrum of possible conditions for each segment of the channel. The centre figure of Figure E.1 illustrates impact zones from dredging a given section of channel under various climatic conditions, i.e. the impact zones stretch away from the dredge channel on both sides. It has been assumed that the three-dimensional model is more dispersive than the two-dimensional model, and thus the two-dimensional impact zone is narrower but stretches further from the channel (assuming the predominant current direction is more or less perpendicular to the channel).

By carrying out the dredging along the entire channel, and combining all relevant climatic conditions, an envelope of impact zones is extended along the channel. The “wider” impact zone from three-dimensional for a single channel segment is covered in the two-dimensional by dredging of the adjacent channel segment. The “longer” impact zone (in terms of impacts with distance from the channel) associated with the two-dimensional model therefore leads to a wider impact zone on either side of the channel. The figure on the right of Figure E.1 shows the impact envelope for the two-dimensional model along the entire channel. The corresponding three-dimensional envelope would be narrower (as indicated in the centre plot of Figure E.1). This may be considered conservative, but on the other hand, it is likely that there will be times where stronger, unidirectional currents dominate, and the higher concentrations simulated by the two-dimensional model may be realised. If such periods are not captured in the simulated climatic conditions, there is a risk that the higher dispersion associated with three-dimensional model may be non-conservative.

Foot-print of full dredging period simulation over 5 seasons.

Composite impacts for 2D/3D dredging along one channel section. 3D model is typically more dispersive and 2D impact zone stretches further from source

Composite impacts with 2D model (all scenarios combined with dredging for all climatic conditions along entire channel length)

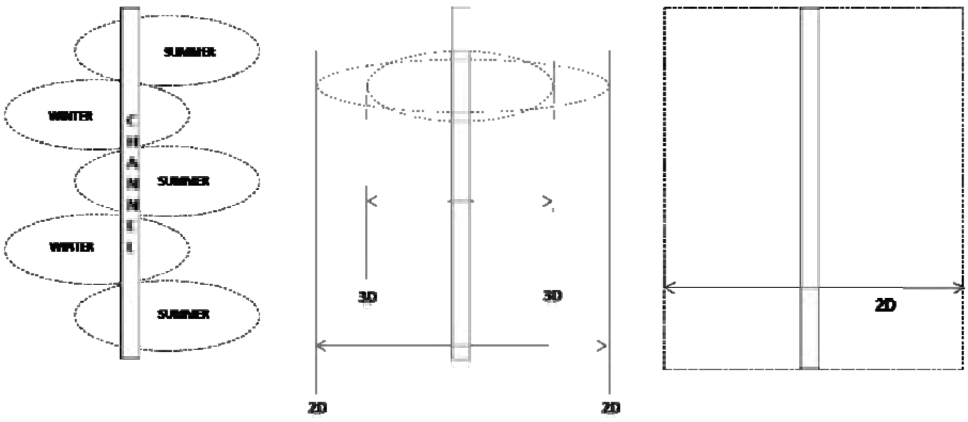

Figure E.1 Outline of impact zones for various models and simulation strategies.

E.2 Model Selection

An overview of the pros and cons of two-dimensional versus three-dimensional models is presented in Table E.1. As outlined, three-dimensional models have their strengths in being able to resolve processes in all directions and therefore resolve some vertical processes whereas depth-averaged models (two-dimensional) are computationally more efficient and can be used in cases where the three-dimensionality is limited and the current profile sufficiently resolved by the assumption of a logarithmic profile.

Table E.1 Pros and Cons for 2D versus 3D modelling

Model	Pros	Cons.
2D 2D	Computationally effective, which leads to the possibility of: High Horizontal resolution Large Coverage Acceptable Computational Simulation Periods Large Number of Scenarios	Do not resolve all processes accurately if there are 3D hydraulic processes involved. This includes: Vertical velocities Stratification Complex sediment profiles Not suitable for all problems – a careful scoping must be carried out to address the potential drawbacks
3D 3D	Resolves 3D processes (assuming the model scale and setup is adequate) including: Vertical velocities Stratification Sediment profiles	Computationally demanding and therefore often leads to compromises in terms of: Lower Horizontal resolution Smaller Coverage Long Computational Simulation Periods Fewer scenarios possible

The choice of model complexity is based on the analysis of the problem and its governing processes. Potential three-dimensional processes to be considered include:

- The advection/dispersion effect of vertical velocities. In two-dimensional models the effect on dispersion of the vertical velocity profile is assumed to be small.
- The advection/dispersion effect of directionality of horizontal velocity over the water depth e.g. in combined wind-, and tidal-driven flow. Two-dimensional models assume unidirectional flow over the depth in the direction of the resulting force.
- Stratification or three-dimensional buoyancy effects. Two-dimensional models use depth-averaged values and pre-specified concentration and flow profiles are often assumed such as a logarithmic profile.

The above processes can be evaluated by looking at available data and dumping/dredging specifications.

Vertical velocities are mainly induced by:

- Horizontal gradients in the bathymetry. This component is generally less important outside the immediate work area where the sediments in the plume are very fine and follow the streamlines. Moreover the details of bathymetrical data and model resolution (in particular in three-dimensional oceanographic models) are normally too coarse to fully resolve vertical-induced velocities accurately (flow separation in particular).
- Tidal waves: The tidal wave propagation induces only small vertical velocities which are not considered essential in the advection/dispersion processes.
- Helical flows. This is not considered important as the curvature of streamlines in the open water is limited and eddies are either absent or part of larger scale flow structures.
- Buoyancy effects and other density driven currents from gradients in salinity, temperature or concentration. This mechanism can be very important and can induce highly three-dimensional flows. Density currents due to high sediment concentrations are important near the dumping/dredging sources, but the effect will rapidly diminish away from the near-field areas. It is noted that an oceanographic three-dimensional model that needs to cover the entire potential impact area will not be able to resolve the complex near field dynamics of a dredger discharging sediment laden water.

Apart from the effects outlined above, vertical velocities induced by wind-driven waves can be important. These are however not included in oceanographic flow models; the effect is often introduced through a higher dispersion factor in both two-dimensional and the simpler three-dimensional models.

Depth-resolved flow and concentration profiles are often important as different fractions have different retention times and therefore are dispersed and deposited differently. Note, however, that DHI's two-dimensional sediment transport model is considered a semi-three-dimensional model when it comes to deposition. The MIKE 21 MT makes use of the same deposition functions as that used in the three-dimensional model by assuming the Teeter or Rouse profile, which is considered a reasonable assumption in non-stratified and uniform flows.

In the vicinity of the dredger, density driven currents from the release of sediments from the dredging operation can lead to important vertical velocity fields. DHI has through numerical testing shown that a very fine grid spacing (in the order of a couple of meters) is required to resolve the density driven currents and the resulting concentration profiles. The modelling and experience from the field shows that after a short period of time (or distance from the source), the sediment plume mixes over the depth. Outside of this mixing zone, a two-dimensional model can simulate the dispersion, sedimentation and re-suspension of the sediments.

E.3 Wheatstone Conditions

An assessment of the data for Wheatstone has shown well mixed flow conditions over the depth throughout the relatively shallow coastal area traversed by the navigation channel. Apart from minor wind effects, there are as expected for this type of environment no signs of any significant stratification. The assumption of a logarithmic current profile is generally valid in this area according to the current measurements. In deeper water out by the potential off-shore spoil ground, there is at times a stronger dominance of wind driven current profiles. The two-dimensional flow model established for the area has calibrated very well against the measurements and captures wind and pressure driven current fields in addition to the tidal current fields very well (see Section on model validation), which confirms that the hydrodynamics is predominately two-dimensional . The assessment of a predominant well mixed area with the absence of stratification has further been confirmed by consultants with extensive field experience from the area.

There are reefs, shoals and outcrops within the potential area of impact/influence, but very limited in the immediate vicinity of the proposed channel alignment. A very detailed 3D model would be required to resolve the turbulence and details of the flow around the outcrops, but as the sediments in the plume in this area is expected to be fines that more or less follow the streamlines of the flow, resolution of the three-dimensional flow will not lead to results significantly different from the corresponding two-dimensional model. It is considered much more critical to capture the dredging/climatic scenarios that give the highest flux of sediment towards the sensitive habitats, and resolve the horizontal flow patterns.

The main three-dimensional effects expected for the Wheatstone site are related to the density driven currents in the immediate vicinity of the dredger. This will comprise an area over and in the near vicinity of the dredged channel. In terms of impacts, full mortality is assumed in this zone, and a detailed distribution of the sediments over depth in this zone is therefore not required. The sediments will mix over the water depth close to the dredger, and outside this near-field area, extensive experience from similar environments have shown that the two-dimensional model can be calibrated as well as the three-dimensional model.

Most of the sensitive marine habitats are located at a fair distance from the channel corridor, and far from the three-dimensional effects close to the dredger. With appropriate sediment source(s) at the dredger that take the three-dimensional effects into account, a two-dimensional model is therefore considered appropriate for modelling the spreading of the plume and siltation/re-suspension processes.

The potential area of influence is relatively large, and the model coverage will have to be relatively large to properly resolve the currents within this area.

E.4 Model Testing

The differences between two-dimensional and three-dimensional modelling have been investigated for a variety of dredging and dumping scenarios during various stages of the model studies.

Results from comparisons at an early stage of the project showed that overall, the concentration fields are very similar for two-dimensional and three-dimensional, which confirms that there are no major three-dimensional effects captured within the simulation period. A sensitivity analysis of important input parameters such as horizontal and vertical dispersion factors, the numerical scheme for the advection terms in the AD model, critical shear stresses for the re-suspension of the fine sediments as well as the resistance of the seabed (Manning value) showed that differences between two-dimensional and three-dimensional plumes are small compared to the potential differences for the various parameters tested.

E.4.1 Scenario Testing

The three-dimensional model described in Appendix H has been established for a number of the dredge and climatic scenarios to test the hypothesis for Wheatstone that the two-dimensional model will generally provide a slightly conservative impact envelope when combined with a scenario modelling approach (Section E.5).

For the comparison, depth-averaged concentration fields were derived from the three-dimensional model results to enable a comparison as well as the derivation of impact zones from the three-dimensional results for comparison. The following Sections show comparisons for mean excess concentrations, exceedance of 5mg/l and sedimentation rate for selected climatic conditions for Dredge Scenarios 6 and 7 with “realistic” sediment spill rates. The following is noted for both sets of results:

- The two-dimensional and three-dimensional plumes are generally very similar.
- Some of the lower concentrations extend slightly further in the three-dimensional than the two-dimensional model for summer and transitional conditions, whereas the lower concentration plumes extend significantly further westward during winter for the two-dimensional model.
- The higher concentration limits (which primarily determine the impact zones), generally seem to extend similar or further in the two-dimensional model.

E.4.2 Scenario 6

2D **3D (vertically integrated)**

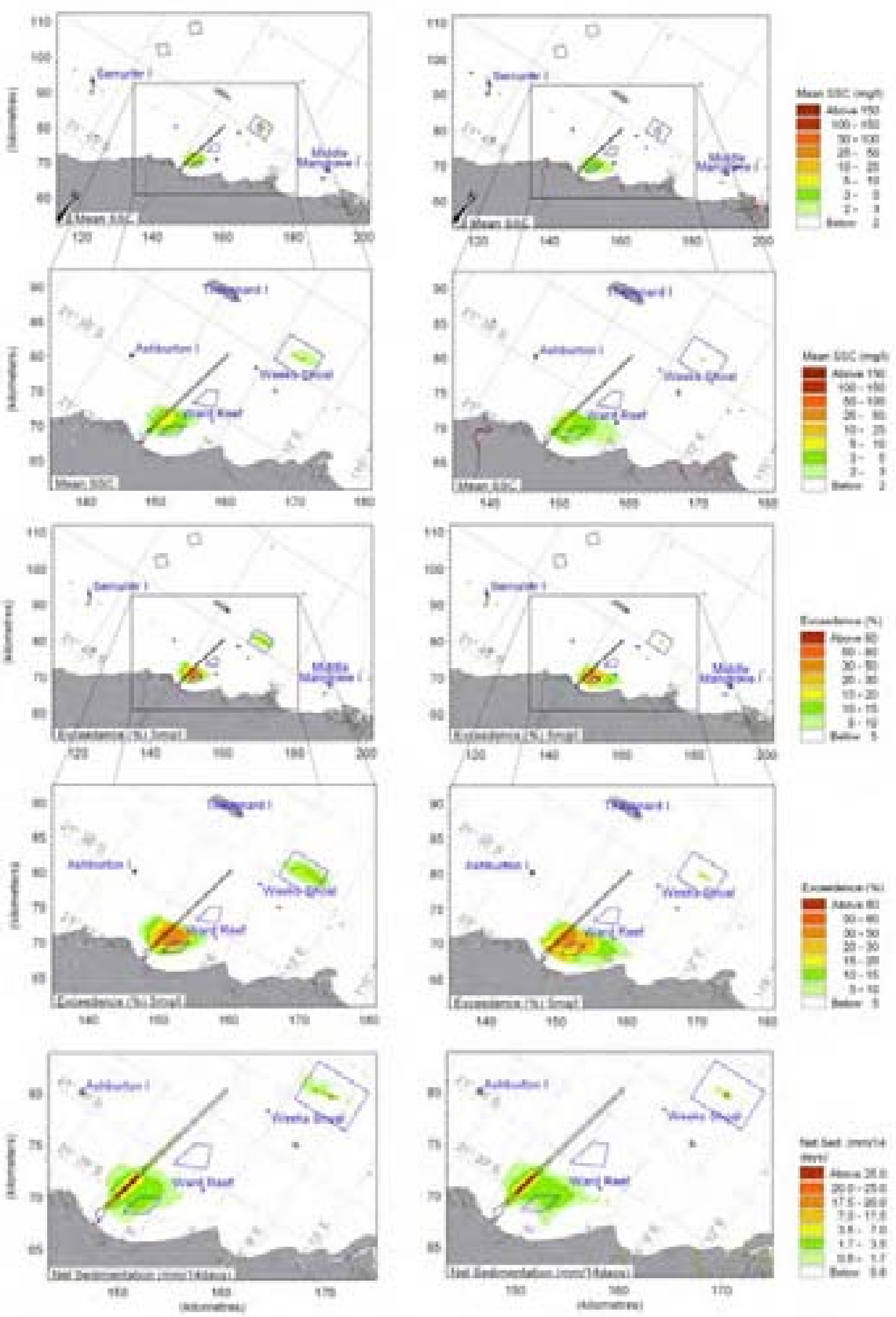

Figure E.2 *Scenario 6 summer with low (realistic) sediment spill rates. Left column shows the 2D results and the right column shows the corresponding depth-averaged 3D results.*

2D **3D (vertically integrated)**

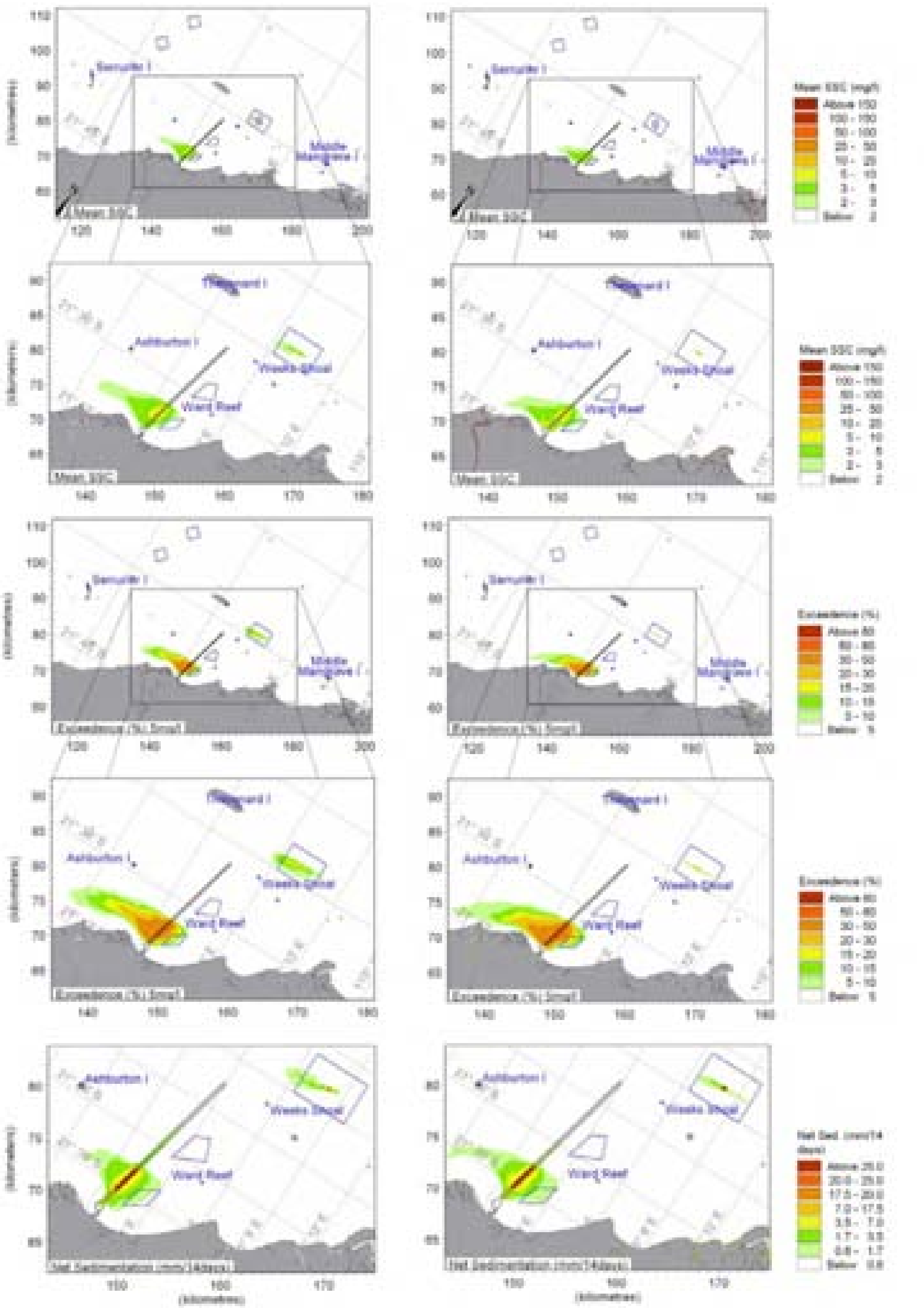

Figure E.3 Scenario 6 transitional with low (realistic) sediment spill rates. Left column shows the 2D results and the right column shows the corresponding depth-averaged 3D results.

2D **3D (vertically integrated)**

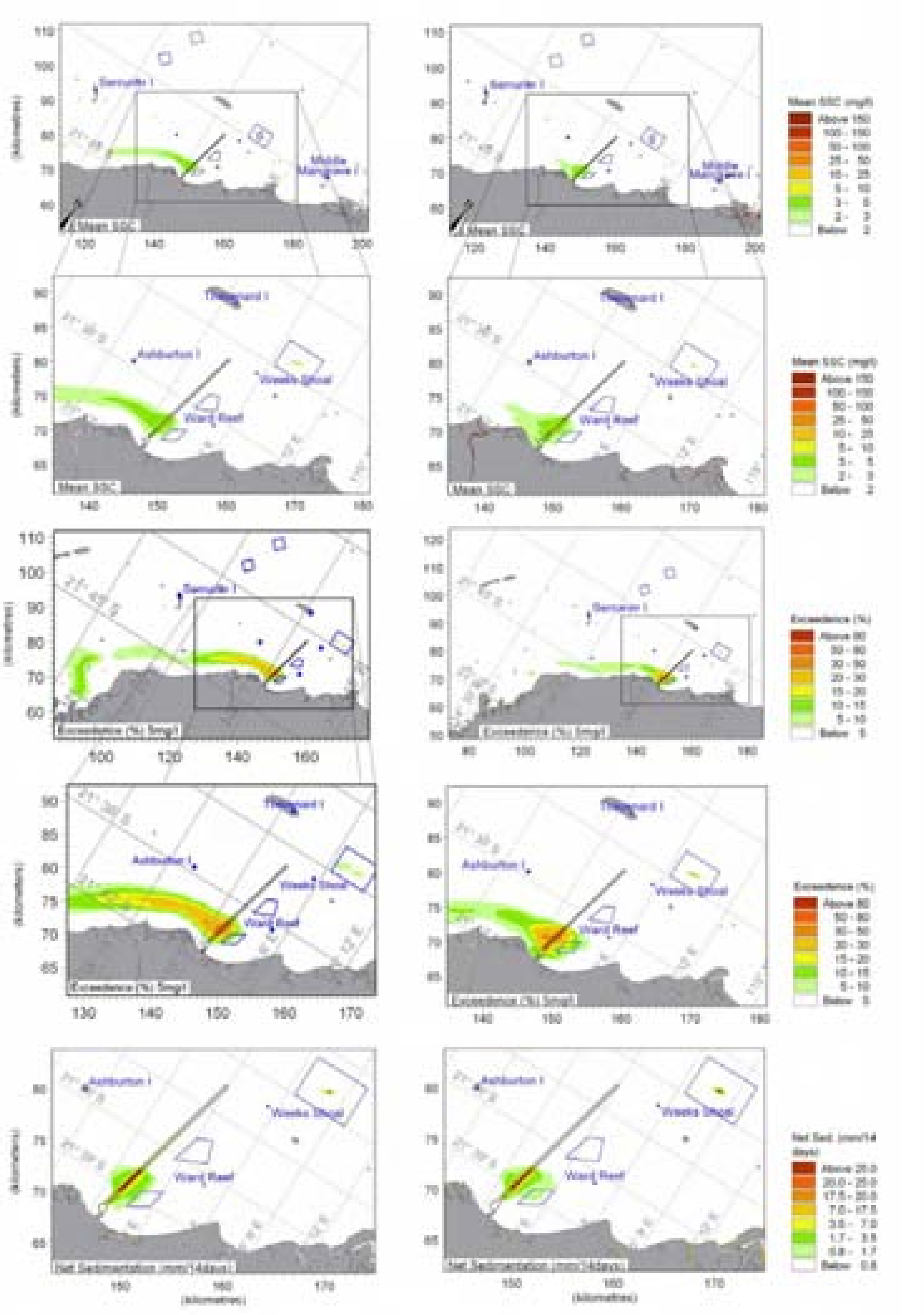

Figure E.4 *Scenario 6 winter with low (realistic) sediment spill rates. Left column shows the 2D results and the right column shows the corresponding depth-averaged 3D results..*

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E.4.3 Scenario 7

2D **3D (vertically integrated)**

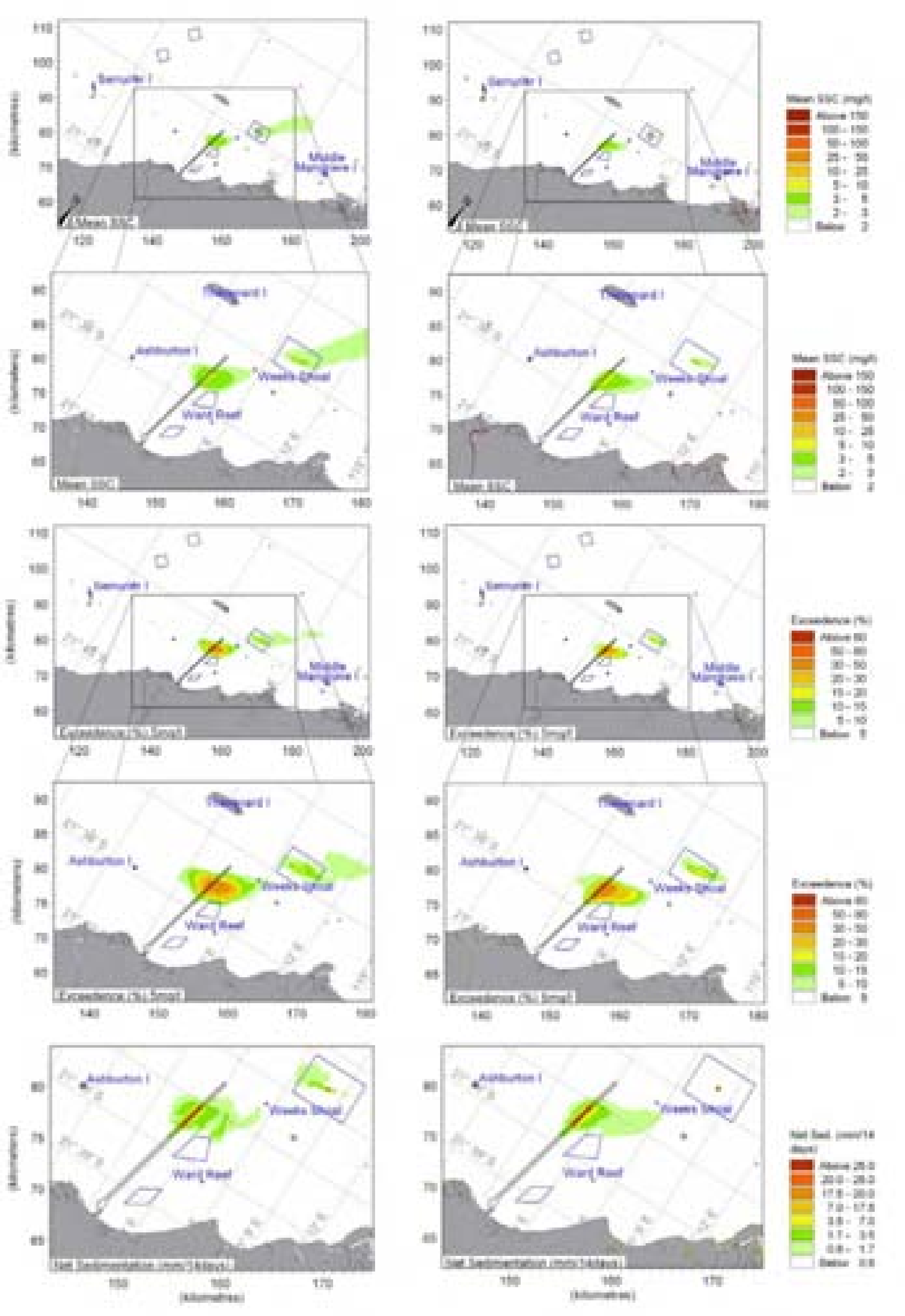

Figure E.5 Scenario 7 summer with low (realistic) sediment spill rates. Left column shows the 2D results and the right column shows the corresponding depth-averaged 3D results.

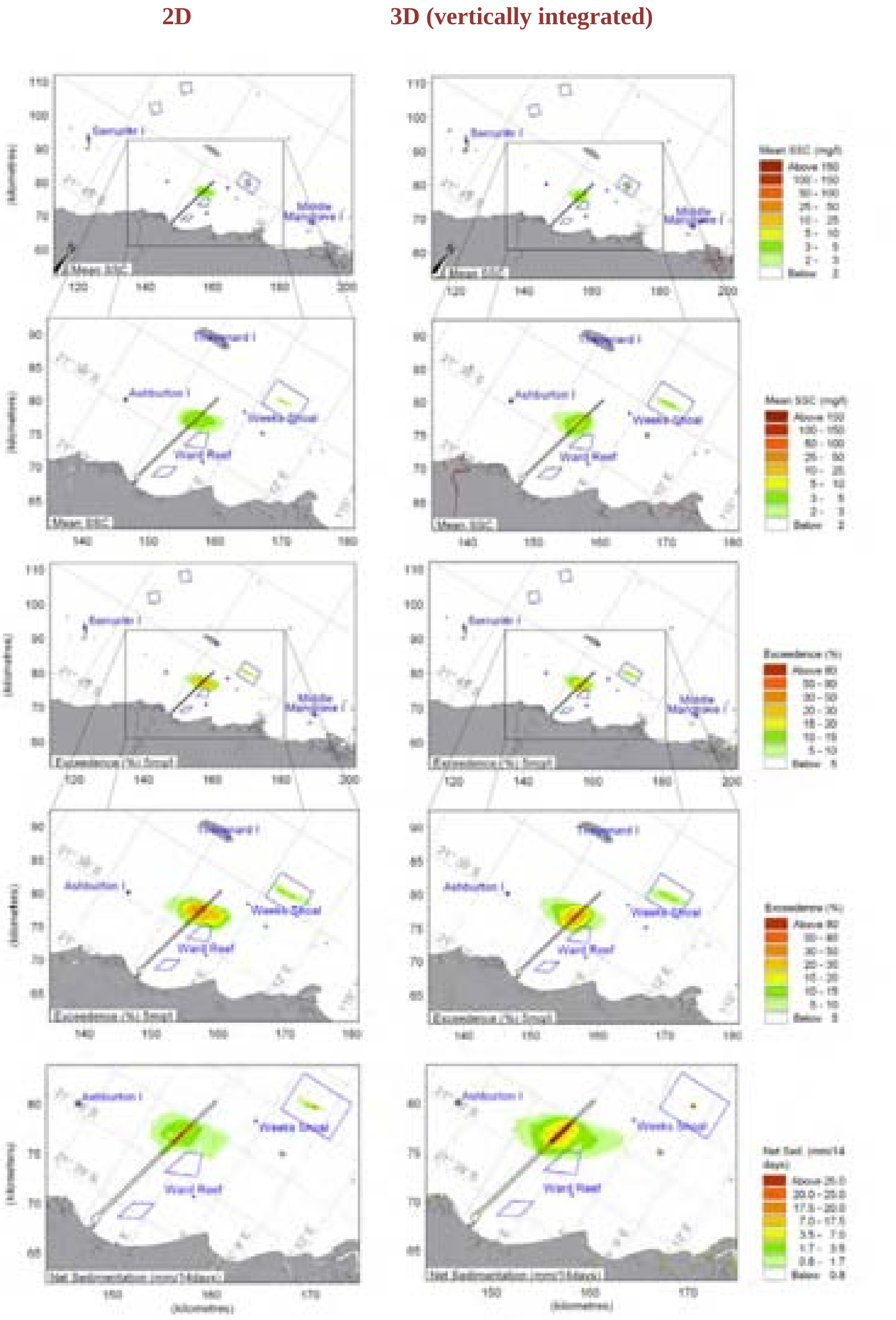

Figure E.6 *Scenario 7 transitional with low (realistic) sediment spill rates. Left column shows the 2D results and the right column shows the corresponding depth-averaged 3D results.*

E-12

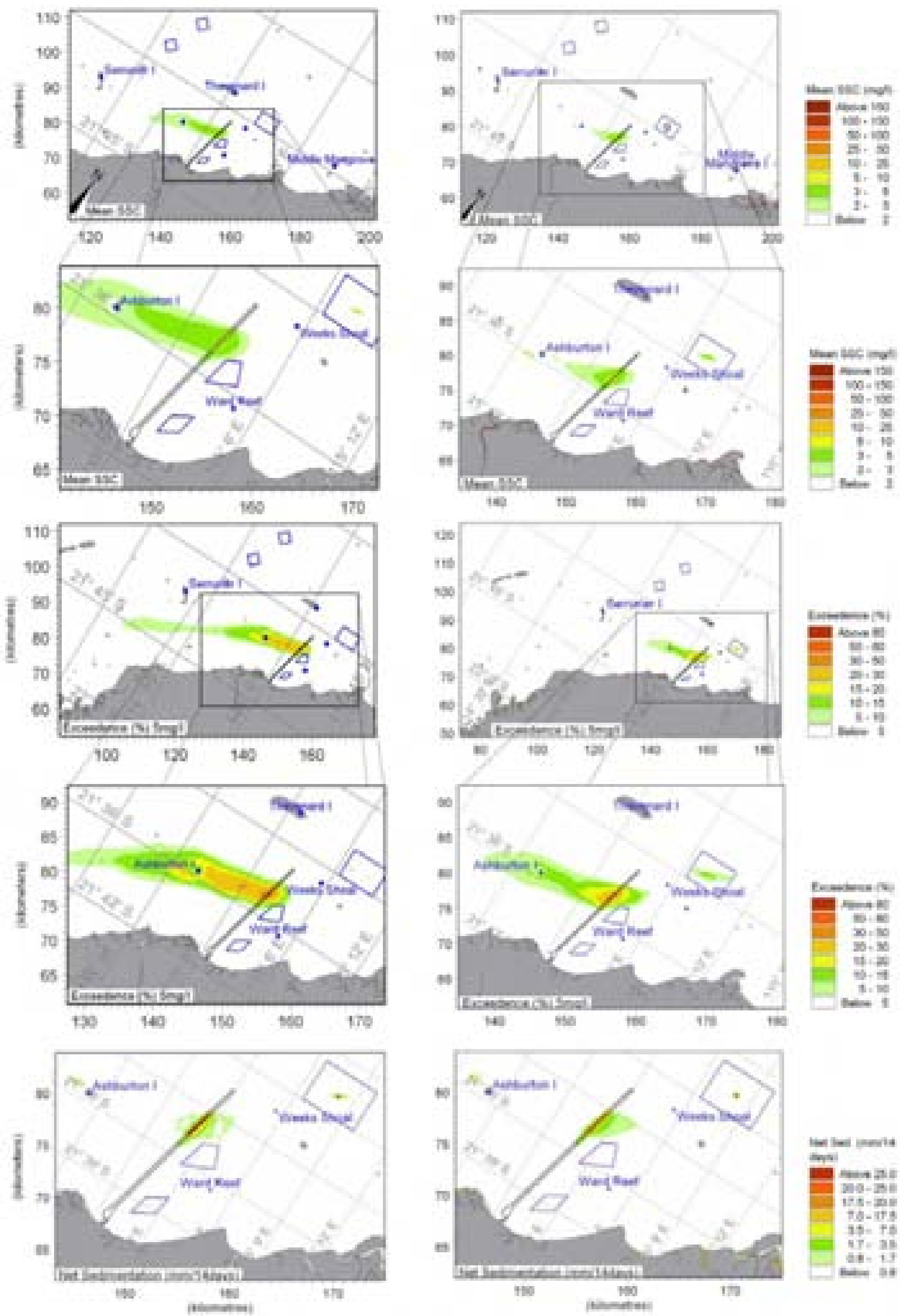

Figure E.7 Scenario 7 winter with low (realistic) sediment spill rates. Left column shows the 2D results and the right column shows the corresponding depth-averaged 3D results.

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E.5 Impacts Zones Derived using 2D or 3D Hydrodynamics

The key outputs from the modelling are the impact zones, which are derived from the model output and the impact criteria.

The impact zones derived from the two-dimensional and three-dimensional modelling of individual scenarios have been compared to assess the potential differences from the two models.

It is noted that different impact criteria are used and therefore different impact zones derived for different stress factors (suspended sediments and sedimentation) as well as receptors (corals and sea-grasses). The results are principally the same, and only selected results for corals have been shown here.

The following is noted:

- The impact zones derived based on TSS are generally similar or extend further away from the spill sources for the two-dimensional modelling.
- In particular during winter conditions are the two-dimensional derived TSS impact zones larger than the three-dimensional derived impact zones.
- The impact zones derived based on sedimentation are generally similar, but with a tendency to slightly larger impact zones from three-dimensional during summer and transitional

Overall, the impact zones show the expected tendency with similar or mostly slightly larger impact zones from the two-dimensional modelling.

The differences between the two-dimensional and the three-dimensional derived impact zones are insignificant compared to the differences due to for instance different dredge, climatic or spill scenarios.

E.5.1 Scenario 6

E.5.1.1 Suspended Sediment Spill on Coral Habitats

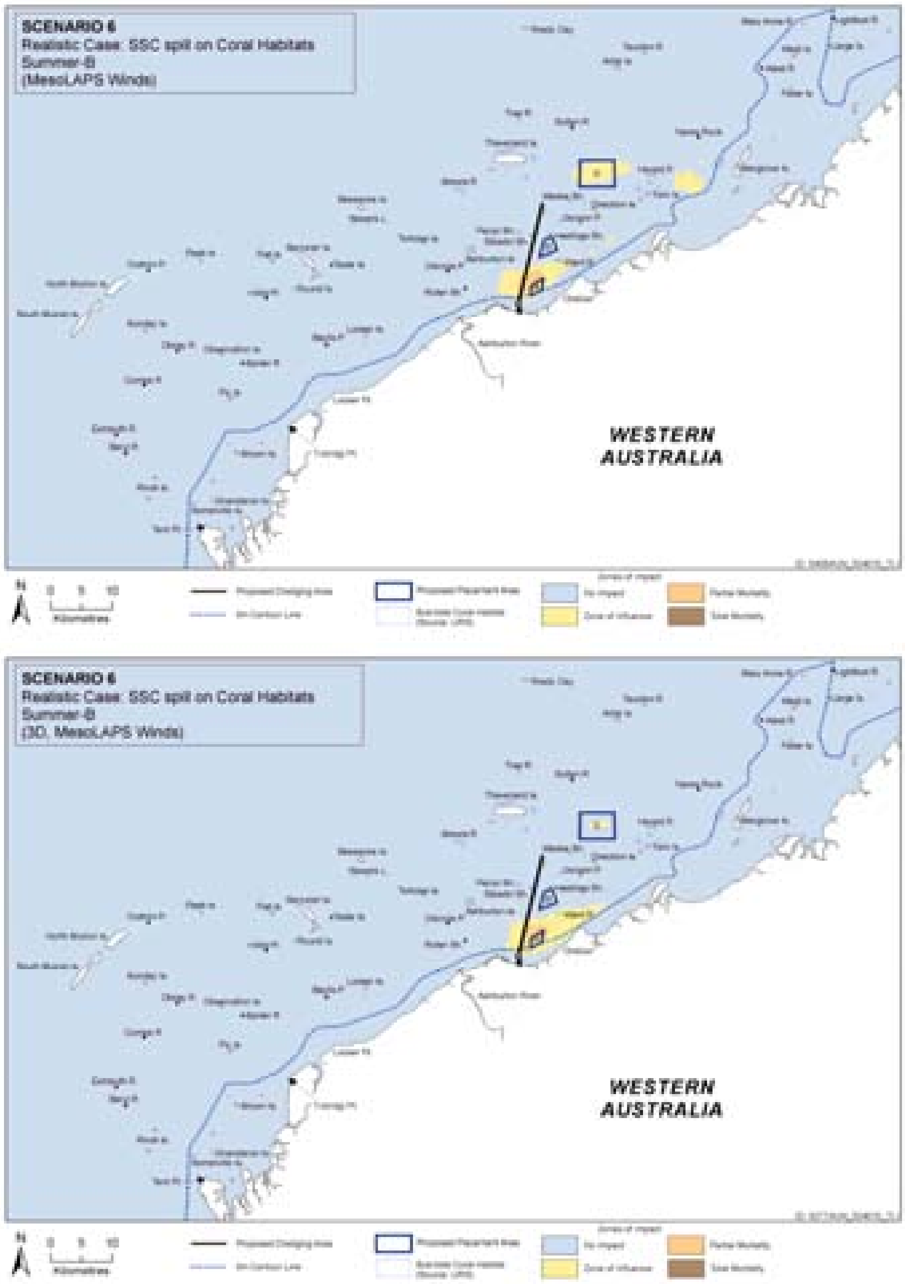
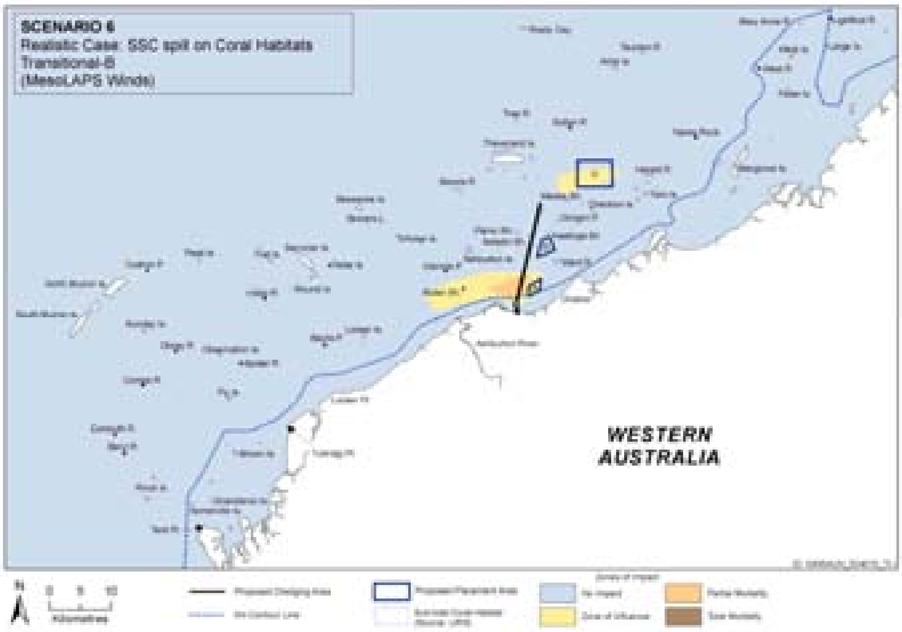


Figure E.8 Scenario 6 summer, suspended sediment spill on coral habitats. Top 2D model and bottom 3D model.

E-15



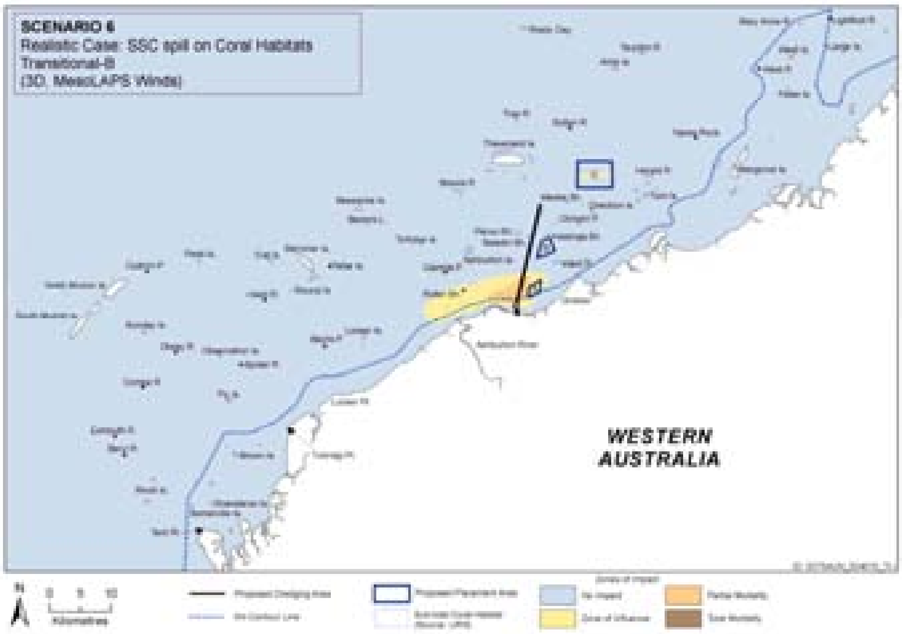


Figure E.9 Scenario 6 transitional, suspended sediment spill on coral habitats. Top 2D model and bottom 3D model.

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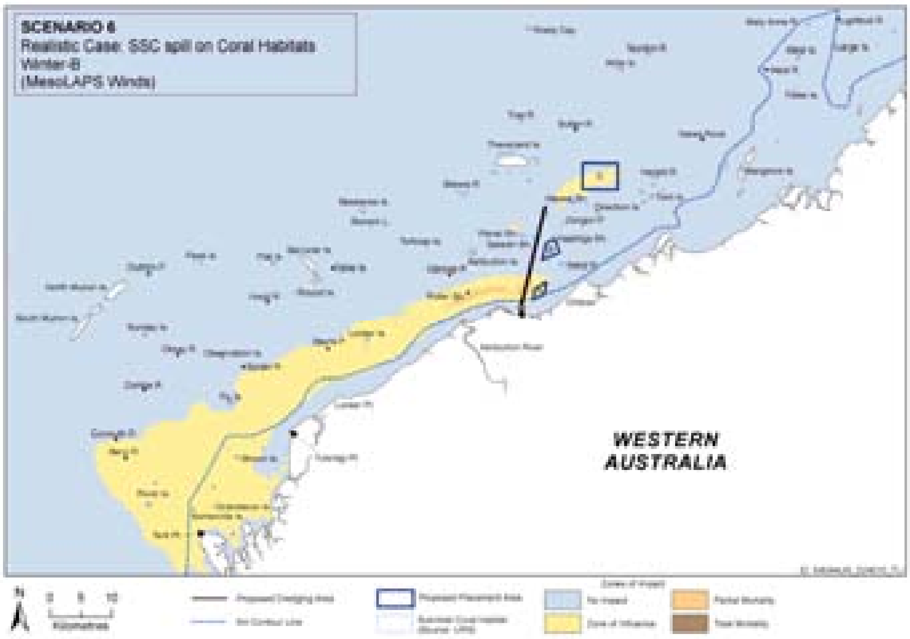
E-16



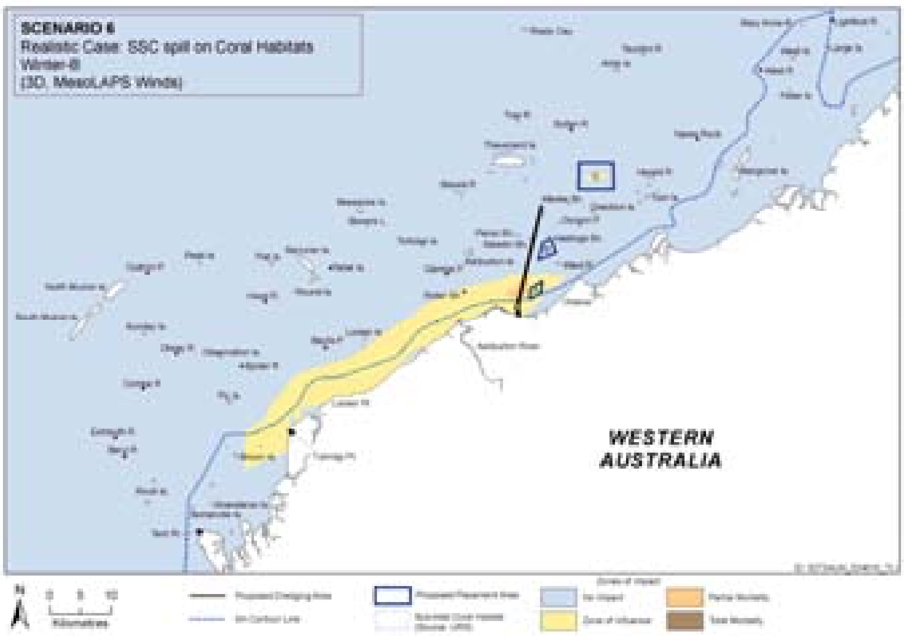


Figure E.10 Scenario 6 winter representative: suspended sediment spill on coral habitats. Top 2D model and bottom 3D model.

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E.5.1.2 Sedimentation on Coral Habitats

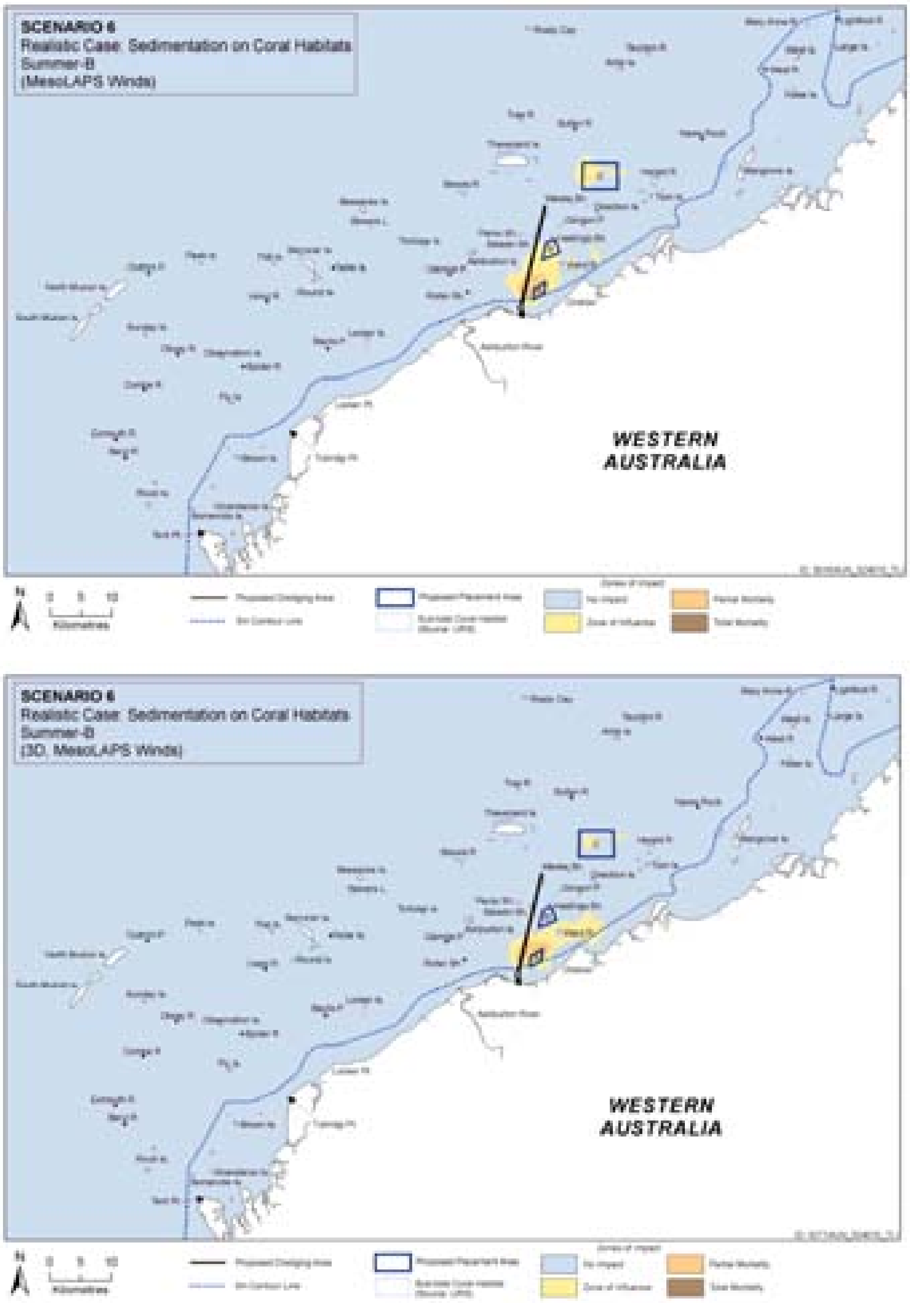


Figure E.11 Scenario 6 summer, sedimentation on coral habitats. Top 2D model and bottom 3D model.

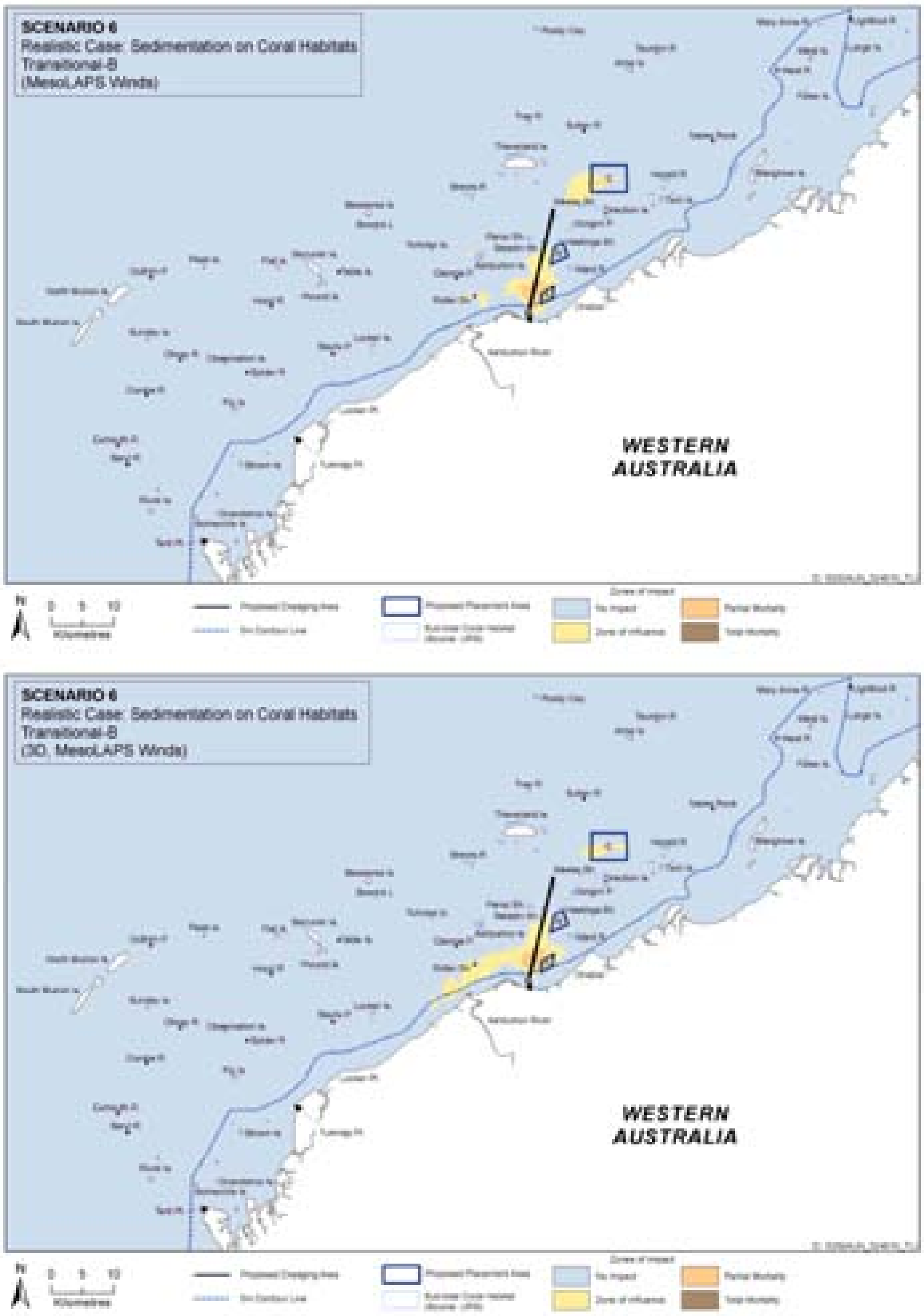
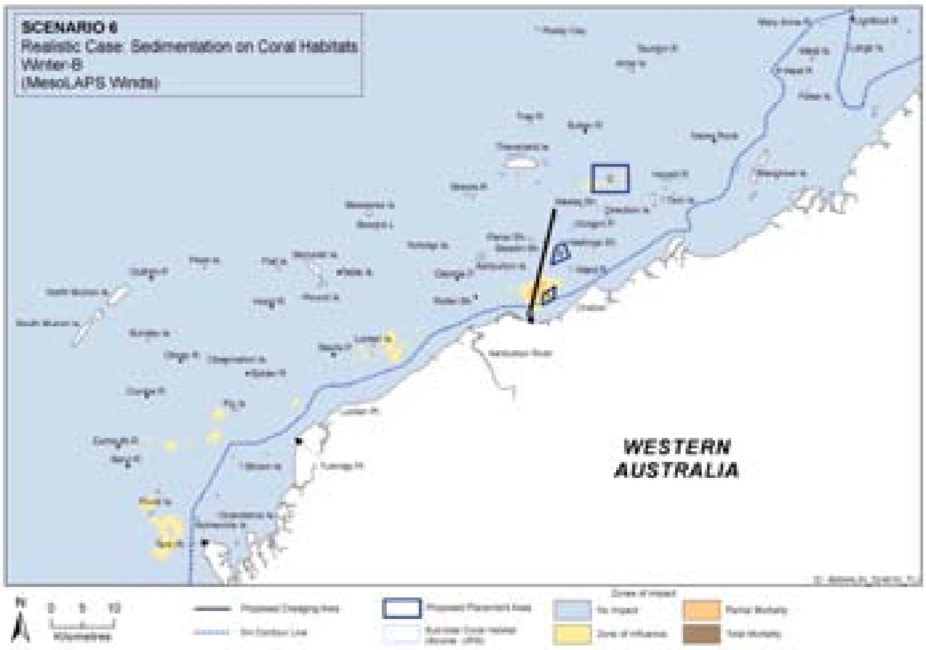


Figure E.12 Scenario 6 winter, sedimentation on coral habitats. Top 2D model and bottom 3D model.



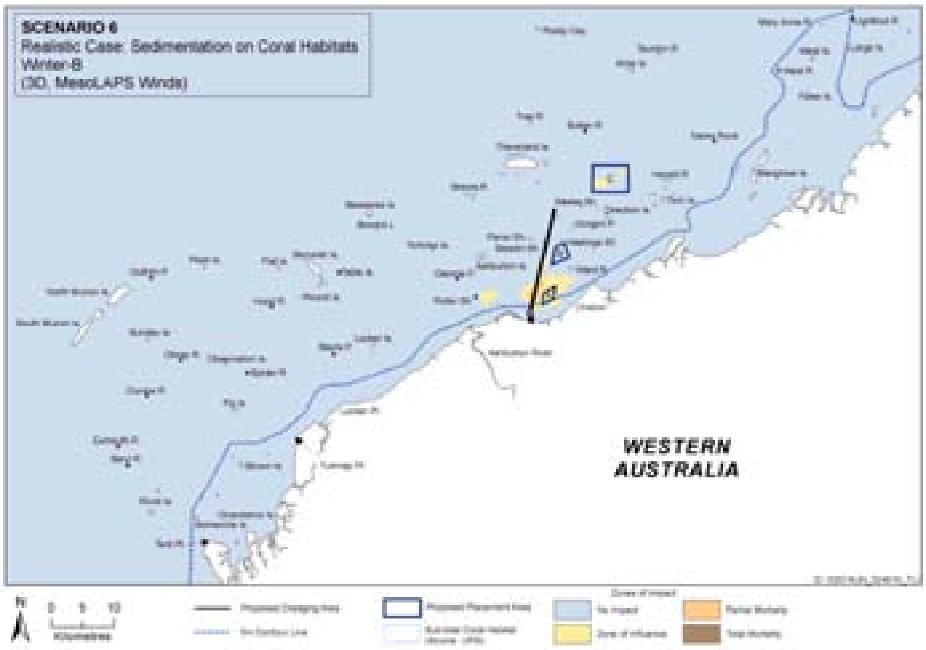
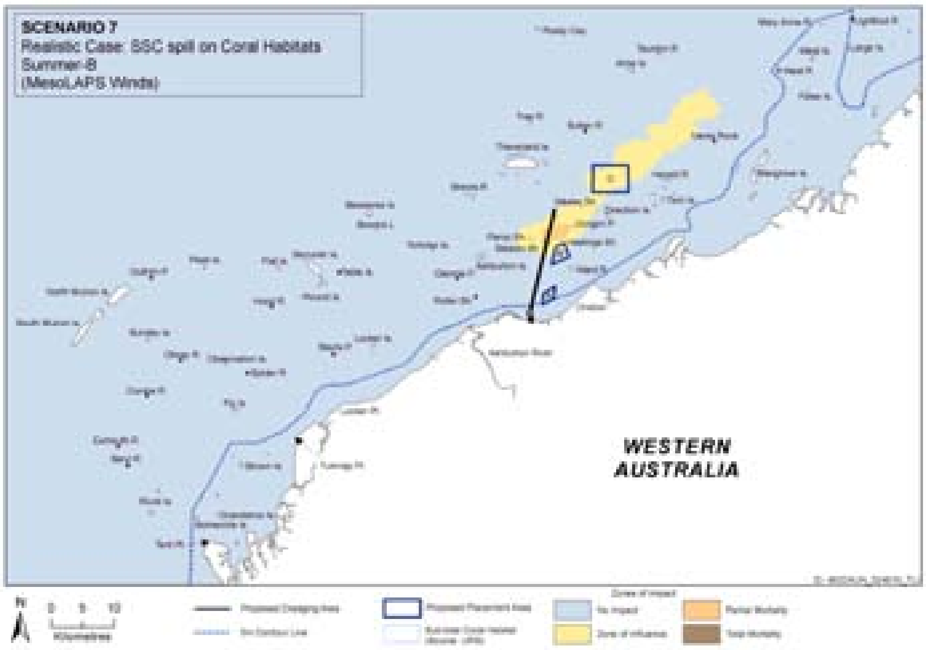


Figure E.13 Scenario 6 winter, sedimentation on coral habitats. Top 2D model and bottom 3D model.

E.5.2 Scenario 7

E.5.2.1 Suspended Sediment Spill on Coral Habitats



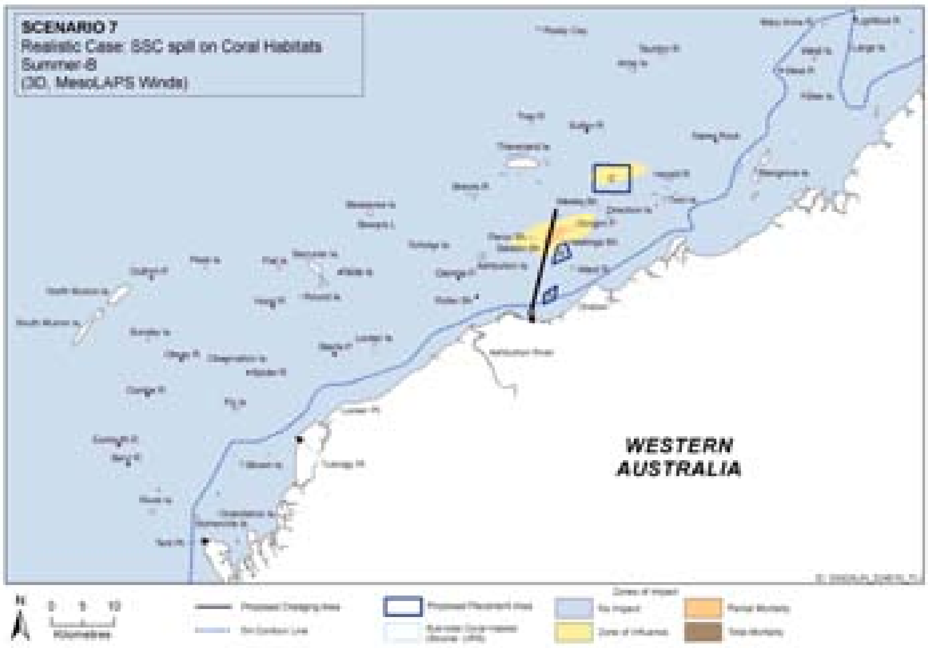


Figure E.14 Scenario 7 summer, SSC spill on coral habitats. Top 2D model and bottom 3D model

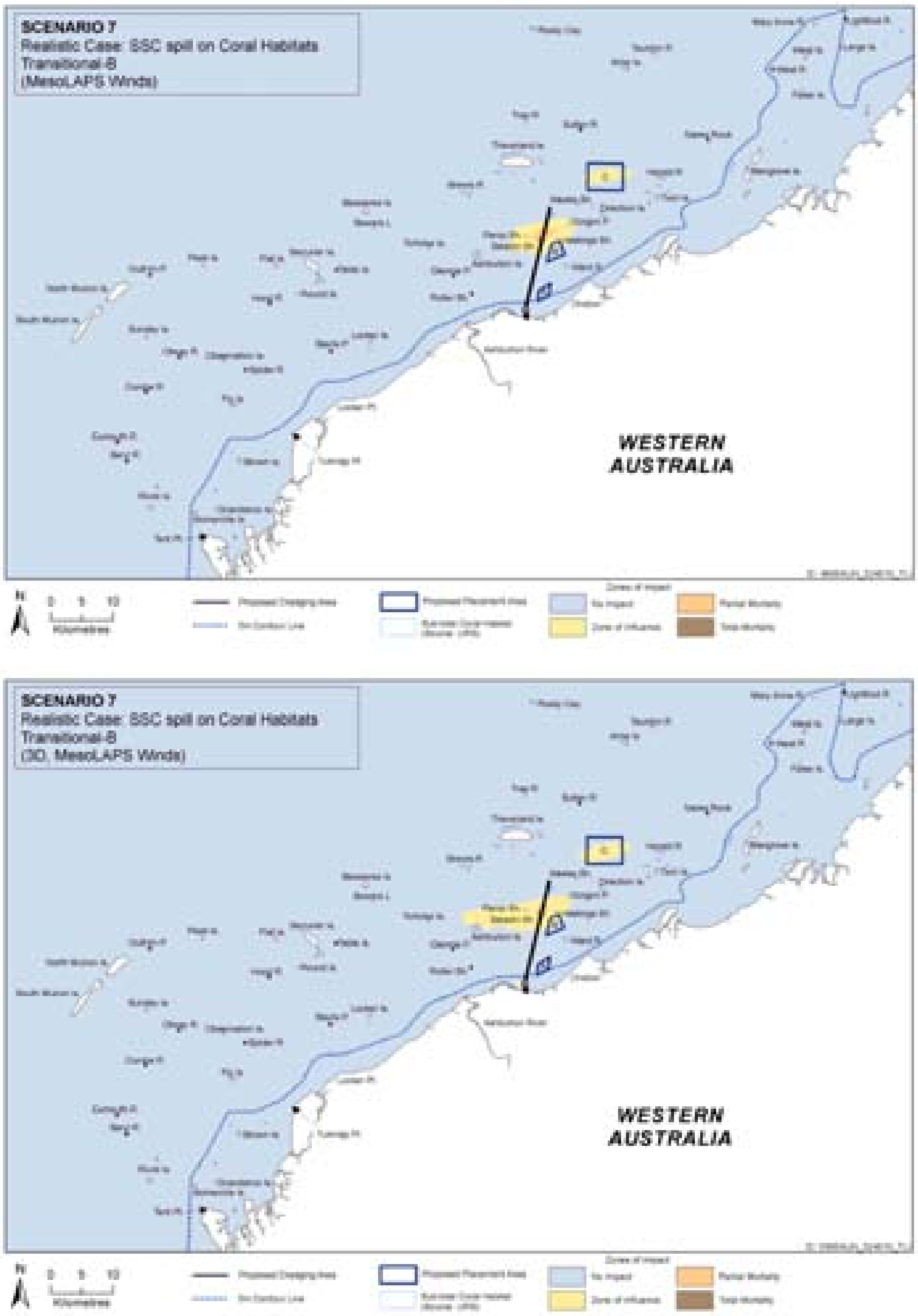


Figure E.15 Scenario 7 transitional, SSC spill on coral habitats. Top 2D model and bottom 3D model.

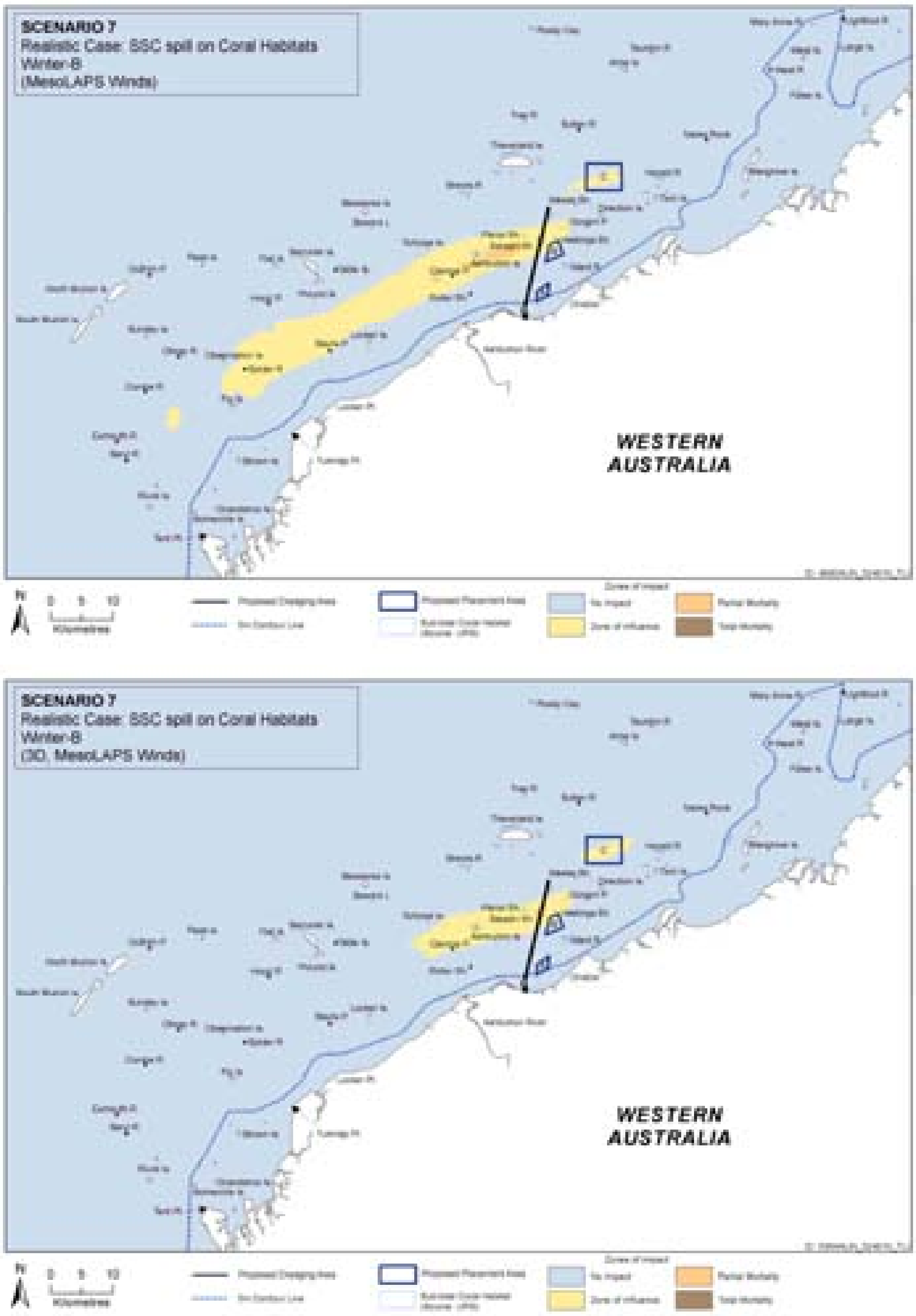


Figure E.16 Scenario 7 winter, SSC spill on coral habitats. Top 2D model and bottom 3D model.

E.5.2.2 Sedimentation on Coral Habitats

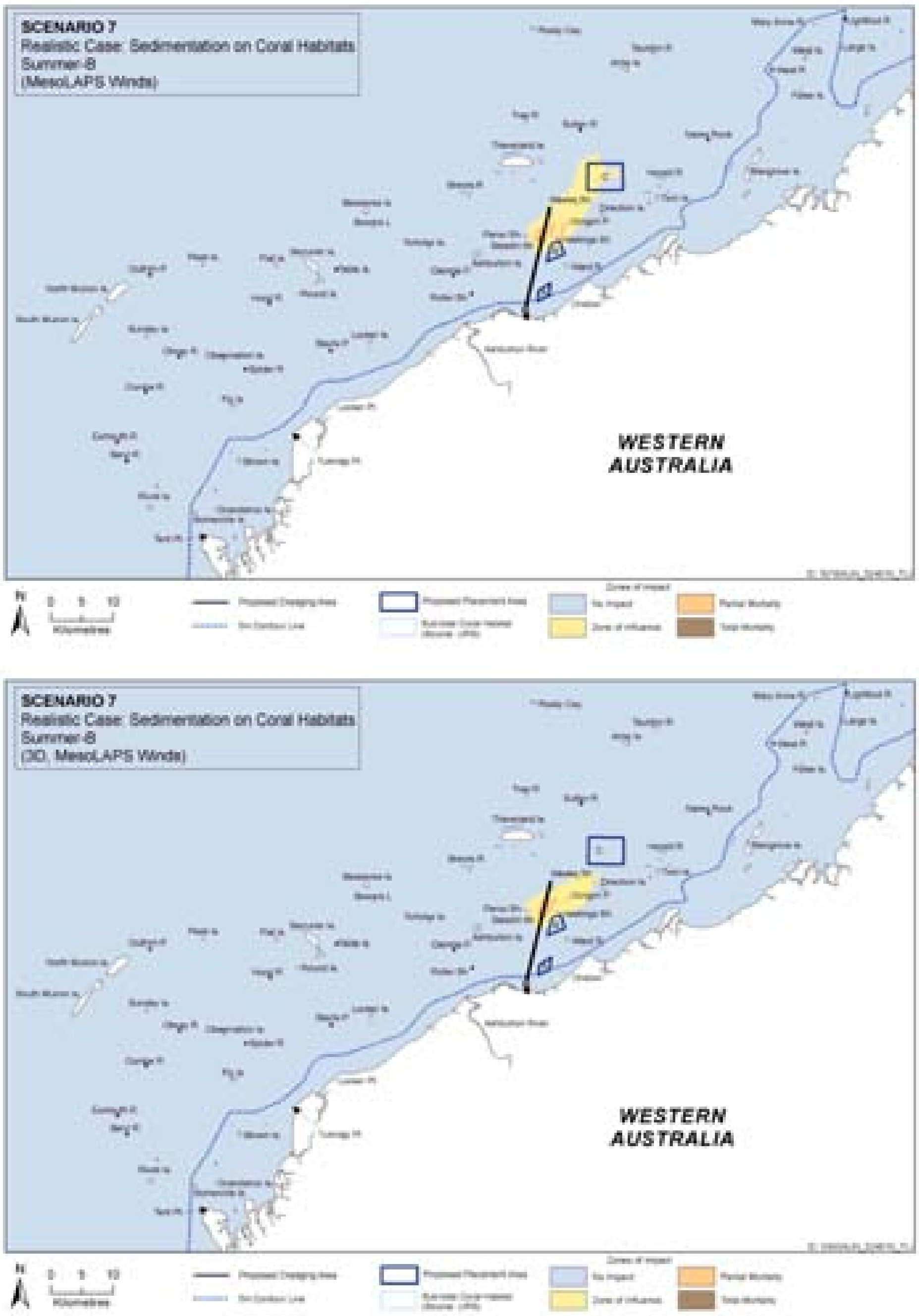


Figure E.17 Scenario 7 summer, sedimentation on coral habitats. Top 2D model and bottom 3D model.

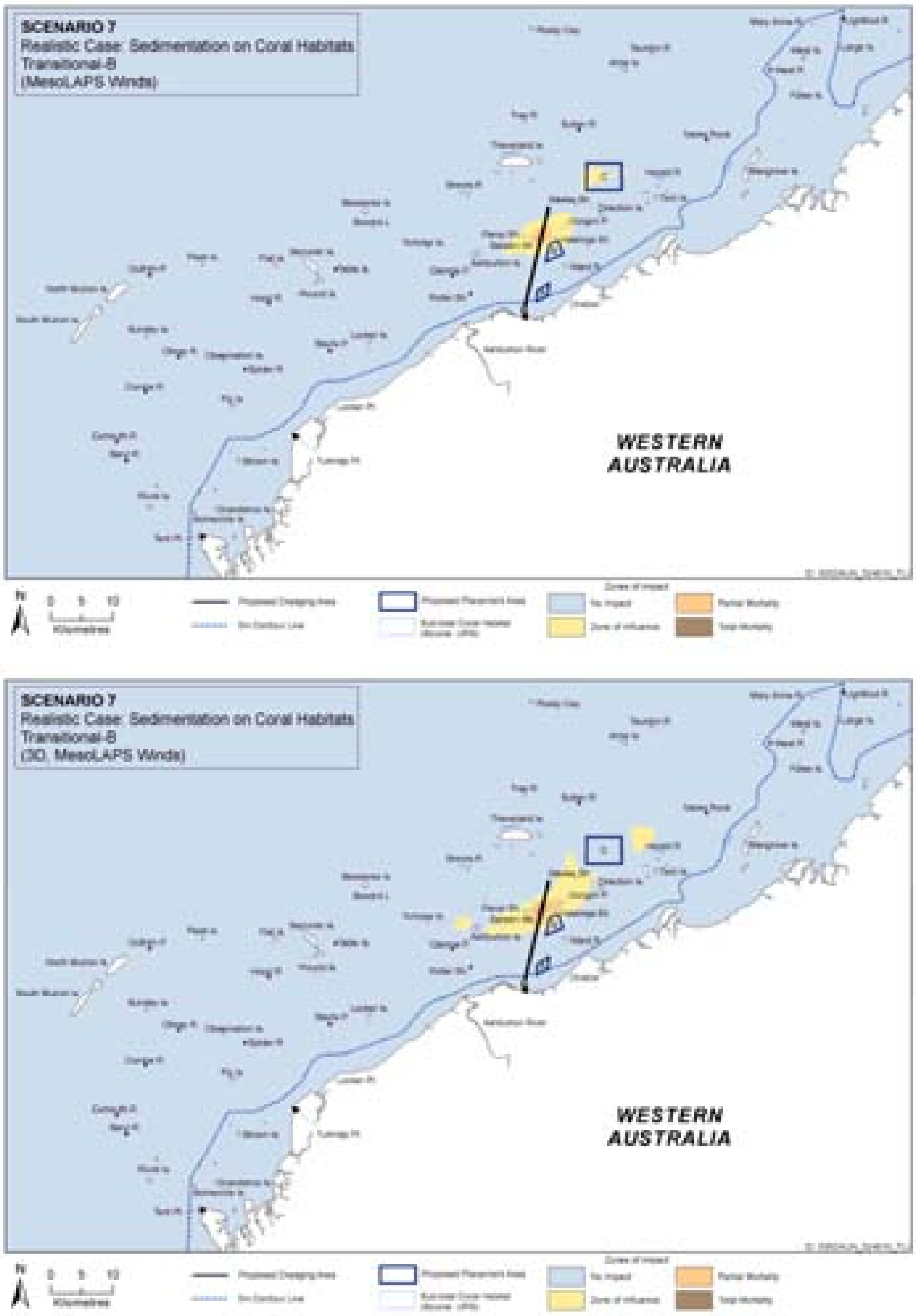


Figure E.18 Scenario 7 transitional, SSC spill on coral habitats. Top 2D model and bottom 3D model.

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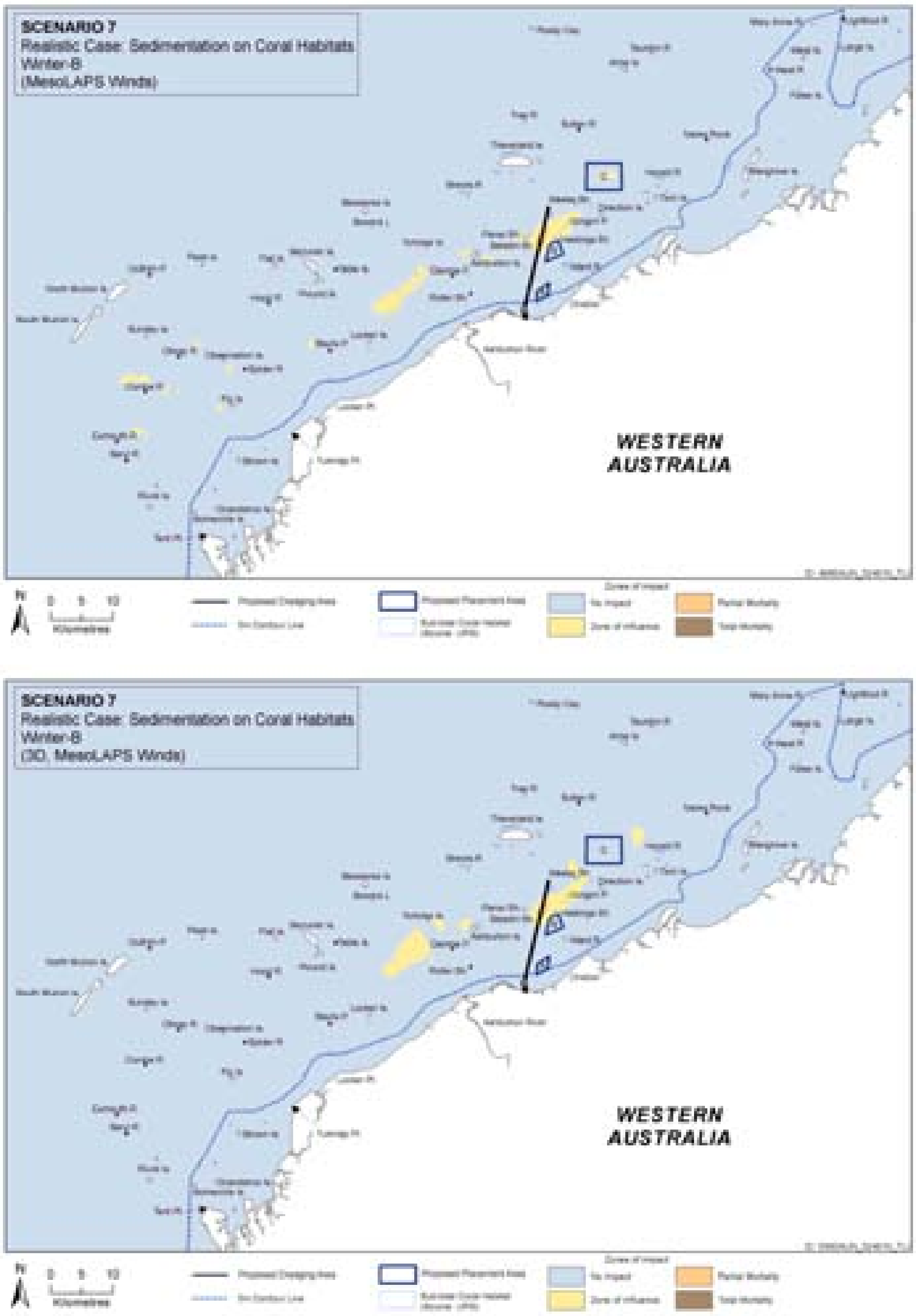

Figure E.19 Scenario 7 transitional, SSC spill on coral habitats. Top 2D model and bottom 3D model.

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E.6 Summary and Strategy for Wheatstone

In summary, the available data and local experience from the site indicate that the water column is well mixed within the relatively shallow coastal waters of the project with no significant 3D processes. This is confirmed by the very good calibration/validation obtained using a 2D (depth-integrated) model approach. The main 3D effects will be associated with density driven currents, pressure wave and propeller wash generated by the dredging plant. The area in the immediate vicinity of the dredge corridor is already considered to suffer 100 % mortality, and the flow and sedimentological details are therefore not required in this area. The key is to simulate the sediment excursion to the mid and far fields to determine the boundaries between zones of high and moderate impacts as well as the zone of influence.

The comparisons of 2D and 3D model results have illustrated that in general the 2D model allows the sediment plume to travel further from the source at higher concentration, increasing the impacts on coral reefs and seagrass habitats. The differences between 2D and 3D results are insignificant compared to the uncertainties related to the dredge programme and other parameters such as spill rates, and the 2D model has been adopted as the preferred tool for the assessment as it maintains a slight conservatism when applied in conjunction with the scenario modelling approach, and further allows efficient assessment of a much larger array of variables than the more computationally demanding 3D approach.

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A P P E N D I X F :

Studies in Support of the Scenario Approach

DHI Water & Environment

CONTENTS

FIGURES AND TABLES

F SCENARIO MODELLING

At the EIA stage of a dredging project, there are significant uncertainties that will influence the overall impacts from the project. This includes, but is not limited to, parameters that can broadly be divided into three classes:

1. Dredging programme and methodology
2. Sediment characteristics and spill from the dredging
3. Climatic conditions during dredging

The "hazard" in terms of sediment plume excursion and concentrations from the dredging at any given time and place is a function of the combinations of these parameters. The dredging programme and methodology determines where (and partly at what rate) sediments are released into the water column. The sediment characteristics together with the dredging methodology determine the overall spill rate, and the climatic conditions during the operation determine how and where to the sediment plume is carried.

A Dredging and Disposal Plan (DDP) which sets out a realistic schedule and methodology for the proposed dredging for the Wheatstone Project has been developed. However, the actual programme will be planned by the dredging contractor yet to be appointed, and is likely to change even during the dredging period. A reasonable soil classification for the soil to be dredged is available from the Geotechnical Investigations. This is valuable for the estimate of spill rates and sediment properties for the sediment dispersed into the water column. Spill rates are, however, dependent both on sediment properties of the material to be dredged, the type of operation, climatic conditions and the actual operation of the equipment. Only upon start of the actual dredging can the spill rates be better estimated. As the climatic conditions are extremely important for where the sediment plumes are carried to, the timing of the dredging at a given location is crucial for the potential impacts. The DDP contains a first pass of a dredge schedule, but this is bound to change as the project progresses.

In recognition of the uncertainty in the actual dredge programme, it is crucial that the modelling and impact assessment are sufficiently flexible to cover a range of potential programmes. The scenario modelling approach addresses this by typically combining a range of dredging, spill and climatic conditions to form an envelope of scenarios for impact evaluation.

F.1 Shorter versus Full Dredging Period Scenario Modelling

There are two principally different approaches for scenario modelling:

1. Simulate the full dredge period (~ 36 months for the Wheatstone Project)
2. Simulate shorter periods which are sufficiently long to establish a "quasi-equilibrium" state for the given sediment plume excursion for a given climatic and dredge condition. The period will typically as a minimum cover a neap-spring tidal cycle (with a "hot" start of the initial plume concentrations).

Simulation of the full dredge period maintains the full history of the sediment throughout the simulation, but may be very time consuming for long dredge periods and limit the combination with other relevant drivers for the plume dispersion and impacts such as e.g. the climatic conditions. The approach using simulations for the full dredge period are best suited in situations where:

- The dredge programme is short relative to e.g. climatic changes such that climatic conditions are quasi-stable throughout the dredge period
- The dredge programme is well defined with no or minimal risk of changes to timing and methodology
- Re-suspension is a dominant factor and it is crucial to maintain the full "history" of the released sediments throughout the dredge period.

Shorter period scenario modelling generally assumes that "quasi-equilibrium" plumes and related impacts can be established. When "quasi-stationary" conditions can be achieved, the approach based on shorter duration simulations typically allows better resolution and provides a much greater flexibility in terms of testing different scenarios, performing sensitivity analysis and adapting/testing new conditions as they are developed through the project period. The shorter period scenario modelling is well suited for capturing the potential impacts from a large array of potential climatic, dredge and spill conditions.

The two approaches have been compared and some of the main pros and cons listed in Table F.1 below. The main difference for long dredging periods such as Wheatstone are related to the large simulation requirements for the full period simulation approach, which typically severely limits the model resolution and number of scenarios that can be achieved for a given project.

Table F.1 Pros and Cons for short scenario versus full dredge period modelling approaches

Approach	Pros	Cons
Full Dredge Period Modelling	"History" of sediment plume maintained History of sedimentation maintained, inclusive of effects of re-suspension	Results closely related to the assumed dredging programme. Variations to (long) dredge programmes not easily captured. Very time consuming for long dredge programmes, which typically limits the resolution and the number of scenarios that can be simulated Not easy to perform sensitivity analysis and test new scenarios.
Short Scenario Modelling	Simulations are fast for individual scenarios, which means that typically a higher resolution and a larger number of scenarios can be simulated The possibility of simulating a large number of scenarios ensures that critical conditions in time and space can be captured, and a "total envelope" for the potential impacts can be developed.	History of sedimentation not maintained. If total sedimentation is required it must be constructed by statistically adding the scenarios together. If re-suspension is critical, it may be difficult (potentially not possible) to achieve quasi stationary conditions.

The choice of preferred approach is project and site specific. In general terms, DHI typically prefers the approach based on shorter duration scenarios for longer period dredge programmes spanning over an array of different climatic conditions and with significant uncertainties on the dredge schedule and methodology (such as that for Wheatstone), whereas full dredge period simulations may be preferred for shorter duration dredging or reclamation programmes.

F.2 Wheatstone Conditions and Approach

Wheatstone is characterised by:

- Distinct (although variable) seasonal currents.
- A long duration dredge programme (nominally about 36 months for capital dredging) stretching over multiple seasons.
- Dredging along a long stretch of channel with potential impact to sensitive receptors highly dependent upon the spill locations and climatic conditions.
- An outline dredge programme and schedule which will only be "finally" determined upon the appointment of a dredging contractor, and even then is likely to change through the dredging period.

The high dependency of the potential impacts on a number of variables requires simulation of a large number of cases to ensure that the worst case is captured for a given receptor. Assuming that sediment re-suspension does not play a significant role in the delineation of impact zones, the Wheatstone site and conditions clearly favour a shorter term scenario approach with combinations of relevant climatic, dredge and spill conditions.

The shorter scenario approach has been tested and used extensively for projects conducted in DHI's Malaysian and Singaporean offices, and a modelling and impact strategy based on the following components has been developed:

- Establishing impact criteria for the environmental receptors. The impact criteria are typically related to medium term exceedences of certain threshold limits for environmental indicators that can be quantified trough modelling (typically excess sediment concentrations and sedimentation rates, but could also be for instance light attenuation). The threshold limits and impact criteria are site and receptor specific.
- Identifying the main variables and uncertainties controlling the spillage and sediment dispersion from the dredge programme (or other activities causing impacts).
- Establishing a range of conditions for the above variables to be covered in the modelling. This should include conservative values without being overly conservative.
- Establishing a suite of scenarios encapsulating the defined ranges for the main variables.
- Using the suite of modelled scenarios and the established impact criteria to assess the environmental impacts and risks. The impact evaluation will provide information on the potential impacts of individual dredge operations for given climatic conditions, and by combining the suite of model output from the various scenarios, an envelope of potential impact zones for all combinations of dredging and climatic scenarios.

The use of the individual scenario outputs for the impact assessment can be tailored to the project. Some possibilities include:

- Option (1): Producing an envelope for the potential impacts by combining the individual impacts from all the scenarios. This represents an outer boundary for the individual footprints of any dredging programme that is reasonable represented by the various dredge scenarios.
- Option (2): Estimating footprints from individual dredge programmes by combining the relevant scenarios to emulate the programme.

The first approach provides a good indication of the receptors at risk, but should not be confused with an actual "footprint" of the project. The second approach provides an estimate of an actual footprint of the project for a given dredge plan. It should be stressed that this is closely tied in with the assumptions for the dredge plan, and is generally not a good indication of the receptors at risk from the overall programme given potential changes to the dredge schedule. The impact zone derived using Option (2) is expected to be a subset of the "envelope" impact zone derived using Option (1).

For Wheatstone, the outline Dredge and Disposal Plan is likely to be changed by the dredging contractor. To maintain conservatism, the impact assessment has therefore been carried out based on the envelope of impacts derived through the first approach listed above, although it is recognised that this leads to impact zones that are likely significantly larger than the actual project footprint.

In addition to assessing the impacts and risks associated with a given dredge programme, the suite of scenarios established through the above outlined procedure can readily be used for:

- Assessing impacts of changes to a given dredge programme, both in terms of timing and use of different approaches if the associated spill rate can be assessed.
- Identifying critical stages or components of the dredging programme
- Optimisation of dredge programme to minimise impacts (e.g. avoiding dredging in critical areas during certain climatic conditions, minimising spill in critical sectors, etc.)
- Identifying most effective mitigation measures.
- Establishing limits on control variables to stay within specified impacts (one option is based on a spill budget approach which determines the maximum allowable sediment spill for defined zones and conditions on critical variables, e.g. variable with climatic conditions) This approach maintains a large degree of flexibility as it typically relates impacts to the spill generated, irrespective of how this is generated.

F.2.1 Wheatstone Scenarios

The scenario selection for Wheatstone is described in Section 5 and Section 6.1.1 of the main document and is only very briefly outlined below.

- 6 climatic conditions, 2 each representing summer, transitional and winter, have been selected. These are based on "real" conditions driven by simultaneous tides, winds and waves, and thus show significant variations through the individual periods.
- The dredge scenarios have undergone several rounds based on ever developing project descriptions and related changes to the Dredge and Disposal Plan (DDP). For the final assessment, 7 base scenarios representing the dominant activities causing sediments to be released into the water column have been defined. In addition, one scenario representing a mitigation (dredge programme optimisation) option has been simulated.
- The spill rates from dredging activities are highly uncertain. For each key activity, two spill rates have been defined: A best estimate "realistic" spill rate and a "worst case" spill rate. These spill rates have been developed by LWI and DHI in conjunction.

The full envelope of all combinations of climatic, dredge and spill scenarios have been simulated, leading to 96 scenarios. In addition, it has been found that different wind sources for driving the model have different problems, and the 96 scenarios have been run for both measured Onslow winds and MesoLAPS wind maps (see also Section 4.1.3.2 of the main report).

F.3 Simulation Length

The length (duration) of each simulation scenario is a balance between a number of factors including:

- Suitable analysis conditions for impact assessment on critical receptors
- Ability to represent climatic conditions
- Ability to represent dredging conditions
- Simulation "warm-up" time

Tides are usually an important consideration for plume dispersion. A 14 day neap-spring tidal cycle is considered essential to encompass the main tidal induced variations within the analysis period.

Environmental receptors can typically cope with "severe" conditions (e.g. in the form of high turbidity levels) for a "short" period of time, but can also be impacted by "less magnitude, but longer duration" events. The period for impact assessment must thus accommodate statistical analysis that caters for both short and somewhat extended duration events. DHI has over many years and projects developed and had good experience with impact criteria based on exceedence probabilities derived from 14 day neap-spring tidal cycles. This approach has been adopted for Wheatstone.

The numerical model complex needs a "warm-up" period prior to the analysis period to ensure that both hydrodynamics (a matter of hours up to a couple of days) and sediment plume characteristics (depending on site conditions, but usually a matter of days) are well established. It is DHI's experience that a week "warm-up" period is usually ample for sediment plume modelling. For the Wheatstone Project, a conservative approach of a full month simulation, i.e. in excess of a 14 days neap-spring cycle warm-up, has been adopted.

It is further noted that for each of the "summer", "transitional" and "winter" conditions, two months continuous simulation periods have been adopted with two "assessment periods" at the end of each month such that the second assessment period in fact has a warm-up period of 1 ½ months.

F.3.1 Demonstration of Quasi-stationary Conditions

As the modelling is carried out based on measured winds and waves, the conditions are variable throughout the scenarios, and it is thus not straight forward to make a simple analysis of when a "quasi-stationary" condition, i.e. when statistical results are not impacted by the "warm-up" period, has been achieved.

To demonstrate that the assumption of quasi-stationary conditions is valid for the present case of a minimum of 14 day warm-up period, the following test has been carried out.

3. A dredge scenario (Summer conditions with Onslow winds which leads to a large plume extension eastward in the nearshore) has been simulated from "cold", i.e. from start of dredging for a 14 day period.
4. The concentration and sedimentation fields have been derived at the end of the simulation (after 14 days).
5. A second simulation has been carried out for the same period and driving forces, but with the concentration and sedimentation fields derived from the first simulation as initial fields.
6. Concentration and sedimentation fields have been derived from the end of the second round simulation.

7. A third simulation has been carried out for the same period and driving forces with the concentration and sedimentation fields derived from the second simulation as input.

Based on this, it should be expected that the concentration fields and sedimentation rates should be different from the first to the second simulation, but virtually identical from the second to the third simulation if quasi stationary conditions had developed at the end of the first simulation.

Statistical output as used for the impact assessment is presented at the end of the three simulation periods in Figure F.1 to Figure F.3. It is noted that the sedimentation rates are derived for the individual periods, i.e. for Simulation 3 it is the total sedimentation at the end of the simulation subtracted the sedimentation at the beginning of the period. The plots show the expected variation with a slight increase in the far-field plume coverage from Simulation 1 to Simulation 2, but virtually identical concentration and sedimentation fields in Simulation 2 and Simulation 3. This confirms that the “warm-up” period is sufficiently long, and the small difference between Simulation 1 and Simulation 2 in fact indicates that the more than 14 days warm-up applied is very conservative.

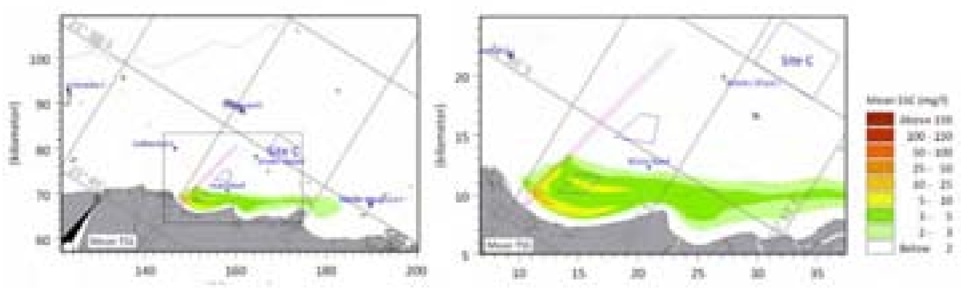

Figure F.1 Mean excess concentrations over the 14 day simulation period for Simulation 1 with “cold start”.

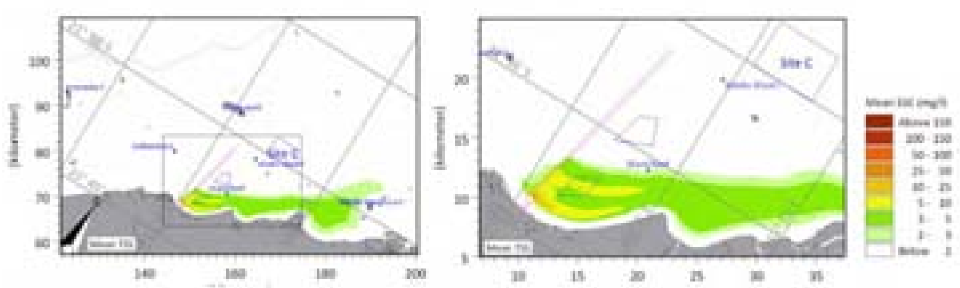

Figure F.2 Mean excess concentrations over the 14 day simulation period for Simulation 2 with initial concentration and sedimentation fields from Simulation 1.

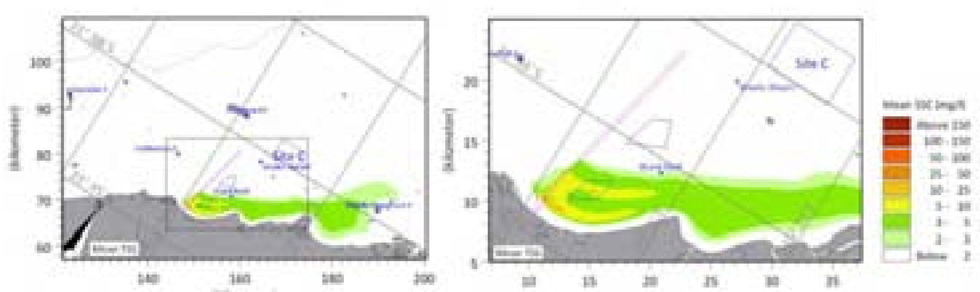

Figure F.3 Mean excess concentrations over the 14 day simulation period for Simulation 3 with initial concentration and sedimentation fields from Simulation 2.

F.4 Effects of Re-suspension

Re-suspension of fine material originating from the dredging and dumping activities can have a significant impact on the plume dispersion, in particular the low concentrations of the finest fractions.

Simulations have shown that in particular combinations of spring tide and strong wind driven net currents can lead to significant and repeated re-suspension of material, which can carry low concentration plumes relatively far from the dredge location. This has the potential to extend the zone of influence away from the origin of the sediment.

Waves have two main effects on sediment plume dispersion:

- Introducing additional turbulence and mixing in the water column through wave breaking
- Introducing shear stresses on the bottom which will impact the deposition and re-suspension of sediments.

Whereas the wave climate in the Wheatstone nearshore area under normal conditions is characterised as benign, the relatively low water depths and occasional long wave periods associated with swell waves does allow some effect of the waves to be felt at the bottom.

The MT model calculates the bottom shear stresses in combined current and wave action.

In the models, the fines originating from the dredging and disposal processes can deposit and re-suspend under the influence of waves and currents throughout the model area. In additions to the sediment originating from the spill sources introduced in the models, a layer of fine sediment available for re-suspension is introduced in the models at dredged areas and within the placement sites. The layer available for re-suspension within the placement sites and dredge corridor is not limited in thickness within the scenario period.

Figure F.4 illustrates the effects of re-suspension by currents and waves over a 2 months simulation period. The plots shows net sedimentation over the 2 months period on the left-hand side and maximum concentrations throughout the simulation period on the right-hand side. The following is noted when re-suspension and the effects of waves are included:

- A slight decrease in net sedimentation close to the sources (i.e. some of the sediment has re-suspended)
- An increase in the area where low level concentrations of suspended sediments are reached at some stage during the simulation.
- The areas covered by higher concentrations plumes are largely un-changed.

It is noted that the maximum plots may give the impression of very large differences, and it is clear that the re-suspension can significantly increase the area affected by low concentration plumes. However, much of the re-suspension happens in relatively short bursts during spring tide, and the duration of the resulting plumes are low. Most environmental receptors are tolerant to short bursts of low concentrations, and the large increase in size of the low concentration “maximum” plumes does therefore generally not translate into a significant increase in environmental impacts.

In terms of the modelling carried out for Wheatstone, each modelled scenarios is carried out over two months (corresponding to the simulation presented in Figure F.4), and the effects shown in this figure are thus included in the modelling. The potential incremental impacts due to re-suspension at the higher concentration fields in the vicinity of the spill sources are thus included in the scenario modelling.

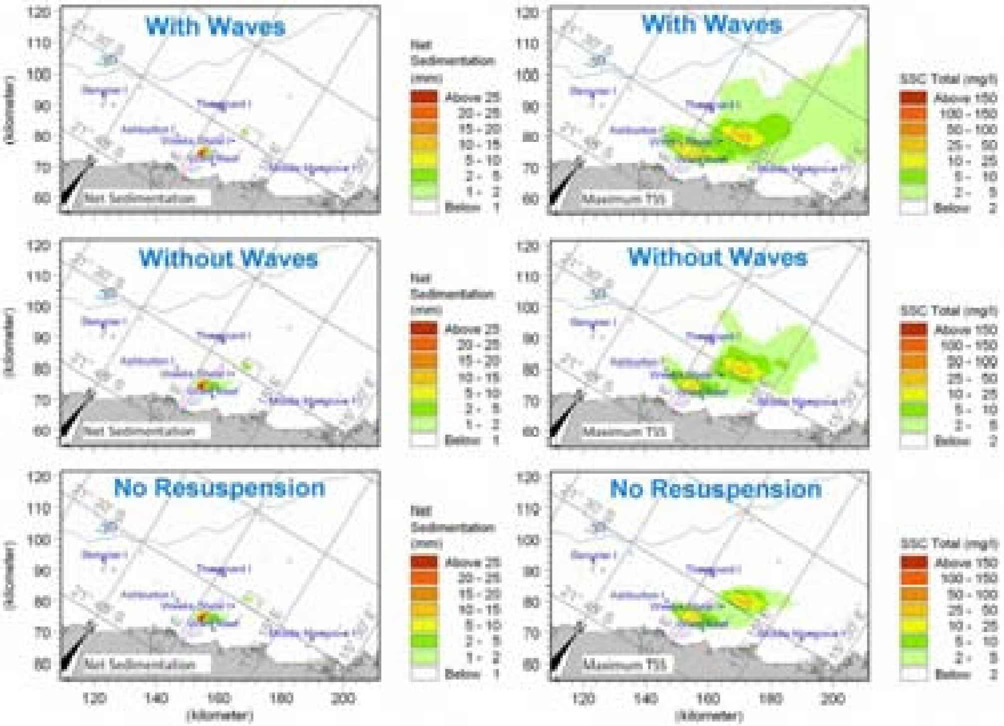

Figure F.4 *Effect of re-suspension and waves. Maximum concentration (right) and sedimentation (left) over a 2 month summer period with TSHD dredging and dumping at site C for 3 cases. Bottom: High critical shear stress for erosion (allowing no re-suspension); Centre: Normal critical shear stresses for erosion, excluding waves in simulation; Top: Normal critical shear stresses for erosion, including waves in simulation.*

In terms of impacts from dredge spoils, it can be discussed at what point in time the re-suspended sediment looses its identity and becomes part of the ambient concentration. If a sediment particle settles out in an area with only coarse sediment present which does not easily go into suspension, it is reasonable to assume that the re-suspension of a similar particle would not have occurred if the particle had not been brought into suspension through the dredging activities and subsequently settled out there. If, however, a particle settles out in an area with predominantly as fine or finer sediments than the particle, it can be argued that the ambient potential for re-suspension in this area is higher than that of the particle, and the particle would not cause additional re-suspension in this area. In addition, cohesive forces and consolidation may gradually prevent a particle from re-suspending.

The model can be set up to represent these factors, e.g. by producing a map of critical shear stresses for erosion depending on the type of sediment present. Consolidation can be included through multiple layers with different characteristics and a transfer function between layers.

For the 2 month scenario modelling, a conservative approach of omitting any consolidation effects and allowing particles to re-suspend throughout the model area has been adopted.

The main potential drawback from the shorter-term scenario approach is that the full sediment history throughout the dredging period is not maintained. A basic assumption for the shorter-term modelling approach is that re-suspension of sediments leads to limited excess concentrations, which are generally not causing mortalities on its own, and does not add significantly to the more severe impact zones generated by the higher density plumes emitted from the spill sources. It is expected that the continued re-suspension of material in the long dredge simulations may lead to an increase in the zone of influence, but not any significant increase in the other impact zones. It is thus expected that perhaps apart from the zone of influence, the impact zones derived from longer dredge period simulations will lie within the envelope of impact zones developed through the shorter scenario simulation.

This assumption has been tested in two ways:

1. An extension of the “repetition” of the driving conditions shown in Section F.3.1 to a much longer period. If re-suspension is important this should gradually change the results to show larger plumes.
2. A simulation for an extended dredge period (2 years of dredging comprising all dredging of loose material with the higher spill rates) has been carried out for a realistic scenario per the DDP.

Results from the two tests have been reported in the following sub-sections.

F.4.1 Repetitive Periods

The repetition of 14 day periods has been carried out for Dredging Scenario 6 for summer conditions driven by Onslow wind and winter conditions driven by MesoLAPS winds. Each simulation has been run for 16 repetitions of the 14 day period.

Figure F.5 to Figure F.8 show the summer conditions after 1, 2, 8 and 16 repetitions of the 14 day period for summer conditions, while Figure F.9 to Figure F.12 show similar plots for the simulated winter period driven by MesoLAPS winds.

Figure F.13 illustrates the net sedimentation over the entire simulation period after 1, 2 and 16 14 days simulation periods for winter and summer conditions.

The following is evident for both summer and winter conditions:

- There is an increase in the far-field concentrations from period 1 to period 2.
- After period 2, the concentration fields represented through mean concentrations and exceedences remain virtually unchanged, indicating that the changes due to additional re-suspension not captures through a month period, is only for very low concentrations and below the threshold limits for the impact assessment.
- Sedimentation rates are fairly constant (due to the repeated climatic conditions with similar shear-stress distributions), and there is a gradual build-up of the net sedimentation.

For the simulated summer and winter conditions, the effect of re-suspension on the statistics used to derive the impact zones is negligible.

Dredge Scenario: 6

Climate Scenario: Summer (onslow winds)

Spill Rate: Low (realistic)

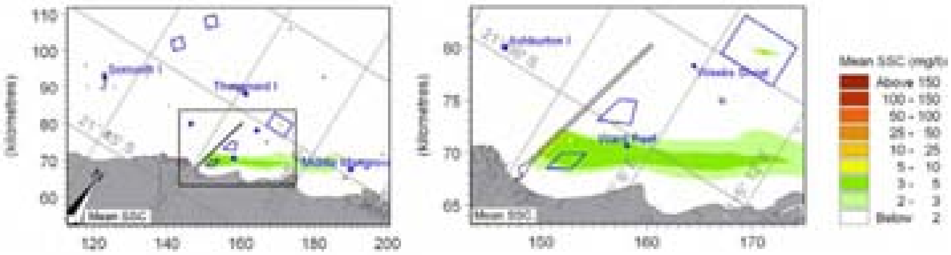

Figure F.5 Mean excess concentrations, over the 14 day simulation period . 1st 14 day period with "cold start".

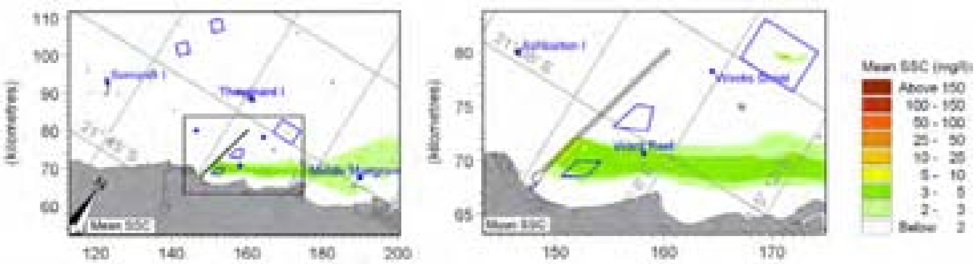

Figure F.6 Mean excess concentrations over the 14 day simulation period. 2nd 14 day period with initial concentration and sedimentation fields from end of 1st period.

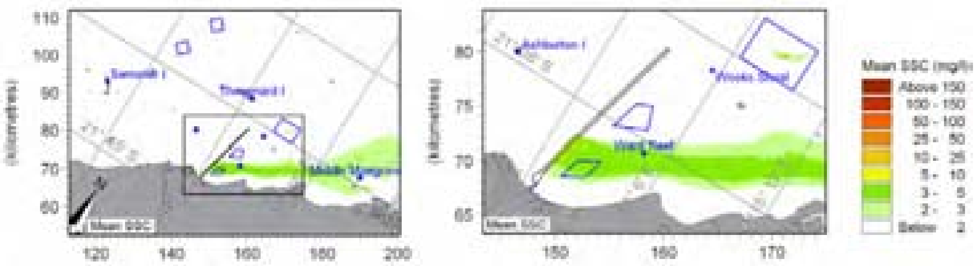

Figure F.7 Mean excess concentrations. 8th 14 day period with initial concentration and sedimentation fields from end of the previous 7 periods.

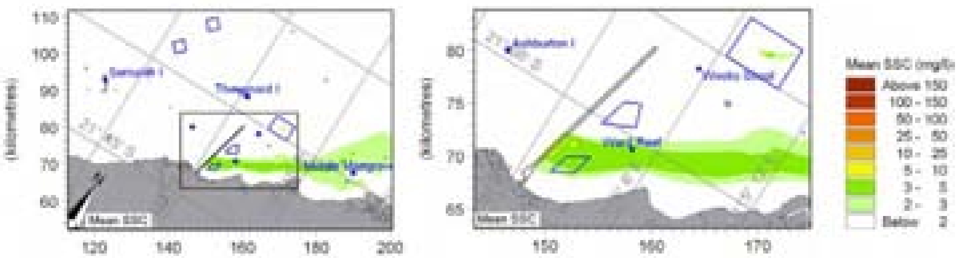

Figure F.8 Mean excess concentrations 16th 14 day period with initial concentration and sedimentation fields from end of the previous 15 periods.

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Dredge Scenario: 6

Climate Scenario: Winter (onslow winds)

Spill Rate: Low (realistic)

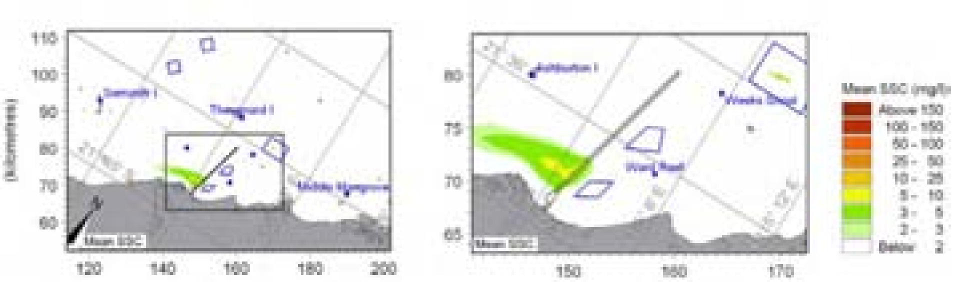

Figure F.9 Mean excess concentrations 1st 14 day period with "cold start".

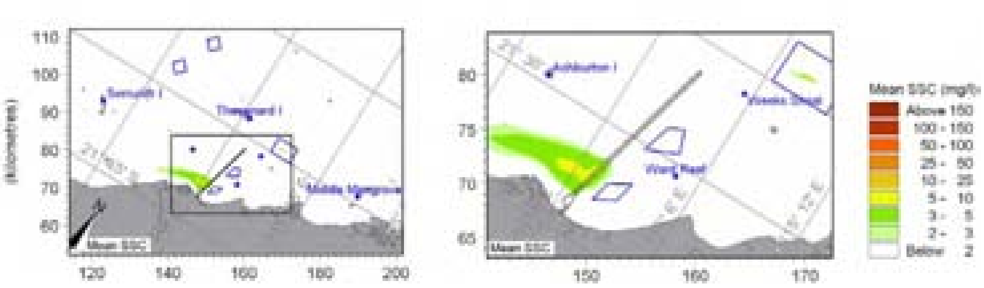

Figure F.10 Mean excess concentrations. 2nd 14 day period with initial concentration and sedimentation fields from end of 1st period.

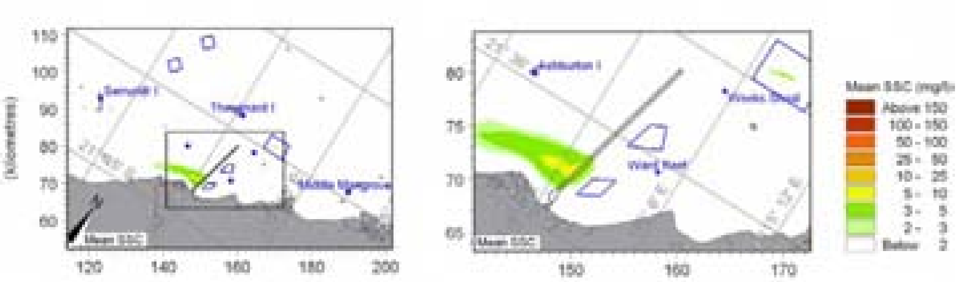

Figure F.11 Mean excess concentrations. 8th 14 day period with initial concentration and sedimentation fields from end of the previous 7 periods.

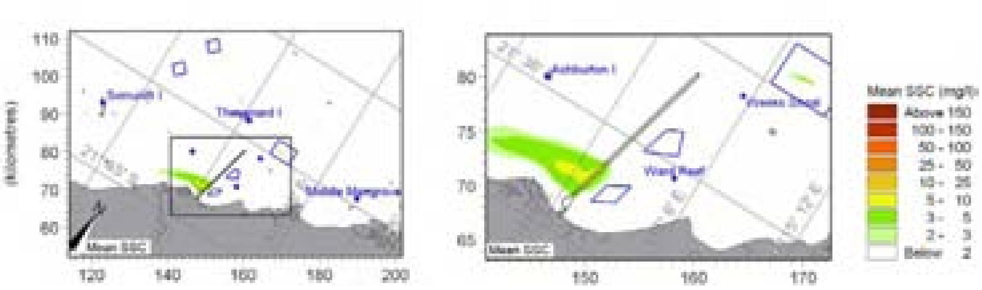

Figure F.12 Mean excess concentrations. 16th 14 day period with initial concentration and sedimentation fields from end of the previous 15 periods.

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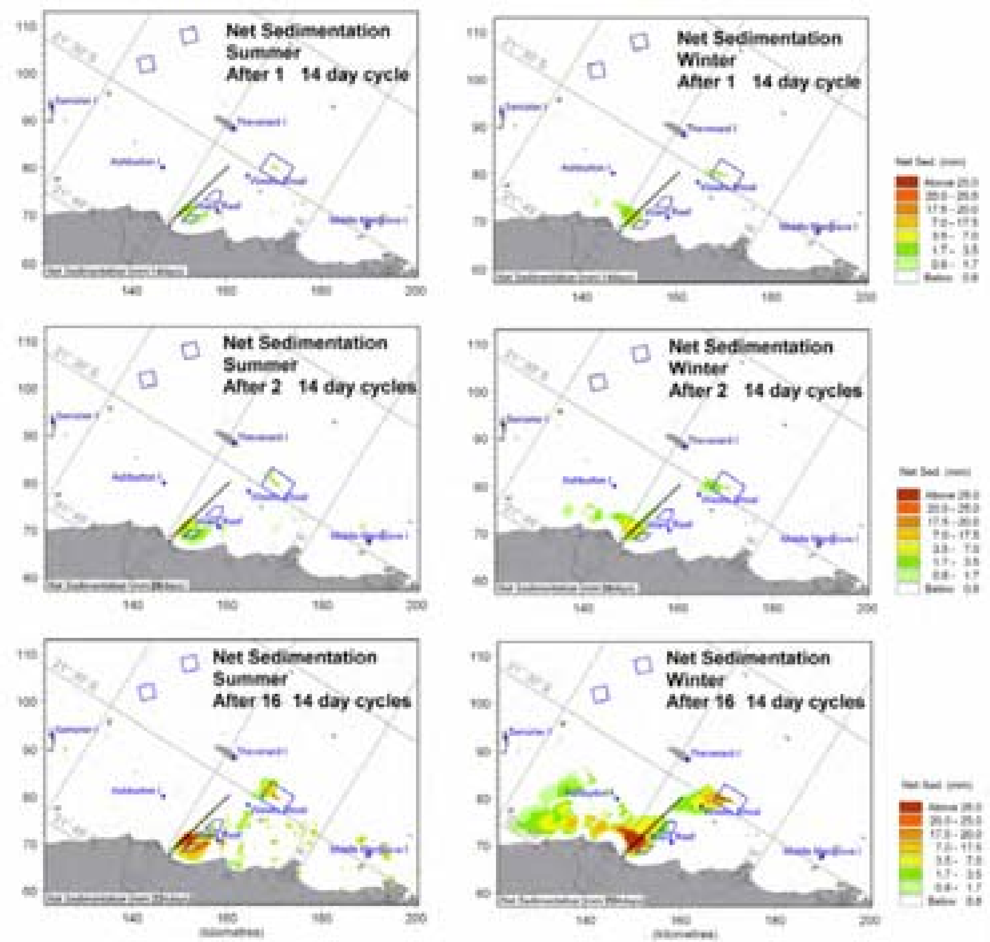

Figure F.13 Net sedimentation over full simulation period after 1, 2 and 16 14 day simulation periods for Dredge Scenario 6 for Summer (left-hand side) and Winter (right-hand side).

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F.4.2 Longer Dredge Period Simulation

Section F.4.1 demonstrated that the effects of build-up of sediments and related changes to re-suspension on the statistical values for the sediment plumes are negligible for a repeated 14 day period.

A "real" dredge period will encompass larger variations in the climatic drivers as well as differences in the dredging and spill conditions.

A two-year simulation has been carried out to further investigate the hypothesis that the re-suspension will not lead to significant increases in the impact zones, and that the footprint derived from a long term modelling exercise will fall within the footprint envelope developed through the shorter scenario modelling.

The dredge programme, which defines timing, location, production and spill assumptions for each individual operation, was developed based on the outline DDP. Some of the main

F.4.2.1 General Modelling Considerations

Similar to the shorter dredge scenarios, the model has been set up to model the movements and spills as realistically as possible. The full dredge programme simulations have been set up with climatic conditions corresponding to the period 2006 – 2009, for which the most complete data set is available to drive the models. Statistical analysis of wind records over a 10 year period showed fairly typical net winds during the selected period. It could further be argued that any trends due to climate changes should be best captured in records from the most recent years.

Some of the assumptions/procedures applied in the modelling include:

- The model bathymetry is progressively updated as the dredging progresses.
- A layer of material available for re-suspension is introduced in the channel and dredged areas as they are dredged.
- A layer of fines available for re-suspension is included at the placement sites. Although placement site B is provisional, a layer for re-suspension has been included at this site as well.
- Spill rates applied in the modelling are based on the "realistic" spill rates agreed between LWI and DHI to get a best estimate of impacts.
- The dredge schedule outlines simultaneous dredge activities. The full dredge activities are captured in the modelling in accordance with the schedule.
- The DDP specifies production rates, cycle times and spill rates for loose material and weak rock. In reality, the TSHDs are likely to encounter a mix of materials at it dredges along the channel. Based on the soil information, the top soils are predominantly loose materials, and high production rates have been maintained for the upper part of the profile with lower production rates for the lower part of the channel profile. This will ensure that extended periods of high production rates are captured in the modelling.
- The production rates have been adjusted to fit with the schedule, sailing distance and related sailing time. This has led to slightly lower production and spill rates for the "best estimate" longterm dredge simulation compared to the shorter scenario approach.

The impact assessment is carried out based on 14 day statistics. To maintain a level of conservatism, the dredging operations have been split into 14 day periods along various channel segments. The programme is very briefly outlined below:

- The dredging is assumed to start in November
- Over a period of about 8 months, a CSD works its way from the -7m LAT contour and shoreward to dredge a temporary access channel, the MOF channel and MOF basin, and the PLF channel down to about -8 m LAT. The material is initially pumped to Site A through bottom diffuser and then to barges with overflow in the inner PLF basin for transport to Placement Site C.
- A TSHD starts dredging in parallel with the CSD. It is assumed that the TSHD starts at the off-shore end of the channel and initially removes a loose topsoil, progressively moving shoreward. Removal of the loose topsoil is assumed to take about 10 months, after which it dredges weak rock with corresponding lower production rates along the approach channel.
- Another TSHD continues the dredging of the PLF down to the final depth after the CSD has completed it down to – 8m LAT. The TSHD initially dredges loose material with corresponding high production and spill rates, and then proceeds with weak rock with lower production and spill rates.

F.4.2.2 Presentation of Individual Periods

Selected plots of plume statistics derived from individual 14 day cycles are presented in Figure F.14 to Figure F.21.

Some notes and observations include:

- The nearshore CSD dredging is largely carried out during the summer and transitional periods. The model for the long term plume modelling was driven by the MesoLAPS winds, and with the under-prediction of the nearshore summer winds by MesoLAPS, the nearshore plume does not extend very far eastward during the summer season.
- The TSHD dredging of the approach channel starts in late summer, and primarily runs through the transitional and winter periods for the high spill rates in loose material. This causes the plumes to primarily extend westward.
- The impact zones are defined by the higher production and spill rates. The dredging in weak rock has very low production rates, and therefore low spills in kg/s, and the resulting plumes are much smaller in size and with lower concentrations than the corresponding plumes from dredging in loose material.
- For the present simulation of the long period dredging programme, it has been assumed that the loose material is at the surface and is removed along the channel through the first year. The overall footprint is largely defined by the activities in the first year as spill rates thereafter are too low to add to the impact zones (see sample in Figure F.21 for two TSHDs working in weak rock).

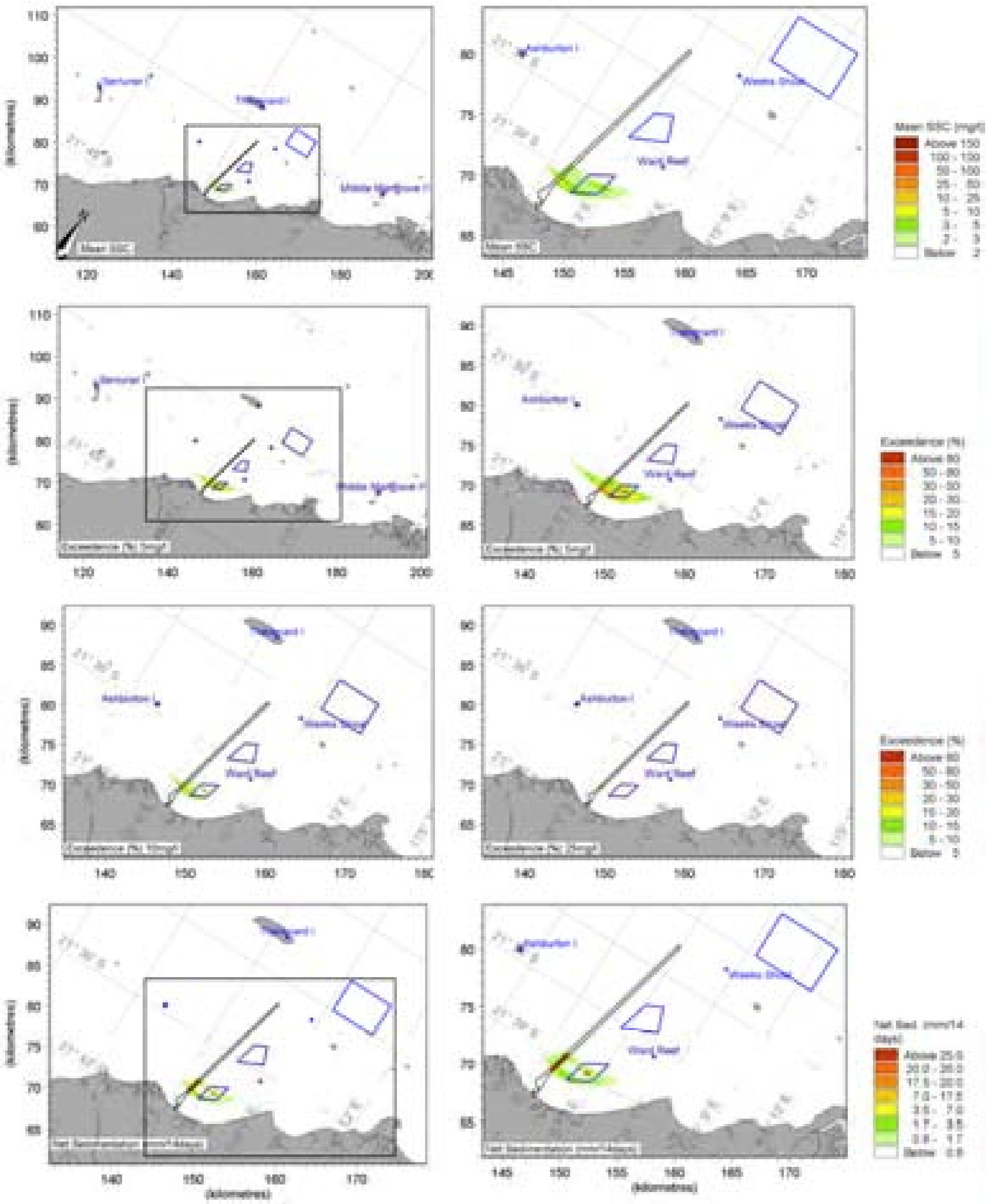

Figure F.14 14 day statistics for the first 14 day cycle in November with a CSD dredging a temporary access channel with bottom placement at Disposal Site A.

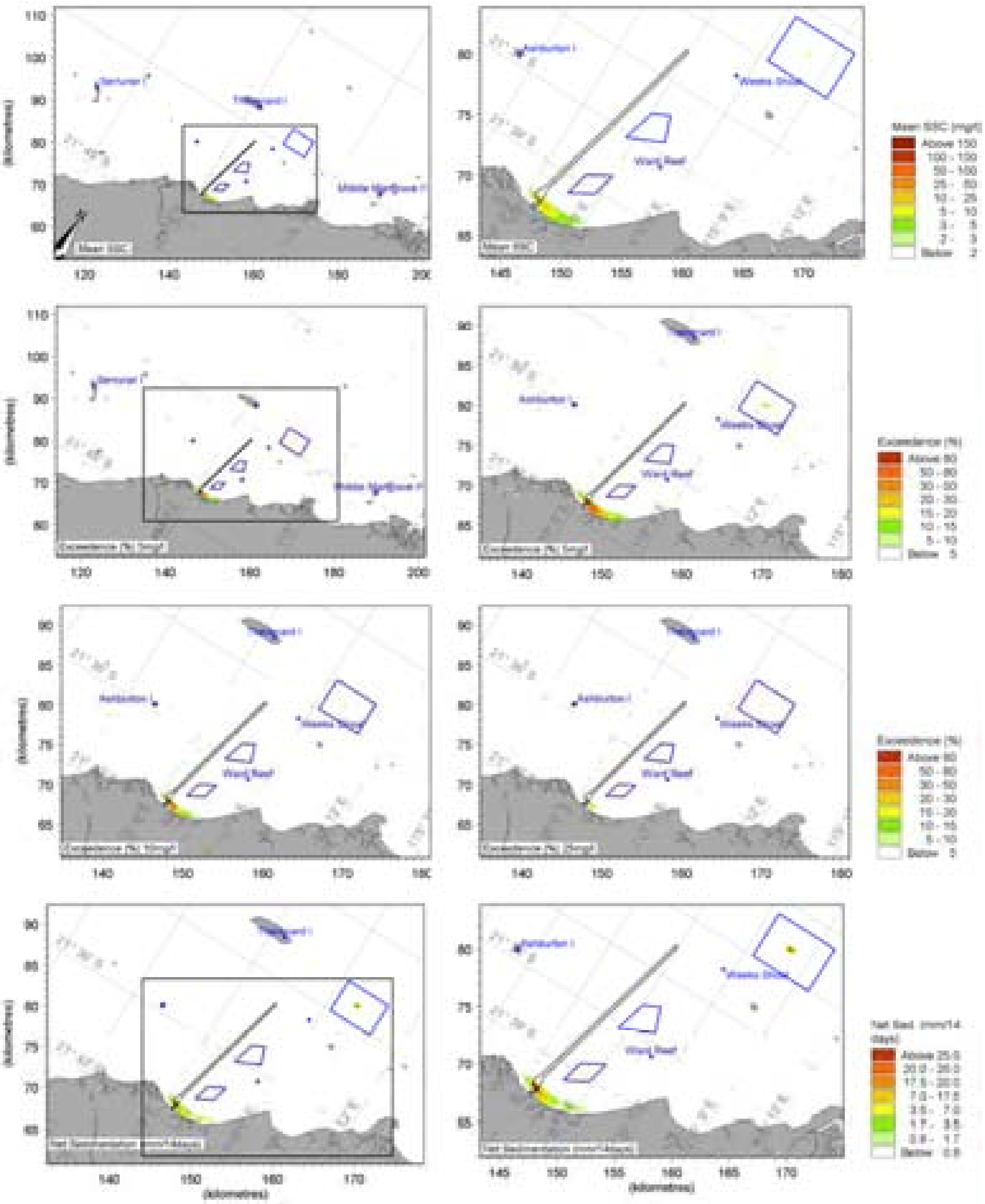

Figure F.15 14 day statistics for the fourth 14 day cycle in December with a CSD dredging the inner PLF and MOF approach channel with overflow of barges and transport and dumping at Placement Site C.

F-18

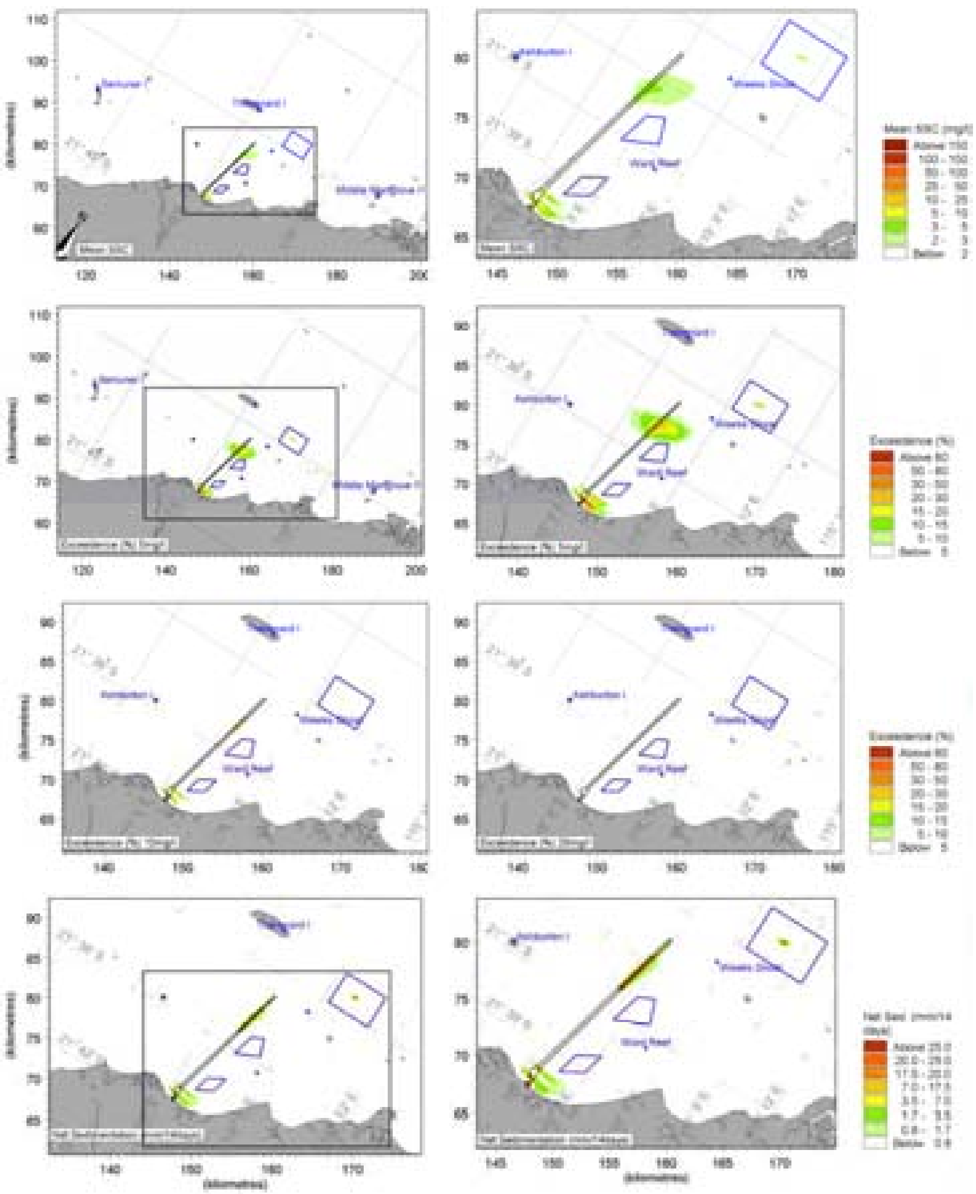

Figure F.16 14 day statistics for the seventh 14 day cycle in February with a CSD dredging the outer PLF with overflow of barges and transport and dumping at Placement Site C. In addition, a TSHD is dredging in the outer part of the Approach Channel.

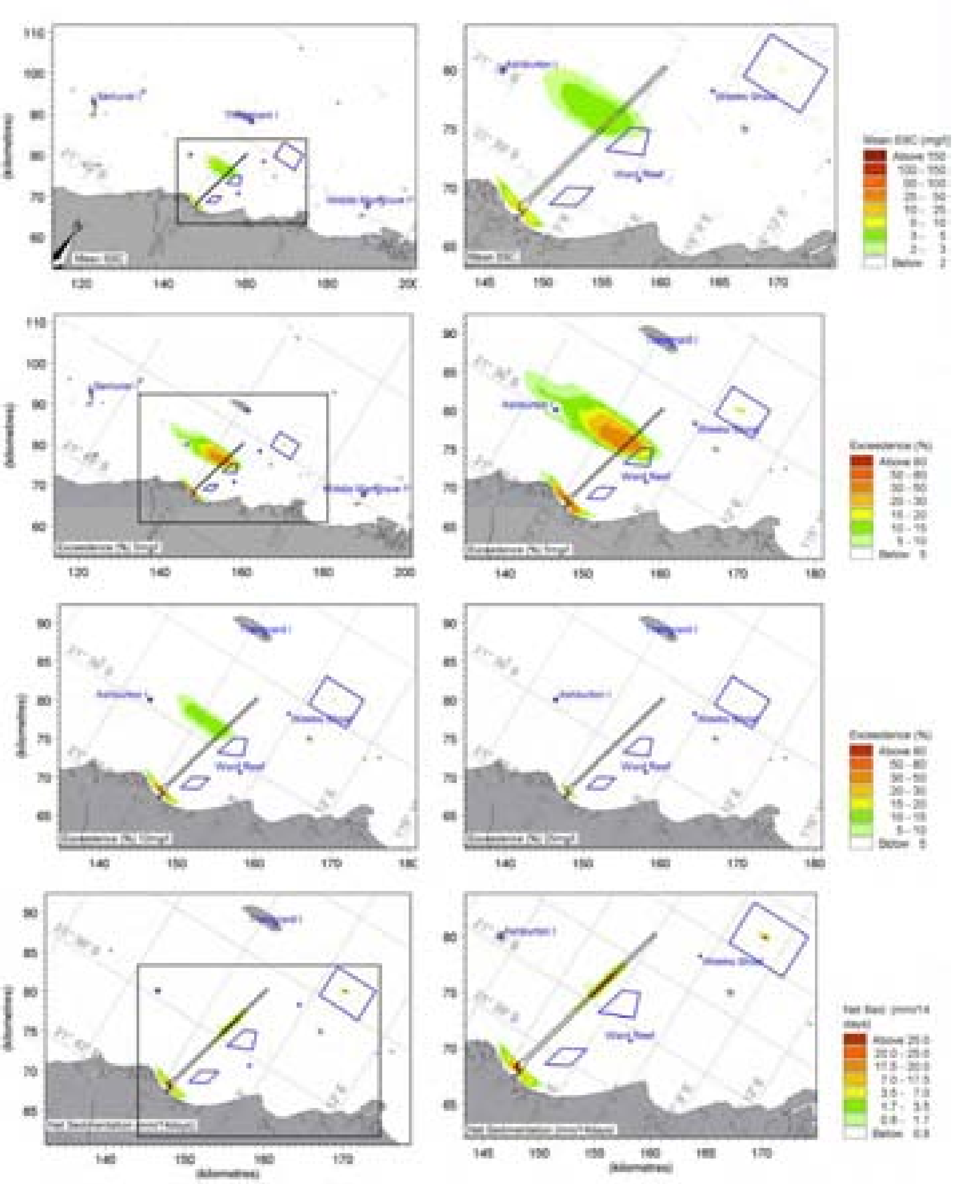

Figure F.17 14 day statistics for the tenth 14 day cycle in March with a CSD dredging the outer PLF with overflow of barges and transport and dumping at Placement Site C. In addition, a TSHD is dredging in the outer part of the Approach Channel.

F-20

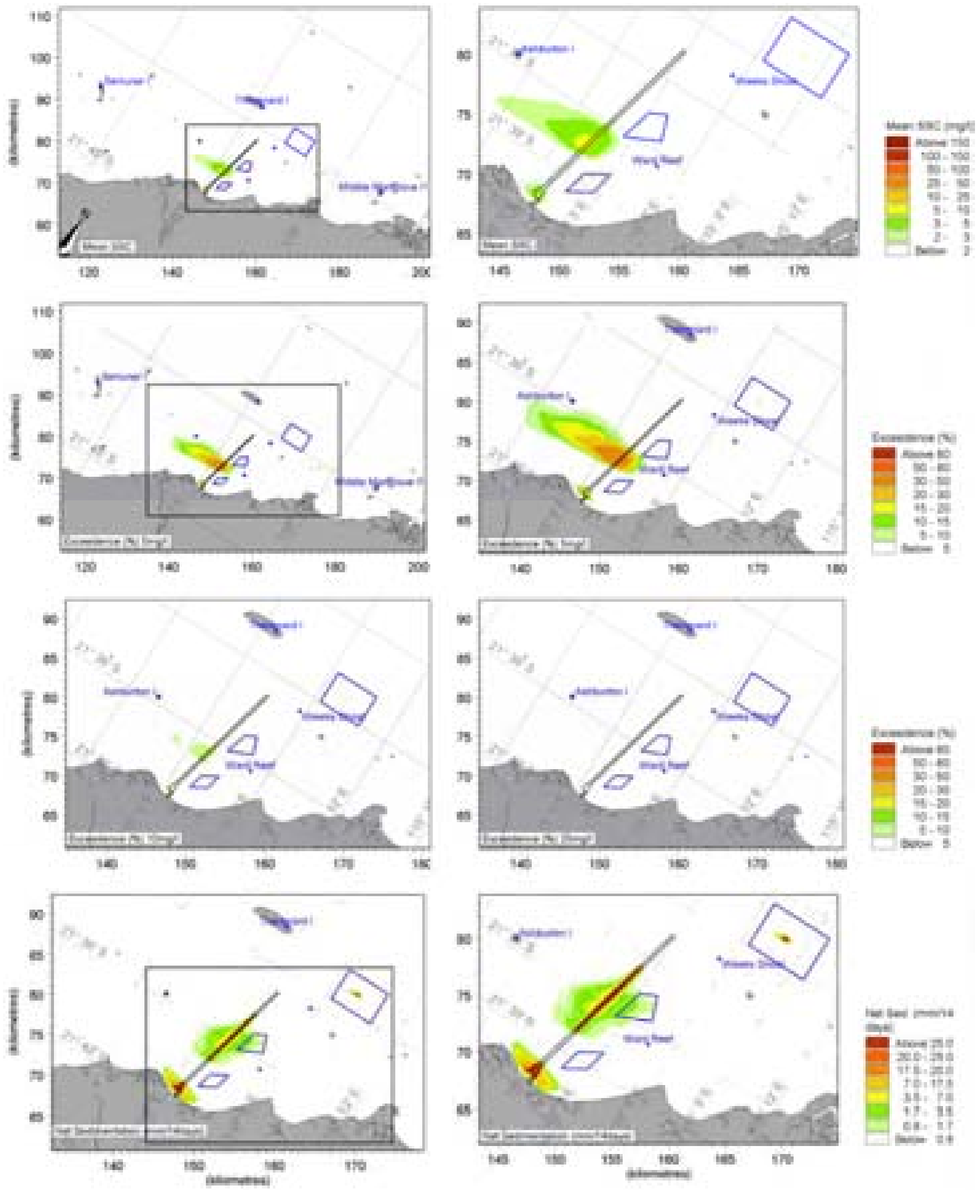

Figure F.18 14 day statistics for the fourteenth 14 day cycle in May with a TSHD dredging the PLF and another TSHD dredging in the central part of the Approach Channel.

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F-21

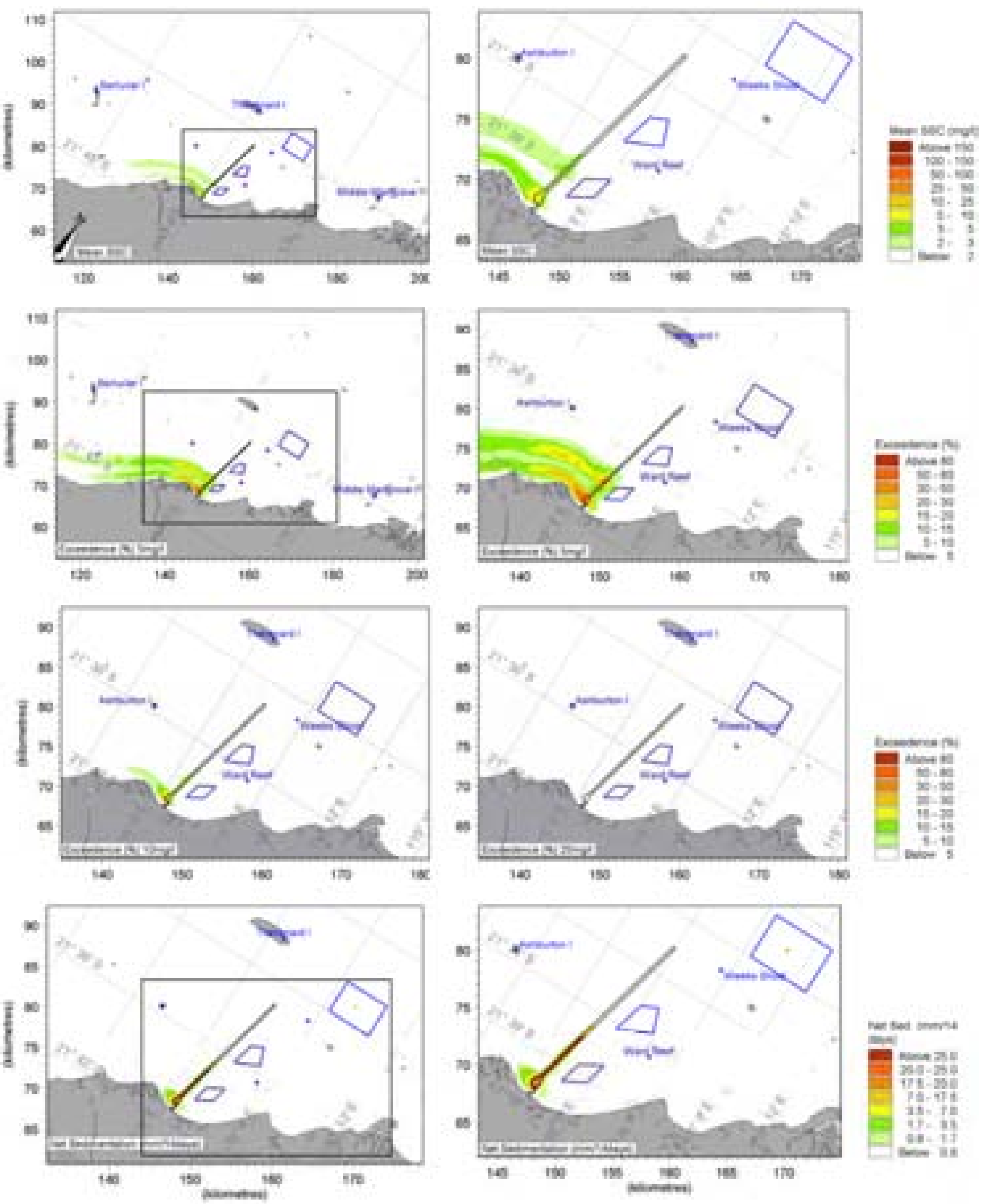

Figure F.19 14 day statistics for the eighteenths 14 day cycle in July with a TSHD dredging the PLF and another TSHD dredging in the inner part of the Approach Channel.

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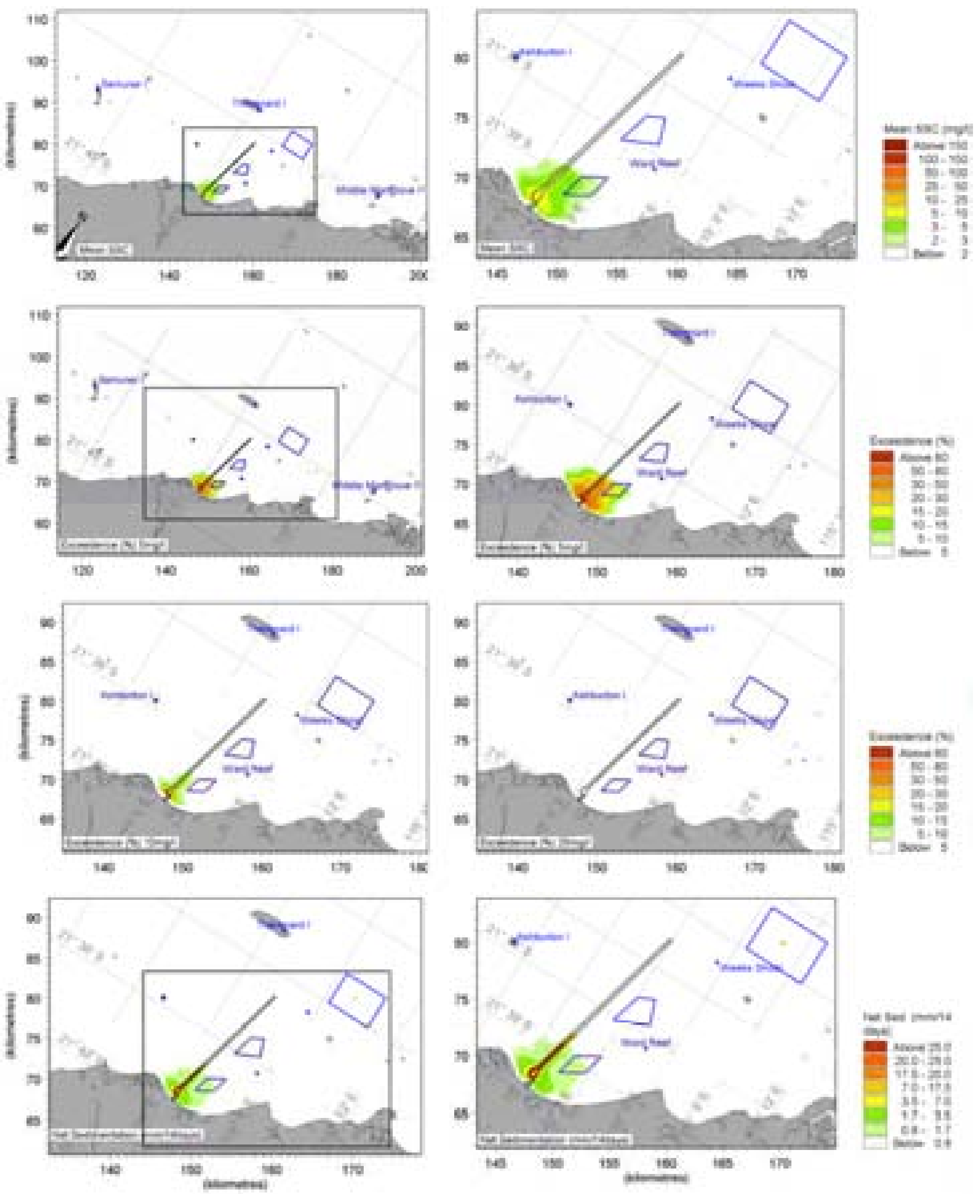

Figure F.20 14 day statistics for the twenty second 14 day cycle in September with a TSHD dredging the PLF and another TSHD dredging in the inner part of the Approach Channel.

F-23

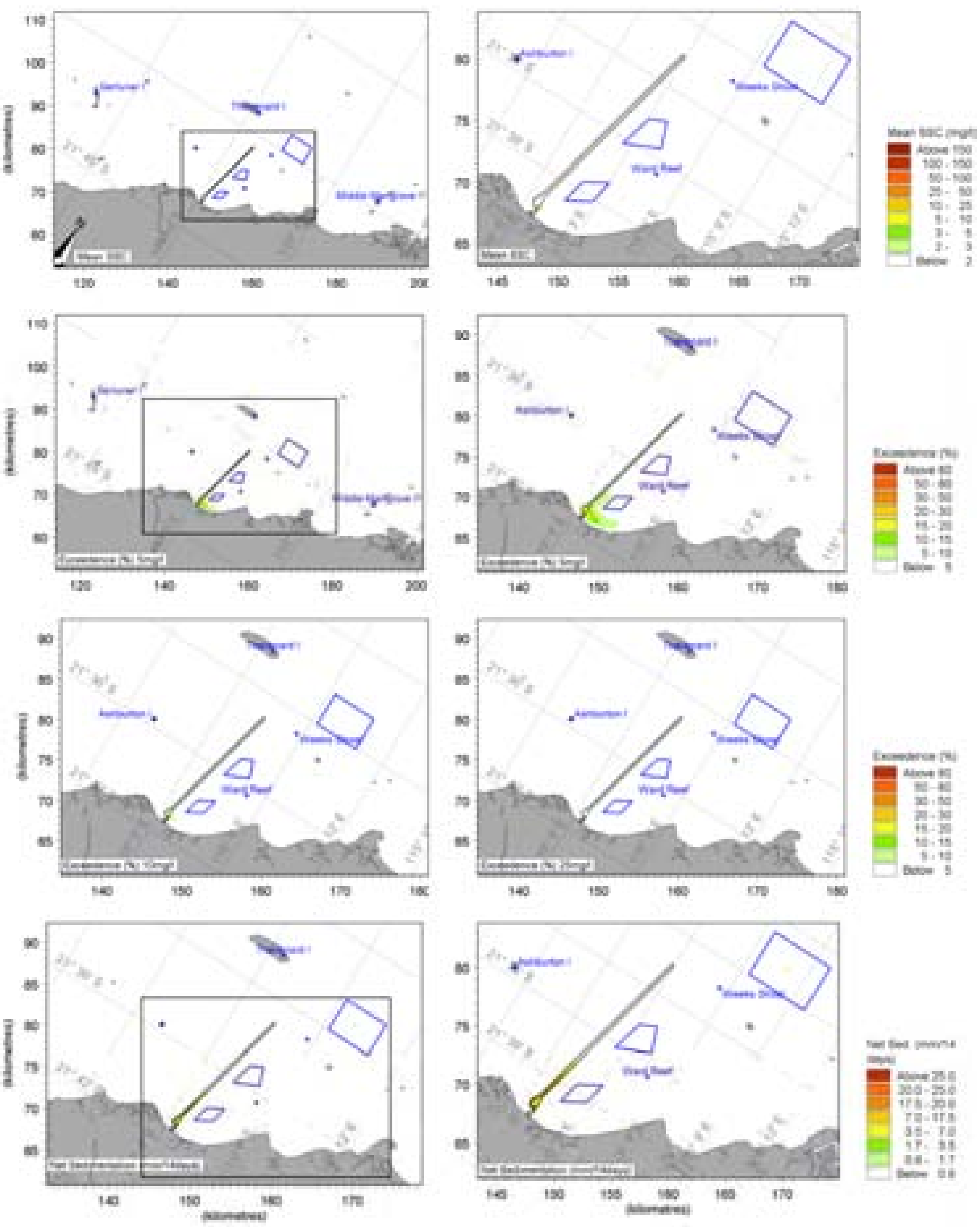

Figure F.21 14 day statistics for the twenty fourth 14 day cycle in October with a TSHD dredging the PLF and another TSHD dredging in the inner part of the Approach Channel – both with low production rates in assumed weak rock.

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F.4.2.3 Presentation of Composite Results

Figure F.22 shows the footprint of the simulated long dredge period in terms of 14-day mean concentrations (top) compared to the envelope of 14-day mean concentrations derived through the shorter term scenario modelling using a combination of MesoLAPS and Onslow winds (bottom).

Figure F.23 and Figure F.24 make a similar comparison between the footprint in terms of impact zones derived from the long period simulation and the envelope of impact zones derived through the shorter-term scenario modelling for SSC impacts on coral habitats. A similar comparison for Sedimentation impacts on coral habitats is shown in Figure F.25 and Figure F.26.

Two clear and important observations from the comparisons between the footprint of the long-term simulation and the envelopes developed from the scenario modelling are:

1. The footprint derived through the long-term simulation generally lies well within the envelope developed through the scenario modelling as expected. This supports the notion that the shorter-term scenario modelling has sufficient conservatism built in and captures the critical combinations of spills and climatic drivers to establish the outer bounds for the impact zones. It also supports the assumption that re-suspension from sediment derived from the long-term dredging programme will not add significantly to the impact zones. There are two minor exceptions to this when looking at the mean excess concentrations:
    a. The 3-5 mg/l area stretches slightly further to the west in the footprint from the long-term simulation at a location to the west of Ward Reef. This is due to limited overlap along the channel of the defined dredge segments. For the final delineation of the impact zones, the “edges” of the zones are interpolated between the individual scenarios to ensure that the full area is covered.
    b. A slight further extension westward of the 3 mg/l contour for the same area. This is due to the same effect potentially combined with added re-suspension in relation to a “strong climatic burst”. This does not affect the important impact zones for partial mortality.
2. The footprint derived through the long-term simulation primarily stretches westward of the channel. This is due to the fact that MesoLAPS winds do not capture the nearshore eastward trend during summer well, and the dredging along the approach channel in loose material with high spill rates takes place predominantly during transitional and winter months. This clearly demonstrates the fact that the long-term simulation represents one scenario – the footprint would be very different with a different starting time relative to the seasons, or a different (and equally possible) definition of the dredging sequence. For long-term (changeable) dredging programmes in variable climatic conditions, it requires a large number of simulations to ensure that critical combinations of dredging and climatic drivers are captured. The strength of the shorter term scenario modelling is that the critical dredging, spill and climatic conditions can be isolated and combined in all possible ways to ensure that the critical combinations are captured, and the model results will provide insight into which combinations are critical and should be avoided in the planning of the campaign.

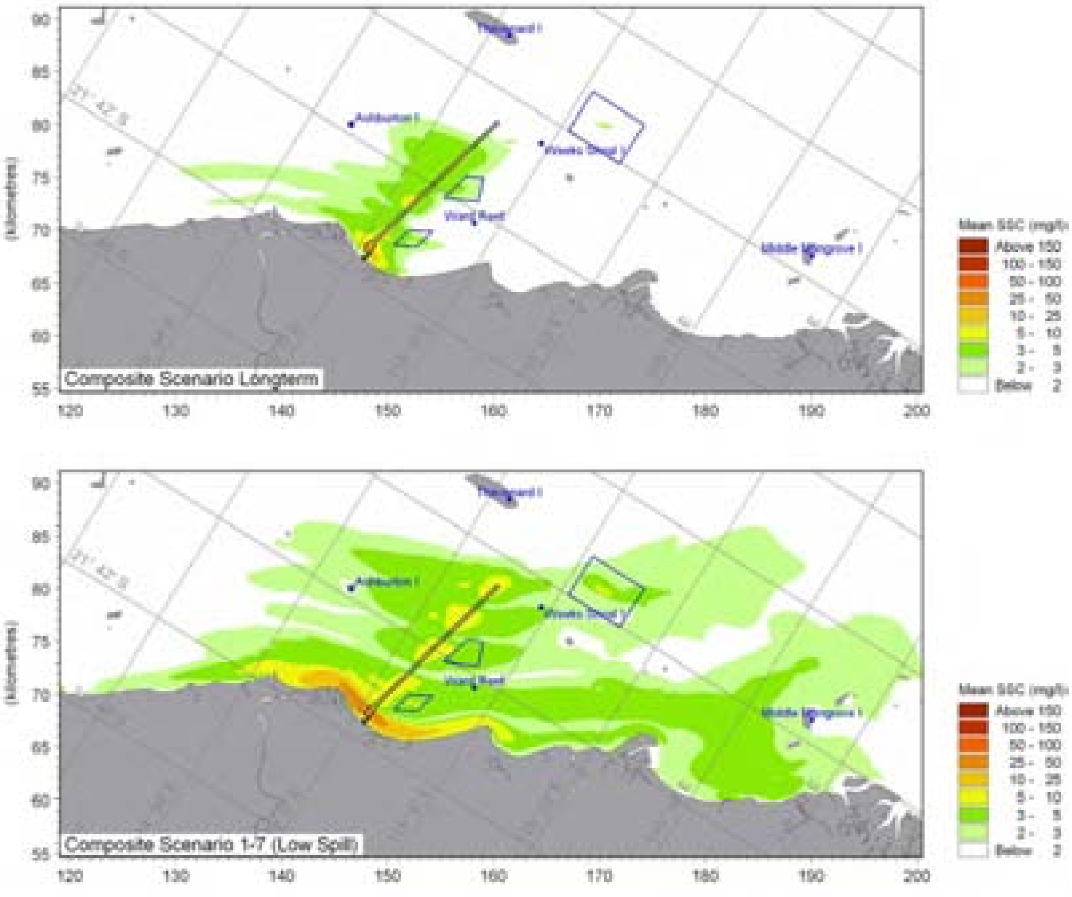

Figure F.22 Footprint of longer-term scenario (top) and composite of maximums of 14 day mean concentrations derived from the shorter-term scenario modelling driven by MesoLAPS and Onslow winds (bottom).

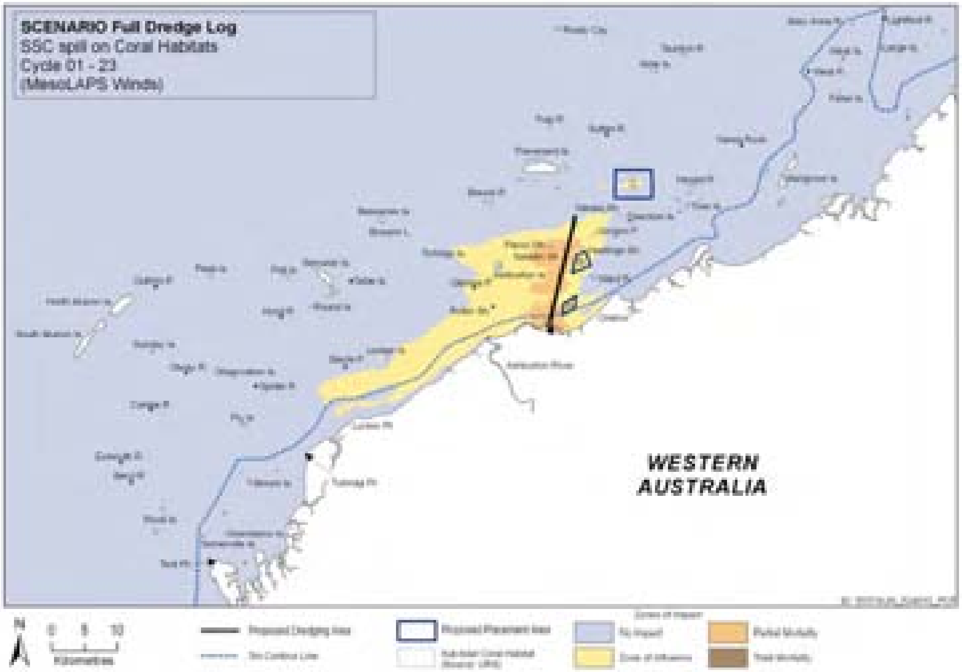

Figure F.23 Footprint in terms of impact zones from SSC on corals derived from the long period dredge simulation.

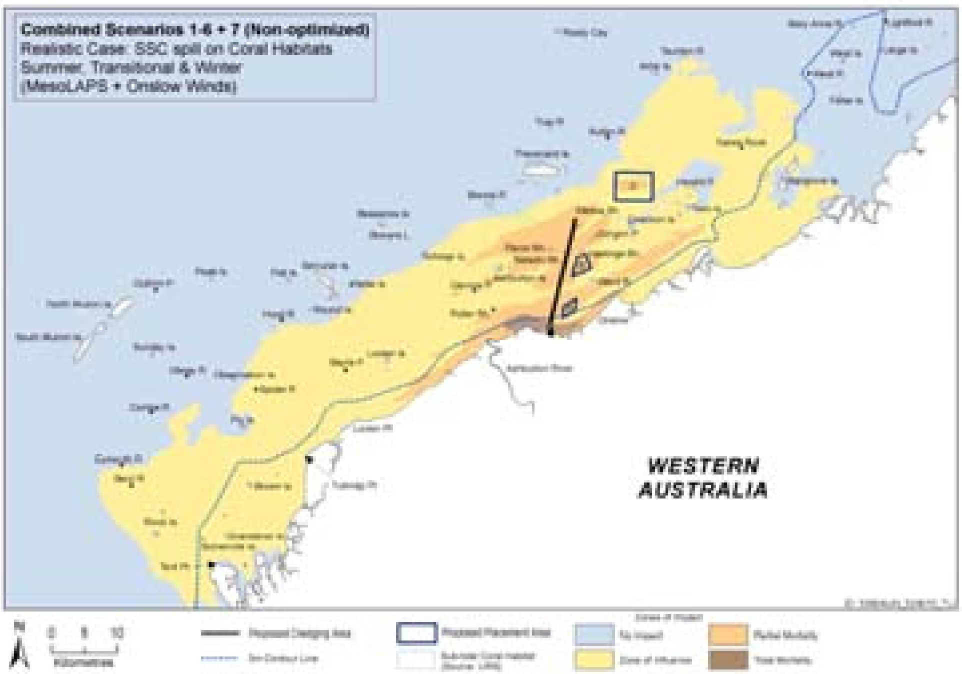

Figure F.24 Envelope of impact zones for SSC on corals derived from the shorter-term scenario modelling.

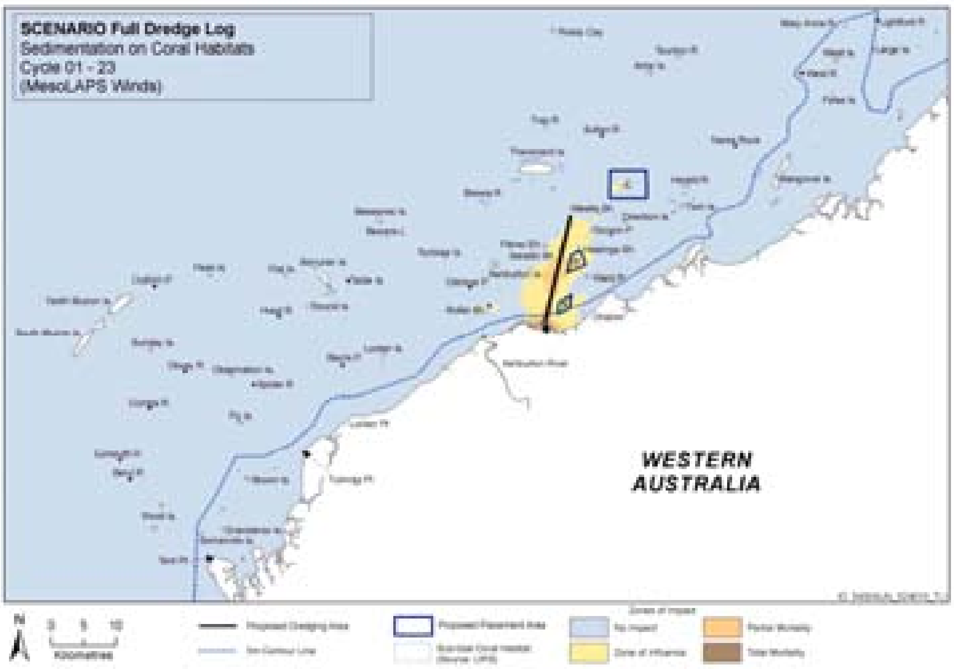

Figure F.25 Footprint in terms of impact zones from sedimentation on corals derived from the long period dredge simulation.

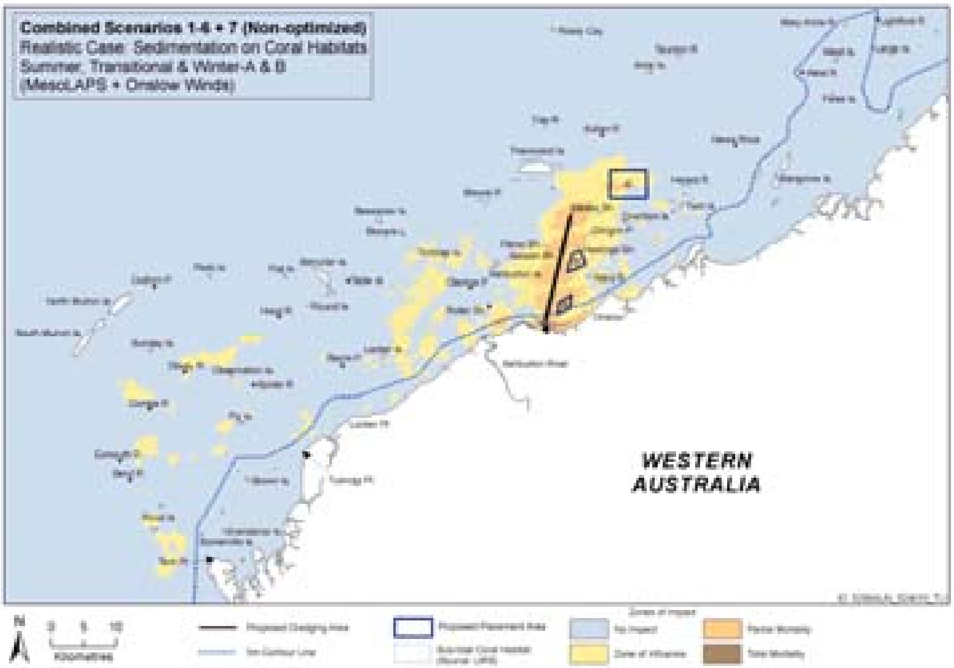

Figure F.26 Envelope of impact zones for sedimentation on corals derived from the shorter-term scenario modelling.

Wheatstone Project
Dredge Spoil Modelling

APPENDIX G:

Characterisation of Sediment within the Sediment Transport Model

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CONTENTS

FIGURES AND TABLES

G CHARACTERISATION OF SEDIMENT WITHIN THE SEDIMENT TRANSPORT MODEL

This appendix explores the sensitivity of the results of the sediment transport model to the number of fractions used to represent the particle size distribution.

Information relevant to this appendix may be found in the following sections of the main report and supporting appendices:

- Section 2.3 *Dredge Spill Rates*
- Section 4.3 *Development of the Sediment Transport Model*
- Section 5 *Climate Scenario Selection*
- Section 6.1.1 *Dredge Scenarios*

G.1 Sediment Characterisation

Determination of spill rates and characterisation of the (spilled) sediment are key tasks for the setup of the plume modelling.

For Wheatstone, the spill rates have been assessed by both LWI and DHI, and a set of “realistic” and “worst case” spill rates have been agreed upon for the expected key operations and type of material.

The representation of the sediments to be simulated in the model is obviously critical for the results. In the sediment plume model, the sediment is represented by a number of individual sediment fractions with a weight (total percentage) and settling characteristics for each.

The number of fractions included in the simulations should reflect the range of sediments that should be modelled as well as the level of “certainty” of these fractions – i.e. there is no point in producing a high resolution grain distribution curve in the model unless there is good information available on the sediment being discharged into the water column.

The material released into the water column is not only dependent upon the type of material to be dredged, but also the type of equipment and operation of the equipment, among other factors. At the EIA stage, prior to start of dredging, there is therefore rarely very good information available on the expected properties of the sediment discharged.

G.1.1 Fractions and Settling Velocities

Key parameters for sediment plume modelling are the sediment fractions and associated setting velocities. During dredging, the spill generally contains a significant portion of coarse material in addition to the fines. The coarse material generally settles within the dredge corridor or in the immediate vicinity, and does not contribute significantly to the plume dispersion outside the dredge corridor and immediate adjacent areas. This component is disregarded in the modelling which concentrates on the fines (silt and finer fractions), which are more easily transported away from the dredging and dumping areas. The spill rates defined in Section 2.3 (of the main report) likewise concentrate on the fines leaving the immediate dredge and disposal areas.

The settling velocities of the fine material released during the dredging operation will depend upon many factors, not least the degree of flocculation within the overflow and whether these flocs are broken up by the turbulence of the overflow and/or on the boundaries of the density current phases of the setting process where the fine materials are released into the water column. This process will in turn depend on (amongst other issues) the specific nature of the dredger, pumping rates, presence of environmental valve (for TSHD), the chemical composition of the fine material, prevailing water depth, current speed and whether or not the density plume is disturbed by the propeller wash (for TSHD). It can thus be seen that defining settling characteristics at the present stage of the project development is fraught with a significant degree of uncertainty, and for environmental management projects, DHI is updating setting velocities based on site specific measurements on a weekly basis.

Through the course of such environmental management projects, DHI has undertaken a large number of settling tube measurements in overflow samples from silty sand material with bed silt/clay content in the 10 to 30% range. Settling tube measurements from overflow samples are provided in Figure G.1. It is recognised that the percentage fines in the parent material is towards the lower bound of the silt content present in the dredge area for the Wheatstone project. However, as Figure G.1 does not indicate any clear trends between lower bed fines and higher bed fines, and in the absence of site specific measurements (which will only become available after start of dredging), Figure G.1 is considered the best available basis for defining the appropriate settling velocities for the spill material.

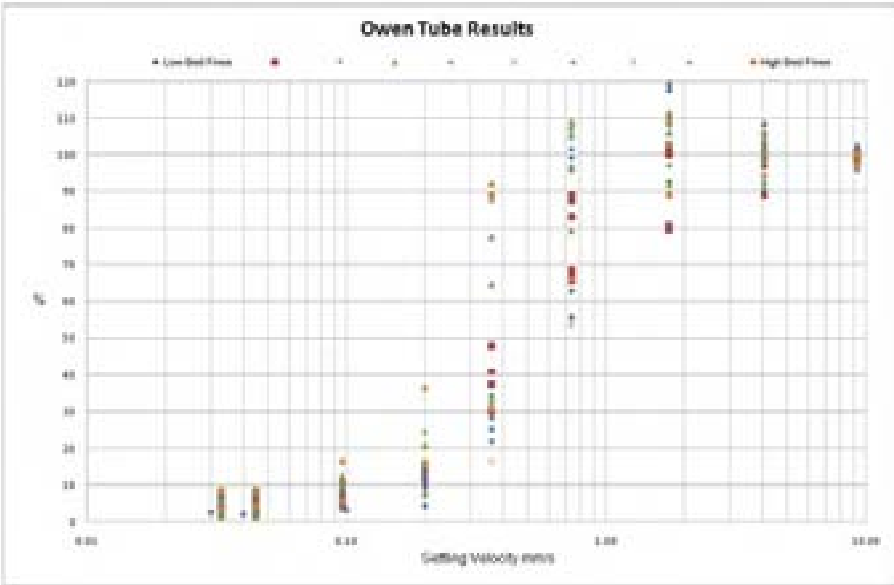

Figure G.1 Example measured setting velocity characteristics of sediment plume material escaping the immediate work area

It is noted that Figure G.1 indicates percentages higher that 100% for some data points. This is an indication of the uncertainties involved in the analysis and is reflective of the inhomogeneous nature of the overflow material and the flocculation processes ongoing in the settling tube during the tests. All settling tests are run at a base concentration chosen to mimic concentrations of the material leaving the density plume phase of the overflow and thus the floc size that will be present in the material leaving the immediate work area.

Based on the setting velocity curves presented in Figure G.1 it has been chosen to adopt a 6 fraction sediment description as described in Table G.1, with a higher number of fractions on the lower settling velocities.

Table G.1 Model sediment settling characteristics

Fraction	% Contribution	Settling velocity mm/s
1	5	0.03
2	15	0.24
3	20	0.39
4	20	0.48
5	20	0.68
6	20	1.00

With the relatively large uncertainty on the characteristics of the sediments released into the water column, it could be argued that the scenario approach should include different assumed grain size / settling curves. The approach adopted is to use a “best estimate” grain size distribution, and include the uncertainties related to the grain size distribution and spill rates through two different spill rates.

G.2 G.2 Model Sensitivity to the Number of Sediment Fractions

An investigation of the contribution of each fraction and a sensitivity test on the number of fractions adopted to represent the settling velocity curve (Figure G.1) has been carried out.

Initially, the finest 5% was split onto 3 fractions while the other fractions were maintained the same, leading to the distribution given in Table G.2. This was further extended to 16 fractions by a finer distribution along the entire curve.

Table G.2 Representation of settling curve extended to 8 fractions.

Fraction	Settling velocity mm/s	% Contribution	Accumulated % Contribution
1	0.01	1	1
2	0.03	2	3
3	0.06	2	5
4	0.24	15	20
5	0.39	20	40
6	0.48	20	60
7	0.68	20	80
8	1.0	20	100

Figure G.2 to Figure G.4 show the standard statistics over a 14 day period for Dredging Scenario 6 during summer with “realistic” spill rates for 6, 8 and 16 fractions applied in the model. Figure G.5 to Figure G.7 show a similar comparison for winter conditions. Both sets of figures show:

- Very small (insignificant) differences between the results for the various number of fractions included.
- There is a very slight tendency to higher concentrations for 8 fractions, but lower concentrations for 16 fractions. This is related to how the weight is distributed on the individual fractions.

The relative contributions to the mean concentrations of the individual fractions are illustrated for summer and winter conditions for the simulation with 8 fractions in Figure G.8 and Figure G.9 for summer and winter conditions, respectively. Please note different scales between the top figure (for the “total” mean SSC) and the means for the individual components. The following is noted:

- The relative contribution of fractions 1, 2 and 3 is low due to the low weight on each fraction (the three combined constitutes 5% of the spill).
- Fraction 4 dominates due to the higher weight, and the relatively low settling velocity.
- As the settling velocities increase for the various fractions, the relative contribution to the plume in suspension drops, with Fraction 8 only having a minor contribution.

Based on the sensitivity analysis, it is concluded that changes to the plume statistics used to derive the impact zones are insignificant if additional fractions are added. The applied 6 fractions are adequate to represent the settling curve.

Dredge Scenario: 6

Climate Scenario: Summer

Spill Rate: Low (realistic)

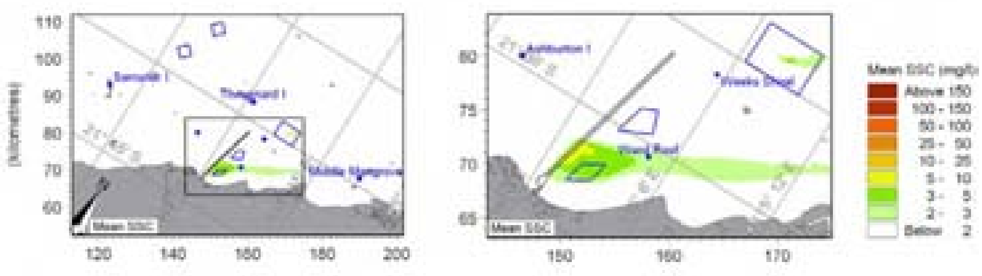

Figure G.2 Mean excess concentration based on 6 fractions.

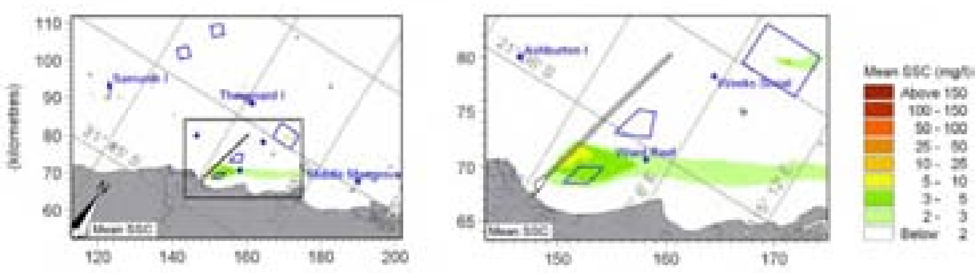

Figure G.3 Mean excess concentration based on 8 fractions

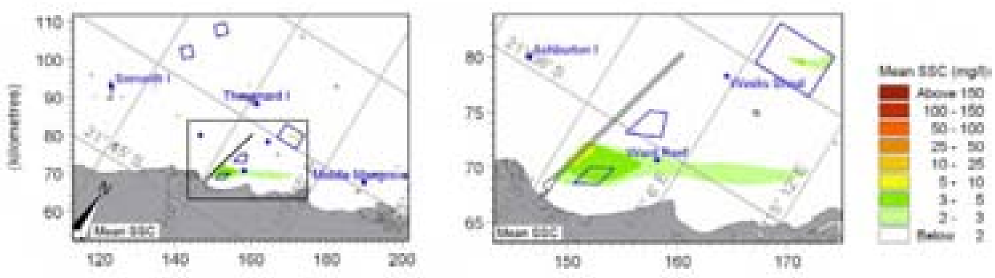

Figure G.4 Mean excess concentration based on 16 fractions.

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Dredge Scenario: 6

Climate Scenario: Winter

Spill Rate: Low (realistic)

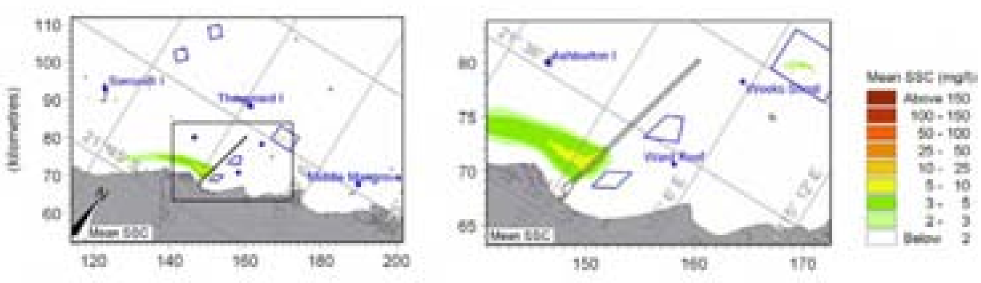

Figure G.5 Mean excess concentration based on 6 fractions

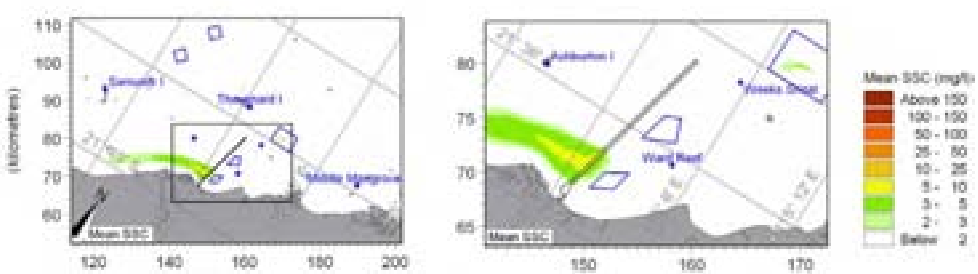

Figure G.6 Mean excess concentration based on 8 fractions.

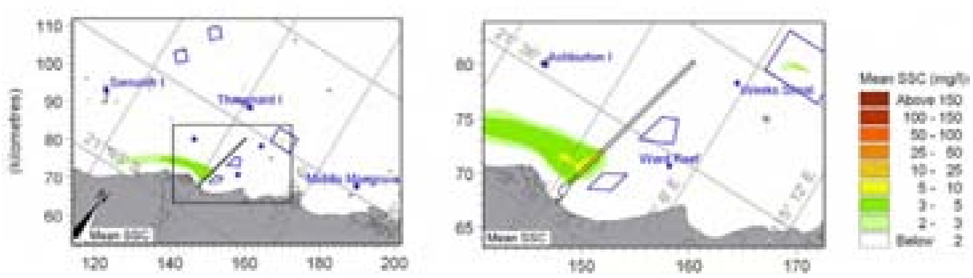

Figure G.7 Mean excess concentration based on 16 fractions.

G-7

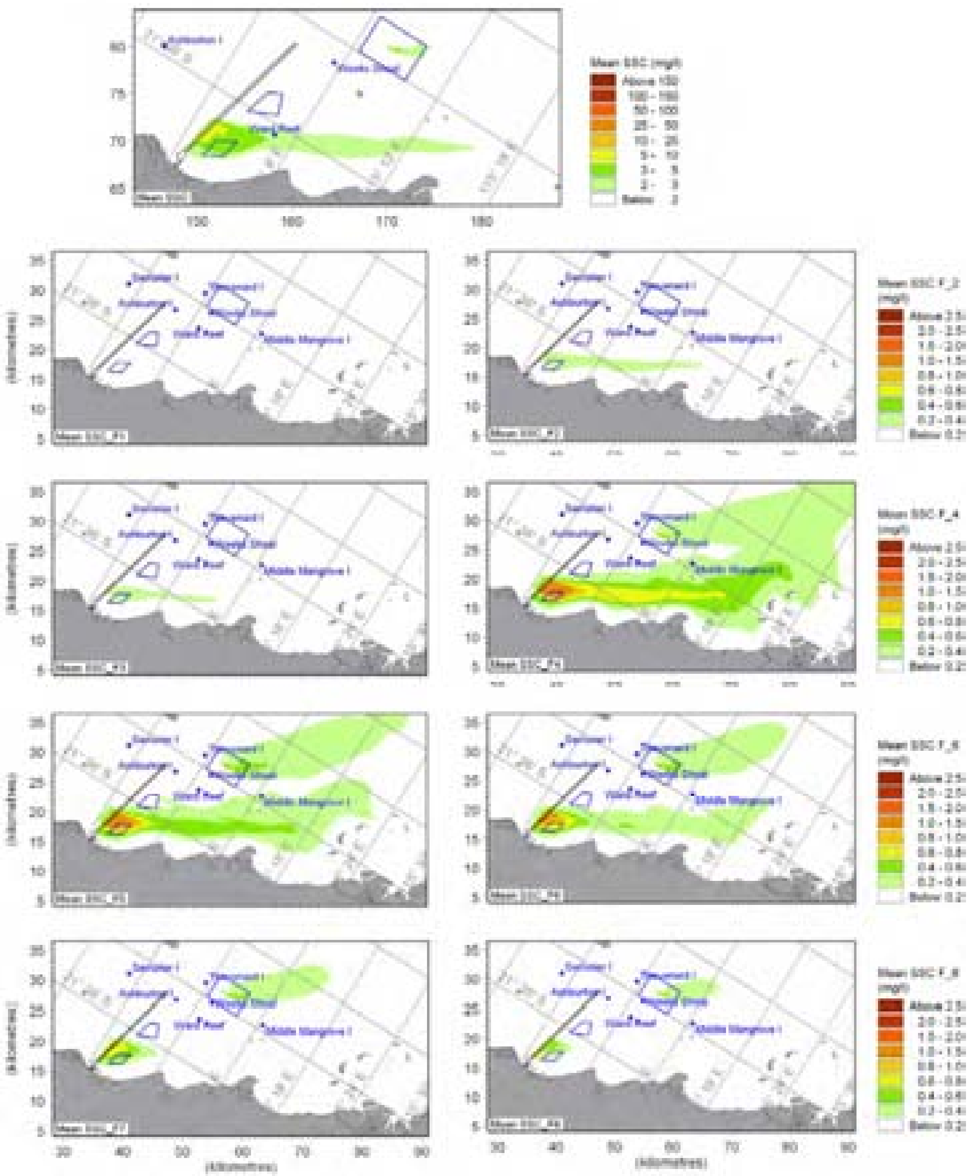

Figure G.8 Contribution to mean concentrations of each individual fraction for Scenario 6, low (realistic) spill rates for summer conditions.

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G-8

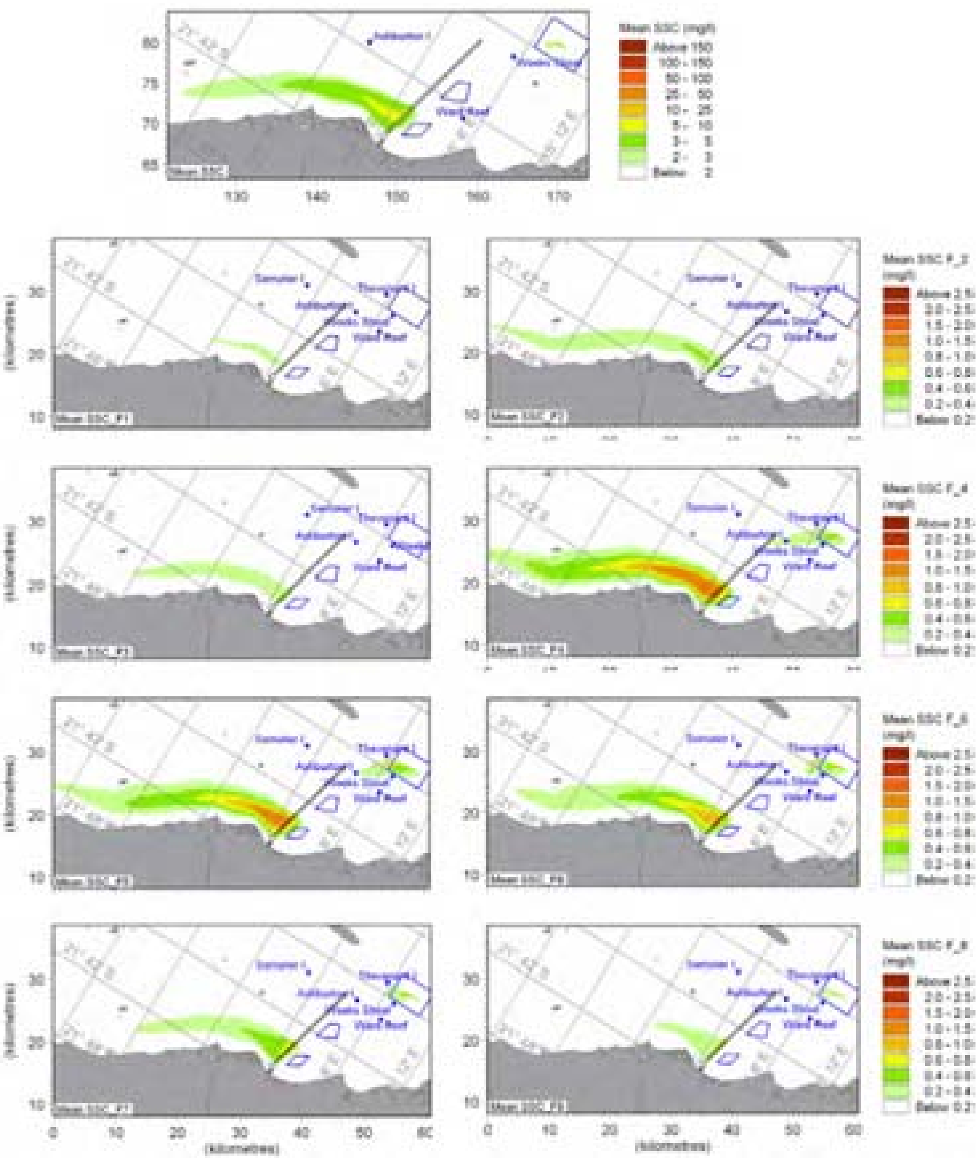

Figure G.9 Contribution to mean concentrations of each individual fraction for Scenario 6, low (realistic) spill rates for winter conditions.

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A P P E N D I X H :

3D Hydrodynamic Model Setup and Validation

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FIGURES AND TABLES

H THREE-DIMENSIONAL HYDRODYNAMIC MODEL

The differences between 2D and 3D modelling have been investigated for representative scenarios for the Dredge Spoil Modelling. This appendix presents a short description of DHI's 3D hydrodynamic model, the setup and the validation of the model against ADCP data from 2006 and 2009.

A description of the two-dimensional hydrodynamic model set up and validation is presented in Appendix D *Hydrodynamic Model Validation and Calibration*.

H.1 3D Model Setup

A three-dimensional flexible mesh model (MIKE 3 FM) was applied. MIKE 3 FM is a modelling system based on the flexible mesh approach that optimizes the discretization of the spatial domain into elements of different sizes.

The Mud Transport module (MIKE 3 FM - MT) was applied for the calculation of the sediment dispersion, sedimentation and re-suspension.

H.1.1 Short Description of the Models

H.1.1.1 MIKE 3 FM

The model system is based on the numerical solution of the three-dimensional incompressible Reynolds averaged Navier-Stokes equations invoking the assumptions of Boussinesq and of hydrostatic pressure. Thus, the model consists of continuity, momentum, temperature, salinity and density e2quations and is closed by a turbulent closure scheme. In the horizontal domain both Cartesian and spherical coordinates can be used. The free surface is taken into account using a sigma-coordinate transformation approach.

The spatial discretization of the primitive equations is performed using a cell-centered finite volume method. The spatial domain is discretized by subdivision of the continuum into non-overlapping element/cells. In the horizontal plane an unstructured grid is used while in the vertical domain a structured discretization is used. The elements can be prisms or bricks whose horizontal faces are triangles and quadrilateral elements, respectively. An approximative Riemann solver is used for computation of the convective fluxes, which makes it possible to handle discontinuous solutions.

For the time integration a semi-implicit approach is used where the horizontal terms are treated explicitly and the vertical terms are treated implicitly.

H.1.1.2 MIKE 3 FM – Mud Transport (MT)

The calculation of the fine sediment processes in the modeling system is performed in the first instance by the inclusion of the advection-diffusion equation that calculates the transport processes due to the water flow. The erosion, deposition and bed processes are calculated in the mud transport module. The Figure H.1 presents the general scheme of the MT model.

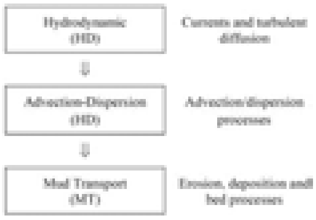

Figure H.1 MT module scheme.

All model descriptions and scientific documentations can be found at www.dhigroup.com

H.1.2 Flexible Mesh

Five equidistant sigma layers were applied in the vertical domain in a numerical mesh with approximately 51,000 elements. The area close to the project site was represented through a combination of triangular and quadrangular elements with the minimum definition of around 155m x 115m. The quadrangular elements have the advantage of being less dispersive numerically, and have therefore been applied close to the sources. The numerical mesh is presented in Figure H.2.

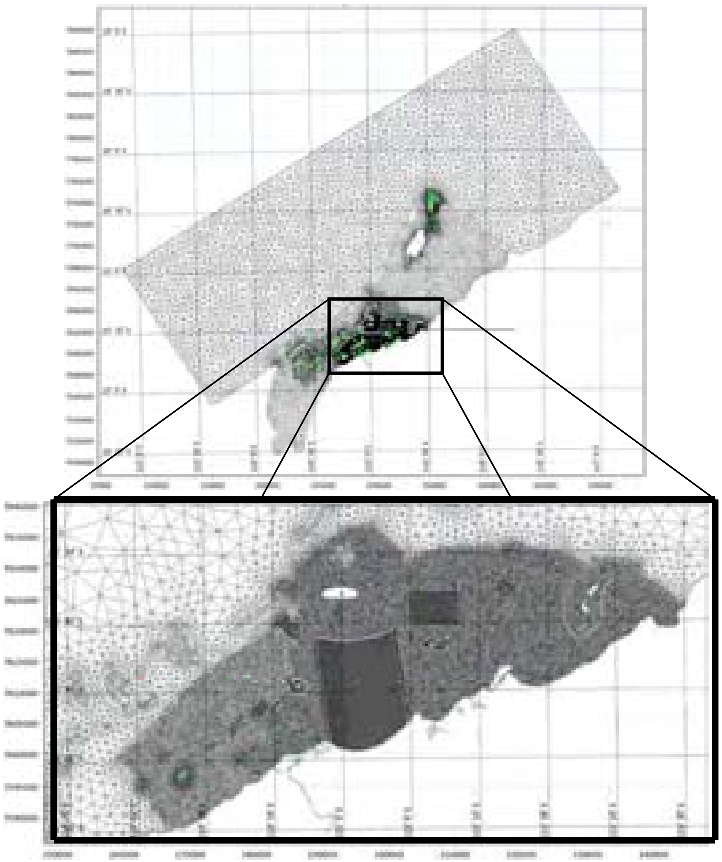

Figure H.2 Numerical mesh applied on the study. Top, model domain, at the bottom, detail in the region of the project site. The mesh is aligned with North.

H.1.3 Model Parameters

The 3D model complex has a slightly different description of e.g. the bottom resistance and furthermore uses a different mesh from the 2D model. The two models are therefore not directly comparable grid-point by grid-point, but the model grids are established from the same bathymetry data set with the same overall domain, and the same drivers in terms of the boundary conditions and wind and pressure fields have been applied.

Some of the model parameters applied are briefly listed below.

H.1.3.1 Hydrodynamic Model

Solution Technique

Lower order in time and space shallow water equations

Shallow water and Transport equations

Minimum time step: 0.01s

Maximum time step: 20s

Critical CFL number: 0.7

Flooding and Drying

Drying depth: 0.2m

Flooding depth: 0.3m

Wetting depth: 0.5m

Barotropic Density

Eddy Viscosity

Constant horizontal eddy formulation: $0.002m^2/s$

Constant vertical eddy formulation: $0.002m^2/s$

Bed Resistance

Roughness height map

Varying Coriolis acceleration in domain

Wind forcing varying in time and domain: MesoLAPS wind and pressure matrix.

Constant wind friction factor: 0.0026

Boundary Conditions: East, North and West boundaries driven by water levels from KMS model, varying in time and space as per 2D simulations.

Hydrodynamic output files saved every 30 minutes.

H.1.3.2 3D Mud Transport Model

The MT model is set up similar to the 2D model complex to only simulate excess concentrations (concentrations of sediments originating from the dredging activities) with 6 representative fractions and including a layer of fine sediment available for re-suspension within the dredge corridor and at the placement sites.

The same wave fields that were applied in the 2D model are applied in the 3D model.

The dredging activities and related spills are simulated similarly to the 2D model with moving sources for the TSHD dredging.

The dispersion coefficients in the 3D model are much lower than the dispersion coefficient in the 2D model due to the fact that the dispersion coefficients in 2D emulate some of the effects of a 3D current profile.

Dispersion in 3D:

Horizontal: constant coefficient formulation of $0.00001 m^2/s$

Vertical: dispersion coefficient formulation of $0.01 m^2/s$

H.2 Calibration & Validation of the 3D Model

The 3D model was calibrated against current speeds at different levels through the water column for 2006 and 2009 and validated for summer and winter 2009. For 2006 the current speeds were compared with the ADCP data at point 3 (P3) and point 4 (P4). The 2009 comparison was made at the Spoil Ground (Ground) and Jetty for the summer period and Channel for the winter. The current speeds were extracted from the model layer corresponding to the ADCP depth.

The 2006 simulations were performed using Onslow wind, while for the 2009 simulations the MesoLAPS wind field was applied.

The location of the 2006 and 2009 stations are outlined in Figure H.3. Comparisons of simulated and measured (near) bottom and (near) surface currents are shown for the 5 locations for month long periods on the following pages.

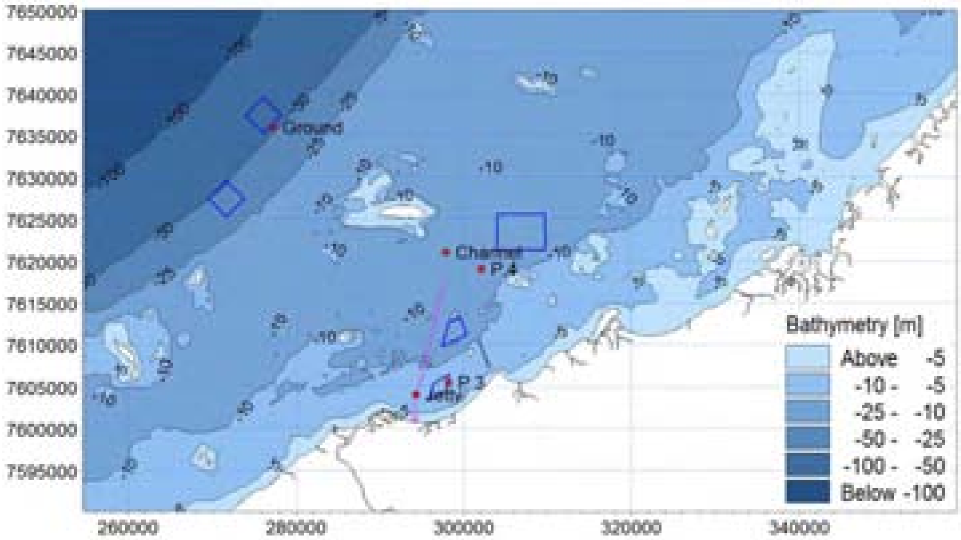

Figure H.3 Locations of the ADCP current measurements. Depths refer to MSL.

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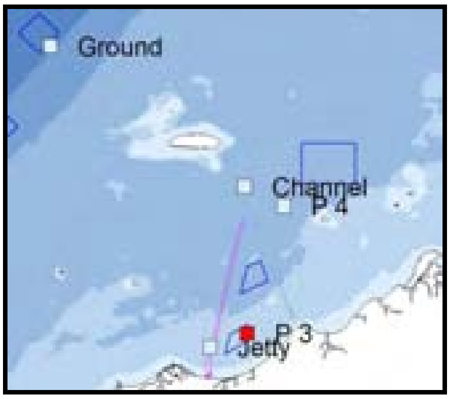


Current Validation

Data Station: Point 3

Position: 298189; 7605521 (MGA-50)

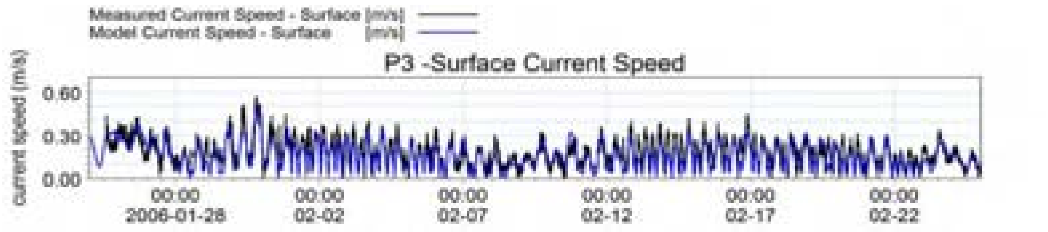
Depth: 9.5m (CD)

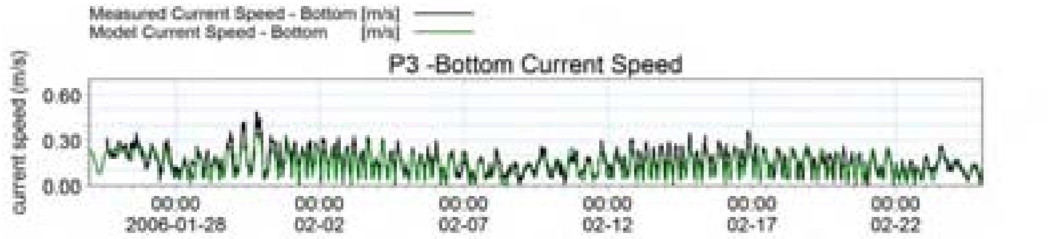
ADCP bottom current: 4.24m above sea bed (CD)

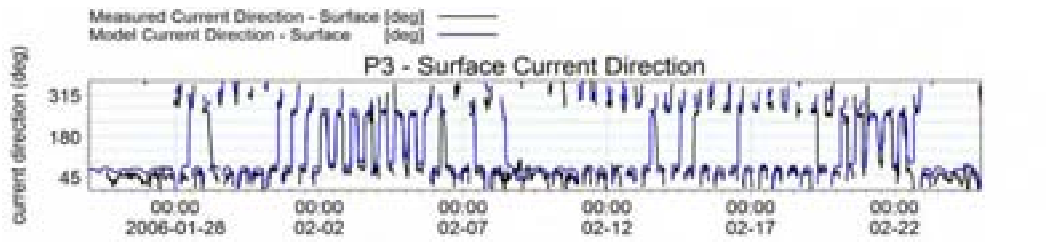
Period: Summer 2006

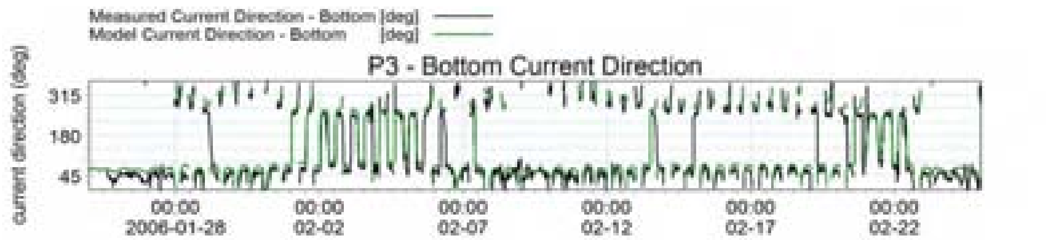
Date: 25th of January to 25th of February

Surface Spd RMS	Bottom Spd RMS	Surface Dir RMS	Bottom Dir RMS
0.067	0.074	11.89	12.09









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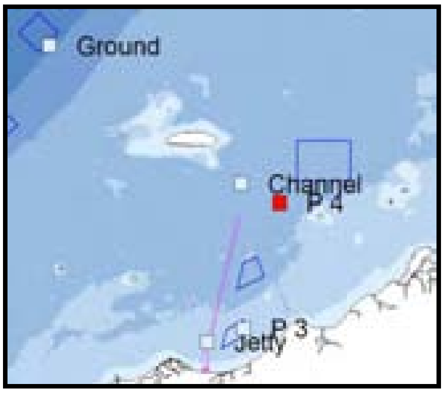


Current Validation

Data Station: Point 4

Position: 302044; 7619062 (MGA-50)

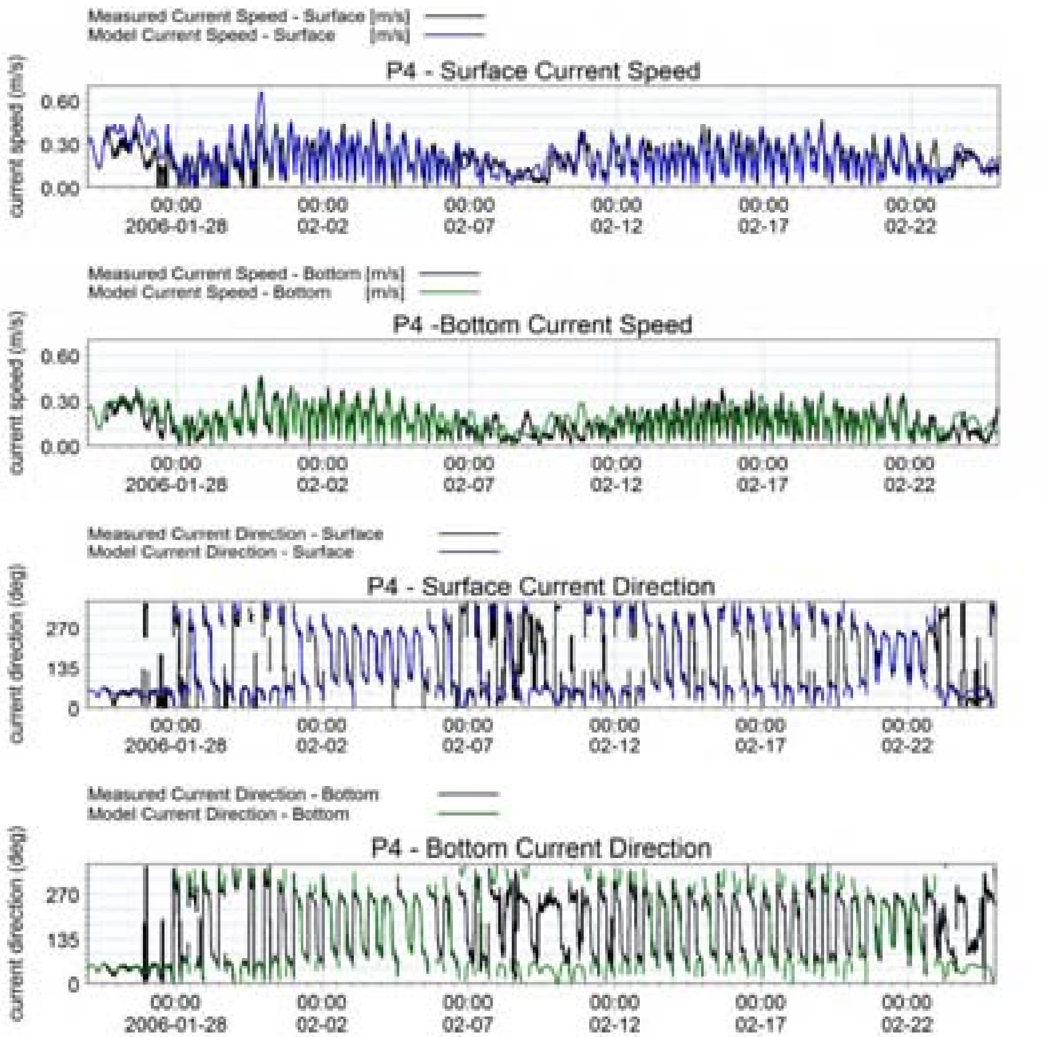
Depth: 13.5m (CD)

ADCP bottom current: 4.24m above sea bed (CD)

Period: Summer 2006

Date: 25th of January to 25th of February

Surface Spd RMS	Bottom Spd RMS	Surface Dir RMS	Bottom Dir RMS
0.059	0.048	17.92	16.97



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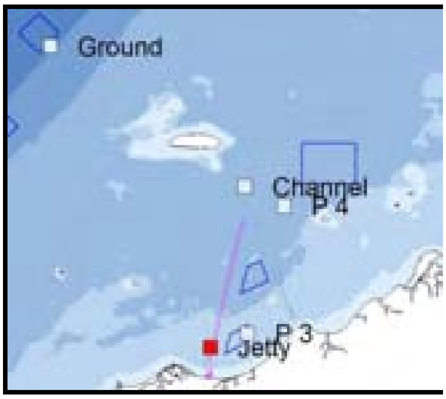


Current Validation

Data Station: Jetty

Position: 294253; 7604050 (MGA-50)

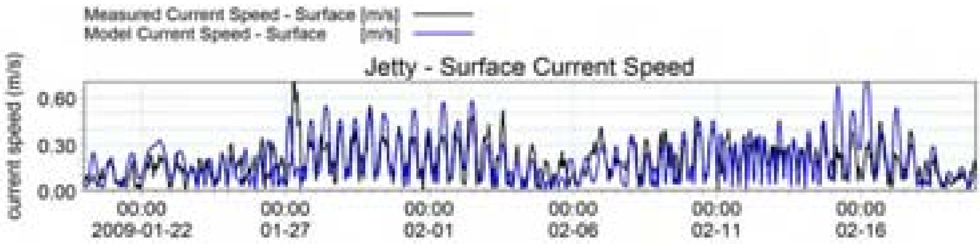
Depth: 7.5m (CD)

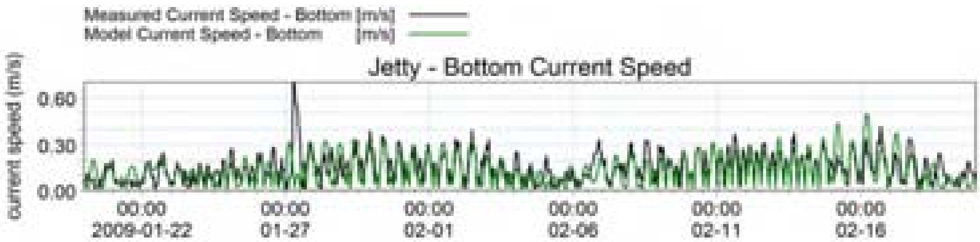
ADCP bottom current: 2.25m above sea bed (CD)

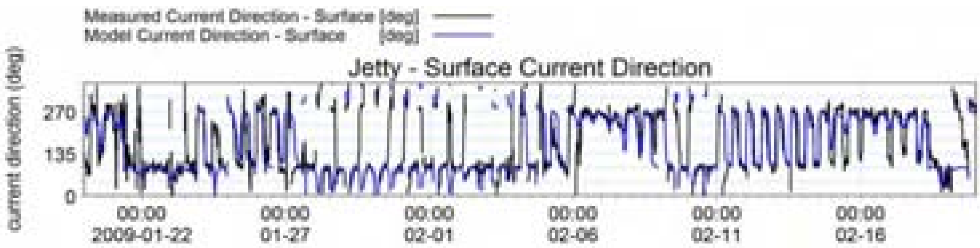
Period: Summer 2009

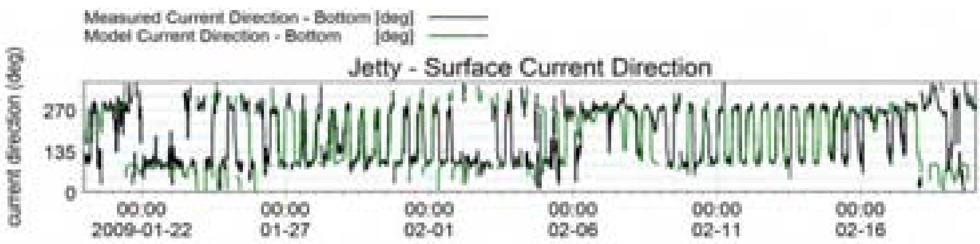
Date: 20th of January to 20th of February

Surface Spd RMS	Bottom Spd RMS	Surface Dir RMS	Bottom Dir RMS
0.087	0.076	12.77	14.83









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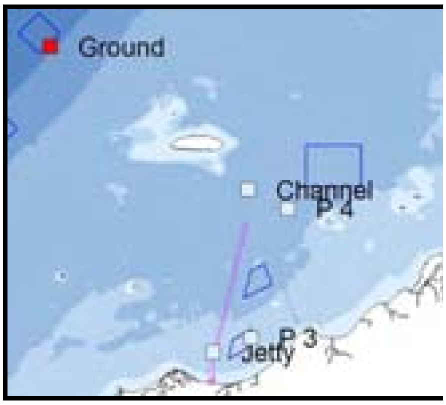


Current Validation

Data Station: Spoil Ground

Position: 277256; 7636011 (MGA-50)

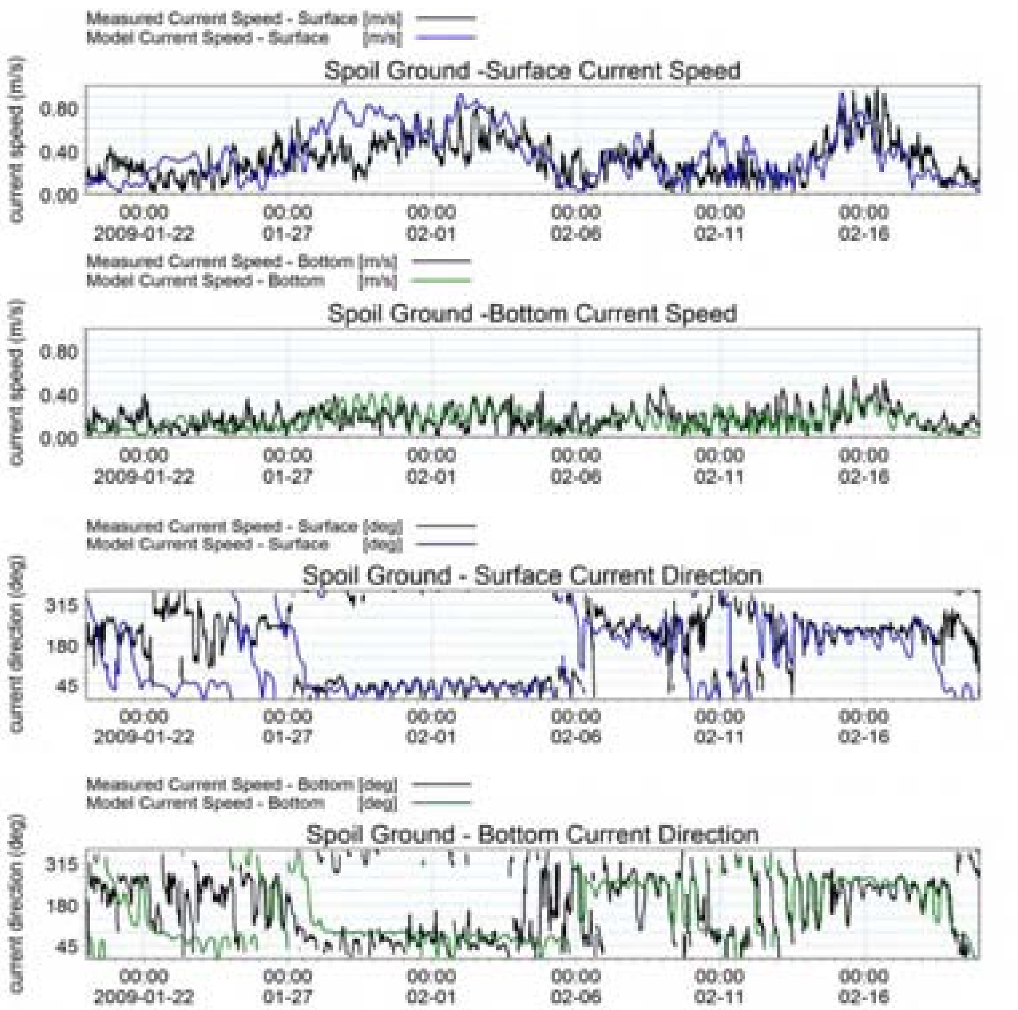
Depth: 55m (CD)

ADCP bottom current: 6.94m above sea bed (CD)

Period: Summer 2009

Date: 20th of January to 20th of February

Surface Spd RMS	Bottom Spd RMS	Surface Dir RMS	Bottom Dir RMS
0.103	0.072	19.97	22.15



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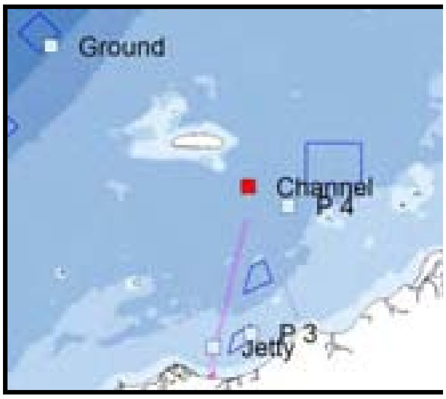


Current Validation

Data Station: <u>Channel</u>

Position: 297891; 7621063 (MGA-50)

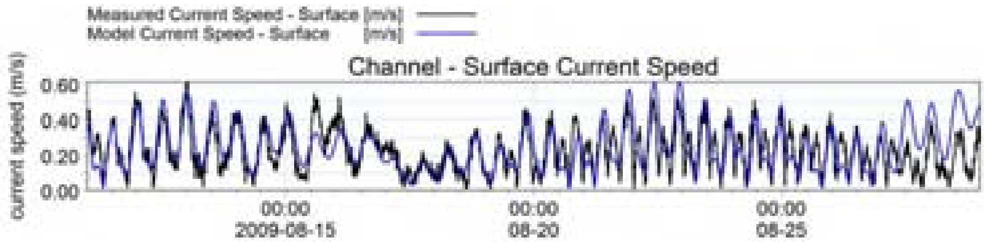
Depth: 15m (CD)

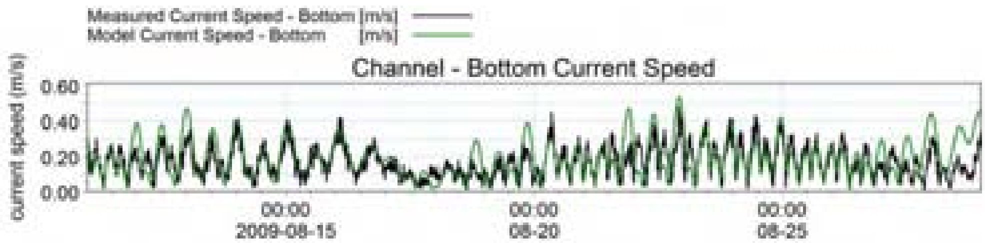
ADCP bottom current: 3.45m above sea bed (CD)

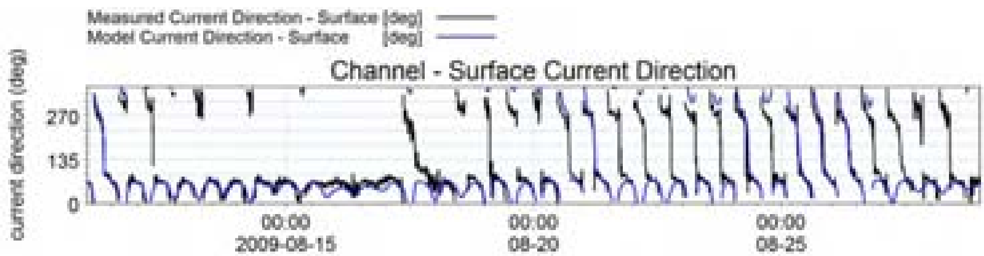
Period: <u>Winter 2009</u>

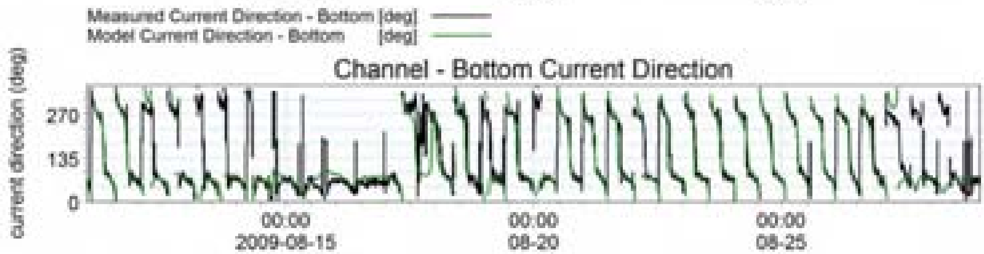
Date: 11th of August to 29th of August

Surface Spd RMS	Bottom Spd RMS	Surface Dir RMS	Bottom Dir RMS
0.066	0.069	12.89	13.09









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In general the model represents the current speed and directions satisfactorily in both surface and bottom layers.

In the nearshore area, the water column is generally well mixed and the current profiles are generally logarithmic. Some directional shearing over the depth takes place in particular for stronger winds during neap tides.

At the deeper areas, such as at the spoil ground (at 55m depth), the directionality over the depth is stronger. The model is capable of re-producing this based on the wind as the driver at the surface.

H.2.1 Wind Driven Vertical Shearing

Whereas the water column in the shallow coastal area is generally well mixed, dominant winds that are often perpendicular to the tidal currents can give rise to some vertical shearing of current directions, i.e. the surface currents are deflected from the tidal current directions by the wind friction.

The capability of the 3D model to pick up the wind driven vertical shearing has been investigated. A twelve hour period was chosen to demonstrate the directionality of the flow. Figure H.4 below shows the wind and current directions at the surface and bottom for the model and ADCP data at the Spoil Ground. The black arrows show the wind direction, red arrows the surface current direction (filled red = data, filled white = model result) and blue arrows the bottom current direction (filled blue = data, filled white = model results). The figure on the bottom shows the wind speed, the dotted box indicates the period of the first plot.

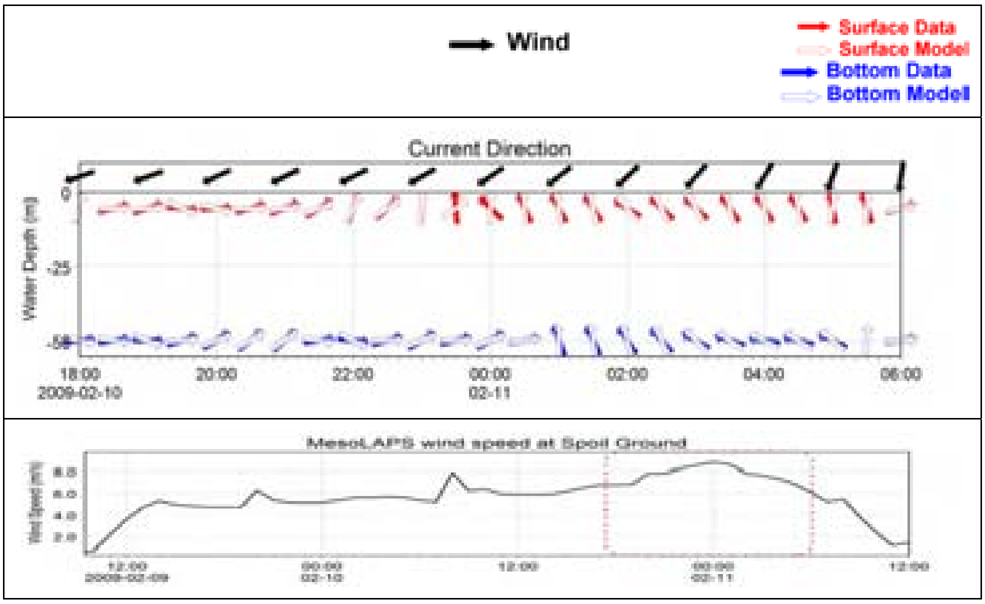

Figure H.4 *Top: Wind and current direction at surface and bottom for measured and model results at the Spoil Ground. Bottom: Wind speed at the Spoil Ground. The red dashed line indicates the corresponding period of the top figure.*

Initially, the influence of the wind in driving currents is small and the flow is opposite the wind direction. As the wind increases towards the end of the day (2009-02-10) the currents at the surface layer change direction. The bottom layer follows the surface direction a couple of hours later. The model follows the measured directions fairly well. Instantaneous 2D plots of surface and bottom currents are shown for two time steps

Figure H.5 and Figure H.6 present examples of the current fields at surface and bottom for two different moments of the period analyzed above.

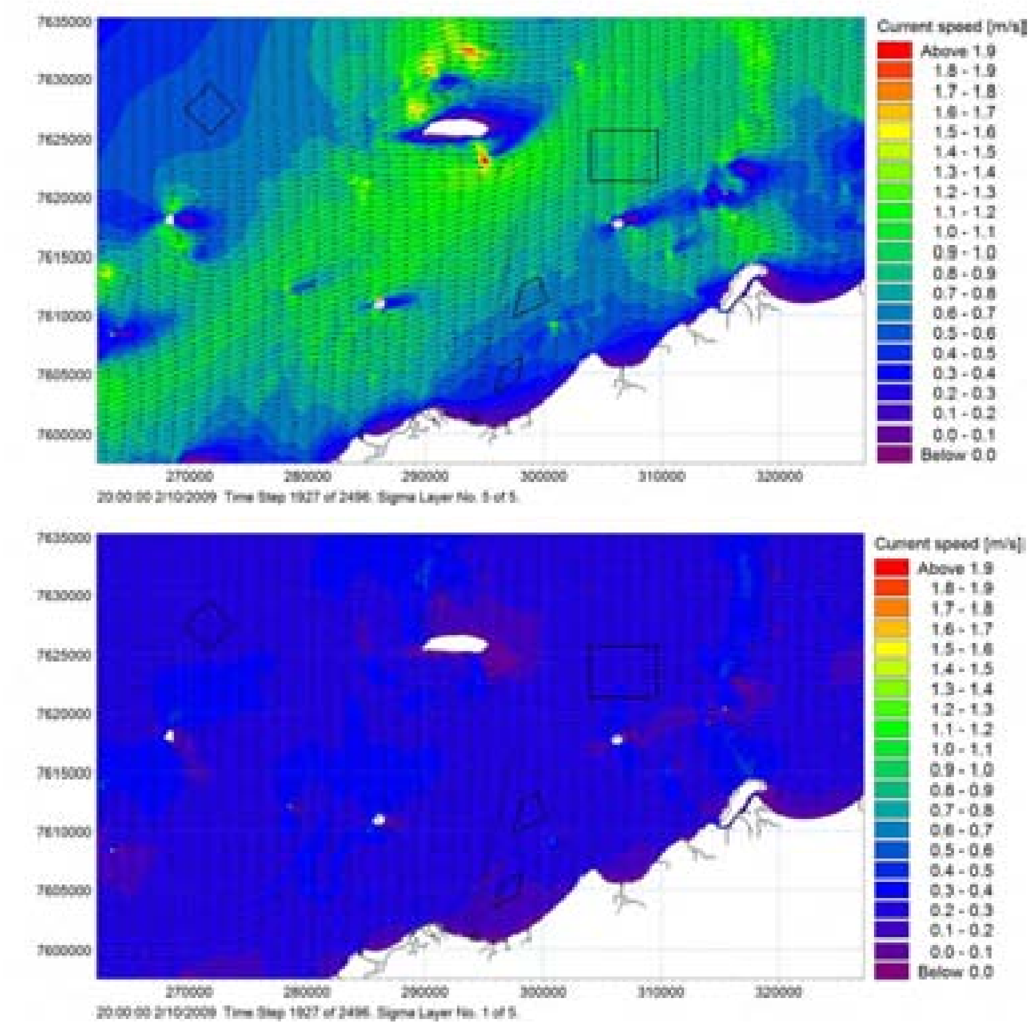

Figure H.5 Surface (top figure) and bottom (bottom figure) current fields for 10 of February 2009 at 20:00.

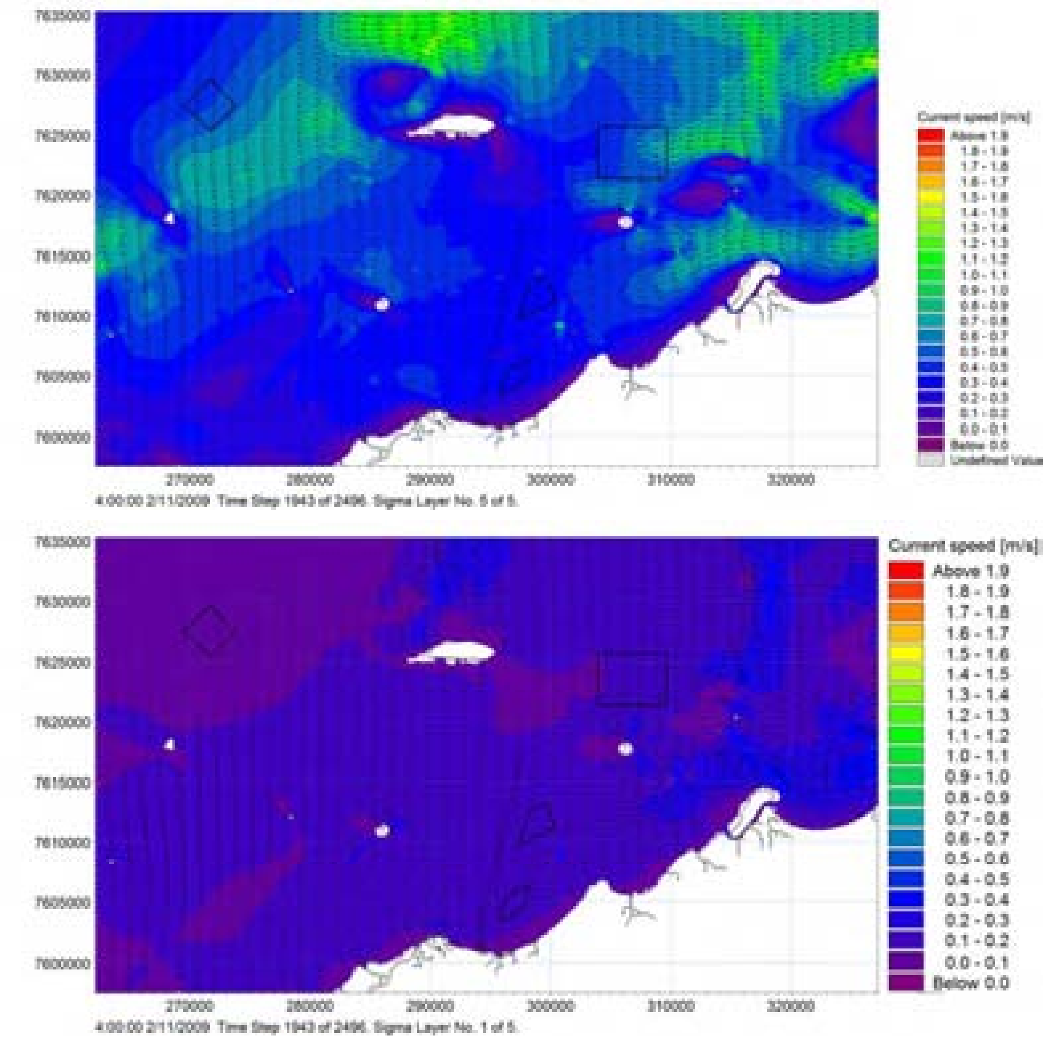

Figure H.6 Surface (top figure) and bottom (bottom figure) current fields for 11 of February 2009 at 04:00.

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APPENDIX I:

MIKE 21 HD Scientific Documentation

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MIKE 21 FLOW MODEL

Hydrodynamic Module

Scientific Documentation

MIKE BY DHI 2009

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February 2004
June 2005
April 2006
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January 2009

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CONTENT

1 INTRODUCTION

The present Scientific Documentation aims at giving an in-depth description of the equations and numerical formulation used in the hydrodynamic module of the MIKE 21 Flow Model, MIKE 21 HD.

First the main equations and the numerical algorithm applied in the model are described. This is followed by a number of sections giving the physical, mathematical and numerical background for each of the terms in the main equations.

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2 MAIN EQUATIONS

The hydrodynamic model in the MIKE 21 Flow Model (MIKE 21 HD) is a general numerical modelling system for the simulation of water levels and flows in estuaries, bays and coastal areas. It simulates unsteady two-dimensional flows in one layer (vertically homogeneous) fluids and has been applied in a large number of studies.

The following equations, the conservation of mass and momentum integrated over the vertical, describe the flow and water level variations:

$$\frac{\partial \zeta}{\partial t} + \frac{\partial p}{\partial x} + \frac{\partial q}{\partial y} = \frac{\partial d}{\partial t} \qquad (2.1)$$

$$\frac{\partial p}{\partial t} + \frac{\partial}{\partial x}\left(\frac{p^2}{h}\right) + \frac{\partial}{\partial y}\left(\frac{pq}{h}\right) + gh\frac{\partial \zeta}{\partial x} \qquad (2.2)$$

$$+ \frac{gp\sqrt{p^2+q^2}}{C^2 \cdot h^2} - \frac{1}{\rho_w}\left[\frac{\partial}{\partial x}(h\tau_{xx}) + \frac{\partial}{\partial y}(h\tau_{xy})\right] - \Omega_q$$

$$- fVV_x + \frac{h}{\rho_w}\frac{\partial}{\partial x}(p_a) = 0$$

$$\frac{\partial q}{\partial t} + \frac{\partial}{\partial y}\left(\frac{q^2}{h}\right) + \frac{\partial}{\partial x}\left(\frac{pq}{h}\right) + gh\frac{\partial \zeta}{\partial y} \qquad (2.3)$$

$$+ \frac{gq\sqrt{p^2+q^2}}{C^2 \cdot h^2} - \frac{1}{\rho_w}\left[\frac{\partial}{\partial y}(h\tau_{yy}) + \frac{\partial}{\partial x}(h\tau_{xy})\right] + \Omega_p$$

$$- fVV_y + \frac{h}{\rho_w}\frac{\partial}{\partial y}(p_a) = 0$$

The following symbols are used in the equations:

$h(x, y, t)$	water depth (= ζ -d, m)
$d(x, y, t)$	time varying water depth (m)
$\zeta(x, y, t)$	surface elevation (m)

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$p, q(x, y, t)$	flux densities in x- and y-directions ($m^3/s/m$) = (uh,vh); (u,v) = depth averaged velocities in x- and y-directions
$C(x, y)$	Chezy resistance ($m^{1/2}/s$)
g	acceleration due to gravity (m/s^2)
$f(V)$	wind friction factor
$V, V_x, V_y(x, y, t)$	wind speed and components in x- and y-directions (m/s)
$\Omega(x, y)$	Coriolis parameter, latitude dependent (s^{-1})
$p_a(x, y, t)$	atmospheric pressure ($kg/m/s^2$)
ρ_w	density of water (kg/m^3)
x, y	space coordinates (m)
t	time (s)
$\tau_{xx}, \tau_{xy}, \tau_{yy}$	components of effective shear stress

3 INTRODUCTION TO NUMERICAL FORMULATION

MIKE 21 HD makes use of a so-called Alternating Direction Implicit (ADI) technique to integrate the equations for mass and momentum conservation in the space-time domain. The equation matrices that result for each direction and each individual grid line are resolved by a Double Sweep (DS) algorithm.

MIKE 21 HD has the following properties:

- Zero numerical mass and momentum falsification and negligible numerical energy falsification, over the range of practical applications, through centering of all difference terms and dominant coefficients, achieved without resort to iteration.
- Second- to third-order accurate convective momentum terms, i.e. "second- and third-order" respectively in terms of the discretisation error in a Taylor series expansion.
- A well-conditioned solution algorithm providing accurate, reliable and fast operation.

The difference terms are expressed on a staggered grid in x, y-space as shown in Figure 3.1.

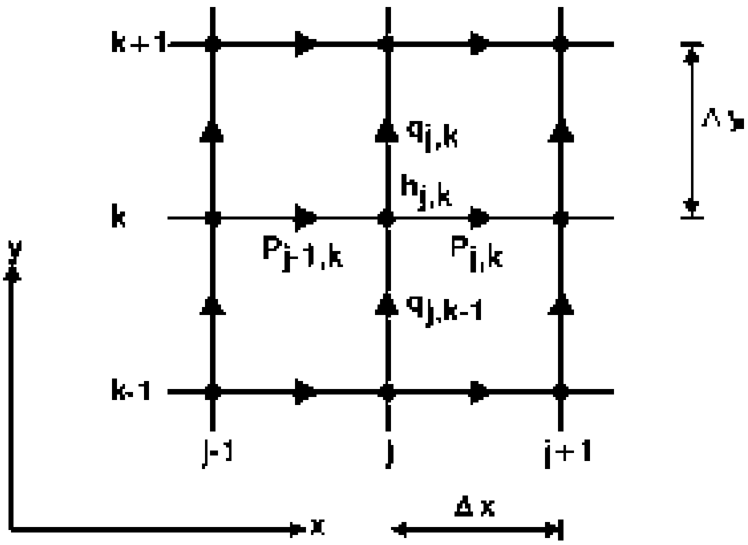

Figure 3.1 Difference Grid in x,y-space

Time centering of the three equations in MIKE 21 HD is achieved as illustrated in Figure 3.2.

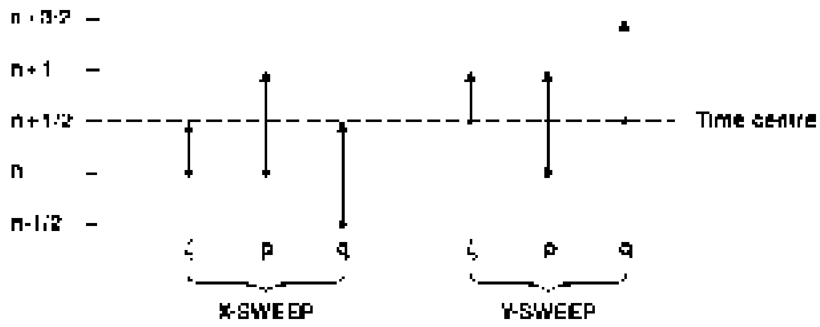

Figure 3.2 Time Centering

The equations are solved in one-dimensional sweeps, alternating between x and y directions. In the x-sweep the continuity and x-momentum equations are solved, taking ζ from n to n+½ and p from to n to n+1. For the terms involving q, the two levels of old, known values are used, i.e. n-½ and n+½.

In the y-sweep the continuity and y-momentum equations are solved, taking ζ from n+½ to n+1 and q from n+½ to n+$^{3}/_{2}$, while terms in p use the values just calculated in the x-sweep at n and n+1.

Adding the two sweeps together gives "perfect" time centering at n+½, i.e. the time centering is given by a balanced sequence of operations. The word perfect has been put in quotation marks because it is not possible to achieve perfect time centering of the cross derivatives in the momentum equation. The best approximation, without resorting to iteration (which has its own problems), is to use a "side-feeding" technique.

At one time step the x-sweep solutions are performed in the order of decreasing y-direction, hereafter called a "down" sweep, and in the next time step in the order of increasing y-direction, the "up" sweep.

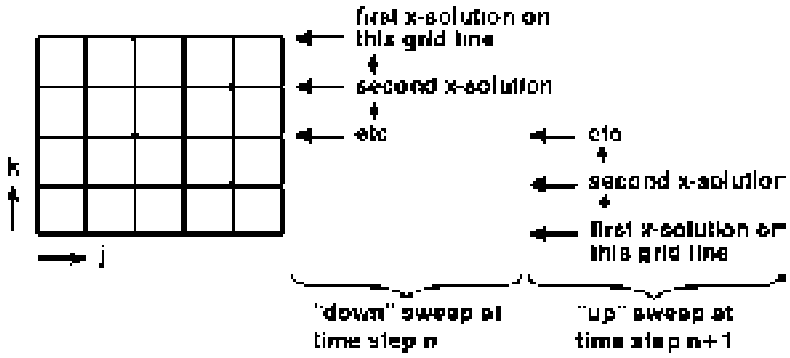

Figure 3.3 Side-feeding

During a "down" sweep, the cross derivative ∂p/∂y can be expressed in terms of $p^{n+1}_{j,k+1}$ on the "up" side and $p^{n}_{j,k-1}$ on the "down" side, and vice versa during an "up" sweep. In this way an approximate time centering of ∂p/∂y at n+½ can be achieved, albeit with the possibility of developing some oscillations (zigzagging).

The use of side-feeding for the individual cross differentials is described in more detail in the following sections.

Finally it should also be mentioned here that it is not always possible to achieve a perfect time centering of the coefficients on the differentials.

Centering in space is not generally a problem as will be seen in the next sections.

A mass equation and momentum equation thus expressed in a one-dimensional sweep for a sequence of grid points lead to a three-diagonal matrix

$$MV^{n+1} = W^{n} \qquad (3.1)$$

$$\begin{aligned} A_j \cdot p^{n+1}_{j-1} + B_j \cdot \zeta^{n+½}_j + C_j \cdot p^{n+1}_j &= D_j\big|_k \\ A^*_j \cdot \zeta^{n+½}_j + B^*_j \cdot p^{n+1}_j + C^*_j \cdot \zeta^{n+½}_{j+1} &= D^*_j\big|_k \end{aligned} \qquad (3.2)$$

where the coefficients A, B, C, D and A*, B*, C*, D* are all expressed in "known" quantities. Note that p here may be q and j may as well be k.

The system (3.1) is then solved by the well-known Double Sweep algorithm. For reference one may see, for example, Richtmyer and Morton, Ref. /1/. In developing the algorithm one postulates that there exist relations

$$p_j^{n+1} = E_j^* \cdot \zeta_j^{n+½} + F_j^*$$
$$\zeta_{j+1}^{n+½} = E_j \cdot p_j^{n+1} + F_j \tag{3.3}$$

Substituting these relations back into the Equations (3.2) give recurrence relations for E, F, E* and F*.

$$E_j^* = \frac{-A_j^*}{B_j^* + C_j^* \cdot E_j}$$

$$F_j^* = \frac{D_j^* - C_j^* \cdot F_j}{B_j^* + C_j^* \cdot E_j}$$

$$E_{j-1} = \frac{-A_j}{B_j + C_j \cdot E_j^*} \tag{3.4}$$

$$F_{j-1} = \frac{D_j - C_j \cdot F_j^*}{B_j + C_j \cdot E_j^*}$$

It is clear that once a pair of E_j, F_j values is known (or E_{j+1}^* ,F_{j+1}^*) then all E, F. and E*, F* coefficients can be computed for decreasing j. Introducing the right-hand boundary condition into one of the Equations (3.2) starts the recurrence computation for E, F and E*, F* - The E, F-sweep. Introducing the left-hand boundary condition in (3.3) starts the complimentary sweep in which N and q are computed.

As discussed earlier, sweeps may be carried out with a decreasing complimentary coordinate or an increasing complimentary coordinate. This is organised in the cycle shown in Figure 3.4.

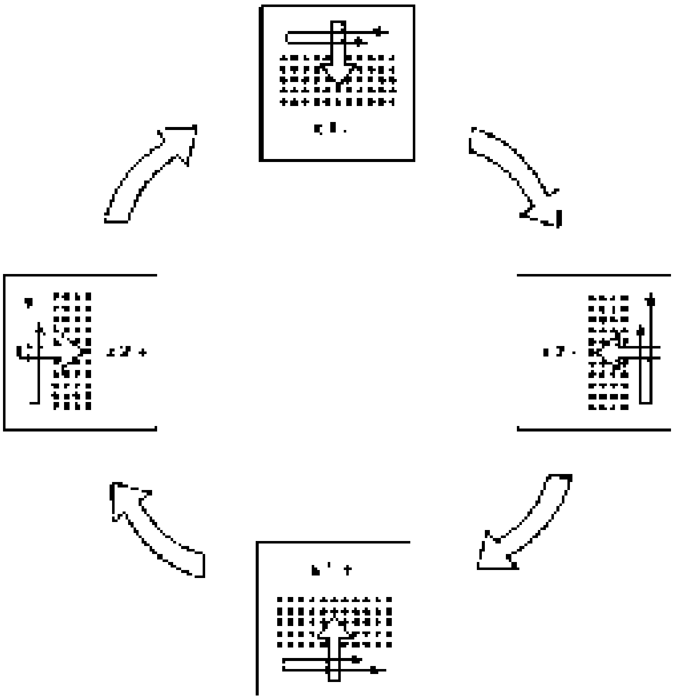

Figure 3.4 Cycle of Computational Sweeps

In Section 6 the numerical properties of the difference scheme in terms of amplification and propagation errors are discussed. Before this, we shall present various difference approximations.

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4 DIFFERENCE APPROXIMATIONS FOR POINTS AWAY FROM COAST

We shall mainly look at the mass and momentum equations in the x-direction. As the mass equation in the y-direction influences the centering of the x-mass equation we shall also consider the difference approximation of this equation. The momentum equation in the y-direction is analogous to the momentum equation in the x-direction and is, accordingly, omitted here.

4.1 Mass equation in the x-direction

The mass equation reads

$$\frac{\partial \zeta}{\partial t} + \frac{\partial p}{\partial x} + \frac{\partial q}{\partial y} = \frac{\partial d}{\partial t} \qquad (4.1)$$

The x- and y-sweeps are organised in a special cycle as shown in the preceding section. In Section 6 it is shown how the computation proceeds in time and how the equations are time centered.

In order to fully understand the balance between the difference approximations employed in the various sweeps it is necessary to read Section 6 in conjunction with the following sections. For the moment it is sufficient to say that the x-mass and x-momentum equations bring ζ from time level n to n+½ while bringing p from n to n+1. Together with the y-mass equation the terms are centered at n+½.

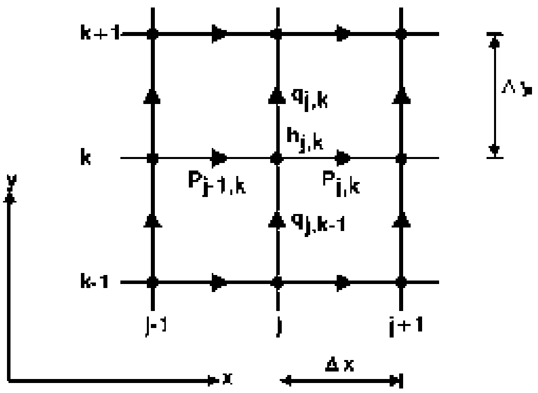

Figure 4.1 Grid Notation: Mass Equation

With the grid notation given in Figure 4.1, Equation (4.1) becomes

$$2 \cdot \left(\frac{\zeta^{n+½} - \zeta^{n}}{\Delta t}\right)_{j,k} + \frac{1}{2} \cdot \left\{\left(\frac{p_j - p_{j-1}}{\Delta x}\right)^{n+1} + \left(\frac{p_j - p_{j-1}}{\Delta x}\right)^{n}\right\}_k + \frac{1}{2} \cdot \left\{\left(\frac{q_k - q_{k-1}}{\Delta y}\right)^{n+½} + \left(\frac{q_k - q_{k-1}}{\Delta y}\right)^{n-½}\right\}_j = 2 \cdot \left(\frac{d^{n+½} - d^{n}}{\Delta t}\right)_{j,k} \quad (4.2)$$

4.2 Mass equation in the y-direction

The y-sweep immediately following the x-sweep, for which the mass equation was just described, brings ζ from time level n+½ to level n+1 and helps to centre the x-mass and x-momentum equations. With the grid notation of Figure 4.1, Equation (4.1) becomes

$$2 \cdot \left(\frac{\zeta^{n+1} - \zeta^{n+½}}{\Delta t}\right)_{j,k} + \frac{1}{2} \cdot \left\{\left(\frac{p_j - p_{j-1}}{\Delta x}\right)^{n+1} + \left(\frac{p_j - p_{j-1}}{\Delta x}\right)^{n}\right\}_k + \frac{1}{2} \cdot \left\{\left(\frac{q_k - q_{k-1}}{\Delta y}\right)^{n+3/2} + \left(\frac{q_k - q_{k-1}}{\Delta y}\right)^{n+½}\right\}_j = 2 \cdot \left(\frac{d^{n+1} - d^{n+½}}{\Delta t}\right)_{j,k} \quad (4.3)$$

Prior to each sweep, the bathymetry (when the landslide option is included) is read from the bathymetry data file and interpolated to the respective time step, i.e. $n+½$ for an x-sweep and $n+1$ for a y-sweep. After completion of each sweep, the water depth is updated to the actual value based on surface elevation and bathymetry, yielding $h^{n+½} = \zeta^{n+½} - d^{n+½}$ after the x-sweep and $h^{n+1} = \zeta^{n+1} - d^{n+1}$ after the y-sweep.

We will not discuss truncation errors at this point. As the approximations are based on a multi-level difference method, centering of terms and the evaluation of truncation errors should be considered in conjunction with a certain set of equations. We will revert to this point in Section 6.

4.3 Momentum equation in the x-direction

4.3.1 General

The x-component of the momentum equation reads:

$$\frac{\partial p}{\partial t} + \frac{\partial}{\partial x}\left(\frac{p^2}{h}\right) + \frac{\partial}{\partial y}\left(\frac{pq}{h}\right) + gh\frac{\partial \zeta}{\partial x} \tag{4.4}$$

$$+\frac{gp\sqrt{p^2+q^2}}{C^2 \cdot h^2} - \frac{1}{\rho_w}\left[\frac{\partial}{\partial x}(h\tau_{xx}) + \frac{\partial}{\partial y}(h\tau_{xy})\right] - \Omega_q$$

$$-fVV_x + \frac{h}{\rho_w}\frac{\partial}{\partial x}(p_a) = 0$$

We shall develop the difference forms by considering the various terms one by one.

The following basic principle is used for the x-momentum finite difference approximations:

All terms in (4.4) will be time-centered at n+½ and space centered at the location corresponding to $P_{j,k}$ in the space-staggered grid. The grid notation is shown in Figure 4.2.

4.3.2 The time derivation term

The straight forward finite difference approximation to the time derivative term is

$$\frac{\partial p}{\partial t} \approx \left(\frac{p^{n+1} - p^n}{\Delta t}\right)_{j,k} \tag{4.5}$$

Using a Taylor expansion centered at n+½ leads to

$$\frac{\partial p}{\partial t} \approx \left(\frac{p^{n+1} + p^n}{\Delta t}\right)_{j,k} - \frac{\Delta t^2}{24} \cdot \frac{\partial^3 p}{\partial t^3} \tag{4.6}$$

$$+ HOT \quad (Higher\ Order\ Terms)$$

In standard hydrodynamic simulations only the first term in (4.6) is included in the scheme. For short wave applications using the BW module (Boussinesq waves) the second term in (4.6) is also included to obtain a higher accuracy of the scheme.

4.3.3 The gravity term

The straight forward approximation to the gravity term reads

$$gh\zeta_x \approx g\left(\frac{h_{j,k}+h_{j+1,k}}{2}\right)^n\left(\frac{\zeta_{j+1,k}-\zeta_{j,k}}{\Delta x}\right)^{n+1/2} \tag{4.7}$$

where

$$h^n_{j,k} = d_{j,k} + \zeta^n_{j,k}$$

In this way the term has been linearized in the resulting algebraic formulation. Truncation errors embedded in (4.7) can be determined by the use of Taylor expansions centered at j+½,k and n+½. This leads to

$$gh\zeta_x \approx FDS + g\left[\frac{\Delta t}{2}\zeta_x\zeta_t - \frac{\Delta t^2}{8}\zeta_{tt}\zeta_x - \frac{\Delta x^2}{8}\zeta_{xx}\zeta_x - \frac{\Delta x^2}{24}h\zeta_{xx}\right] \tag{4.8}$$

$$+\,HOT \quad (Higher\ Order\ Terms)$$

where FDS is the right hand side of (4.7).

In standard hydrodynamic simulations only the FDS term is included in the scheme. For short wave applications using the BW module, the truncation errors proportional to Δt and Δt2 are eliminated by shifting the time level of the first bracket in (4.7) from n to n+½. This is done in an approximative way by explicit use of the continuity equation.

Furthermore, the last term in (4.8) is included in the higher order accuracy scheme used in the BW module.

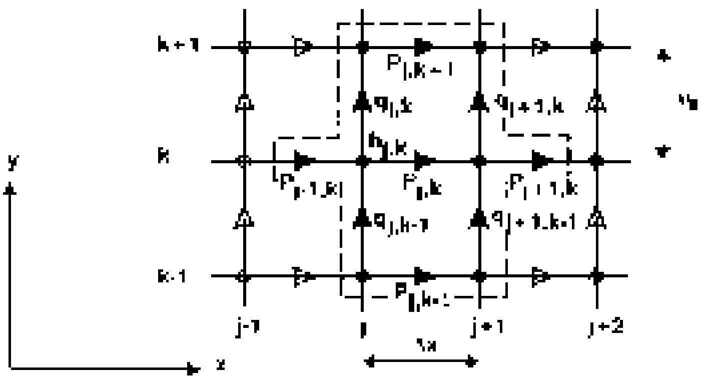

Figure 4.2 Grid Notation: x-Momentum Equation

4.3.4 The convective and cross-momentum correction terms

$$\frac{\partial}{\partial x}\left(\frac{pp}{h}\right)+\frac{\partial}{\partial y}\left(\frac{qp}{h}\right) \tag{4.9}$$

This requires further discussion. One way of approximating both terms would be to form spatially centred differences of time-centered forms of the bracketed terms. For example,

$$\frac{1}{2\Delta x}\left\{\left(\frac{pp}{h}\right)_{j+l}^{n+½}-\left(\frac{pp}{h}\right)_{j-1}^{n+½}\right\}_k \tag{4.10}$$

and a similar form for the cross-momentum term. (How the time centering is achieved will be shown in the final difference forms). However, this approximation is not supported by flux at the central point $p_{j,k}$ and this will give rise to zigzagging of flow patterns if variations close to the highest resolvable wave number have to be described. We may, for example, consider the case of a flow concentration around the tip of a pier. The situation, with and without zigzagging, is illustrated in Figure 4.3. The illustration is taken from Abbott and Rasmussen, Ref./2/, where the problem is discussed, although in a slightly different context.

A popular exposition of the problem is given by Leonard, Ref. /3/. A central difference form has neutral stability for first order differential terms, being insensitive to the central flux $p_{j,k}$. That is, $p_{j,k}$ may vary without a stabilising positive feedback and erroneously affect the time derivative. This, in fact, is what is occurring during the zigzagging process.

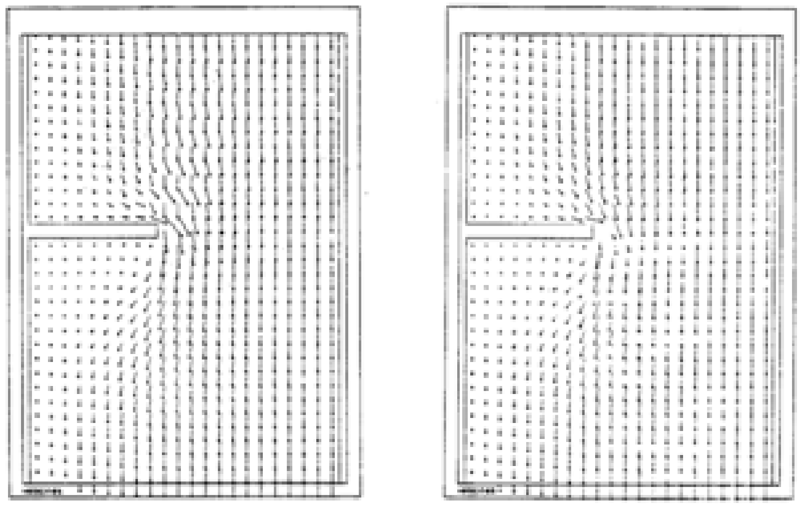

Figure 4.3 Zigzagging in Flow Concentration

To illustrate this point further, consider ∂(pq/h)/∂y in connection with a flow concentration giving the variation of p shown in Figure 4.4.

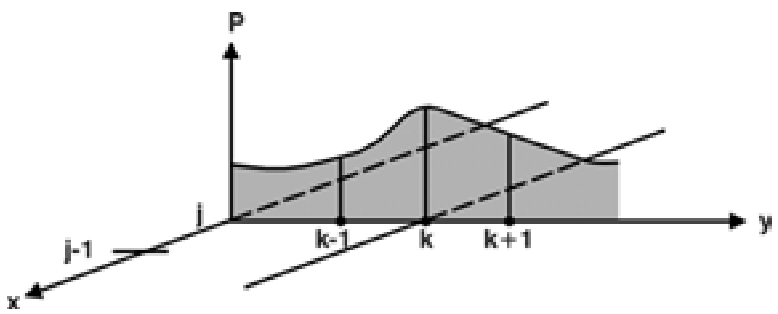

Figure 4.4 Variation of p at a Flow Concentration

Assuming for the present discussion that v = q/h varies much less with y than does u = p/h, we have

$$\frac{\partial}{\partial y}\left(\frac{pq}{h}\right) \approx \frac{\partial p}{\partial y} \qquad (4.11)$$

Now at $y = k \cdot \Delta y$, $\partial p / \partial y \approx 0$ and does not contribute to ∂p/∂t. However, $(p_{k+1} - p_{k-1})/2\Delta y$ is not zero. It may be either positive or negative and give an increase or decrease to ∂p/∂t. Thus, the discrete description introduces an exchange of momentum in the y-direction between sweeps in the x-direction which, in the continuous description, may not be present. A similar argument applies for a variation in p in the x-direction, at or close to the highest resolvable wave number.

To improve the situation, clearly we should introduce the curvature of p. This becomes apparent when the transport nature of the terms are considered.

We may rewrite them as

$$u\frac{\partial p}{\partial x} + p\frac{\partial u}{\partial x} + v\frac{\partial p}{\partial y} + p\frac{\partial v}{\partial y} \tag{4.12}$$

Following the derivation by Abbott, McCowan and Warren, Ref. /4/ (Section 6), we consider the first and third term together with the time derivative, i.e.

$$\frac{\partial p}{\partial t} + u\frac{\partial p}{\partial x} + v\frac{\partial p}{\partial y} \tag{4.13}$$

(we "forget" for the moment the two other terms). This represents a transport of the x-flux with the resultant of the x-and y-velocities. The integral form of the transport equation, which corresponds to an exact solution of the differential form, is,

$$p(x, y, t_2) \;=\; p(x - \int_{t1}^{t2}\bar{u}dt, y - \int_{t1}^{t2}\bar{u}dt, t_1) \tag{4.14}$$

where the velocities and are averaged quantities over the time interval t_2-t_1.

Now, consider the discrete description over Δt. Equation (4.14) may then be written as

$$p(j\Delta x, k\Delta y,(n+1)\Delta t) \;=\; p(j\Delta x - \bar{u}\Delta t, k\Delta y - \bar{v}\Delta t, n\Delta t) \tag{4.15}$$

When the right-hand term and the left-hand term are developed with (n+½)Δt, jΔx, kΔy as the centre, we obtain

$$\left|\frac{\partial p}{\partial t} + \bar{u}\frac{\partial p}{\partial x} + \bar{v}\frac{\partial p}{\partial y}\right|_{j,k}^{n+½} \tag{4.16}$$

$$-\frac{1}{2!}\left\{\bar{u}^2\Delta t\frac{\partial^2 p}{\partial x^2} + 2\bar{u}\bar{v}\Delta t\frac{\partial^2 p}{\partial x\partial y} + \bar{v}^2\Delta t\frac{\partial^2 p}{\partial y^2} + \bar{u}\Delta t\frac{\partial^2 p}{\partial x\partial t} + \bar{v}\Delta t\frac{\partial^2 p}{\partial y\partial t}\right\}_{j,k}^{n+1}$$

$$+\, HOT \quad (Higher\ Order\ Term)$$

Thus, representing the transport terms on a discrete grid with 2nd order discretisation terms requires the introduction of five correction terms. Two of these terms, $\partial^2 p/\partial x^2$ and $\partial^2 p/\partial y^2$, will bring the central point j,k into the difference approximation. We shall retain these two terms and neglect the others (as we have neglected until now the terms $p(\partial u/\partial x)$ and $p(\partial v/\partial y)$. This appears rather arbitrary and, in fact, it is. We cannot argue that, in general, the terms that we intend to neglect are necessarily smaller than the two terms we wish to retain. It should, however, be remembered that in computations with a time scale of the order of tidal motion, the correction terms will all be fairly small. Thus they will not contribute significantly to the accuracy of the principle solution. However, neglecting in particular the terms $\partial^2 p/\partial x^2$ and $\partial^2 p/\partial y^2$ deprives the solution of the support in the central point, allowing small local disturbances to grow to finally poison the entire solution. Experience with MIKE 21 HD has shown that accurate solutions can be obtained with the representation of the convective- and cross-momentum corrections by only two terms.

Now it might be argued that "we just dissipate the higher-order disturbances". Indeed, the second-order space derivatives have the form of stress terms that one would use, for example, in a second-order dissipative interface. However, they are much more selective, being effective only where u or v are large and then they work towards a more correct solution.

4.3.5 Convective momentum

We can now write the difference form for

$$\frac{\partial}{\partial x}\left(\frac{pp}{h}\right) - \frac{1}{2}\bar{u}\Delta t\frac{\partial^2 p}{\partial x^2} \tag{4.17}$$

Momentum equation in the x-direction

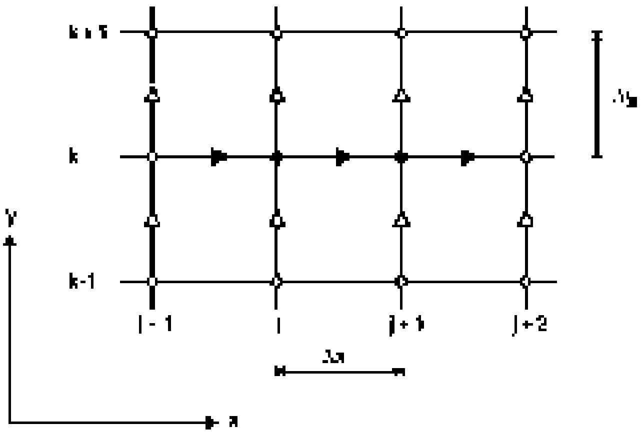

Figure 4.5 Grid Notation: x-Momentum Equation

On the grid below, we can represent the terms as follows:

$$\frac{\partial}{\partial x}\left(\frac{pp}{h}\right) \tag{4.18}$$

$$\approx \left[\frac{(p_{j+1}+p_j)^{n+1}}{2}\cdot\frac{(p_{j+1}+p_j)^{n}}{2}\cdot\frac{1}{h^n_{j+1}} - \frac{(p_j+p_{j-1})^{n+1}}{2}\cdot\frac{(p_j+p_{j-1})^{n}}{2}\cdot\frac{1}{h^n_j}\right]_k$$

$$\cdot\frac{1}{\Delta x}$$

$$\bar{u}^2\Delta t\frac{\partial^2 p}{\partial x^2} \approx \Delta t\left(\frac{p^n_{j,k}}{h*}\right)^2\cdot\left(\frac{p_{j+1,k}-2p_j+p_{j-1}}{(\Delta x)^2}\right)^{n+1}_k \tag{4.19}$$

with

$$h* = \frac{1}{2}\cdot(h_{j+1}+h_j)^n_k \tag{4.20}$$

One will note that the difference form in (4.18) in fact involves 5 diagonals in the matrix of difference equations, whereas we employ a "3-diagonal" algorithm for its solution. One can extend the "3-diagonal" algorithm to a "5-diagonal" algorithm. Here we have chosen to reduce the form (4.18) to a 3-diagonal form by local substitution.

In the form (4.19) we note that we approximate , the average velocity over the interval from $t_1 = n\cdot\Delta t$ to $t_2 = (n+1)\cdot\Delta t$, by $p_{j,k}/h*$.

Also, the difference form is written fully on the forward time level. In view of the other errors - neglecting other correction terms - this approximation error is of a higher order.

The difference form in (4.18) is used for flow at low Froude Numbers. For flow at high Froude Numbers, a scheme as described below is used. In this scheme selective introduction of numerical dissipation has been used to improve the robustness of the numerical solution in areas of high velocity gradients, and to provide MIKE 21 with the capability to simulate locally super-critical flows. This numerical dissipation has been introduced through selective "up-winding" of the convective momentum terms, as *Fr* increases. The rationale behind this approach is that the introduction of numerical dissipation at high Froude Numbers can be tuned to be roughly analogous to the physical dissipation caused by increased levels of turbulence in high velocity flows.

Effects of up-winding

The fully space centred description of the convective momentum term considered in (4.17) can be approximated by:

$$\frac{\partial}{\partial x}\left(\frac{p^2}{h}\right)_j \approx \frac{1}{\Delta x}\left[\left(\frac{p^2}{h}\right)_{j+½} - \left(\frac{p^2}{h}\right)_{j-½}\right] \tag{4.21}$$

For positive flow in the x-direction, the up-winded form of the convective momentum term can be approximation by:

$$\frac{\partial}{\partial x}\left(\frac{p^2}{h}\right)_{j-½} \approx \frac{1}{\Delta x}\left[\left(\frac{p^2}{h}\right)_j - \left(\frac{p^2}{h}\right)_{j-1}\right] \tag{4.22}$$

Allowing for the back-centring in space, the up-winded term can be shown to be equivalent to the original space-centred term, plus an additional second order term, as follows:

$$\frac{\partial}{\partial x}\left(\frac{p^2}{h}\right)_{j-½} \approx \frac{1}{\partial x}\frac{p^2}{h}_j - \frac{\Delta x}{2}\frac{\partial^2}{\partial x^2}\left(\frac{p^2}{h}\right)_j \tag{4.23}$$

This second order term is highly dissipative for high frequency oscillations, but has little effect on lower frequencies. That is, it will tend to damp out high frequency numerical instabilities, while having little effect on the overall computation.

Selective up-winding

To ensure that the dissipative effects of up-winding are only included when necessary, a Froude Number dependent weighting factor α has been introduced where:

$$\alpha = 0,\ Fr \le 0.25 \tag{4.24}$$

$$\alpha = \frac{4}{3}(Fr - 0.25),\ 0.25 < Fr < 1.0$$

$$\alpha = 1,\ Fr \ge 1$$

The weighting factor α is applied to the convective momentum terms, such that:

$$\frac{\partial}{\partial x}\left(\frac{p^2}{h}\right)_j \approx (1-\alpha)\frac{\partial}{\partial x}\left(\frac{p^2}{h}\right)_j + \alpha\frac{\partial}{\partial x}\left(\frac{p^2}{h}\right)_{j-½} \tag{4.25}$$

This brings the effects of up-winding in gradually as the Froude Number increases from 0.25 to 1.0. For Froude Numbers of $Fr = 1.0$ or more, the convective momentum term is fully up-winded.

Computational form

In the form described in (4.18), the actual representation of the convective momentum equation (for positive flow in the x-direction) can be expressed as follows:

$$\frac{\partial}{\partial x}\left(\frac{p^2}{h}\right)^{n+½}_{j,k} \approx \left[\frac{[(1-\alpha)p_{j+1} + (1+\alpha)p_j]^{n+1}}{2} \cdot \frac{[(1-\alpha)p_{j+1} + (1+\alpha)p_j]^{n}}{2}\right. \tag{4.26}$$

$$\cdot \frac{1}{[(1-\alpha)h_{j+1} + \alpha h_j]^n}$$

$$- \frac{[(1-\alpha)p_j + (1+\alpha)p_{j-1}]^{n+1}}{2} \cdot \frac{[(1-\alpha)p_j + (1+\alpha)p_{j-1}]^{n}}{2}$$

$$\left.\cdot \frac{1}{[(1-\alpha)h_j + \alpha h_{j-1}]^n}\right]_k \cdot \frac{1}{\Delta x}$$

The weighting factor α for each grid point is calculated every time step, immediately prior to the calculation of the momentum equation coefficients. This ensures that numerical dissipation is only introduced at grid points where high Froude Number flow is occurring, and that the normal high accuracy solution of MIKE 21 is obtained throughout the rest of the model domain.

Selective up-winding is only included on the convective momentum terms and not the cross momentum terms.

With the introduction of selective up-winding of the convective momentum terms, it has been possible to virtually eliminate the unrealistic oscillations and local instabilities that occurred previously when modelling high Froude Number flows. This has improved significantly the robustness of MIKE 21's solution procedure at high Froude Numbers, and has enhanced significantly MIKE 21's capability to include (qualitatively at least):

- Locally super-critical flows
- Weir and levee bank flows (on a grid scale)
- Hydraulic jumps

Selective up-winding also ensures that the high accuracy of solutions in other areas remains unaffected.

4.3.6 Cross-momentum

$$\frac{\partial}{\partial y}\left(\frac{pq}{h}\right) - \frac{1}{2}\bar{v}^2 \Delta t\left(\frac{\partial^2 p}{\partial y^2}\right) \qquad (4.27)$$

The difference approximation will differ between an "up" sweep and a "down" sweep. We shall use "side feeding" as a means to centre the term at level (n+½) Δt.

Momentum equation in the x-direction

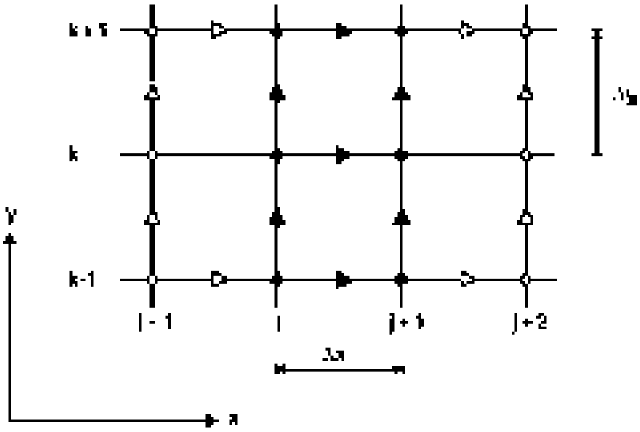

Figure 4.6 Grid Notation: x-Momentum Equation

We write, referring to the grid notation of Figure 4.6,

$$\frac{\partial}{\partial y}\left(\frac{pq}{h}\right) \approx \left[\left(\frac{p^a_{k+1} + p^b_k}{2}\right) \cdot v^{n+½}_{j+½,k} - \left(\frac{p^a_k + p^b_{k-1}}{2}\right) \cdot v^{n+½}_{j+½,k-1}\right] \cdot \frac{1}{\Delta y} \qquad (4.28)$$

where:

a = n+1, b = n for a "down" sweep

a = n , b = n+1 for an "up" sweep

$$v^{n+½}_{j+½,k-1} = \frac{2(q_j + q_{j+1})^{n+½}_k}{(h_{j,k} + h_{j,k+1} + h_{j+1,k} + h_{j+1,k+1})^n} \qquad (4.29)$$

$$v^{n+½}_{j+½,k} = \frac{2(q_j + q_{j+1})^{n+½}_{k-1}}{(h_{j,k-1} + h_{j,k} + h_{j+1,k-1} + h_{j+1,k})^n}$$

$$\bar{v}\Delta t\frac{\partial^2 p}{\partial y^2} \approx \Delta t(v^*)^2 \cdot \frac{\{p^a_{k+1} - (p^{n+1}_k + p^n_k) + p^b_{k-1}\}_j}{(\Delta y)^2} \qquad (4.30)$$

with a and b defined as above and

$$v^* = \frac{1}{2} \cdot (v_{k+½} + v_{k-½})^{n+½}_{j+½} \qquad (4.31)$$

The diagrams in Figure 4.7 and Figure 4.8 may illustrate how the cross terms are built. Note that the main computation we are dealing with in this approximation of the x-momentum equation is in the x-direction. By "down" sweep or "up" sweep we mean in fact computational sweeps in the x-direction, carried out by decreasing or increasing y respectively.

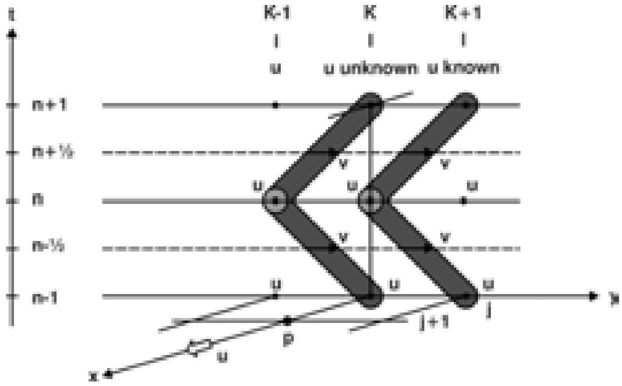

Figure 4.7 *"Side-Feeding" for the Cross-Momentum Term. p(n+1,k+1) known, calculated by a "down" sweep. p(n,k-1) known, calculated by an "up" sweep*

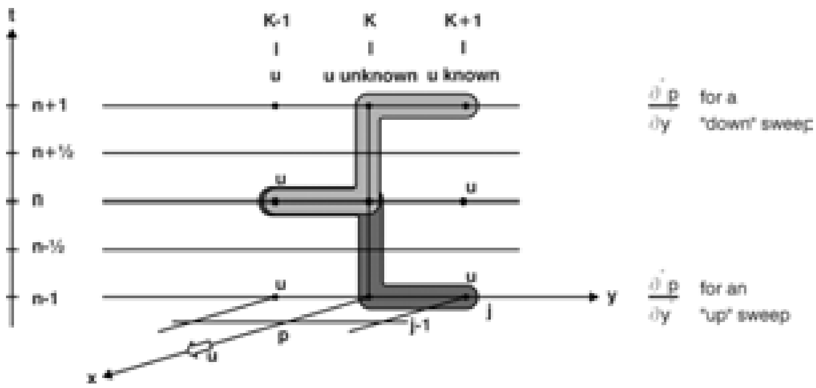

Figure 4.8 *"Side-Feeding" for the 2nd order Cross-Derivative Term*

4.3.7 Wind friction term

The wind friction term reads

$$f(v) \cdot V \cdot V_x \tag{4.32}$$

where all variables are known in each grid point. The wind friction factor is calculated in accordance with Smith and Banke (Ref. /11/), see Figure 4.9.

$$f(v) = \begin{cases} f_0 & for \quad V < V_0 \\ f_0 + \dfrac{V - V_0}{V_1 - V_0} \cdot (f_1 - f_0) & for \quad V_0 \le V \le V_1 \\ f_1 & for \quad V > V_1 \end{cases} \qquad (4.33)$$

where

$$\begin{aligned} f_0 &= 0.00063 \quad , \quad V_0 = 0 \text{ m/s} \\ f_1 &= 0.0026 \quad , \quad V_1 = 30 \text{ m/s} \end{aligned} \qquad (4.34)$$

If the area represented by grid point (j,k) has been specified to be covered by ice, f(V) is set to zero.

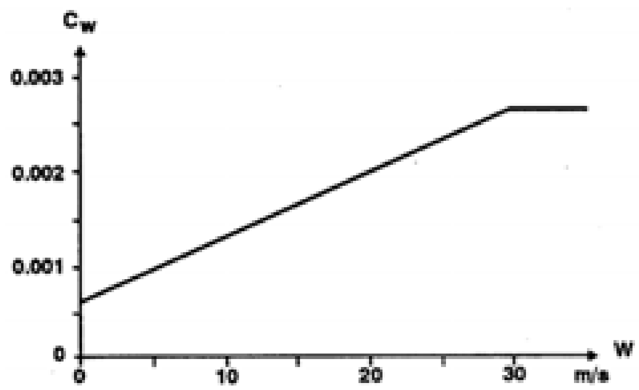

Figure 4.9 Wind Friction Factor

4.3.8 Resistance term

The bed shear stress is represented by the Chezy formulation,

$$\frac{gp\sqrt{p^2 + q^2}}{C^2h^2} \qquad (4.35)$$

which is approximated as

$$\frac{gp_{j,k}^{n+1}\sqrt{p^{*2}+q^{*2}}}{C^2h^{*2}} \tag{4.36}$$

where

$$p^* = p_{j,k}^n$$
$$q^* = \frac{1}{8}\left(q_{j,k}^{n-½} + q_{j+1,k}^{n-½} + q_{j,k-1}^{n-½} + q_{j+1,k-1}^{n-½} + q_{j,k}^{n+½} + q_{j,k-1}^{n+½} + q_{j+1,k-1}^{n+½}\right) \tag{4.37}$$
$$h^* = \begin{cases} h_{j,k}^n & \text{for} \quad p^* \geq 0 \\ h_{j-1,k}^n & \text{for} \quad p^* < 0 \end{cases}$$

Up-winding of the water depth used in the friction term was introduced in release 2001, and appeared to overcome some problems associated with previous versions of MIKE 21 flood and dry scheme. With this approach, the friction for flow from a deep grid point to a shallow grid point is calculated on the basis of the water depth in the deep grid point. That is, $h^* = h_{deep}$. Conversely, the friction for flow from a shallow grid point to a deep grid point is calculated on the basis of the water depth in the shallow grid point. That is, $h^* = h_{shallow}$. This makes it relatively easier for water to flow into a shallow grid point, and more difficult for it to flow out. Intuitively, this was considered to be a more physically realistic approach.

The Chezy number, C, is computed from the Manning number, M, as follows:

$$C = M \cdot h^{*1/6} \tag{4.38}$$

4.3.9 Coriolis term

This term

$$\Omega \cdot q \tag{4.39}$$

is approximated explicitly by using q* as defined in (4.37).

5 SPECIAL DIFFERENCE APPROXIMATIONS FOR POINTS NEAR A COAST

The cross-derivatives in the hydrodynamic equations pose a problem when the computational sweep passes near land. Clearly, concepts such as side-feeding become difficult to use. Inaccuracies, asymmetric behaviour between the "up" sweep and the "down" sweep may, especially at corners, create instabilities.

Land boundaries are defined at flux points, with the flux away from the land boundary set to zero. If for the purpose of this discussion, we consider an X-sweep, one can define the three principal situations given in Figure 5.1 to Figure 5.3 below as Case 1, 2 and 3. They are here shown at the "positive" or "north" side of the sweep but have, of course, their counter parts on the negative side. The principal situations can combine to create situations as shown, for example, in Figure 5.1 to Figure 5.3 . In fact there are 15 possible combinations. The various situations are identified through a grid code or a combination of grid codes. The difference formulations along a land boundary when it is at an angle to the grid (Figure 5.5) is especially demanding.

In the following we shall show possible approximations for the principal cases of Figure 5.1 to Figure 5.3 . The approximations for the other combinations are based on the same principles.

The terms that involve cross-derivatives are - considering an X-sweep - the ∂q/∂y term in the mass equations, the cross-momentum equation with associated correction term, the eddy viscosity term expressed in combination with this correction term and the cross-gravity term. The ∂q/∂y term of the mass equation offers no problems as this term is implicitly described in the definition of the land boundary. The other terms will be considered one by one.

5.1 Cross-momentum term - without correction

Consider the general form (4.28) for a "down" sweep

$$\frac{\partial}{\partial y}\left(\frac{pq}{h}\right) \approx \left[\left(\frac{p_{k+1}^{n+1} + p_k^n}{2}\right)_j \cdot v_{j+½,k+½}^{n+½} - \left(\frac{p_{k+1}^{n+1} + p_k^n}{2}\right)_j \cdot v_{j+½,k-½}^{n+½}\right] \cdot \frac{1}{\Delta y} \qquad (5.1)$$

with

$$v_{j+½,k+1}^{n+½} = \frac{\frac{1}{2}(q_j + q_{j+1})_k^{n+½}}{\frac{1}{4}(h_{j,k} + h_{j,k+1} + h_{j+1,k} + h_{j+1,k+1})^n} \tag{5.2}$$

5.1.1 CASE 1: Land to the "North"

In general we shall assume a reflection condition for p. That is p_{k+1} is assumed to be equal to p_k. We assume a flow situation as shown in Figure 5.1.

There is, in fact, no obvious reason for this assumption to be more correct than, for example, the assumption of a distribution as given in Figure 5.2. (We should, however, not be tempted to think of a distribution connected with a "no-slip" boundary condition. In the spatial description that we are dealing with here - Δx, Δy several tenths or hundreds of meters -such a condition is not resolved). However, the distribution of Figure 5.2 would generally give a greater gradient. We have preferred the distribution of Figure 5.1 as it gives a smaller value. The assumptions must be kept in mind in applications where ∂p/∂y becomes important at the land boundary.

For Case 1 the assumption, however, does not matter. The general form of (5.1) reduces to a reasonable approximation because $v_{j+1/2,k+1/2} = 0$.

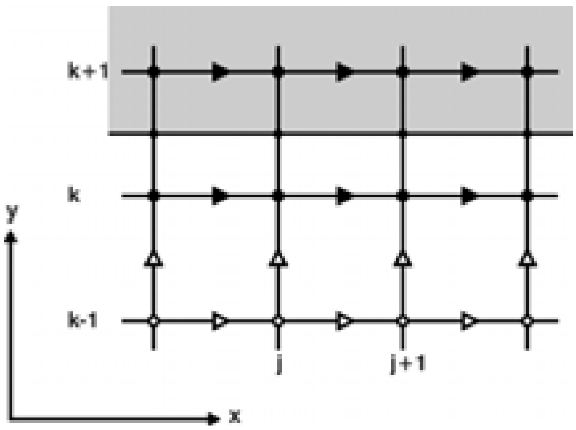

Figure 5.1 Special Situations near Land. Land to the "North" (CASE 1)

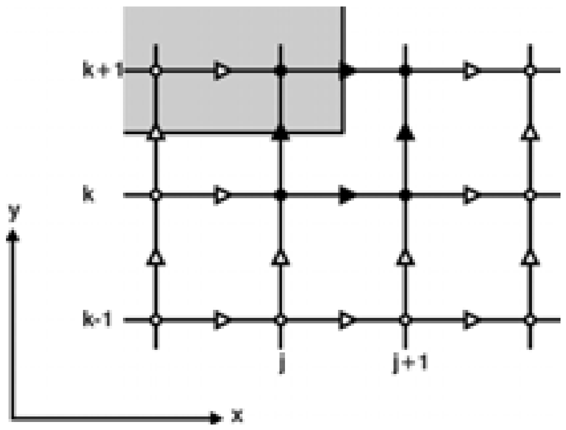

Figure 5.2 Special Situations near Land. Corner - Exit (CASE 2)

5.1.2 CASE 2: Corner - Exit

For *p* the reflection condition is used. The approximation of $v_{j+1/2,k+1/2}$ is more difficult. Experience from the regular grid has shown the following assumptions to give good results in general.

$$h_{k+1} \approx h_{j,k} \quad (5.3)$$

With this assumption $v_{j+1/2,k+1/2}$ can be approximated by the general formula (5.2).

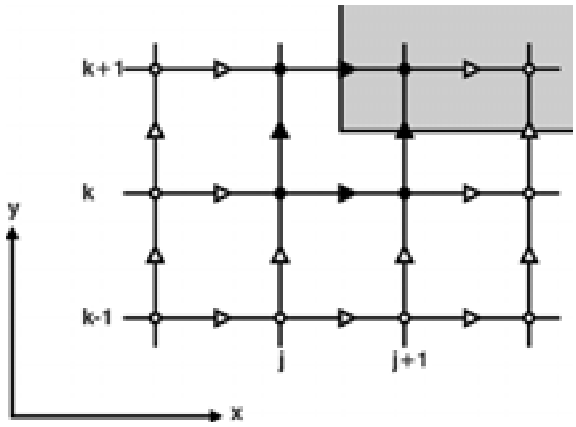

Figure 5.3 Special Situations near Land. Corner - Entry (CASE 3)

5.1.3 CASE 3: Corner - Entry

Similar assumptions to those in Case 2 give reasonable approximations.

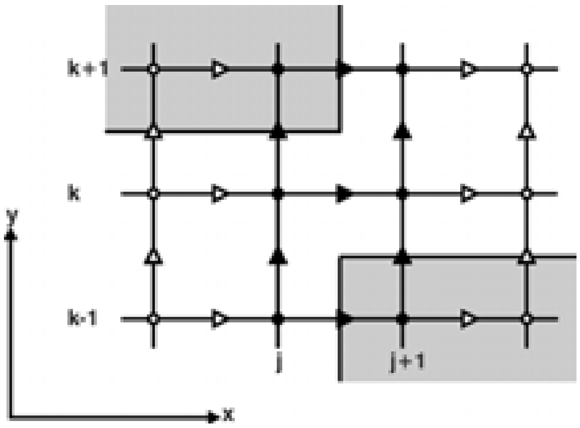

Figure 5.4 Possible Corner Combination (which should be avoided)

5.2 Cross-momentum correction and eddy viscosity term

The correction term and eddy viscosity term (using a constant eddy description) require an approximation for ∂2p/∂y2. Consider the general form of the correction term in (4.27) and introduce an additional eddy viscosity by adding a constant coefficient η. We have

$$\left(\eta + \frac{1}{2} \cdot \bar{v}^2 \cdot \Delta t\right)\frac{\partial^2 p}{\partial y^2} \approx \left(\eta + \frac{1}{2} \cdot v^{*2} \cdot \Delta t\right) \cdot \left\{\frac{p_{k+1}^{n+1} - (p_k^{n+1} + p_k^n) + p_{k-1}^n}{(\Delta y)^2}\right\}_j \qquad (5.4)$$

The 2nd derivative term is approximated using the reflection condition for p. For Case 1, v = 0, so that the general form provides an automatic approximation. For Case 2, v* can be approximated as in Case 2 of Section 5.1 above. For Case 3 a similar approximation can be applied.

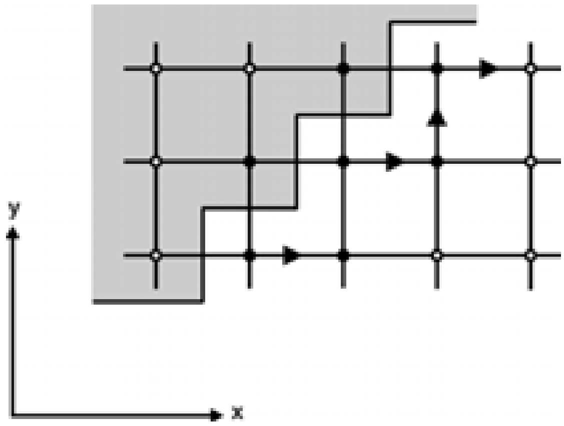

Figure 5.5 Coastline 45º to the grid

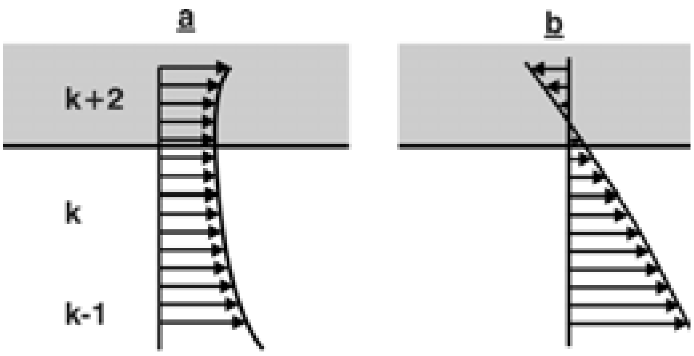

Figure 5.6 Possible Velocity Distributions

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6 STRUCTURE OF THE DIFFERENCE SCHEME, ACCURACY AND STABILITY

6.1 Time centering, accuracy

The difference schemes developed in the previous section must be seen as one component in a computational cycle. Only together with the other component equations in this cycle is time centering obtained. In a simplified, schematic, form we have

x - mass:

$$\frac{\zeta^{n+½} - \zeta^{n}}{½\Delta t} + \ldots + \frac{1}{2}\Lambda_y^{n+½}p + \frac{1}{2}\Lambda_x^{n}p + \frac{1}{2}\Lambda_y^{n+½}q + \frac{1}{2}\Lambda_y^{n-½}q = F_x(p, q) \tag{6.1}$$

x - momentum:

$$\frac{p^{n+1} - p^{n}}{\Delta t} + \ldots + gh\left(\frac{1}{2}\Lambda_y^{n+½}\zeta + \frac{1}{2}\Lambda_y^{n}\ldots\zeta\right) = G_x(p, q) \tag{6.2}$$

y - mass:

$$\frac{\zeta^{n+1} - \zeta^{n+½}}{½\Delta t} + \ldots + \frac{1}{2}\Lambda_x^{n+1}p + \frac{1}{2}\Lambda_x^{n}p + \frac{1}{2}\Lambda_y^{n+3/4}q + \frac{1}{2}\Lambda_y^{n+½}q = F_y(p, q) \tag{6.3}$$

y - momentum:

$$\frac{q^{n+3/2} - p^{n+½}}{\Delta t} + \ldots + gh\left(\frac{1}{2}\Lambda_y^{n+1}\zeta + \frac{1}{2}\Lambda_x^{n}\ldots\zeta\right) = G_y(p, q) \tag{6.4}$$

Where the operator Λ_x indicates a difference form, typically as in

$$\Lambda_x^{n+1} p = \frac{(p_j - p_{j-1})^{n+1}}{\Delta x} \tag{6.5}$$

(Our operation notation in the above equations is not meant to be rigorously correct. The idea in the schematic form is only to stress the time stepping structure).

Now the way in which the above component equations are coupled in time is shown in the computational cycle in Figure 6.1.

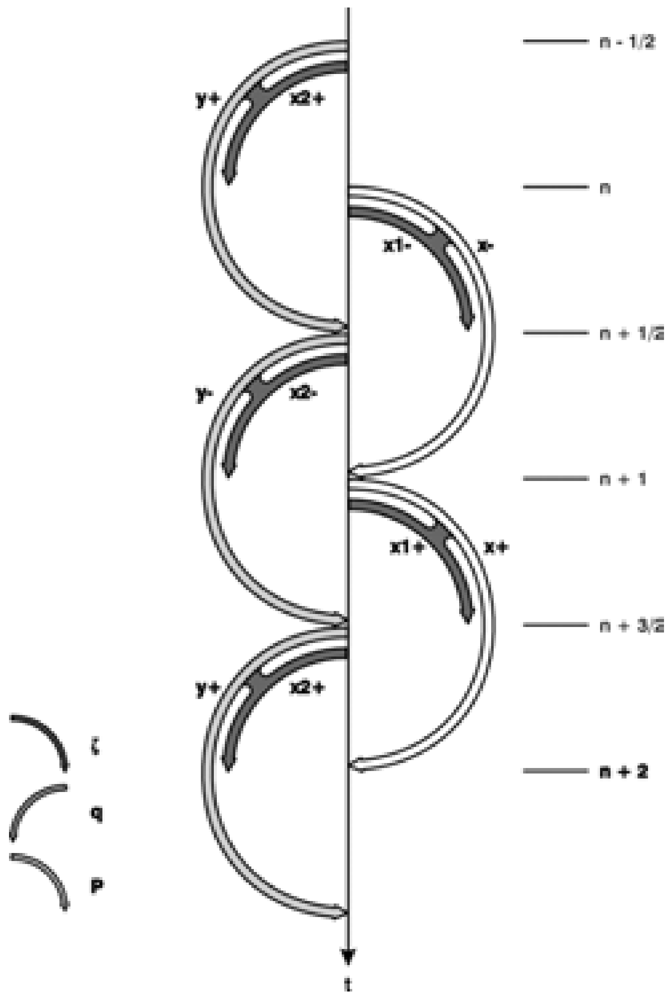

Figure 6.1 Computational Cycle of MIKE 21 HD

Referring to the computational cycle we can now discuss the centering of the various terms in the component equations. Consider the (x-) sweep. Its centre is at n+½. This is clear for the $\Lambda_x p$ term in the mass equation and the time derivative in the momentum equation. For the time derivative of ζ, the centring is not obvious. The (x-) sweep alone will not give a centre at n+½. The mass equation of the following (y-) sweep has to be involved to provide the centering at n+½.

The gravity term in the x-momentum equation $\Lambda_x \zeta$ is correctly centered at n+½.

The spatial derivative for q in the mass equations may at first hand appear peculiar. If the centre of the (x-) sweep is at n+½, then why not only use Λ(n+½ / y)q? The explanation lies in the next (y-) sweep. This sweep has its centre at n+1 and the mass equation therefore has $\Lambda(n+{}^3/_2$ / y)q and Λ(n+½ / y)q. Then, when the mass equation of the (y-) sweep is considered together with the mass equation of the (x-) sweep, the Λ(n-½ / y)q in the (x-) mass equation is needed to balance the $\Lambda(n+{}^3/_2$ / y)q in the (y-) mass equation.

The considerations for the (x-) sweep above can be repeated in a similar manner for the (x+), (y-) and (y+) sweeps.

The open computational cycle of Figure 6.1 is a development of the closed computational cycle employed in an earlier version of MIKE 21 HD. Figure 6.2 shows its structure. This cycle is described in Abbott, Damsgaard and Rodenhuis, Ref. /12/ and in Abbott, Ref./13/. Other implicit difference schemes, for example that of Leendertse, Ref. /14/, are usually based on a closed cycle of similar form. Stability and time centering in such closed cycles is then viewed in terms of a 1 dimensional descent. The x-mass and x-momentum equations, combined in a certain x-sweep, are balanced by the x-mass and momentum equations in a following complimentary x-sweep. Consider, for example, the computational cycle of Figure 6.2. The order of the sweeps is:

x	x-sweep, carried out with decreasing y
y	y-sweep, carried out with decreasing x
y+	y-sweep, carried out with increasing x
x+	x-sweep, carried out with increasing y

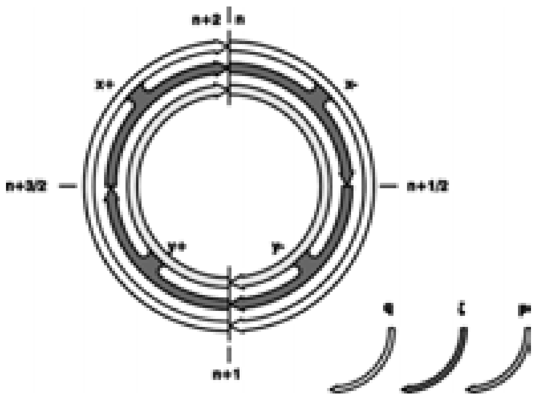

Figure 6.2 Computational Cycle of System 21 Mark 2, an early version of MIKE 21

One observes for terms involving ζ that the (x-) sweep together with the following (x+) sweep provides a centering at n+1. The ∂q/∂y term in the mass equation can only be approximated at the time level in the (x-) sweep, but is centered at n+1 by the ∂q/∂y term in the mass equation of the later (x+) sweep. However, this centring takes place two "y-sweeps" later and the solution may drift too far "off-centre" to be fully corrected. In that respect the open cycle is an improvement, the correction being provided by the sweep immediately following. The open cycle provides a further simplification in that the (x-) and (x+) sweeps are completely identical apart from the way they are carried out. Instead of 8 component equations - 2 per sweep - in the closed cycle of Figure 6.2, we now have 4 component equations.

The difference scheme, by nature of its central difference forms, is generally of second order. It is second order in terms of the discretisation of the Taylor series expansion, as well as in the more classical sense, that of the order of the algorithm. This last concept is defined as the highest degree of a polynomial for which the algorithm is exact. The two definitions are often confused, but they do not necessarily always give the same order of accuracy. For the Laplace equation the usual central difference approximation is of second order in terms of the discretisation error but the algorithm is of third order. See Leonard, Ref. /3/.

6.2 Amplification errors and phase errors

6.2.1 General

The behaviour of a difference scheme can be conveniently expressed through amplification portraits and phase portraits. For an earlier version of MIKE 21 HD and the System 21 Mark 6 (and other schemes of this type), such portraits have been derived in Abbott, McCowan and Warren, Ref. /4/. (The System 21 Mark 6 difference scheme is similar to the one used in MIKE 21 HD, but without higher-order correction terms. Furthermore, the Δx and Δy used in the equations are the distance between a water level point and a flux point, not between two water level points as in MIKE 21 HD). In order to be able to express fully the properties of the scheme with respect to time centering it was found convenient to reduce the scheme to an equivalent 2-level form through a sequence of substitutions. All dependent variables at "half" time levels are written at levels n+1 and n. The resulting scheme is equivalent for the purpose of amplification and phase error analysis, but is algorithmically intractable. The equations are further reduced to principal form by linearization. Convective terms, resistance, Coriolis and wind stress terms are all excluded. We will here summarise the main results of the analysis.

6.2.2 Amplification factors and phase portraits of System 21 Mark 6

For the equations in 2-level form a Fourier transform is obtained through the introduction of Fourier series of the following form

$$f_{j,k}^{n} = \sum_{m} f^{*}(m) e^{i(\sigma_1 j \Delta x + \sigma_2 k \Delta y)} \tag{6.6}$$

with

$$\sigma_1 = \frac{2\pi m}{2L_1}, \sigma_2 = \frac{2\pi m}{2L_2} \tag{6.7}$$

L_1 and L_2 are a characteristic length in the x and y directions respectively and m is the wave number. L_1, L_2 and m are usually so defined that $J\Delta x = L_1$, $K\Delta y = L_2$, and J and K are the number of grid points in the x and y directions respectively. Then, at m = 1, L_1 is the half wave length over the total extent in the x-direction, L_2 the half wave length in the y-direction. One may further define the numbers

$$N_1 = \frac{2L_1}{m\Delta x}, N_2 = \frac{2L_2}{m\Delta y} \tag{6.8}$$

to denote the number of grid points per wave length for a certain wave component m.

We introduce the amplification factor ⊥, so that

$$f_{j,k}^{n+1} = \varphi f_{j,k}^{n} \tag{6.9}$$

Since the equations are linearized and as ζ, p and q are all coupled through the hydrodynamic equations it is sufficient to analyse the amplification and phase error for one and the same component m in the Fourier series.

The Fourier transform of System 21 Mark 6 is then

$$\begin{bmatrix} \varphi-1 & \left(\frac{gh\Delta t}{4\Delta x}\right)(2i\sin\sigma_1\Delta x)(\varphi+1)-\left(\frac{(gh)^2\Delta t^3}{64\Delta y^2\Delta x}\right)(-4\sin^2\sigma_2\Delta y) & 0 \\ \frac{\Delta t}{4\Delta x}(2i\sin\sigma_1\Delta x)(\sigma+1) & (\varphi-1)+\frac{gh\Delta t^2}{16\Delta y^2}\cdot(-4\sin^2\sigma_2\Delta y)(\varphi+1) & \frac{\Delta t}{4\Delta y}(2i\sin\sigma_2\Delta y)\cdot(\varphi+1) \\ 0 & \frac{gh\Delta t}{2\Delta y}(2i\sin\sigma_2\Delta y)\varphi & (\varphi-1) \end{bmatrix} \begin{bmatrix} p^* \\ \zeta^* \\ q^* \end{bmatrix} = 0 \tag{6.10}$$

Setting

$$\frac{gh\Delta t^2}{\Delta x^2}\sin^2\sigma_1\Delta x = C_{rl}^2\sin^2\sigma_1\Delta x_t = \alpha^2 \tag{6.11}$$

$$\frac{gh\Delta t^2}{\Delta y^2}\sin^2\sigma_2\Delta y = C_{r2}^2\sin^2\sigma_2\Delta x_j = \beta^2 \tag{6.12}$$

with Cr1 and Cr2 the Courant numbers in the x and y-directions respectively, and

$$A^2 = \frac{\alpha^2}{4} + \frac{\alpha^2\beta^2}{16} + \frac{\beta^2}{4} \tag{6.13}$$

We find, from the condition that the determinant in (6.10) shall be zero,

$$\varphi^2 = 2\frac{(A^2-1)}{(A^2+1)} + 1 = 0 \tag{6.14}$$

giving,

$$\varphi^2 = \frac{(A^2-1)}{(A^2+1)} \pm \sqrt{\left(\frac{A^2-1}{A^2+1}\right)^2 - 1} \quad (6.15)$$

It then follows that |⊥| = 1, since A is always real. That is the amplification factor is 1 for all combinations of model parameters. In fact it can be shown that the class of models built upon time-centred implicit difference schemes and all schemes of this class have amplification factors equal to 1, Ref. /15/.

The phase portrait follows from the ratio between the numerical and physical celerity, and is

$$Q = -\frac{\arctan\frac{Im(\varphi)}{Re(\varphi)}}{\frac{2\pi Cr}{N}} \quad (6.16)$$

With (6.15) we have

$$\frac{Im(\varphi)}{Re(\varphi)} = \pm\frac{i2A}{1-A^2} \quad (6.17)$$

This gives the phase portraits of Figure 6.3, which are, in fact, the phase portraits of all schemes of the class of time-centred implicit models. The relation for A, (6.13) can be written for propagation along grid lines or for propagation at an angle to the grid lines and this is shown in Figure 6.3 for an angle of 45º. The celerity ratios for all other angles are bounded by the graphs for propagation along grid lines and at 45º. One may observe that for tidal problems, where N can be expected to be large, the phase error can be expected to be small, even for large Courant numbers.

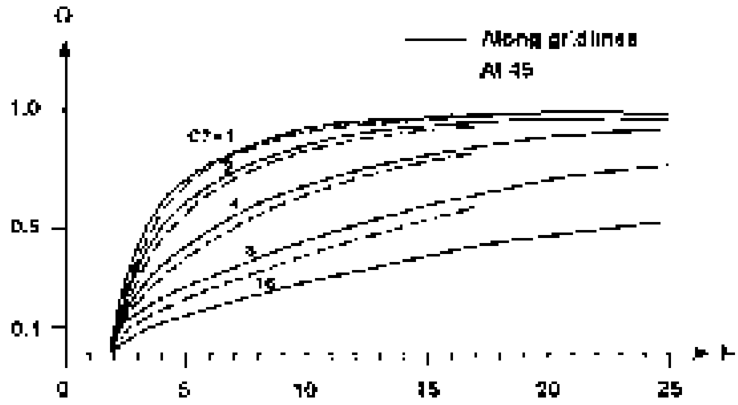

Figure 6.3 Phase Portraits of System 21 Mark 6

7 BOUNDARY CONDITIONS

7.1 General

The main purpose of MIKE 21 HD is to solve the partial differential equations that govern nearly-horizontal flow. Like all other differential equations they need boundary conditions. The importance of boundary conditions cannot be over-stressed.

In general the following boundary data are needed:

- Surface levels at the open boundaries and flux densities parallel to the open boundaries

  or

  Flux densities both perpendicular and parallel to the open boundaries

- Bathymetry (depths and land boundaries)
- Bed resistance
- Wind speed, direction and sheer coefficient
- Barometric pressure (gradients).

The success of a particular application of MIKE 21 HD is dependent upon a proper choice of open boundaries more than on anything else. The factors influencing the choice of open boundaries can roughly be divided into two groups, namely

- Grid-derived considerations
- Physical considerations

The physical considerations concern the area to be modelled and the most reasonable orientation of the grid to fit the data available and will not be discussed further here.

The grid itself implies that the open boundaries must be positioned parallel to one of the coordinate axes. (This is not a fundamental property of a finite difference scheme but it is essential when using MIKE 21 HD).

Furthermore, the best results can be expected when the flow is approximately perpendicular to the boundary. This requirement may already be in contradiction with the above mentioned grid requirements, and may also be in contradiction with "nature" in the sense that flow directions at the boundary can be highly variable so that, for instance "360" flow directions occur, in which case the boundary is a most unfortunate choice.

7.2 Primary open boundary conditions

The primary boundary conditions can be defined as the boundary conditions sufficient and necessary to solve the linearized equations. The fully linearized x-momentum equation reads:

$$\frac{\partial p}{\partial t} + gh\frac{\partial \zeta}{\partial x} = 0 \tag{7.1}$$

The corresponding terms in the x-momentum equation of MIKE 21 HD are:

$$\frac{\partial p}{\partial t} + \ldots + gh\frac{\partial \zeta}{\partial x} + \ldots = 0 \tag{7.2}$$

A "**dynamic case**" we define as a case where

$$\frac{\partial p}{\partial t} \approx -gh\frac{\partial \zeta}{\partial x} \tag{7.3}$$

i.e. a case where these two terms dominate over all other terms of the MIKE 21 HD x-momentum equation.

It is then clear that the primary boundary conditions provide "almost all" the boundary information necessary for MIKE 21 HD when it is applied to a dynamic case. The same set of boundary conditions maintain the dominant influence (but are in themselves not sufficient) even in the opposite of the "dynamic case", namely the steady state (where the linearized equations are quite meaningless). This explains why these boundary conditions are called "primary".

MIKE 21 HD accepts two types of primary boundary conditions:

- Surface elevations
- Flux densities

They must be given at all boundary points and at all time steps.

It should be mentioned that - due to the space staggered scheme -the values of the flux densities at the boundary are set half a grid point inside the topographical boundary, see Figure 7.1.

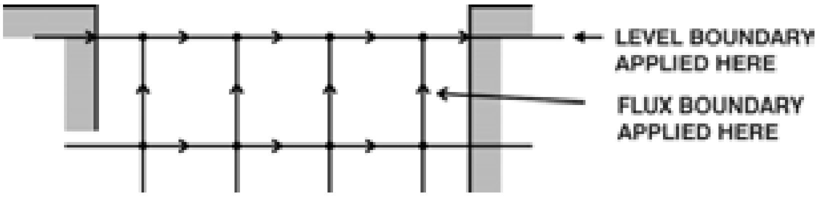

Figure 7.1 Application of boundary data at a Northern Boundary

7.3 Secondary open boundary conditions

7.3.1 General

The necessity for secondary boundary conditions arises because one cannot close the solutions algorithm at **open** boundaries when using the non-linearized equations. Additional information has to be given and there are several ways to give this. MIKE 21 HD is built on the premise that the information missing **is the discharge or flux density parallel to the open boundary**.

This is chosen because it coincides conveniently with the fact that the simplified MIKE 21 HD - the model that is one-dimensional in space - does not require a secondary boundary condition (i.e. the discharge parallel to the boundary is zero).

As a consequence of the transport character of the convective terms, a "true" secondary condition is needed at inflows, whereas at outflow a "harmless" closing of the algorithm is required. This closing may either be obtained by defining the flow direction at the boundary or by extrapolation of the flux along the boundary from the inside. Furthermore, the fluxes outside the boundaries are needed (for the convective momentum term, the eddy term and the non-linear dissipation term).

7.3.2 Fluxes along the boundary

As described in the previous section, the secondary boundary information has been defined as the Flux Along the Boundary, the FAB.

There are four FAB types implemented in MIKE 21 HD:

FAB type	MIKE 21 Action
0	FAB is 0 at all boundary points at all times
1	FAB is obtained by extrapolation mainly in space
2	Flow direction is given whereby FAB can be computed internally in MIKE 21 HD
12	Chooses FAB type = 1 at an outflow and FAB type = 2 at an inflow

The **only** possible FAB type for Flux-boundaries.

FAB type = 0

In this case the FAB will remain 0 at all boundary points during the whole simulation.

Though it appears as a simplification of both FAB type 1 and FAB type 2, it is maintained because it is so simple - both for the user and for MIKE 21 HD.

The physical meaning of FAB type 0 is that one-dimensional behaviour is enforced in the boundary region.

For a two-dimensional model this is principally acceptable only for inflow boundaries, implying that FAB type 0 is a secondary boundary condition typically connected to inflow.

FAB type = 1

This represents extrapolation.

In reality extrapolation gives dummy information and, accordingly, FAB type 1 is meant for outflow boundaries where principally only the primary information is required.

Further, a satisfactory result is often achieved in dynamic simulations (where inflow and outflow replace each other frequently) with FAB type 1.

FAB TYPE = 1 is the default for level-boundaries.

The actual extrapolation is guided by the system parameter

FABD3

where D3 stands for "the Degree of the 3rd derivative".

The FAB is then obtained from the finite difference approximation to the equation, say,

$$\left(\frac{\partial^2 p}{\partial y^2}\right)^{n+1} = FABD3\left(\frac{\partial^2 p}{\partial y^2}\right)^{n} \tag{7.4}$$

The terms are centred one grid point inside the boundary and new FABs are only computed every second time step (when the sweep direction is towards the boundary). The actual flux along the boundary may therefore - at instants of rapid change - appear rather different from extrapolated values.

When extrapolated values have been obtained according to the formula given above, they are damped and smoothed, i.e. multiplied by

FABDAMP

and smoothed according to the formula:

$$P(j) = \text{FABDISP} \cdot P(j-1) + P(j+1) + (1 - 2 \cdot \text{FABDISP}) \cdot P(j) \tag{7.5}$$

where j denotes position along the boundary.

The value FABDISP = 0.25 gives maximum smoothing whilst instability occurs if FABDISP > 0.5.

The applied values are

FABD3 = 5; FABDAMP = .99; FABDISP = .05;

corresponding to the proper use of FAB type 1, i.e. for use at outflows. If FABDAMP = 0 then FAB type 1 becomes identical to FAB type 0.

FAB type = 2

By setting a FAB type to 2 the flow **direction** at this boundary is specified, whereafter MIKE 21 HD can compute the FABs. FAB type 2 is typically connected to inflows.

The computation of the FABs is semi-centred in time in the sense that they are actually obtained as the solution to the equation, say

$$\text{FABFW} \cdot P + (1 - \text{FABFW}) \cdot \text{OLDP} = Q \cdot \text{dir} \quad (7.6)$$

where FW stands for the Weight on the Front. Thus, the new FABs are explicitly computed and the above given formula becomes time centred at the same time as it reaches its stability limit, namely for FABFW = 0.5. It is, however, recommended not to go below the default of FABFW = 0.6.

When the FABs have been computed, they are smoothed in a similar manner to that described in Equation (7.5), the degree of smoothing being described by FABDISPDIR for FAB type 2 boundaries.

The default is that the flow is at right angle to the boundary, or in other words, the default FAB type 2 is identical to FAB type 0.

FAB type = 12

FAB type 12 meets the theoretical requirements for the two-dimensional, nearly horizontal flow equations.

The number 12 is a code for "1 or 2", and if the FAB type is 12 then MIKE 21 HD simply selects either FAB type 1 or FAB type 2. In order to do this, MIKE 21 HD checks on the total flow through the boundary and, if there is **inflow it uses FAB type 2**, while if there is **outflow it uses FAB type 1**.

After having performed this choice, MIKE 21 HD obtains the FABs exactly as previously described for each of the two FAB types.

8 MULTI-CELL OVERLAND SOLVER

The MIKE 21 multi-cell overland solver is designed for simulating two-dimensional flow in rural and urban areas. The overall idea behind the solver is to solve the modified equations on a coarse grid taking the variation of the bathymetry within each grid cell into account. Results are presented on the grid that takes the fine scale bathymetry into account.

8.1 The modified governing equations

The control volume for the governing equations is taken as being one coarse grid cell. Within this grid cell the topography may vary as illustrated in Figure 8.1.

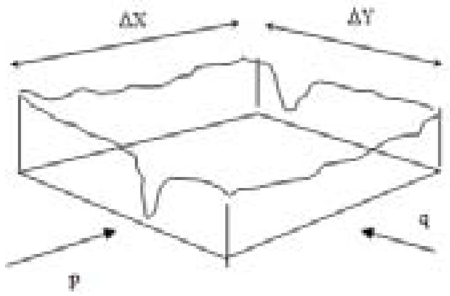

Figure 8.1 The topography within a coarse grid cell illustrating the control box used for deriving the fluxes

The mass balance reads

$$\frac{\partial h}{\partial t} + \frac{\partial p}{\partial y} + \frac{\partial q}{\partial x} = s \tag{8.1}$$

where s is the added sources/sinks per area.

By integration over a coarse grid cell area A, the equation reads

$$\int_A \frac{\partial h}{\partial t}(dx)dy + \int_A \frac{\partial p}{\partial y}(dx)dy + \int_A \frac{\partial q}{\partial x}(dx)dy = \sum_{s(A)} Q_S \tag{8.2}$$

where Q_s are sources and sinks within area A and the summation is to be taken over all sources and sinks with the area.

By selecting the flooded area A within a calculation cell and also assuming that the water level is constant within this cell, we obtain by the use of Green's theorem

$$A_{flood}\frac{\partial h}{\partial t} + \int_{\partial A} p\,dy + \int_{\partial A} q\,dx = \sum_{s(A)} Q_S \tag{8.3}$$

The summation is taken over the whole of the calculation cell.

The momentum equation to be solved is modified from the standard shallow water equation solved in MIKE 21. The approach taken is a "channel" like description for the J and K direction separately. Further, the coriolis force, wind forcing, and wave radiation stress are not included.

$$\int_S \frac{\partial p}{\partial t}dy + \frac{\partial}{\partial x}\left(\int_S \frac{p^2}{h}dy\right) + g\int_S h\frac{\partial \zeta}{\partial x}dy + \int_S \frac{\partial}{\partial y}\left(\frac{qp}{h}\right)dy + \int_S \frac{gp\sqrt{p^2+q^2}}{C^2h^2}dy + \int_S \text{eddy viscosity terms} = 0 \tag{8.4}$$

The integration is taken over the length of a coarse grid cell in the J direction (ΔY). The depth in the convective term and the cross momentum is approximated by

$$h \approx \bar{h} = \frac{A_X}{\Delta Y} \tag{8.5}$$

where A is the "cross sectional area" in the J direction given by

$$A_X = \int_S h\,dy \tag{8.6}$$

The friction term is modified to reflect that the friction is effective along the wetted perimeter thus

$$h^2 \approx R_X\bar{h} = R_X\frac{A_X}{\Delta Y} \tag{8.7}$$

Finally taking the flux as being constant within a coarse grid cell and dividing by ΔY one obtains

$$\frac{\partial p}{\partial t} + \frac{\partial}{\partial x}\left(\frac{p^2 \Delta Y}{A_X}\right) + g\frac{A_X \partial \zeta}{\Delta Y \partial x} + \frac{\partial}{\partial y}\left(\frac{qp\Delta Y}{A_X}\right) + \frac{gp\sqrt{p^2+q^2}}{C^2 R_X A_X}\Delta Y + (\text{eddy visc terms}) = 0 \quad (8.8)$$

The equation for the K direction reads

$$\frac{\partial q}{\partial t} + \frac{\partial}{\partial y}\left(\frac{q^2 \Delta X}{A_Y}\right) + g\frac{A_Y \partial \zeta}{\Delta X \partial y} + \frac{\partial}{\partial x}\left(\frac{qp\Delta X}{A_Y}\right) + \frac{gp\sqrt{p^2+q^2}}{C^2 R_Y A_Y}\Delta X + (\text{eddy visc terms}) = 0 \quad (8.9)$$

The equations are discretized with the cross sectional areas and hydraulic radius at the latest evaluated water level. Both quantities are taken as constant through out the cell. The latter is achieved by taking the mean through out the cell.

8.2 Determination of fluxes on the fine scale

The fluxes on the fine grid scale are determined through linear interpolation in the primary direction and a distribution according to the water depth to the power of 3/2 in the transversal direction.

The interpolated fluxes may be written as

$$p_{j,k,fine} = \left(\frac{j+1+(J-1)N_{factor,J}}{N_{factor,J}}p_{J,K} + \frac{JN_{factor,J}-j-1}{N_{factor,J}}p_{J-1,K}\right) \cdot N_{factor,K}\frac{h_{j,k}^{3/2}}{\sum_{k=(K-1)N_{factor,K}}^{KN_{factor,K}-1} h_{j,k}^{3/2}} \quad (8.10)$$

$$q_{j,k,fine} = \left(\frac{k+1+(K-1)N_{factor,K}}{N_{factor,K}}q_{J,K} + \frac{KN_{factor,K}-k-1}{N_{factor,K}}q_{J,K-1}\right) \tag{8.11}$$

$$\cdot N_{factor,J}\frac{h_{j,k}^{3/2}}{\sum_{j=(J-1)N_{factor,J}}^{JN_{factor,J}-1} h_{j,k}^{3/2}}$$

which are valid for

$$(J-1)N_{factor,J} < j \le JN_{factor,J}$$
$$(K-1)N_{factor,K} < k \le KN_{factor,K}$$

Note that the fluxes estimated through this process are not the result of a mass balance on the fine scale. Thus, the fluxes are indicative of the flow pattern, but are a post processed result and should be evaluated as such.

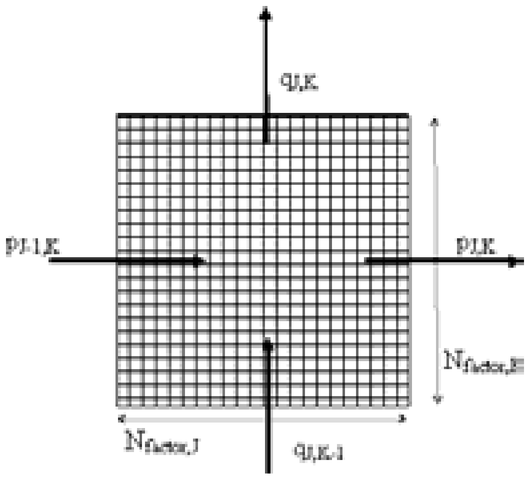

Figure 8.2 Interpretation of fluxes

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Wheatstone Project
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A P P E N D I X   J :

Development of the Bathymetric Data Set

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J DEVELOPMENT OF BATHYMETRIC DATA SET

This appendix presents the extensive amount of bathymetry data that was reviewed and (where appropriate) incorporated into the data set used to develop the model grids. The reader is directed to the following sections of the main report for more information:

- Section 4.1.2 *Numerical Grid*
- Section 4.2.2 *Numerical Grid*

Presented in Table J.1 is a list of the data sets that were made available to DHI for the purposes of developing a bathymetric data set from which to generate the model grids.

Table J.1 List of available bathymetrical data from Chevron. See also Figure J.2.

Bathymetry Data	**LAD_6m**
Raw ascii data	LADS_6m.xyz
Horizontal Datum	GDA-94
Projection	MGA Zone 50
Vertical Datum	Lowest Astronomical Tide (LAT) at Beadon Creek Onslow, being 3.499m below BM DOT001
Data gridded	6m x 6m
Bathymetry Data	**LNG_Bathy_2m (error in datum)**
Raw ascii data	LNG_Bathy_2m.xyz (error in datum)
Horizontal Datum	GDA-94
Projection	MGA Zone 50
Vertical Datum	Lowest Astronomical Tide (LAT) at Beadon Creek Onslow, being 3.499m below BM DOT001
Data gridded	2m x 2m
Bathymetry Data	**TotalAreaPlus2m (corrected version of “LNG_Bathy_2m.xyz”)**
Raw ascii data	TotalAreaPlus2m.xyz (corrected version of “LNG_Bathy_2m.xyz”)
Horizontal Datum	GDA-94
Projection	MGA Zone 50
Vertical Datum	Lowest Astronomical Tide (LAT) at Beadon Creek Onslow, being 3.499m below BM DOT001
Data gridded	2m x 2m

Table J.2 List of available bathymetrical data from Chevron. See also Figure J.2 (continued)

Bathymetry Data	**GeoScience Australia**
Raw ascii data	GA_Data_Lat_Long..xyz
Dataset Title	GeoScience Australia (Australian bathymetry and Topography, June 2005)
Dataset Custodian	Australia
Horizontal Datum	GDA-94
Projection	MGA Zone 50
Vertical Datum	Australian Height Datum
Data gridded	250m x 250m
Bathymetry Data	**DredgeChannel_MBES**
Raw ascii data	P0903_PRELIMINARY_DREDGECHANNEL_MBES_1M_GEOSWATH_GDA94_MGA94_117_LAT.xyz
Project	Wheatstone Downstream/Upstream Nearshore Geophysical Surveys
Location	Dredge Channel Area
Client	Chevron
Fugro Project	P0903
Date Surveyed	Sept - Dec 2008
Vessel	MV Lobo
Dataset	Provisional
Gridding Parameters	1m with interpolation and smoothing when deemed necessary. A lot of data acquired during marginal weather conditions so smoothing has been applied in worst effected areas.
Multi-beam system	Geoswath 250KHz
Horizontal Datum	GDA94
Grid	MGA94
Projection	UTM zone 50 CM 117°E
Vertical Datum	LAT
Tides	Observed tides from tide gauge deployed in survey area.

Table J.3 List of available bathymetrical data from Chevron. See also Figure J.2 (continued)

Bathymetry Data	**MBES**
Raw ascii data	P0903_PRELIMINARY_MBES_1M_GEOSWATH_GDA94_MGA94_117_LAT.xyz
Project	N/A
Location	Onslow
Client	Chevron
Fugro Project	P0903
Date Surveyed	Oct-Dec 2008
Vessel	MV Lobo
Dataset	Provisional
Gridding Parameters	1m with interpolation and smoothing when deemed necessary. A lot of data acquired during marginal weather conditions so smoothing has been applied in worst effected areas. There was not time to run some infill lines so the gaps have been interpolated up to 10m in the absence of targets in side scan data.
Multi-beam system	Geoswath 250KHz
Horizontal Datum	GDA94
Grid	MGA94
Projection	UTM zone 50 CM 117°E
Vertical Datum	LAT
Tides	Observed tides from tide gauge deployed in survey area.
Bathymetry Data	**PIPEROUTE_MBES**
Raw ascii data	P0903_PRELIMINARY_PIPEROUTE_MBES_1M_GEOSWATH_GDA94_MGA94_117_LAT.xyz
Project	N/A
Location	Onslow
Client	Chevron
Fugro Project	P0903
Date Surveyed	Oct-Dec 2008
Vessel	MV Lobo
Dataset	Final
Gridding Parameters	1m with interpolation and smoothing when deemed necessary. A lot of data acquired during marginal weather conditions so smoothing has been applied in worst effected areas. There was not time to run some infill lines so the gaps have been interpolated up to 10m in the absence of targets in side scan data.
Multi-beam system	Geoswath 250KHz
Horizontal Datum	GDA94
Grid	MGA94
Projection	UTM zone 50 CM 117°E
Vertical Datum	LAT
Tides	Observed tides from tide gauge deployed in survey area.

Table J.4 List of available bathymetrical data from Chevron. See also Figure J.2 (continued)

Bathymetry Data	**SBES**
Raw ascii data	P0903_PRELIMINARY_SBES_GDA_MGA_117_ObservedTides.xyz
Project	Wheatstone Downstream/Upstream Nearshore Geophysical Surveys
Location	Marine Facilities Area
Client	Chevron
Fugro Project	P0903
Date Surveyed	Sept - Dec 2008
Vessel	MV Tomahawk
Dataset	Final
Gridding Parameters	Not Applicable. Single beam data
Multi-beam System	Not Applicable. Single beam system used; Odom EchoTrac MkIII
Horizontal Datum	GDA94
Grid	MGA94
Projection	Transverse Mercator, UTM Zone 50, CM 117° East
Vertical Datum	LAT

Figure J.1 and Figure J.2 show the coverage of the various bathymetrical data sets. The data density of the electronic data base of Nautical Charts is illustrated in Figure J.1. Red dots represent available data points and the green line the water/land boundary. The regional hydraulic model area is outlined in pink. In Figure J.2, the combined coverage of dedicated bathymetrical data sets available to the project is outlined.

The bathymetrical surveys are concentrated around the proposed dredged channel, including adjacent areas on the western side of Thevenard Island up to Bessieres Island as well as eastern areas up to the west of Direction Island. Detailed bathymetric surveys along the adjacent proposed pipeline route were included as well.

The purple area (in the inset of Figure J.2) represents a regional gridded bathymetry data base from GeoScience Australia (GA) for the coastal waters of Australia. It is noted that this data is gridded, and it has been found that the grid does not necessarily represent the actual resolution, i.e. the actual data used to produce the grid may be much sparser than the grid in some locations.

The overall coverage and concentration of the bathymetrical data is found to be acceptable, however a few key areas with relatively low concentration of data points or even data gaps have been identified within the extensive modelling area. Areas with limited data are briefly outlined in the following.

An initial bathymetrical map which is based entirely on the information from the electronic database of Nautical Charts, "*C-Map*" has been generated - see Figure J.3. Areas of particular poor resolution that have been identified in the *C-Map* data are encircled in Figure J.3. Areas of limited data coverage include the shallow waters just south of Barrow Island (see inset figure).

The areas not covered in C-Map are covered in the GA data set. The GeoScience Australia data is given on a grid cell size of 0.025 deg (close to 250m). The details of the data used to produce the grid is not known, but on investigation it was found that important channels and detailed morphological features were not resolved in the GSA data. The channels found east of Barrow Island, which are of significant importance for regional flow patterns, is an example of unresolved morphological features in the gridded GeoScience Australia data. These channels are better represented in e.g. the *C-Map* data, therefore the GeoScience Australia data have been discarded here. This is partly due to the grid spacing of the GA data, but also related to expected limited coverage (similar to C-Map) of the data used to produce the GA gridded data, and the gridded data thus has to be applied with caution.

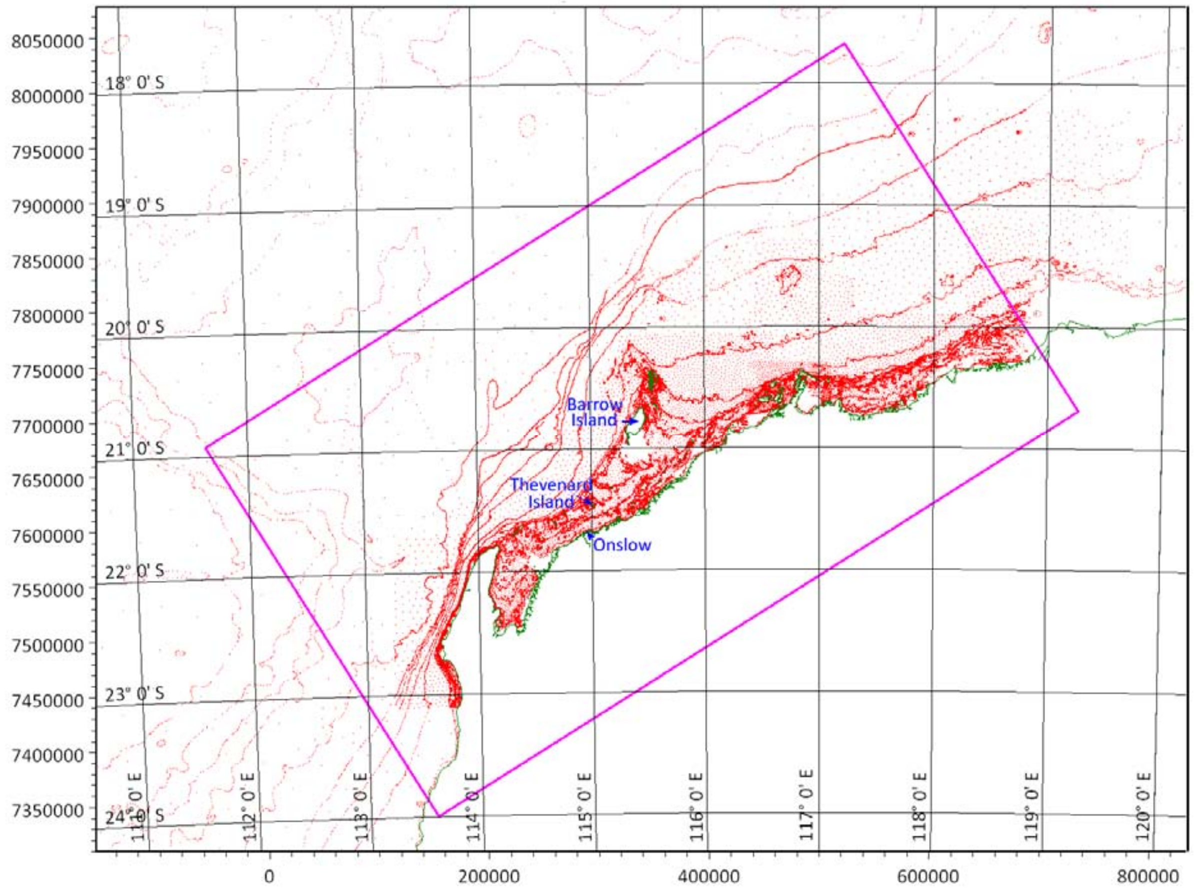

Figure J.1 *Coverage of bathymetrical database derived from C-Map (data points shown with red dots) and outline regional model boundaries (in pink). Water-land boundary is shown in green.*

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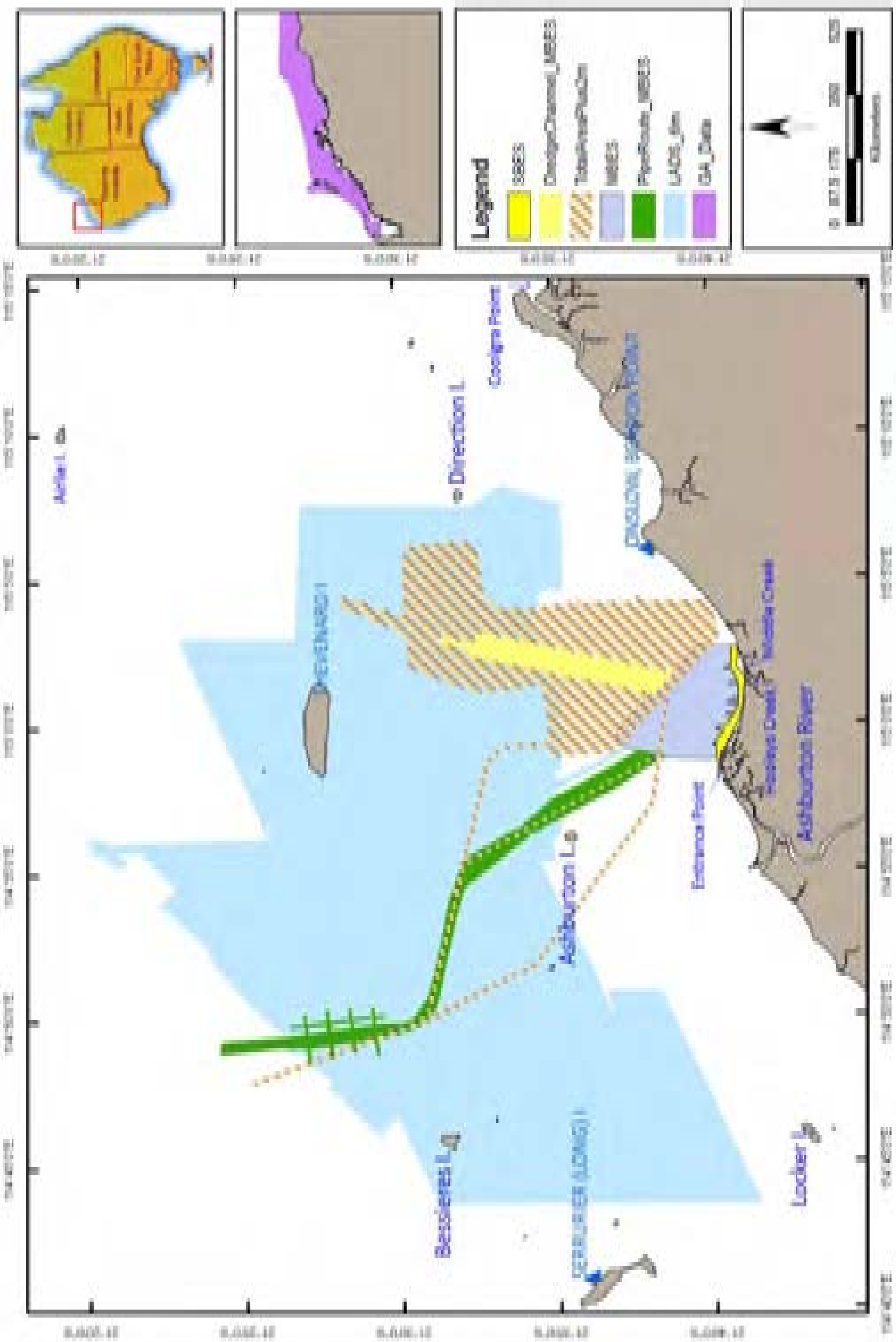

Figure J.2 Coverage of available detailed bathymetrical data sourced through Chevron

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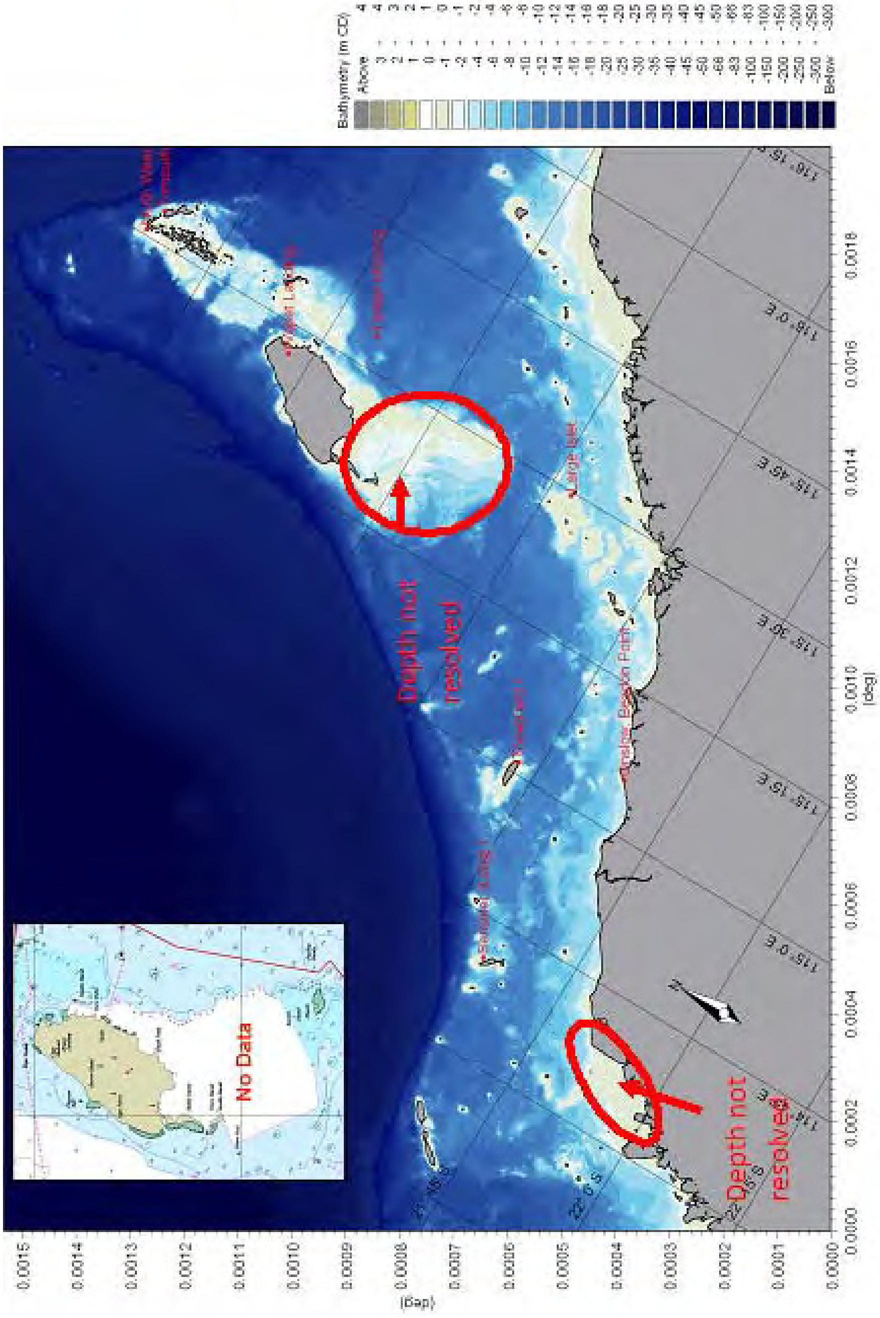

Figure J.3 Bathymetry interpolated from bathymetrical database using "C-Map" (WGS-84) only with vertical datum given in Chart Datum. Areas of poor resolution outlined in red with zoom-in on area south of Barrow Island.

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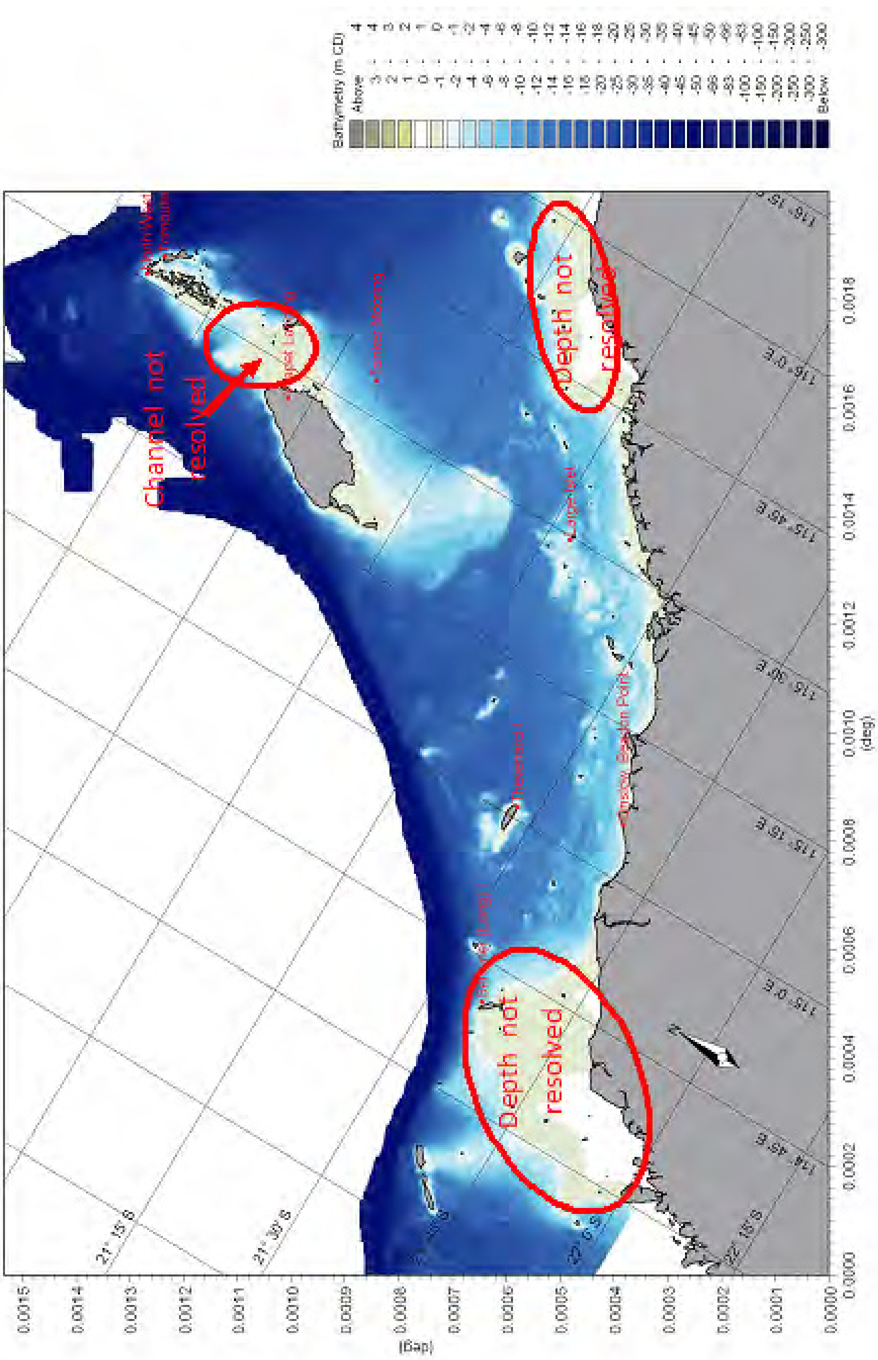

Figure J.4 Bathymetry interpolated from "GA_Data_Lat_Long.xyz" - Horizontal Datum: GDA 94, Projection: MGA Zone 50, Vertical Datum: Lowest Astronomical Tide (LAT)

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Following the identification of the data gaps, the bathymetrical database has been refined in order to resolve nearshore areas adjacent to the site with the most detailed of the data available, in particular for the patches of corals and reefs found around the study area. Due to the limited bathymetry data in the areas south of Barrow islands, in between Tent Island to Urala Creek as well as the area with numerous shoals adjacent to Passage Island, a remote sensing technique has been applied to supplement the data base.

In order to extract useful seabed depth information, a total of three Landsat 7ETM+ image scenes were used for the image processing and analysis for bathymetry classification. The data was sourced from Global Land Cover Facility (GLCF), www.landcover.org. The characteristics of the images used are summarized in Table J.5. The images are also shown in Figure J.5.

Table J.5 Details of LANDSAT 7 ETM+ Images used in analysis

Center XY-coord	Acquisition Date	WRS Row-Col No	Scene Size	Pixel Resolution
114.54ºE, 21.66 ºS	2003-02-26	115-75	185x185km	30 meter
116.08ºE, 21.66 ºS	2003-02-19	114-75	185x185km	30 meter
116.41ºE, 20.22 ºS	2003-02-19	114-74	185x185km	30 meter

The raw satellite images, downloaded from GLCF, were in Geocoded Tag Image file format (geotiff). From geotiff format all the satellite images were converted to image (img) format for remote sensing processing and analysis. The raw digital count in the different bands were then calibrated and converted to surface reflectance. An interactive linear contrast enhancement was applied to all the calibrated images in order to improve its visual quality. As shown in Figure J.5 (image numbers 1 to 3) band combination of red, blue and green was used to display the raw images in standard colour composites. Land and cloud covered areas, which were not included in the image analysis, were masked out (shown as black areas in image number 5). The locations of areas with available recorded depth values were overlaid in the mosaic and masked image in order to identify the areas needed for classification (image number 6). The three areas with insufficient data coverage were selected and analysed in detail (images number 7 to 9).

The image classification and analysis was done using an unsupervised classification method. This type of classification makes use of a clustering algorithm which automatically finds and defines a number of spectral groupings or clusters present in the image scene. The processing basically begins by specifying the number of cluster means and the number of iterations to process the image data. The resulted spectral groupings were determined by overlaying the location of areas with known depth values. The final classified image was converted from raster to ascii format (i.e. as xyz) which were then applied in the bathymetry generation.

It is noted that the resolution and accuracy from the remote sensing analysis varies, and the data has only been applied to the areas of missing data from more reliable direct hydrographic surveys.

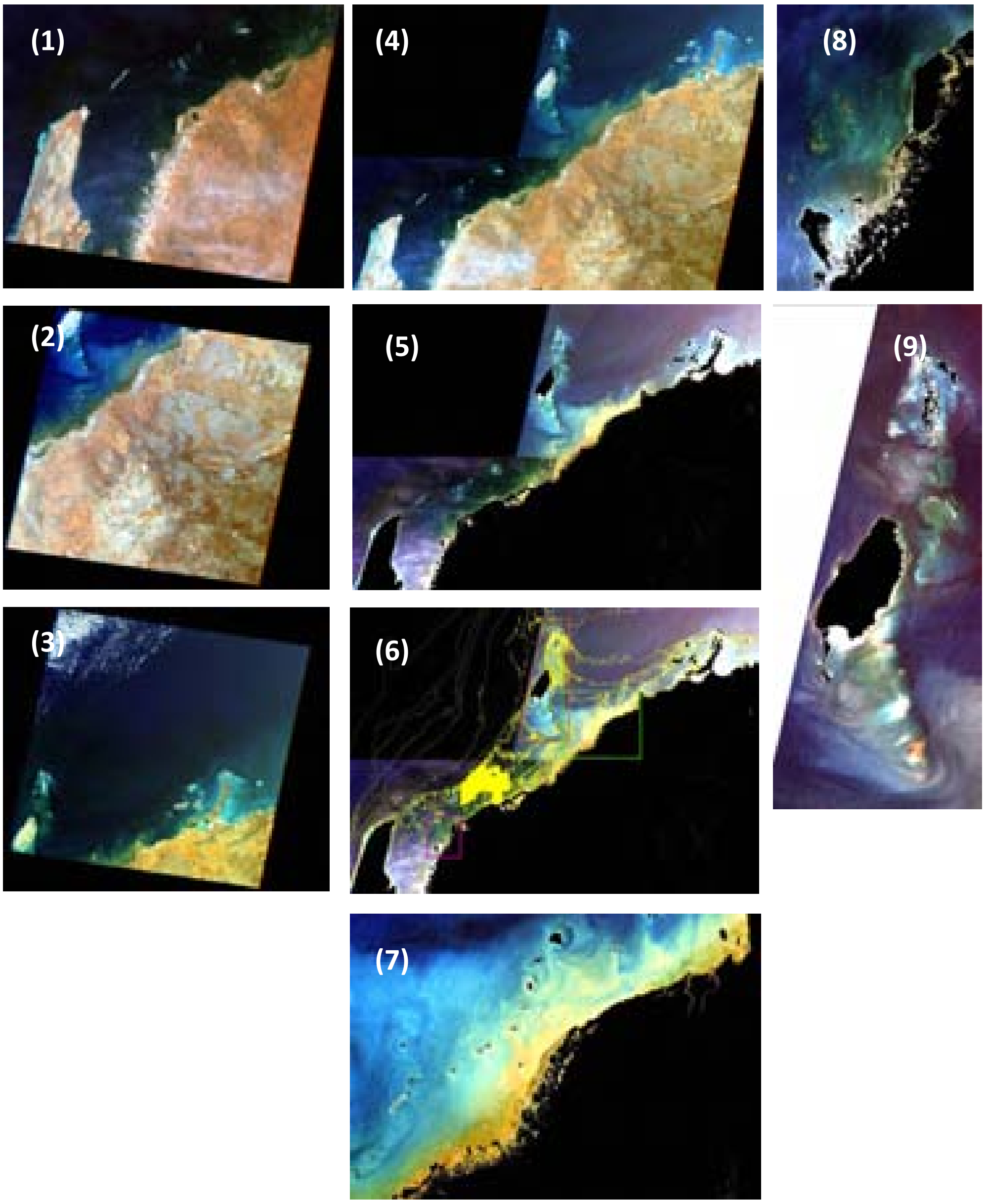

Figure J.5 *Satellite images used for bathymetry classification: 1,2 & 3- raw rectified Landsat 7ETM+ satellite image scenes; 4- mosaicked image of 1,2&3; 5- calibrated, enhanced and masked image; 6- the 5th image highlighting the 3 AOIs (area of interest), points with recorded depth values were represented by the yellow dots ; and 7,8 &9- subset/ cropped images used for classification*

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Wheatstone Project
Dredge Spoil Modelling

A P P E N D I X K :

KMS MODEL TIDAL COMPONENTS

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FIGURES AND TABLES

K KMS MODEL TIDAL COMPONENTS

This appendix presents the KMS model outputs for the eight major tidal constituents K1, O1, P1, Q1, M2, N2, S2, and K2. The reader is directed to Section 4.1.3.1: *Wind Fields* of the main report for additional information.

K.1 Tidal Constituent K1

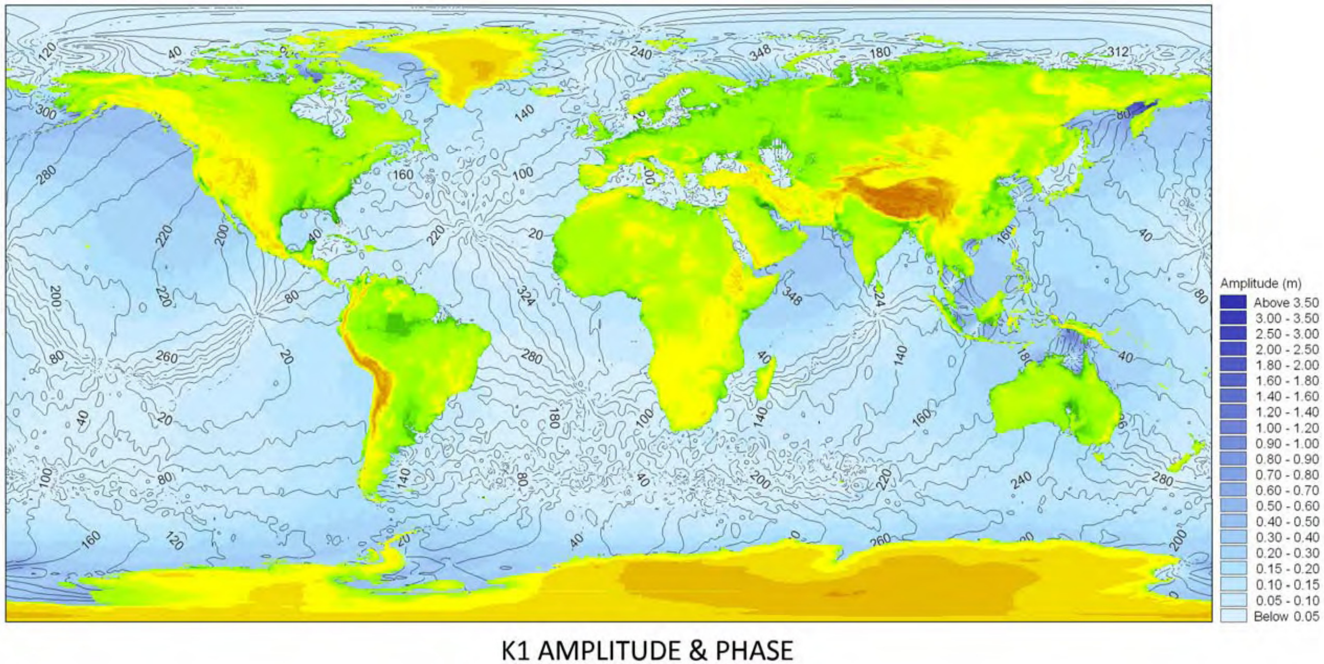

Figure K.1 Map of major diurnal tidal constituents; K1 of the KMS model

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K.2 Tidal Constituent O1

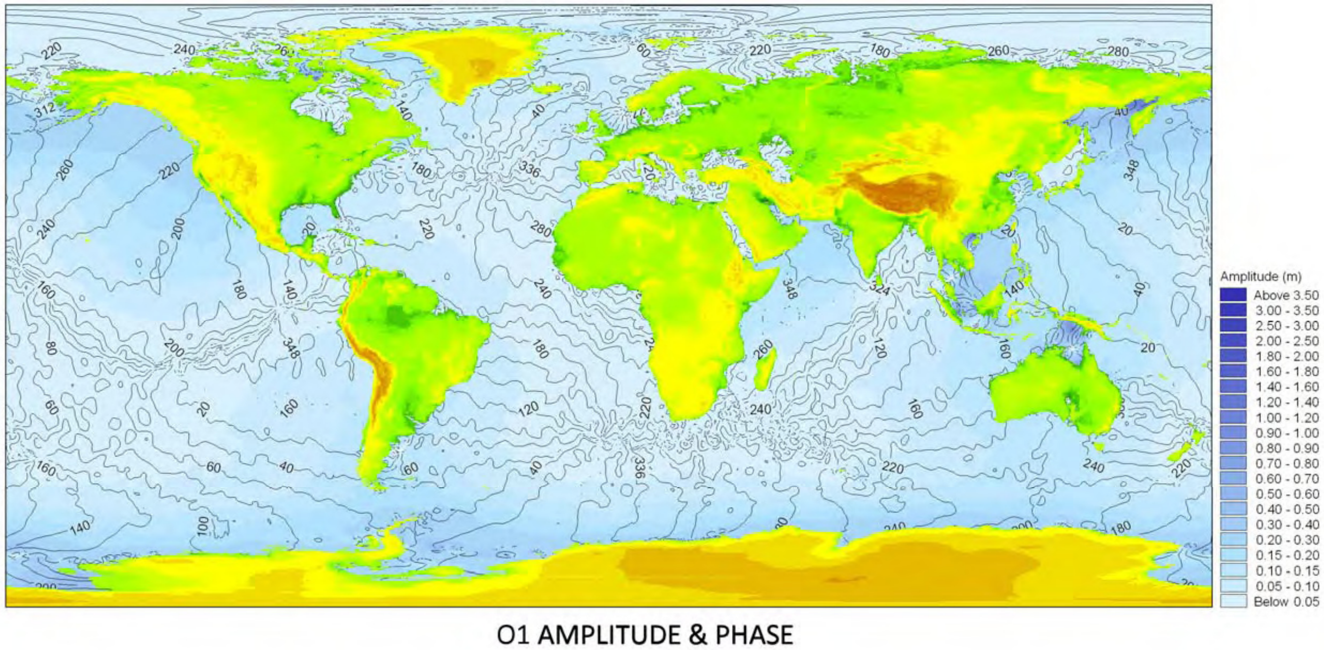

Figure K.2 Map of major diurnal tidal constituents; O1 of the KMS model

K.3 Tidal Constituent P1

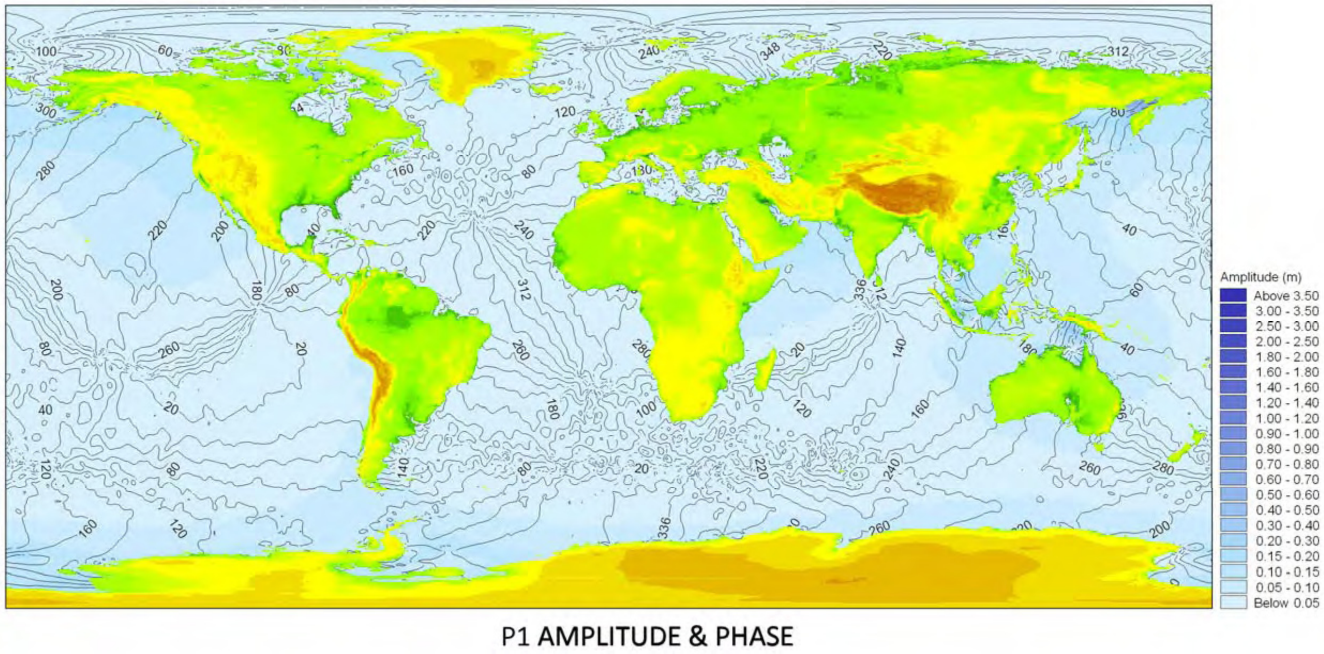

Figure K.3 Map of major diurnal tidal constituents; P1 of the KMS model

K.4 Tidal Constituent Q1

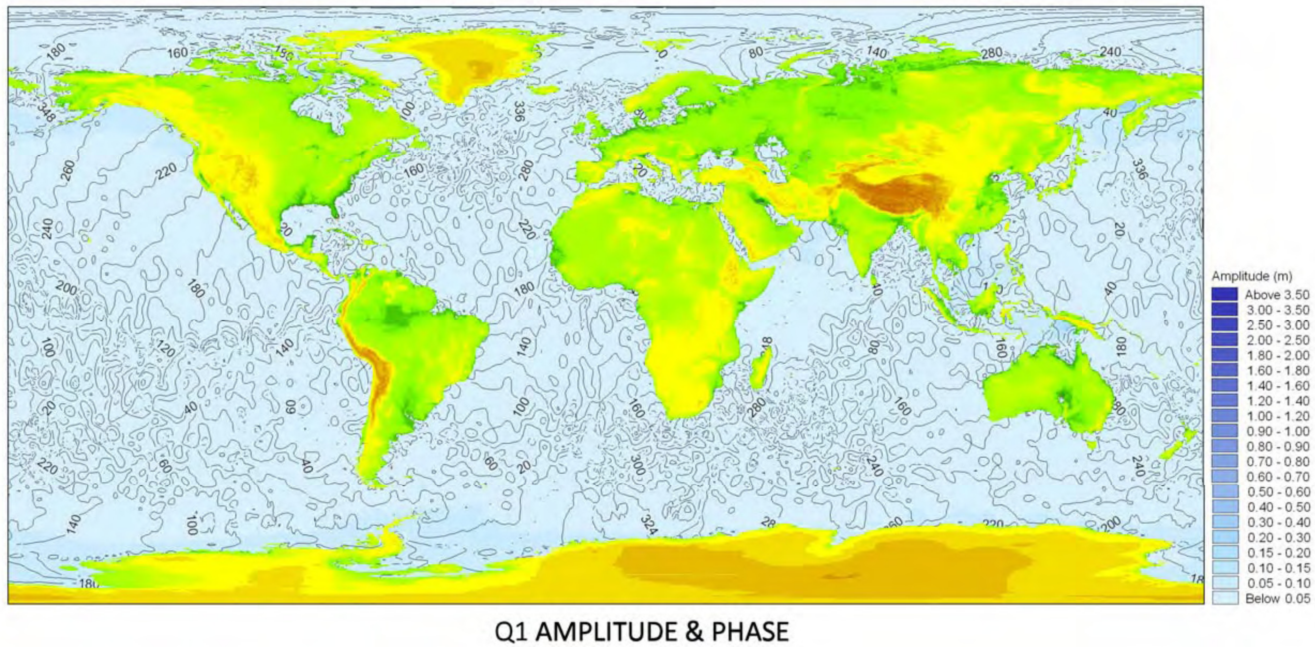

Figure K.4 Map of major diurnal tidal constituents; Q1 of the KMS model

K.5 Tidal Constituent M2

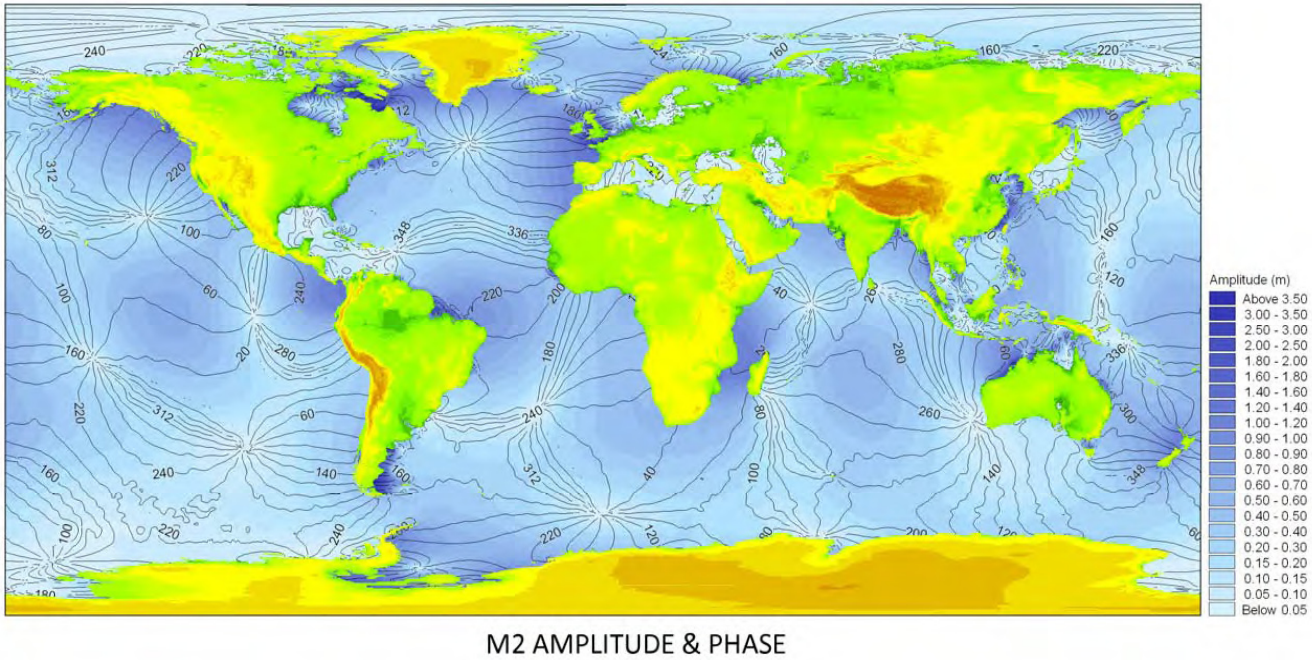

Figure K.5 Map of major semi-diurnal tidal constituents; M2 of the KMS model

K-6

K.6 Tidal Constituent S2

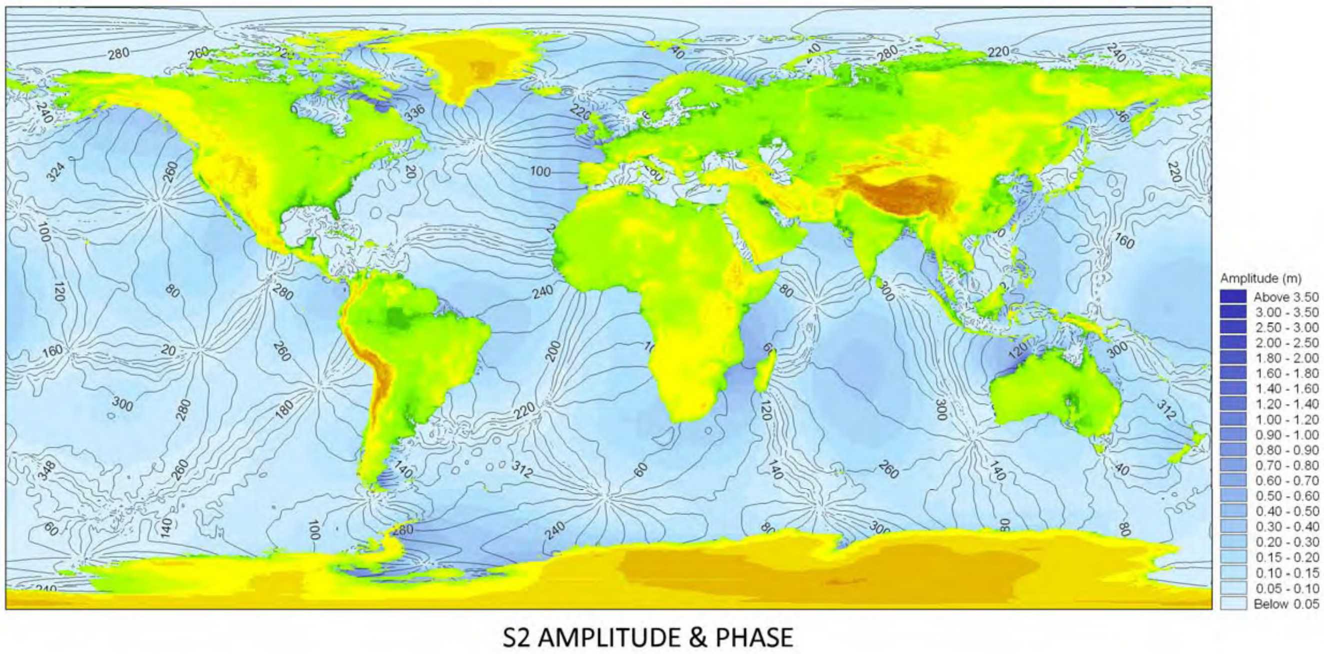

Figure K.6 Map of major semi-diurnal tidal constituent;S2 of the KMS model

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K.7 Tidal Constituent N2

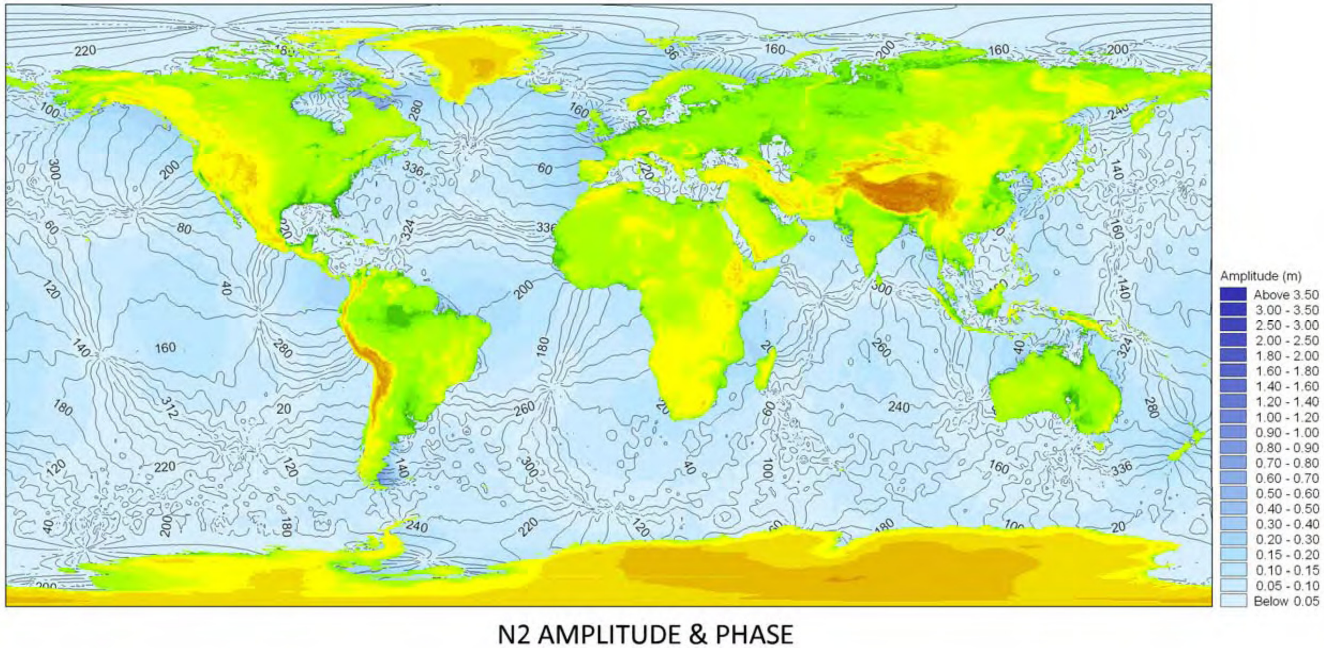

Figure K.7 Map of major semi-diurnal tidal constituents; N2 of the KMS model

K.8 Tidal Constituent K2

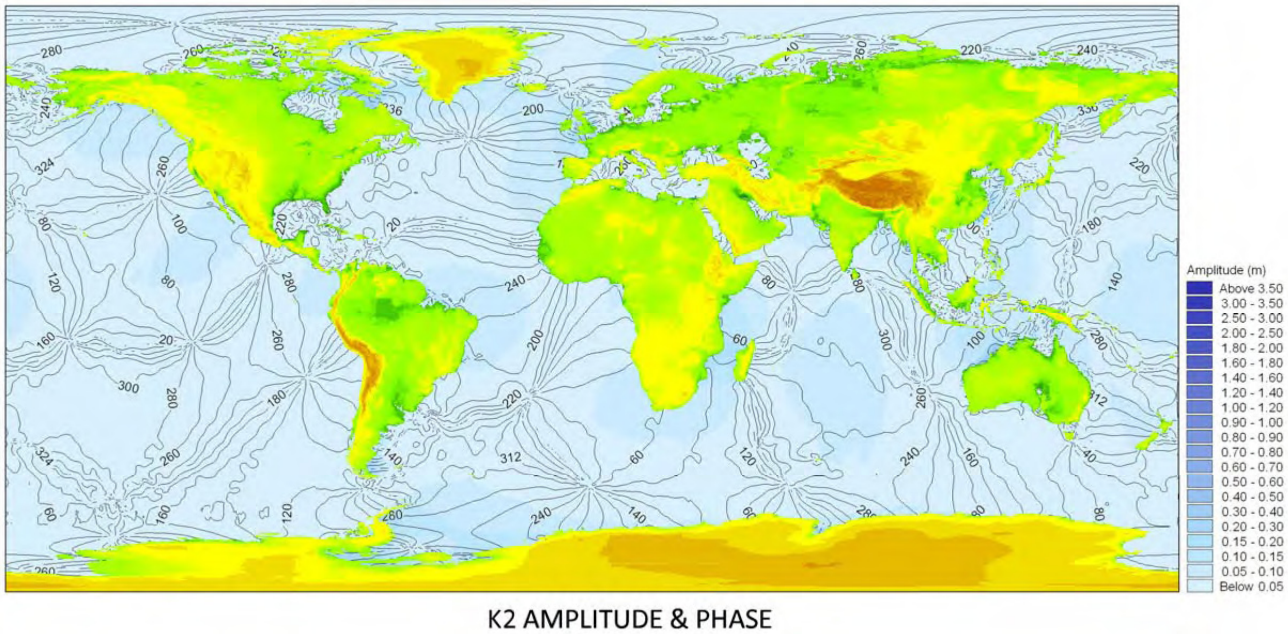

Figure K.8 Map of major semi-diurnal tidal constituents; K2 of the KMS model

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A P P E N D I X L :

MesoLAPS Information from the Bureau of Meteorology (Please refer to Attachment)

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Australian Government
Bureau of Meteorology

HEAD OFFICE
Bureau of Meteorology
GPO Box 1289 Melbourne VIC 3001 Australia

MesoLAPS_PT125

About the model:

The Australian Mesoscale (small) Limited Area Prediction System known as MesoLAPS_PT125 is one of the numerical forecast models operated by the Bureau of Meteorology. It has a higher resolution than the LAPS model. The higher resolution means that this model is better for areas near the coast or in areas of steep topography.

Details:

The relevant MesoLAPS PT125 model details are as follows:

Area:	55.0° S - 4.875 ° N 95.0° E - 169.875° E
Resolution:	0.125 degrees (approximately 12.5 km) 29 vertical sigma levels, top level at ~50 hPa
Available data format:	NetCDF (Network Common Data Form)

Levels:

Level	Height (m)
1	10
2	20
3	45
4	100
5	210
6	320
7	430
8	650
9	880
10	1050
11	1350
12	1800
13	2300
14	2850

Level	Height (m)
15	4050
16	5400
17	6200
18	7050
19	8000
20	9000
21	9600
22	10200
23	10900
24	11700
25	12500
26	13500
27	16000
28	18200
29	20400

Parameters available from MesoLAPS PT125:

Data availability: January 2002 – present

Multi-level parameters

Field	Unit
Zonal wind	ms^{-1}
Meridional wind	ms^{-1}
Air temperature	K
Mixing ratio	$kg\ kg^{-1}$
Omega (vertical velocity)	$Pa\ sec^{-1}$
Geopotential height	m

Surface parameters

Field	Unit
Meridional wind at 10m	ms^{-1}
Zonal wind at 10m	ms^{-1}
Mean sea level pressure	hPa
Daily precipitation (24 hour accumulation)	mm
Surface pressure	Pa
Screen height temperature	K
Screen height dew point	K
Surface geopotential	$m^2\ sec^{-2}$
Surface temperature	K

Other technical parameters may be available, please contact webclim@bom.gov.au for further information.

Further information:

More detailed information about the MesoLAPS model can be found on the Bureau of Meteorology's webpage at http://www.bom.gov.au/nmoc/bulletins/APOB66.pdf and http://www.bom.gov.au/nmoc/bulletins/apob49.shtml

Australia's National Meteorological Service
700 Collins Street Docklands Tel: +61 3 9669 4000 Fax: +61 3 9669 4699 www.bom.gov.au ABN 92 637 533 532

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Wheatstone Project
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A P P E N D I X   M :

Comparison of Mesolaps Wind Fields with Monitoring Data

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FIGURES AND TABLES

M COMPARISON OF MESOLAPS WIND FIELDS WITH MONITORING DATA

This appendix presents a comparison of wind speed and wind direction from MesoLAPS with monitoring data from Thevenard Island, Barrow Island, Onslow and Onslow Airport.

The reader is directed to the following section of the main report and appendices for additional information:

- Section 4.1.3.2 *Wind Fields*
- Section 6.2 *Results for the Dredging of the Shipping Channel*
- Appendix D *Hydrodynamic Model Calibration and Validation*
- Appendix L *MesoLAPS Information from the Bureau of Metereology*

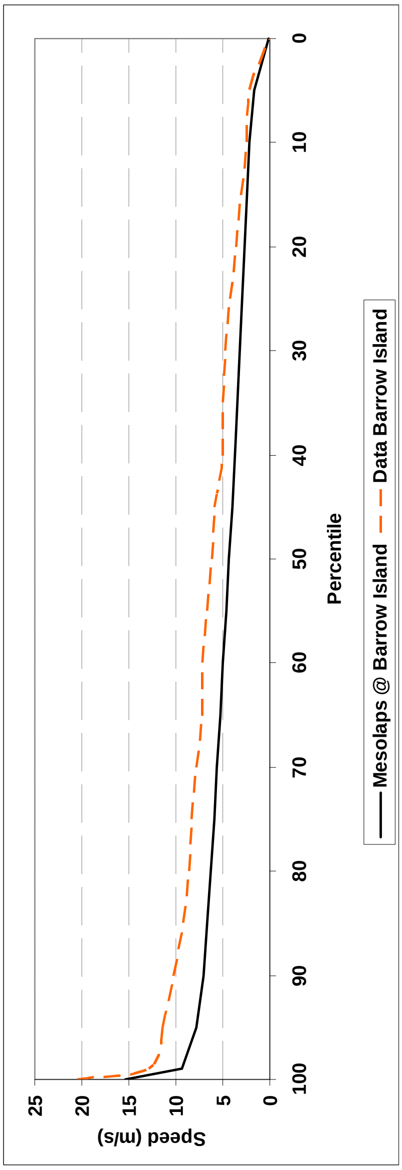
M.1 Wind Speed Percentiles

Presented in Table M.1 are the percentiles of winds speed from MesoLAPS and the Thevenard Island, Barrow Island, Onslow and Onslow Airport monitoring data for 2007. These results are presented graphically in the following figures which also include time series of wind speeds for each site.

Table M.1 Wind speed percentiles from MesoLAPS and observational data

Speed Percentiles	MesoLAPS at Onslow	Data Onslow	Data Onslow Airport	MesoLAPS at Thevanard Island	Data Thevenard	MesoLAPS at Barrow Island	Data Barrow
100	13.5	15.3	15.0	15.8	15.8	15.4	20.6
99	8.6	10.9	10.8	10.6	11.7	9.4	12.8
95	7.2	9.2	9.2	9.2	10.3	7.9	11.4
90	6.5	8.2	8.6	8.6	9.2	7.1	10.3
85	6.1	7.6	7.8	8.0	8.6	6.6	9.2
80	5.7	7.1	7.2	7.6	8.3	6.3	8.6
75	5.4	6.6	6.7	7.3	7.8	5.9	8.3
70	5.1	6.3	6.7	6.9	7.2	5.6	7.8
65	4.9	5.9	6.1	6.6	6.7	5.3	7.2
60	4.6	5.6	5.6	6.3	6.1	5.0	7.2
55	4.4	5.3	5.6	6.0	5.8	4.7	6.7
50	4.1	5.1	5.3	5.7	5.8	4.3	6.1
45	3.9	4.8	5.3	5.3	5.0	4.0	5.8
40	3.7	4.5	4.7	5.1	4.7	3.7	5.0
35	3.4	4.3	4.2	4.7	4.7	3.4	5.0
30	3.2	4.0	4.2	4.4	4.2	3.1	4.7
25	2.9	3.8	3.6	4.0	3.6	2.9	4.2
20	2.7	3.5	3.6	3.6	3.1	2.7	3.6
15	2.5	3.2	3.1	3.2	2.5	2.5	3.1
10	2.2	2.7	2.5	2.7	2.2	2.2	2.5
5	1.8	2.1	1.9	2.0	0.0	1.7	2.2

M-2



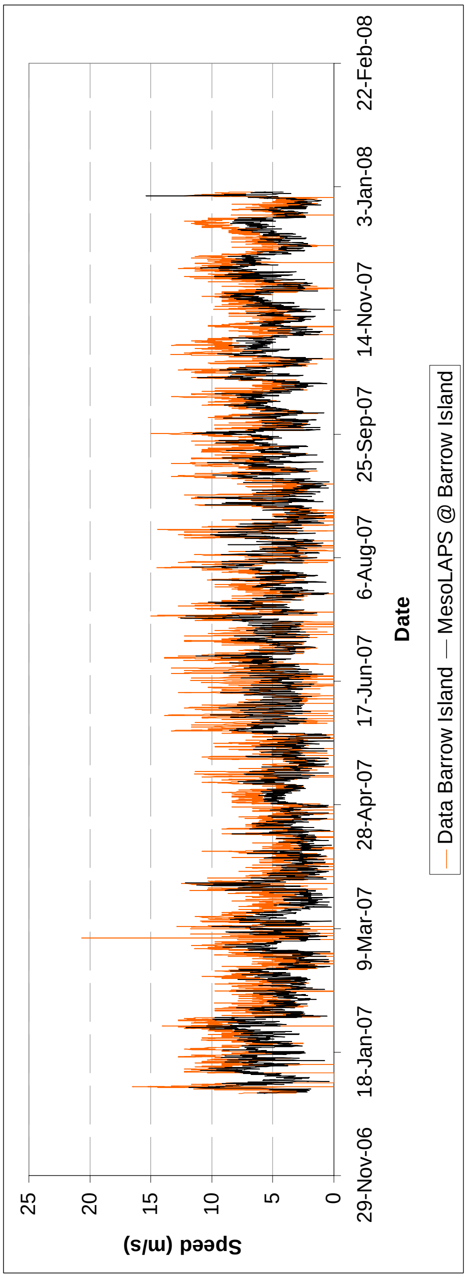


Figure M-1 Percentile of wind speeds (upper) and timeseries of wind speeds (lower) from MesoLAPS and monitoring data from Barrow Island, 2007

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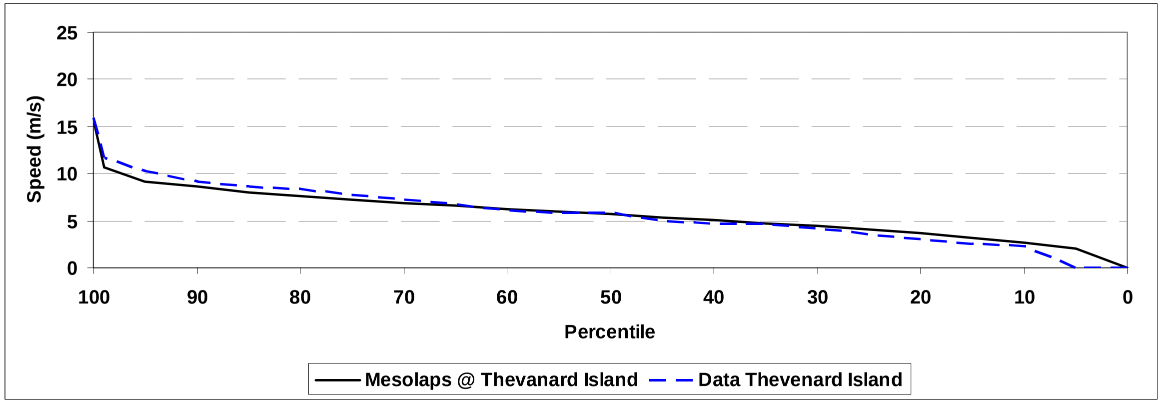
M-3



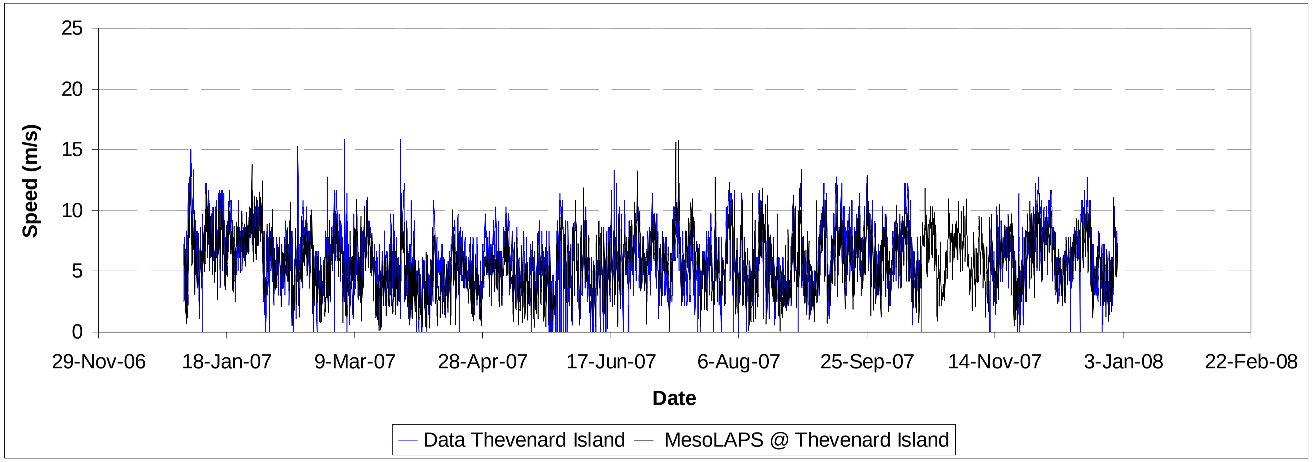


Figure M-2 Percentile of wind speeds (upper) and timeseries of wind speeds (lower) from MesoLAPS and monitoring data from Thevenard Island, 2007

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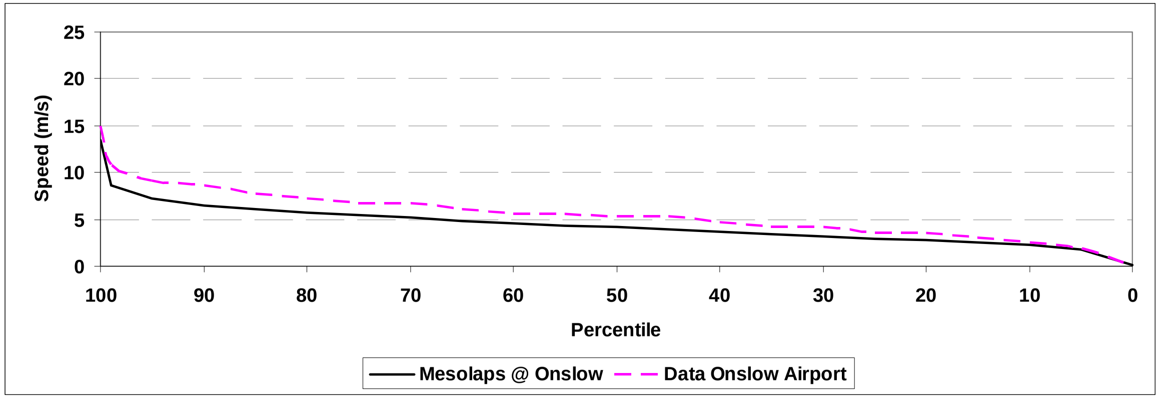


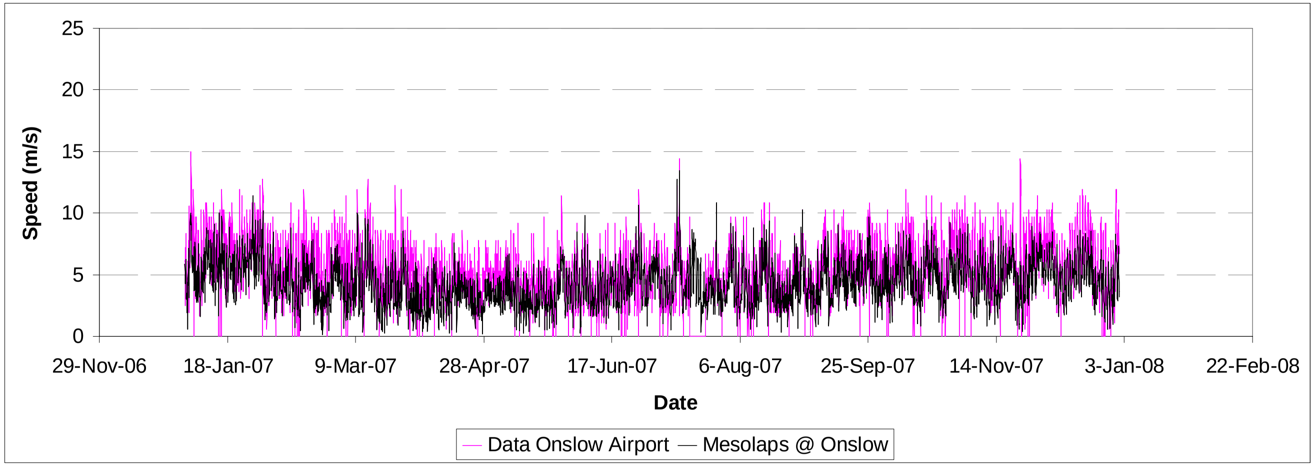
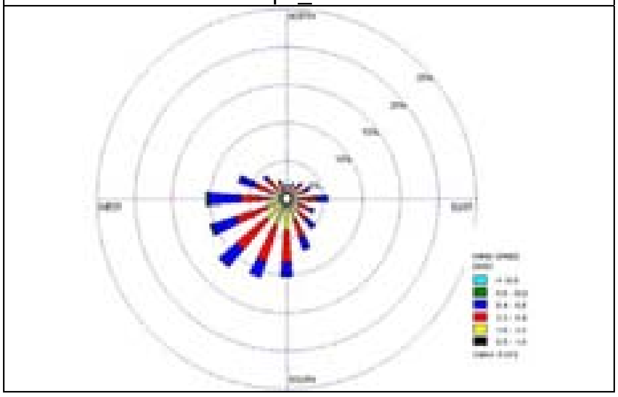


Figure M-3 Percentile of wind speeds (upper) and timeseries of wind speeds (lower) from MesoLAPS and monitoring data from Onslow Airport, 2007

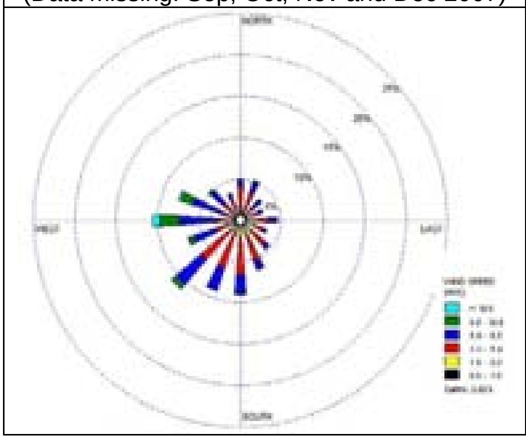
M.2 Annual Wind Roses, 2007

M.2.1 Onslow, Barrow Island and Thevenard

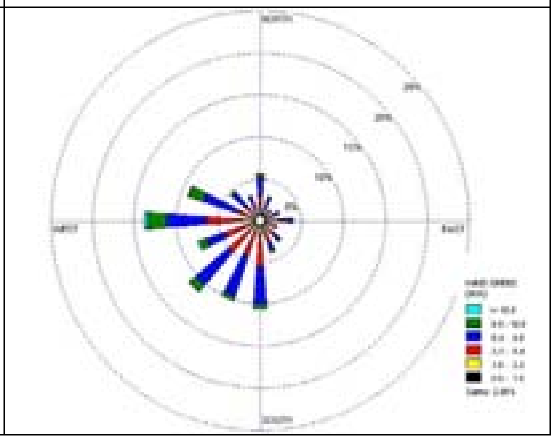
MLaps_Onslow



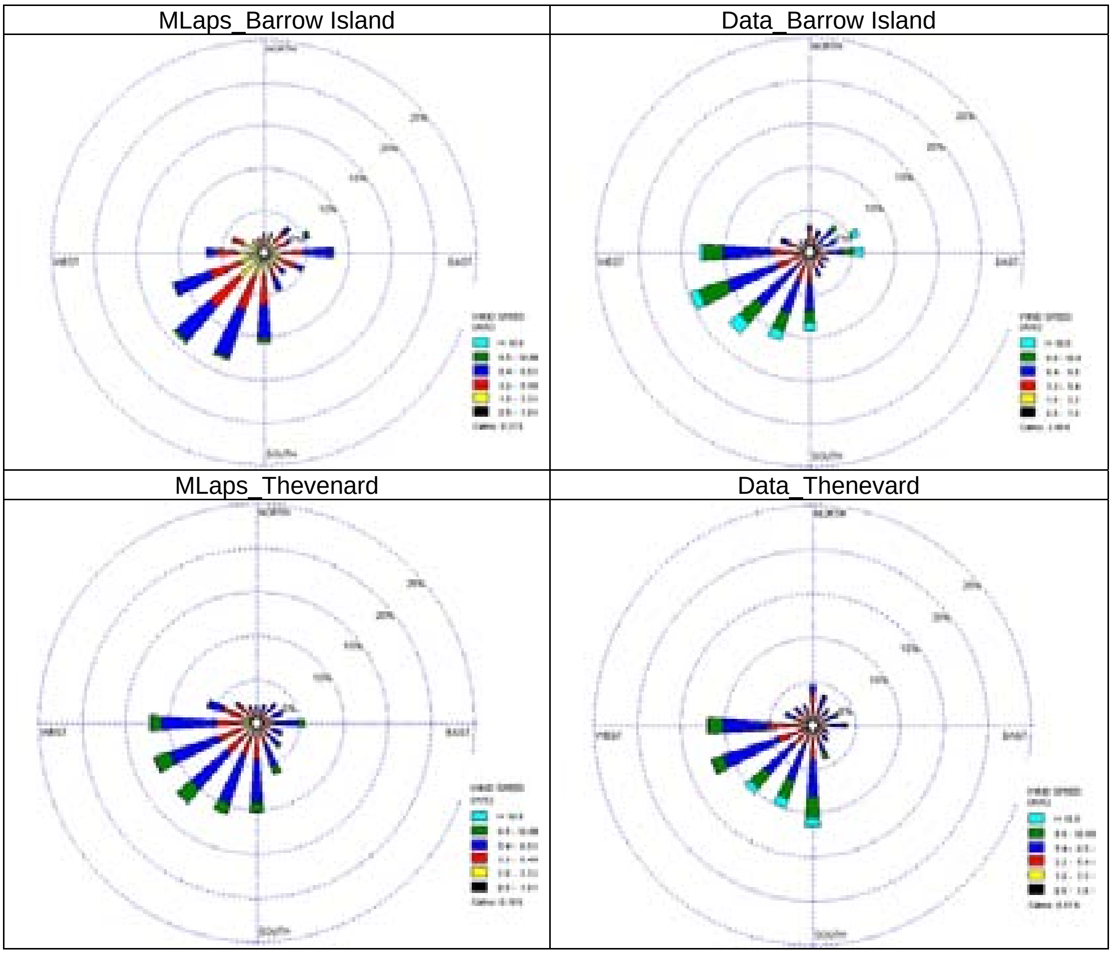
Data_Onslow
(Data missing: Sep, Oct, Nov and Dec 2007)



Data_OnslowAirport



M-6



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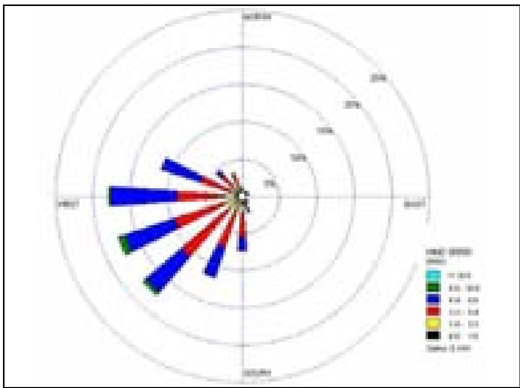
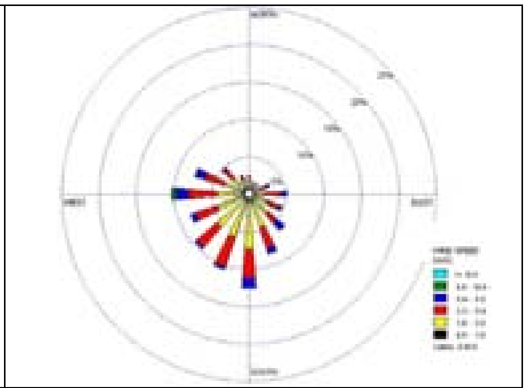
M.3 Seasonal WIndRoses, 2007

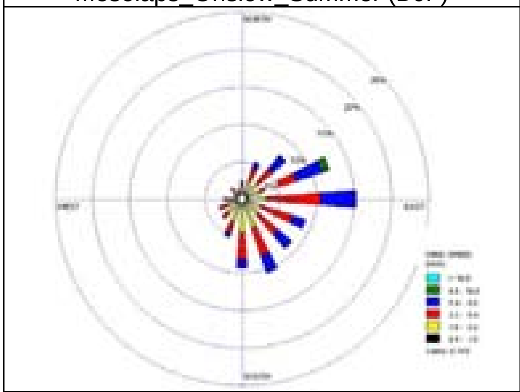
M.3.1 Onslow



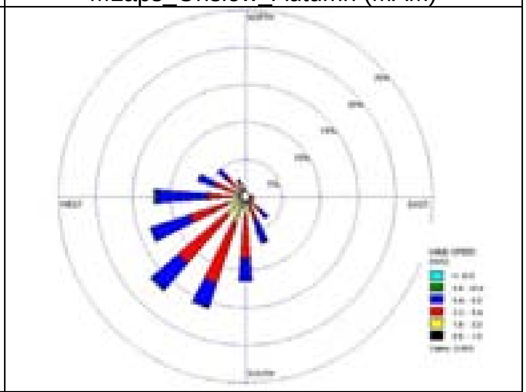
Mesolaps_Onslow_Summer (DJF)



MLaps_Onslow_Autumn (MAM)

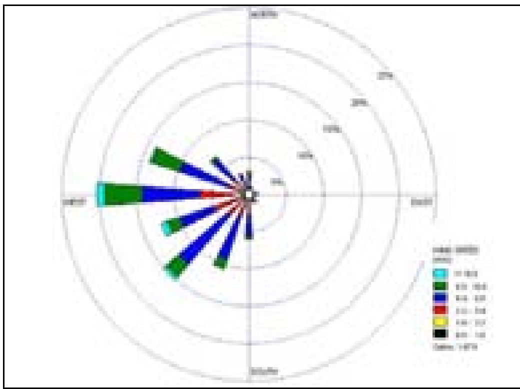


MLaps_Onslow_Winter (JJA)

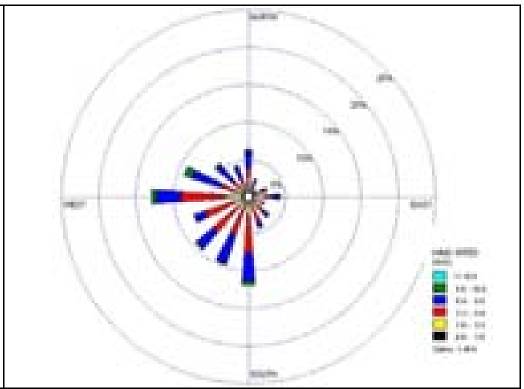


MLaps_Onslow_Spring(SON)

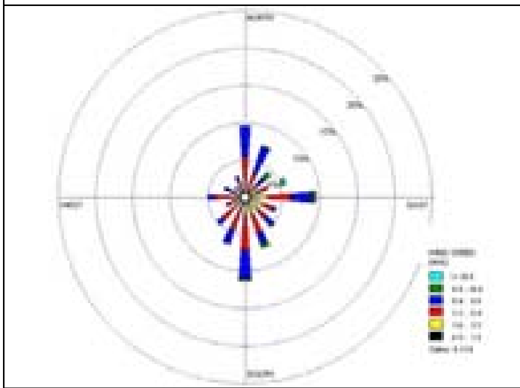
M-8



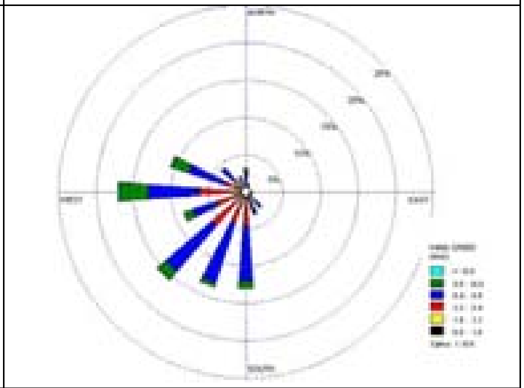
Data_Onslow_airport_Summer (DJF)



Data_Onslow_airport _Autumn (MAM)



Data_Onslow_airport _Winter (JJA)



Data_Onslow_airport _Spring (SON)

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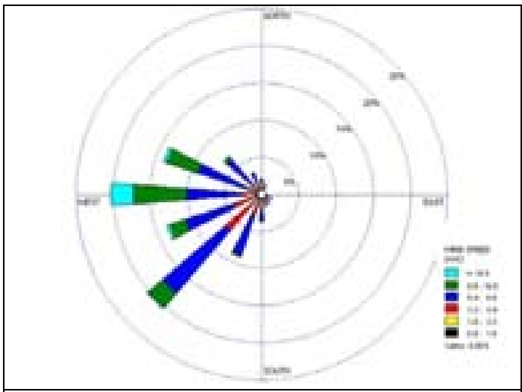
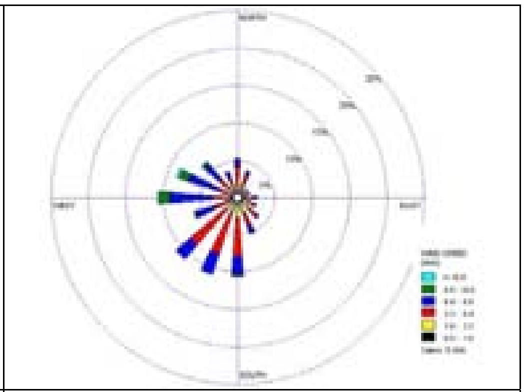
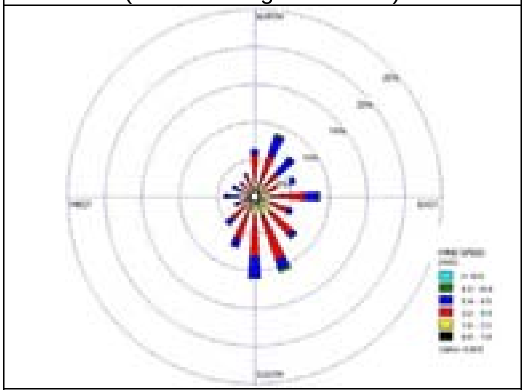


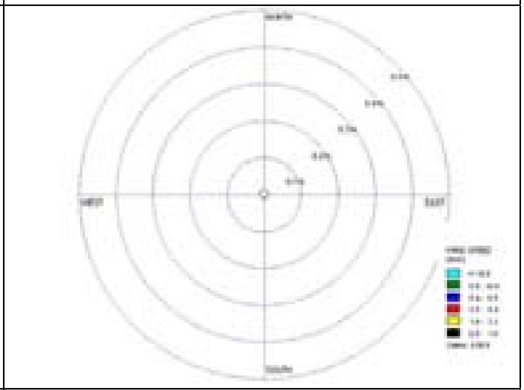
Data_Onslow_Summer (DJF)
(Data missing: Dec 2007)



Data_Onslow _Autumn (MAM)



Data_Onslow _Winter (JJA)



Data_Onslow _Spring (SON)
(Data missing: Sep, Oct and Nov 2007)

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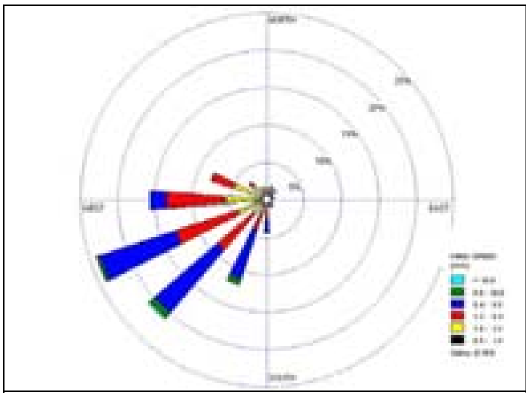
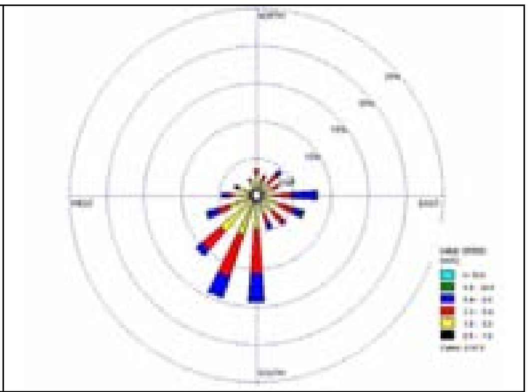
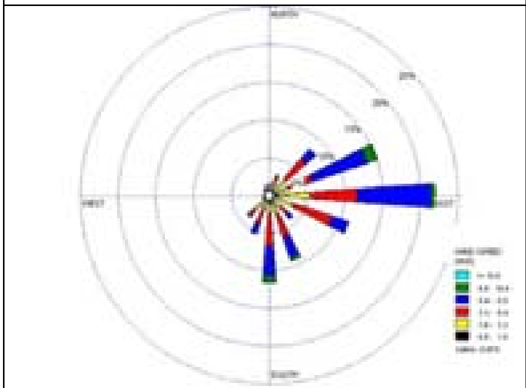
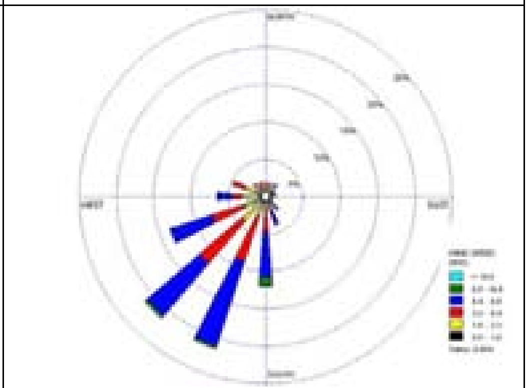
M.3.2 Barrow Island

	
Mesolaps_BarrowIsland_Summer (DJF)	MLaps_BarrowIsland_Autumn (MAM)
	
MLaps_BarrowIsland_Winter (JJA)	MLaps_BarrowIsland_Spring (SON)

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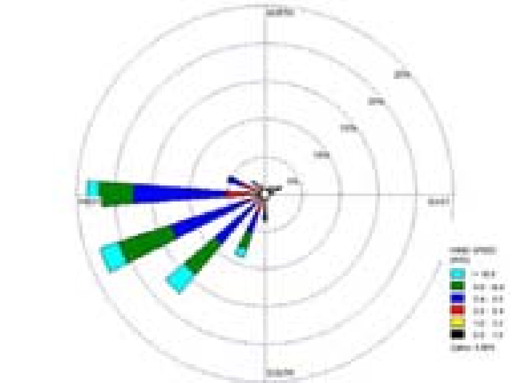
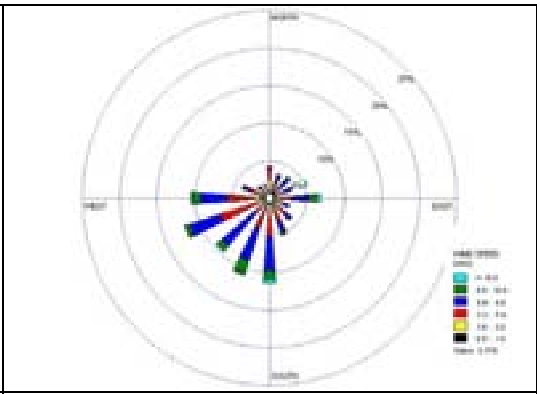
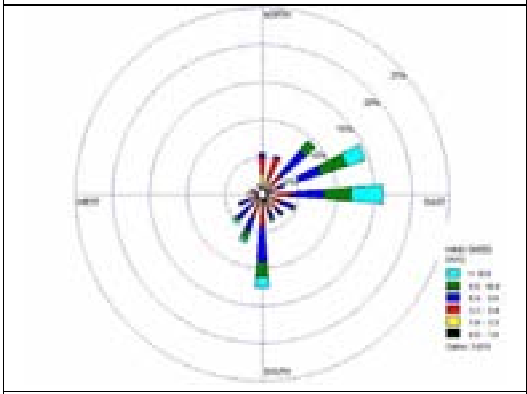


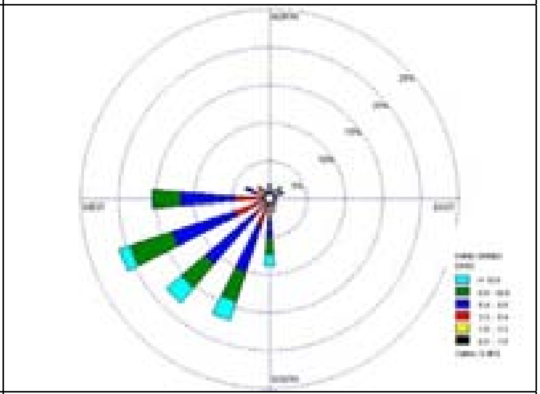
Data_Barrow_Summer (DJF)



Data_Barrow _Autumn (MAM)



Data_Barrow _Winter (JJA)



Data_Barrow _Spring (SON)

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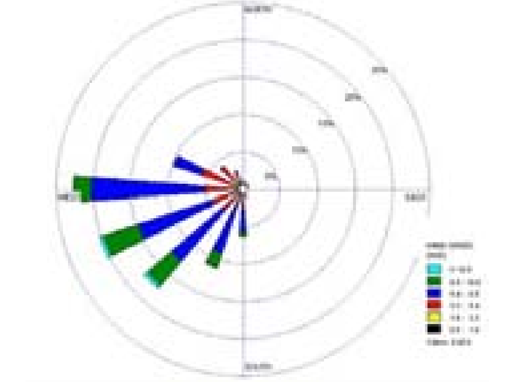
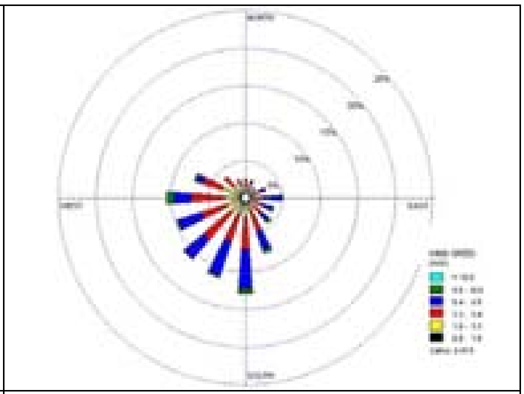
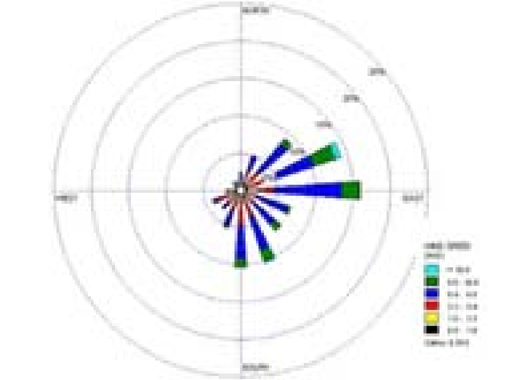
M.3.3 Thevenard Island



Mesolaps_Thevenard_Summer (DJF)



MLaps_ Thevenard_Autumn (MAM)



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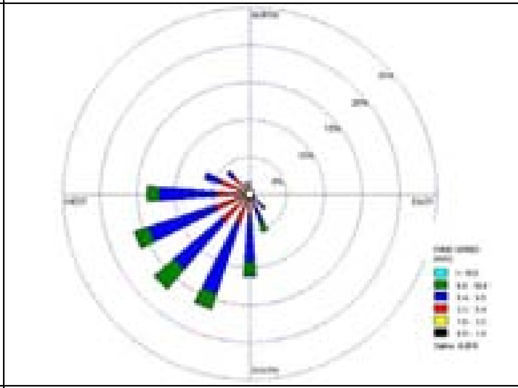
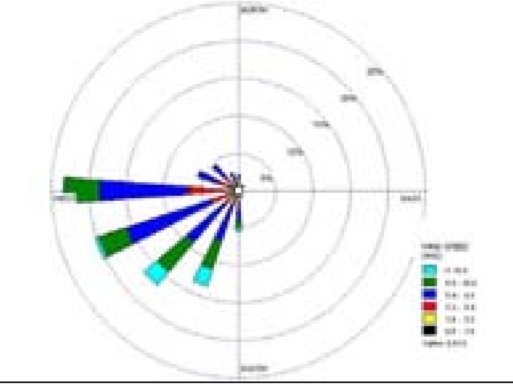
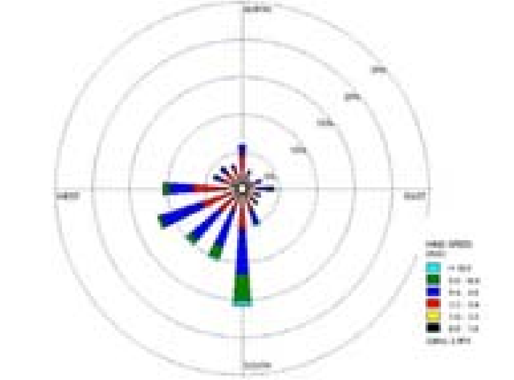
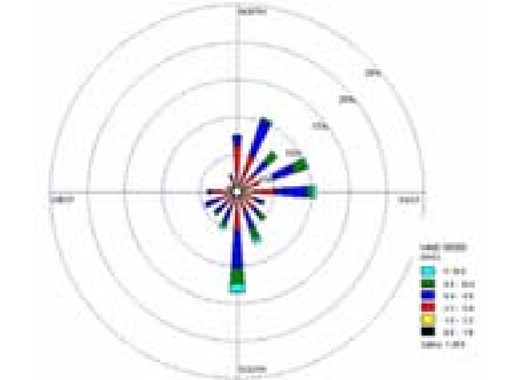
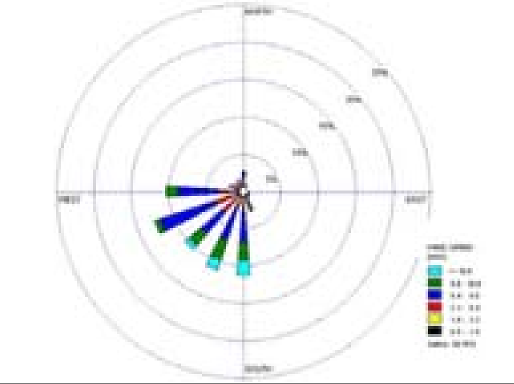


MLaps_ Thevenard_Spring(SON)

M-13

	
Data_Thevenard_Summer (DJF)	Data_Thevenard _Autumn (MAM)
	
Data_Thevenard _Winter (JJA)	Data_Thevenard _Spring (SON)

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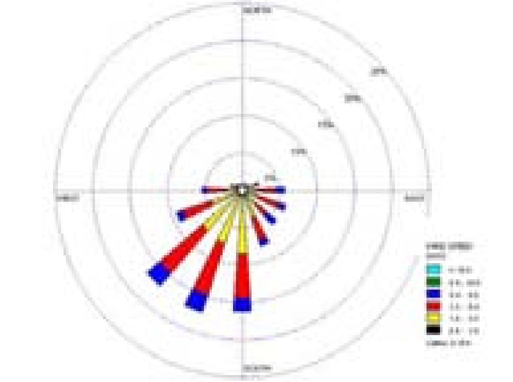
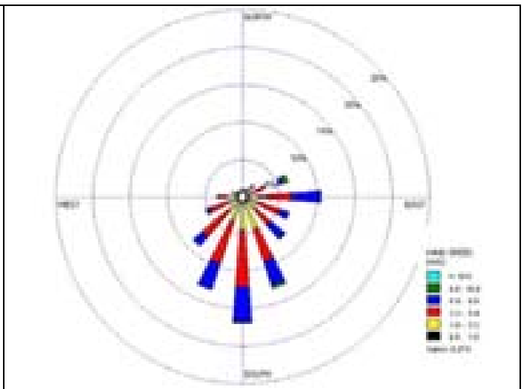
M.4 Hour of Day WIndroses, 2007

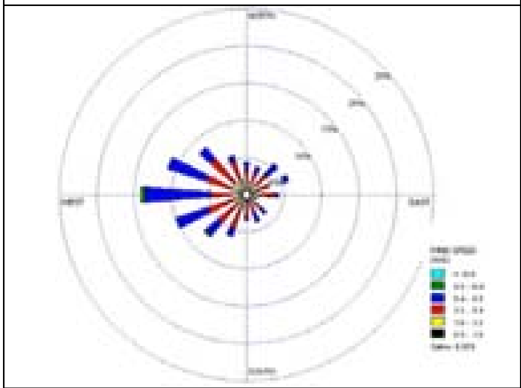
M.4.1 Onslow



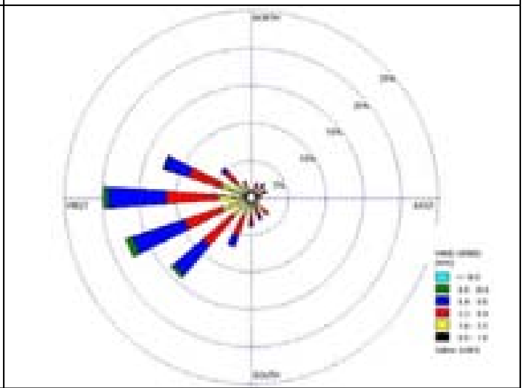
MLaps_Onslow_01 – 06 hours



MLaps_Onslow_07 – 12 hours

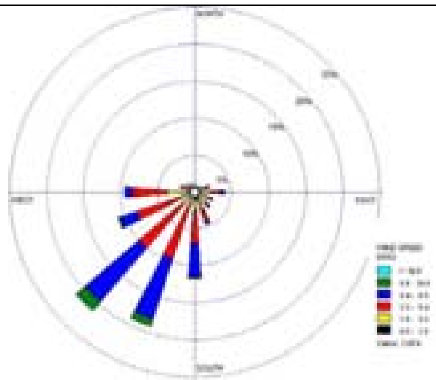
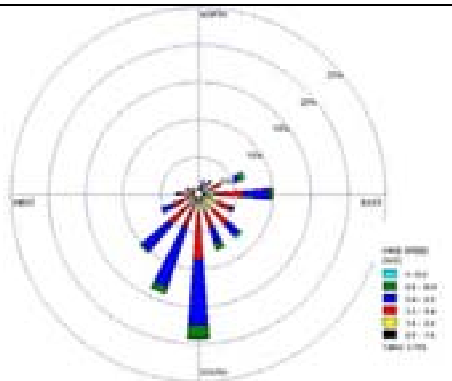
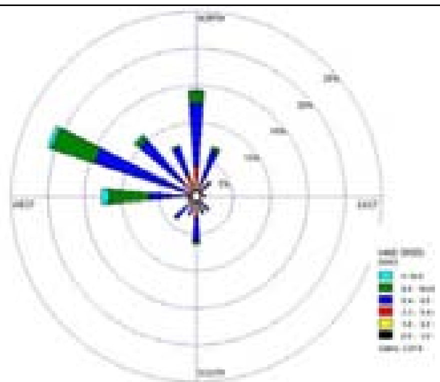
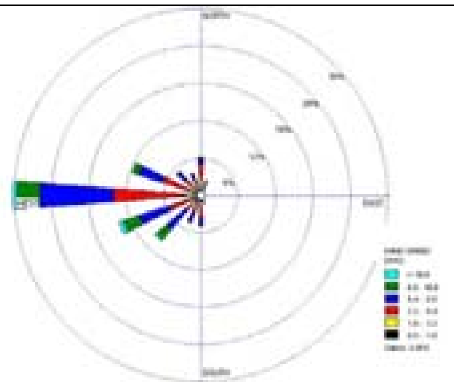


MLaps_Onslow_13 – 18 hours



MLaps_Onslow_19 – 00 hours

M-15

	
Data_Onslow_airport _01 – 06 hours	Data_Onslow_airport _07 – 12 hours
	 Note: The ring scale is 0% - 30% compared to 0% - 25% for all other wind rose in this Appendix.
Data_Onslow_airport _13 – 18 hours	Data_Onslow_airport _19 – 00 hours

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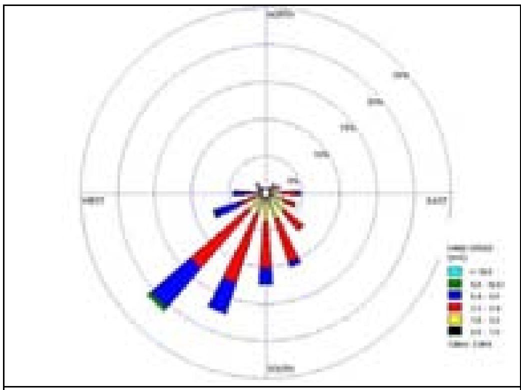
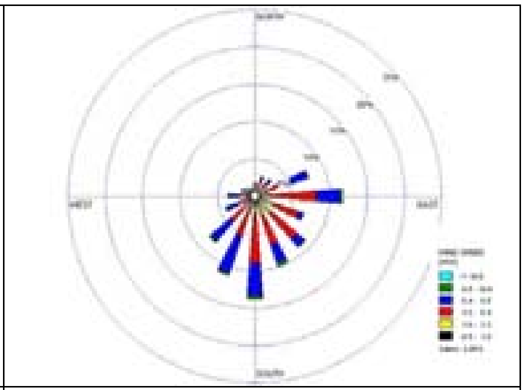
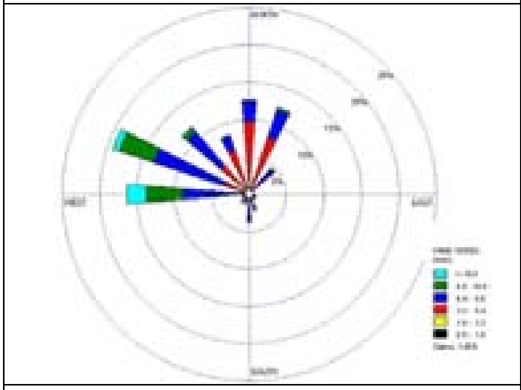


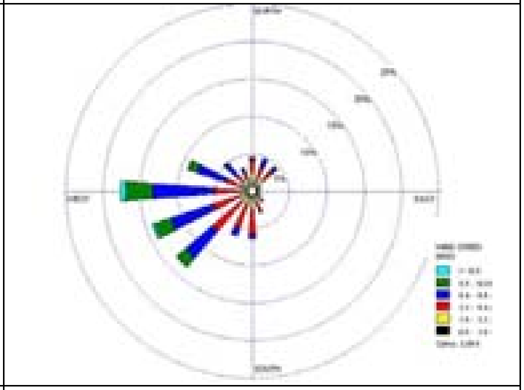
Data_Onslow _01 – 06 hours
(Data missing: Sep, Oct, Nov and Dec 2007)



Data_Onslow _07 – 12 hours
(Data missing: Sep, Oct, Nov and Dec 2007)

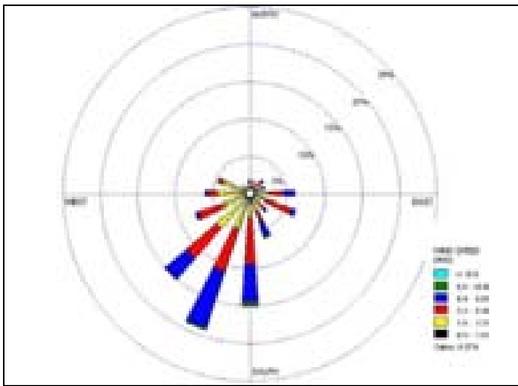
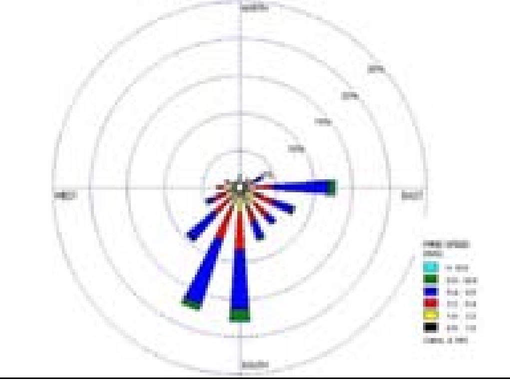
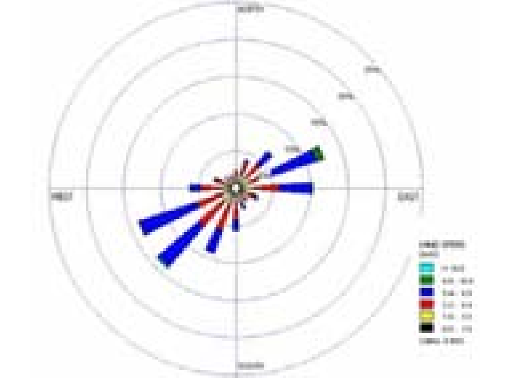
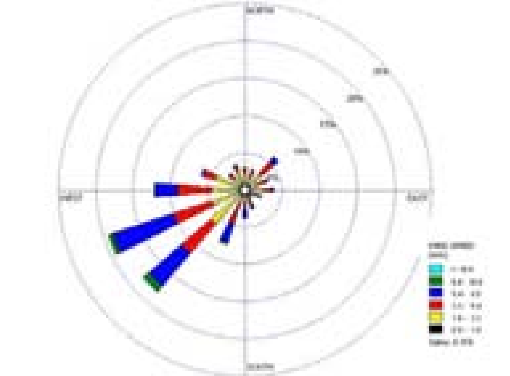


Data_Onslow _13 – 18 hours
(Data missing: Sep, Oct, Nov and Dec 2007)

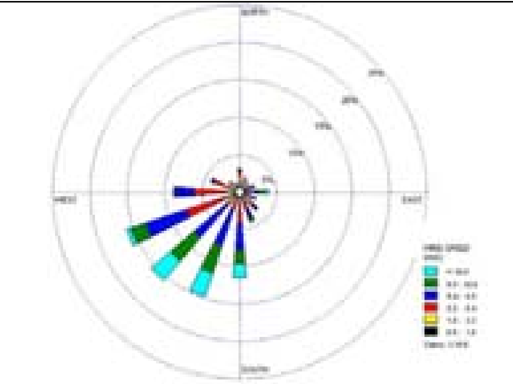


Data_Onslow _19 – 00 hours
(Data missing: Sep, Oct, Nov and Dec 2007)

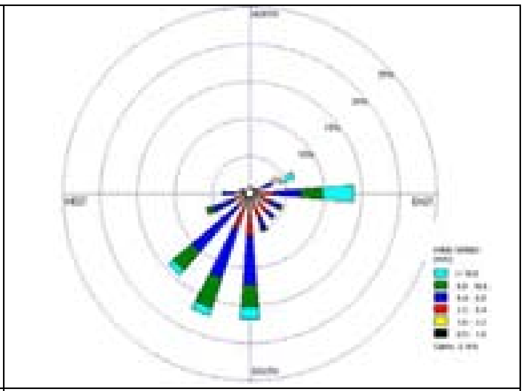
M.4.2 Barrow Island

	
MLaps_BarrowIsland_01 – 06 hours	MLaps_ BarrowIsland _07 – 12 hours
	
MLaps_ BarrowIsland _13 – 18 hours	MLaps_ BarrowIsland _19 – 00 hours

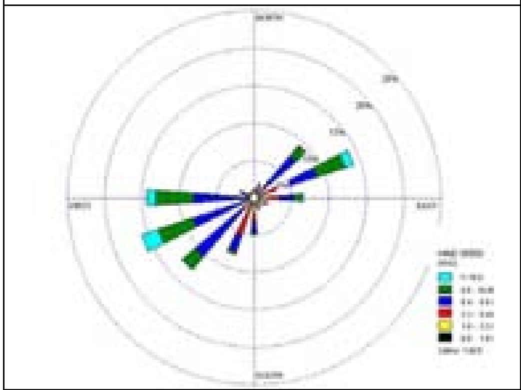
M-18



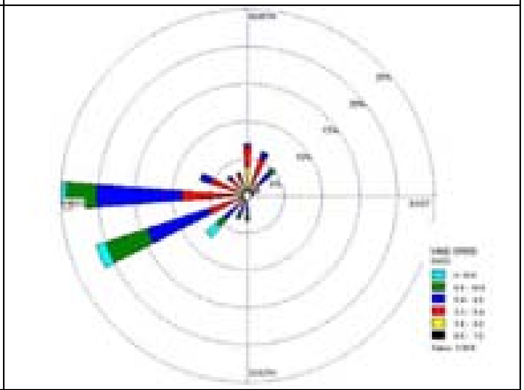
Data_Barrow _01 – 06 hours



Data_Barrow _07 – 12 hours



Data_Barrow _13 – 18 hours



Data_Barrow _19 – 00 hours

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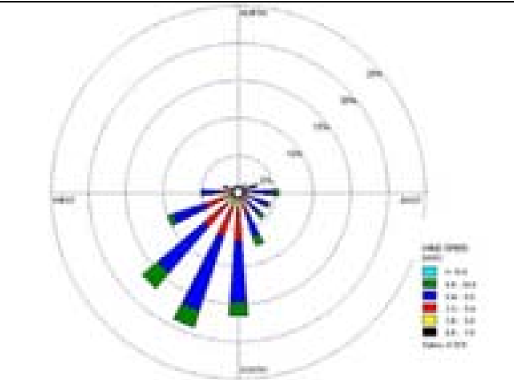
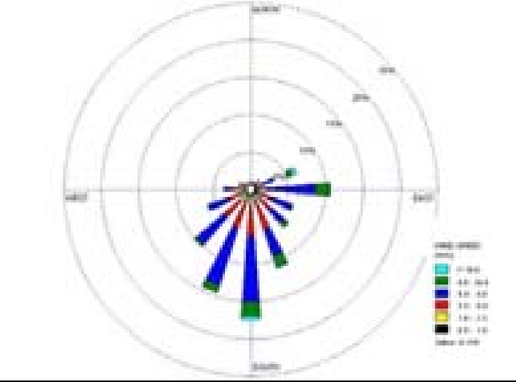
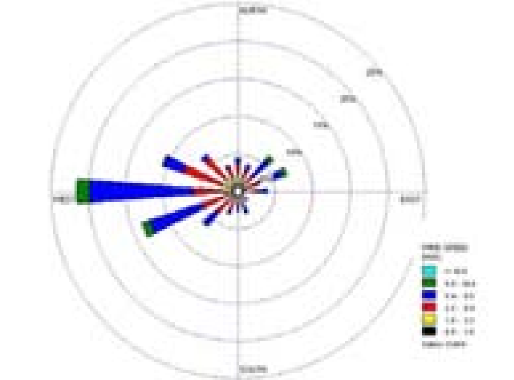
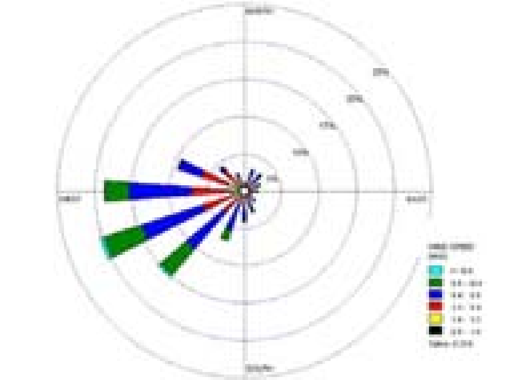
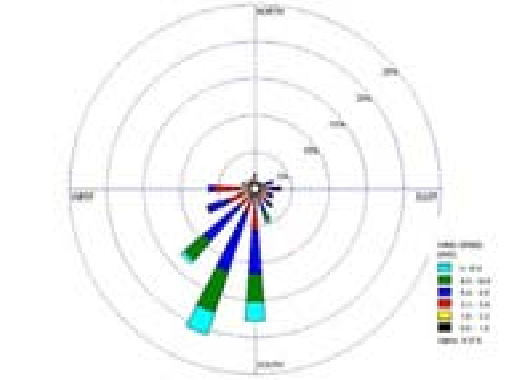
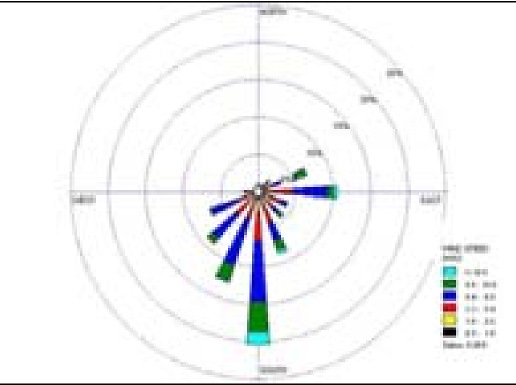
M.4.3 Thevenard Island

	
MLaps_ Thevenard_01 – 06 hours	MLaps_ Thevenard_07 – 12 hours
	
MLaps_ Thevenard_13 – 18 hours	MLaps_ Thevenard_19 – 00 hours

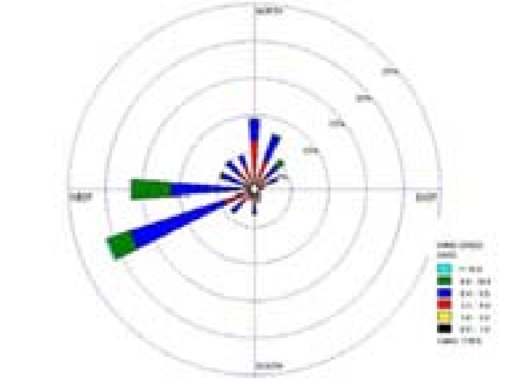
M-20



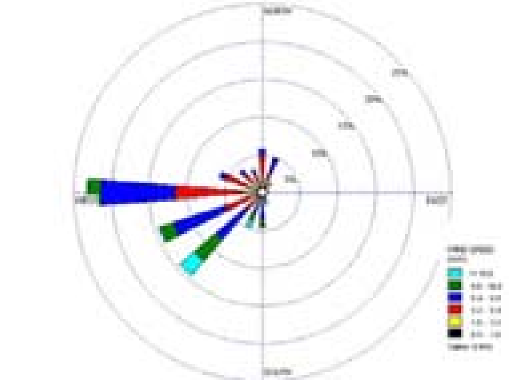
Data_Thevenard _01 – 06 hours



Data_Thevenard _07 – 12 hours



Data_Thevenard _13 – 18 hours



Data_Thevenard _19 – 00 hours

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Wheatstone Project
Dredge Spoil Modelling

APPENDIX N:

Wave Modelling: Setup and Validation

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CONTENTS

FIGURES AND TABLES

N WAVE MODELLING

Waves are important for plume modelling in shallow water as they can generate additional bottom shear stresses that may hinder sediment from settling out or cause re-suspension.

Wave conditions are included in the plume modelling through a wave model that simulates the wave propagation from offshore to the site based on the off-shore wave conditions, local tides and 2D MesoLAPS wind fields.

DHI's MIKE 21 SW model has been utilised for the numerical wave transformation. The model simulates the wave propagation from deep water to nearshore areas, including the effects of shoaling, refraction, bottom dissipation, wave breaking, wind generation and directional spreading which are introduced through a parameterisation of the wave spectra. Wave breaking is represented in the model using the approach of Battjes and Janssen.

N.1 Available Wave Data

A comprehensive field campaign for the project is ongoing, leading to an expanding data base for the project. At the time of writing, six sources of wave data are available to the study as outlined in Table N.1 with locations shown in Figure N.1.

The Exmouth data was specifically acquired to be used for boundary conditions. The limited data from the Wheatstone Platform is used to compare to the Exmouth data.

For calibration/validation, the longest record available is from the older data at the "Basin DWR", covering a period of about 13 months. The field campaign for the site is ongoing, and presently shorter record data is available from the "Jetty", "Channel" and "Spoil Ground" locations. The model has been validated against all these locations, which gives a good spatial representation over the area of interest, albeit the records are still relatively short.

Table N.1 Overview of available wave data.

Location	MGA-50		Water Depth (m)	Overall Period
	Easting (m)	Northing (m)		
"Offshore Wave Data"				
Exmouth	199795.36	7597627.69	54	04-10-2006 to 17-08-2009
Wheatstone Platform	330670.52	7794010.65	100	05-05-2009 to 20-08-2009
SpoilGround	276916.08	7635601.11	52	10-01-2009 to 12-09-2009
"Nearshore Wave Data"				
Jetty	294253.58	7604050.43	8.2	11-01-2009 to 16-04-2009
Basin DWR	298987.60	7605472.62	10	25-01-2006 to 14-03-2007
Channel	297891.86	7621062.75	15	24-07-2009 to 12-09-2009

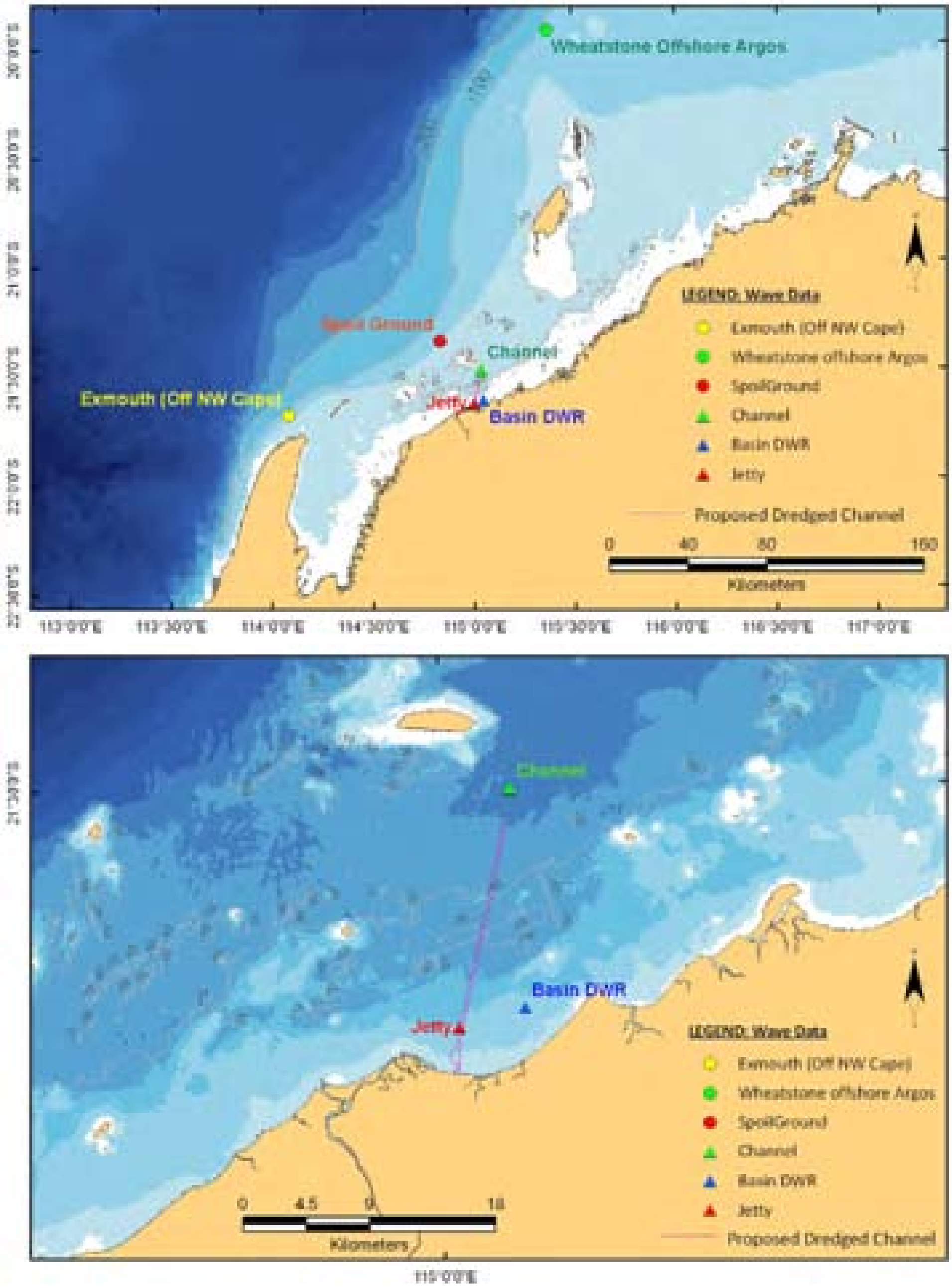


Figure N.1 Locations of wave data available to the study.

N.2 Model Setup

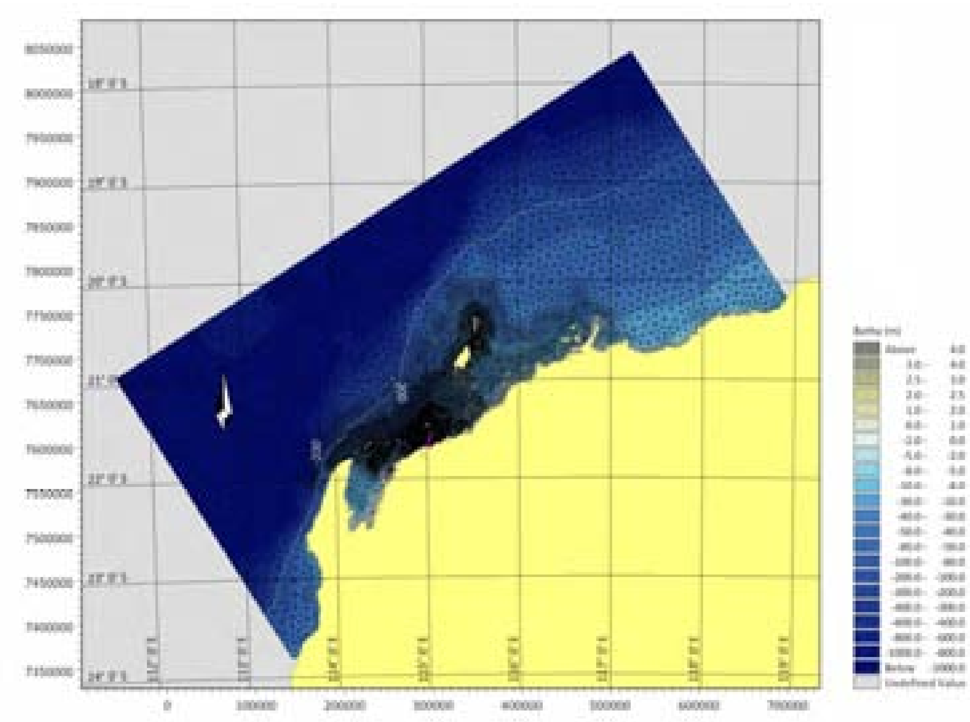
The input to the model is, apart from the digitised bathymetry, the wave conditions along the offshore boundary of the model, spatially varying wind speeds and directions over the model area (MesoLAPS wind fields), bottom roughness, the wave breaking parameters associated with the model of Battjes and Janssen and the water level. Output from the model comprise temporal and spatial resolution of the significant wave heights (Hs), mean wave directions (MWD), mean wave period (T01) as well as directional spreading parameters.

N.2.1 Bathymetry

The model bathymetries are built based on the bathymetry data base established for the project and used to establish the grids for the hydrodynamic models. See Appendix J: Development of Model Bathymetry.

Figure N.2 illustrates the model mesh. It is noted that the mesh is relatively coarse in the surf zone as the model is not set up to provide detailed waves in the surf zone. The model mesh is sufficiently detailed to resolve the variations in wave climate throughout the area of interest, which is used for the bottom shear stress calculations in the MT model.

The model area has been tested extensively together with the boundary conditions. This showed that the waves in the nearshore area are predominantly determined by the locally generated wind waves, and the main requirement for the model domain is that it has to stretch out to deep water and sufficiently far from the site to allow the (relatively small) wind waves to fully develop.



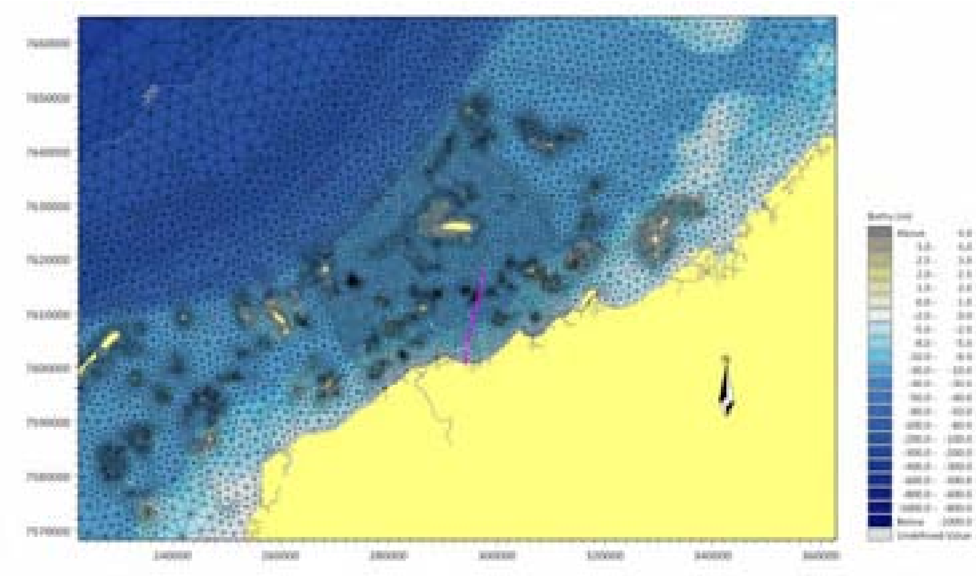


Figure N.2 Unstructured mesh used for the offshore wave transformation; the mesh resolution increases when moving towards the nearshore area. Overall wave model domain (Top) and zoom-in (Bottom)

N.2.2 Boundary Conditions

Offshore wave conditions are dominated by swell waves from the southern ocean, see Table N.2. These waves run basically parallel to the coast at the site, and undergo large-scale refraction into the shallow areas at the site.

Table N.2 Monthly significant wave height statistics summary for Wheatstone and Iago fields offshore North-western Australia.

	Hs (m) statistics		Main direction
Month	**50%**	**1%**	**(coming from)**
Jan	1.7	3.2	SW
Feb	1.7	3.1	SW
Mar	1.6	3.8	SW
Apr	1.6	3.0	SW
May	1.9	3.5	SW
Jun	2.3	3.6	SW
Jul	2.4	3.6	SW
Aug	2.2	3.7	SW
Sep	2.2	3.5	SW
Oct	2.0	3.4	SW
Nov	1.8	2.9	SW
Dec	1.7	2.7	SW

Model testing has shown that the penetration into the shallow coastal waters of the off-shore swell waves is limited, and locally generated wind waves dominate the coastal wave climate most of the time. Some penetration of small swell waves is present during the winter season with off-shore directed winds.

Limited data is available for both boundary conditions and model validation. To make full use of the available data, two approaches have been applied:

1. Simulation with monthly mean statistical wave parameters on the boundary. Sensitivity testing showed little sensitivity to the offshore boundary conditions for the calibration in nearshore waters.
2. Application of directional wind and swell wave data from the Exmouth Bouy on the model boundaries. It is noted that the wave buoy is not located on the model boundary, but it is located in sufficiently deep water and at a sufficiently exposed location for waves from the dominant directions to be representative of the waves along the model boundary for most conditions.

The first approach is only limited in time by the availability of suitable wind data. For the second approach, 3 years of directional wave data is available.

For the dredge spoil modelling, the second approach outlined above has been used in the recent simulations. Data analysis demonstrated fairly consistent wave conditions from year to year, see Section N.2.2.1. As the simulations cover a period of 2 months for each season, and there is a close correlation between the winds and waves in shallow water (i.e. very limited sensitivity to the off-shore wave conditions), any impacts of waves on the boundaries can be assumed to be covered within this period (barring cyclonic conditions which are covered separately, and for which dredging will be ceased).

N.2.2.1 Off-shore Boundary Data

Directional Wave Data has been acquired from the Department of Transport, Government of Western Australia from the buoy off Northwest Cape of Exmouth. Directional wave data is available for about 3 years (with some gaps). The data is split into a sea and a swell component. Monthly wave roses have been produced for sea and swell conditions for the three years, see Figure N.3 to Figure N.8. The consistent SW to W swell conditions are clearly seen with the highest waves during winter. The sea waves show a NE’erly component during winter, although the location has limited exposure during winter. The strongest sea waves from SW’erly directions are found during summer.

A larger swell component from NE reaches the Wheatstone platform location during winter, see Figure N.9. This is expected given the exposed location with significant fetch towards NE. The same level of penetration is not found at the “offshore spoil ground”, see monthly wave roses in Figure N.10, which is sheltered by Barrow Island and the shoals between Barrow Island and the Mangrove Islands. The site will similarly be sheltered against the NE’erly swell waves, which are expected to have limited penetration to the site.

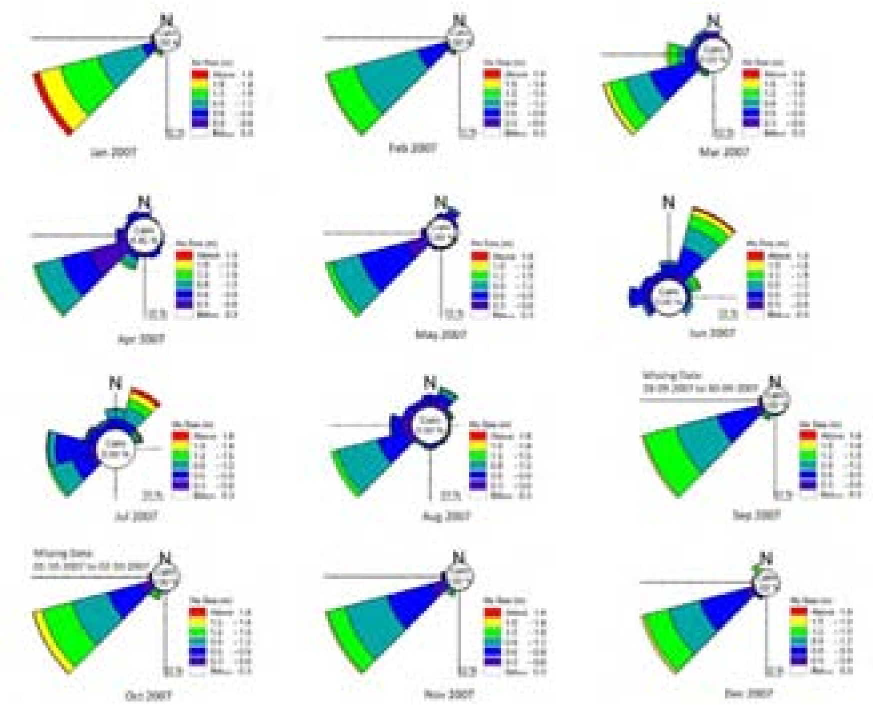


Figure N.3 Monthly wave roses for 2007 for sea waves off Northwest Cape, Exmouth.

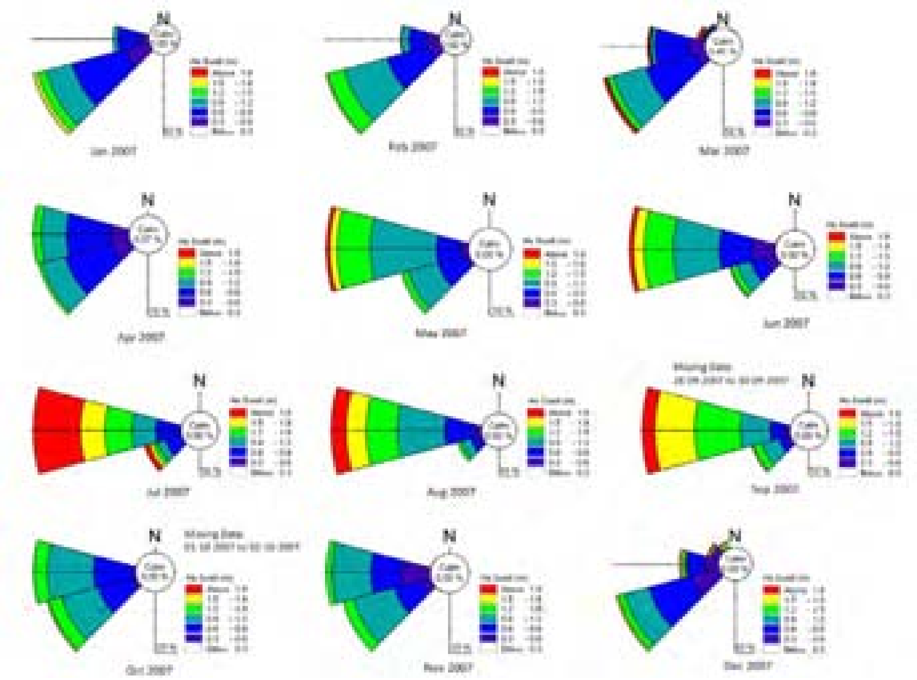


Figure N.4 Monthly wave roses for 2007 for swell waves off Northwest Cape, Exmouth.

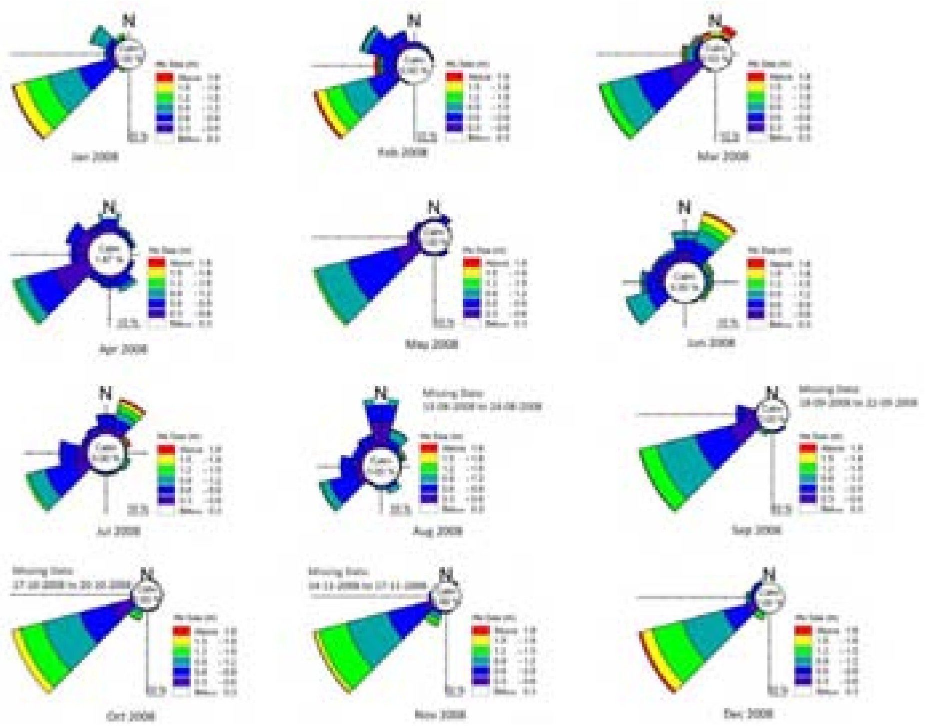


Figure N.5 Monthly wave roses for 2008 for sea waves off Northwest Cape, Exmouth.

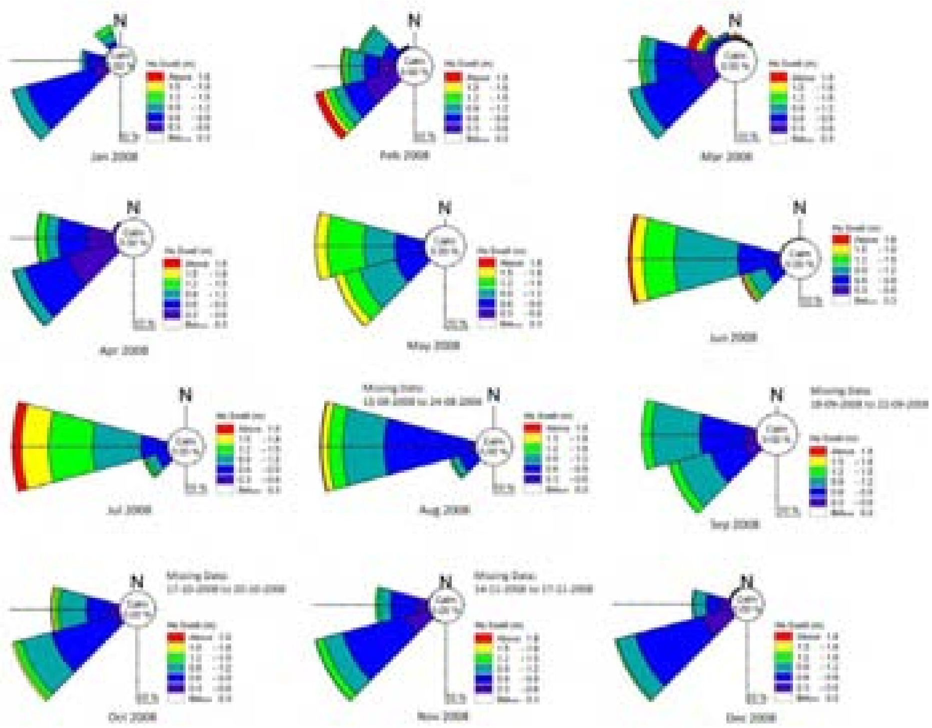


Figure N.6 Monthly wave roses for 2008 for swell waves off Northwest Cape, Exmouth.

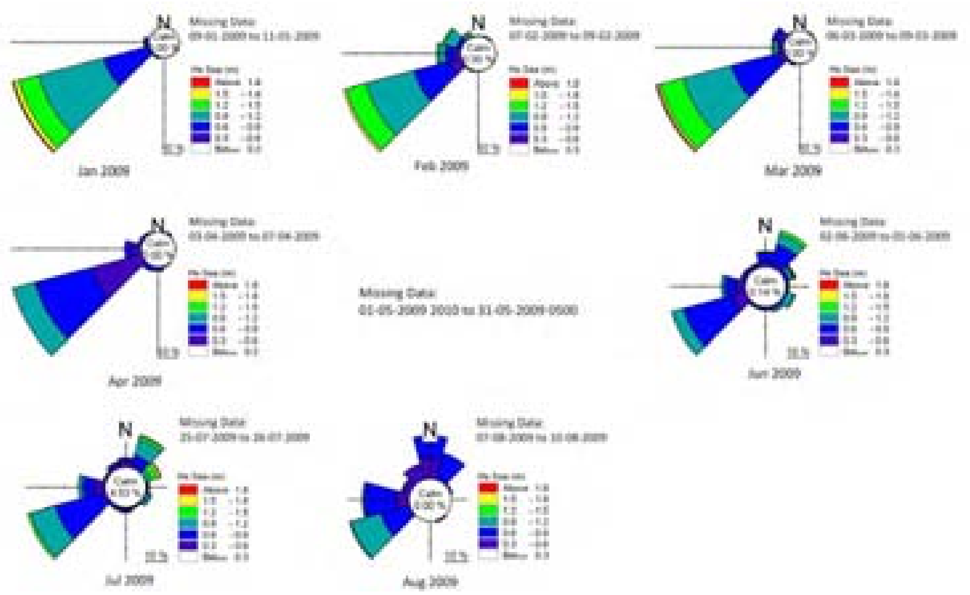


Figure N.7 Monthly wave roses for 2009 for sea waves off Northwest Cape, Exmouth.

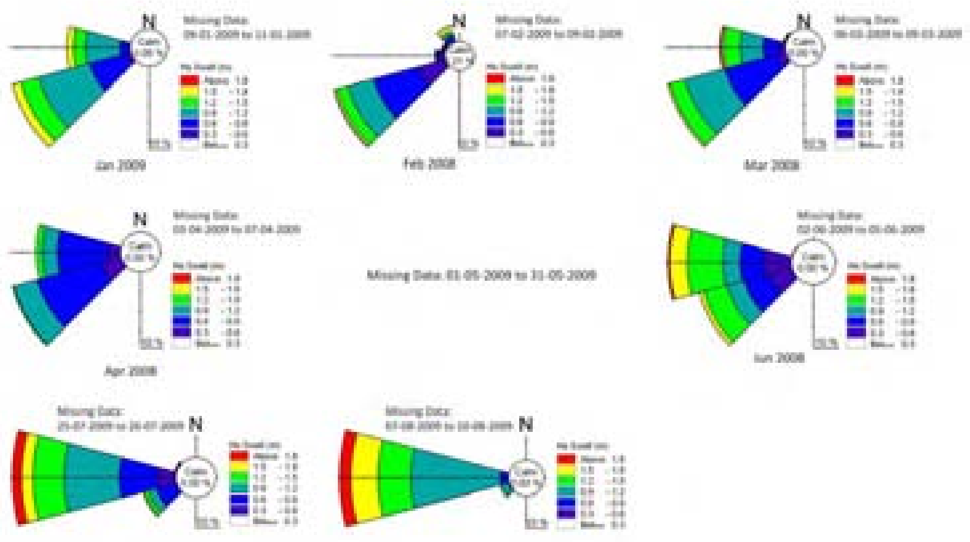


Figure N.8 Monthly wave roses for 2009 for swell waves off Northwest Cape, Exmouth.

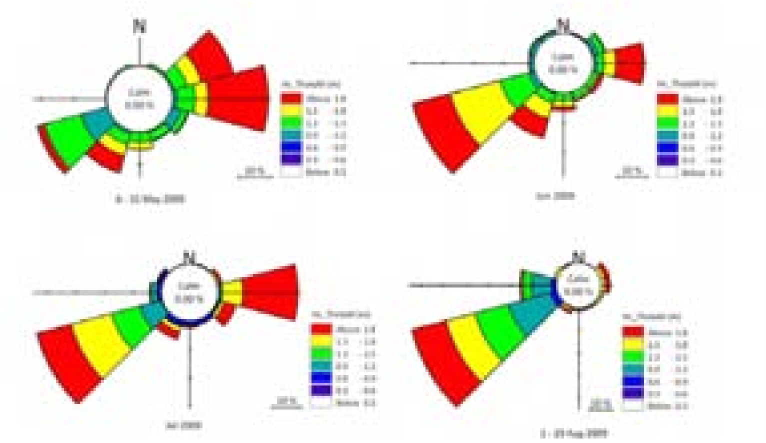


Figure N.9 Monthly wave roses for data available from Wheatstone Platform

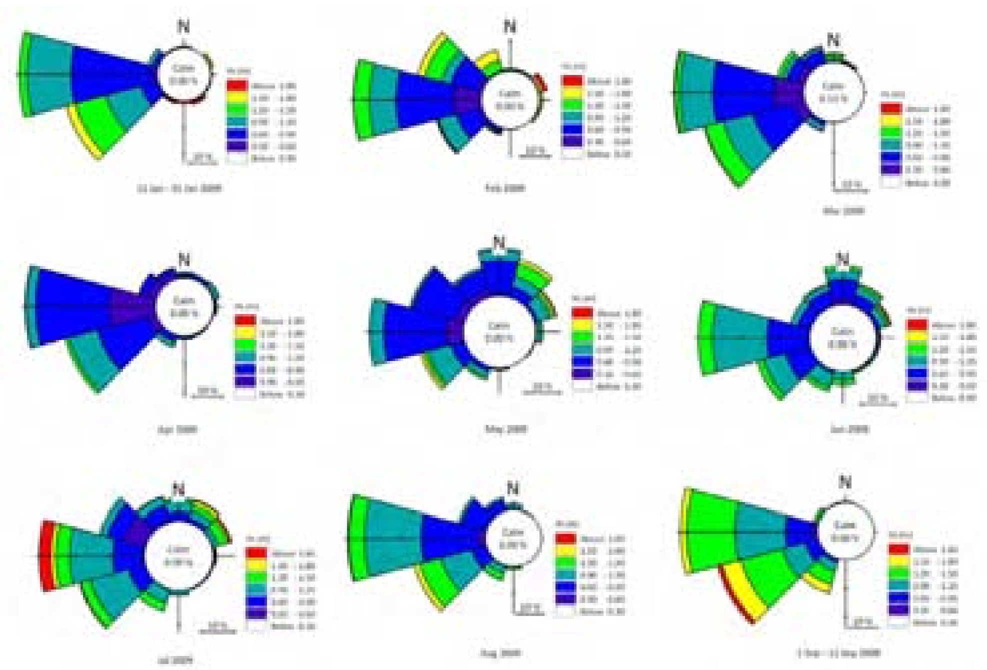


Figure N.10 Monthly wave roses for data available from Offshore Spoil Ground

N.2.3 Water Levels

For the transformation of wave conditions to the nearshore areas the water level becomes important as higher water levels result in less wave energy dissipation due to bottom friction and wave breaking. Water levels derived through tidal prediction from a tidal station nearest to the study area has been applied in the SW model. Figure N.11 shows one year predicted water levels at Onslow.

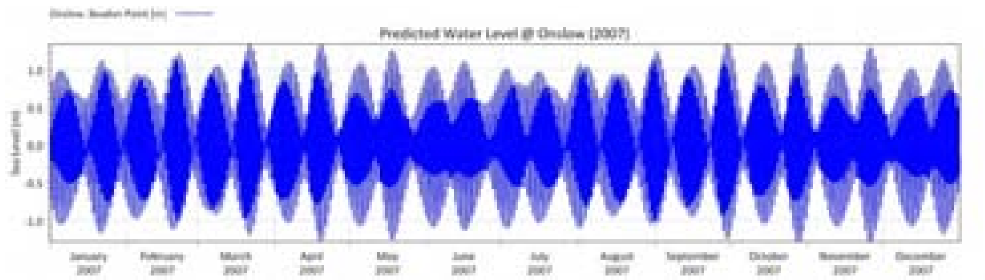


Figure N.11 Predicted water level from Onslow, Beadon Point

N.2.4 Wind Conditions

As waves propagate from the offshore region towards the site, they loose energy through dissipation over offshore shoals, strings of coral reefs located near the site and through large-scale wave refraction. Consequently, energy input from the wind becomes increasingly important. Therefore, for sea waves, it is important to include wind in the nearshore wave simulations.

Similar to the current model, different sources of wind fields have been tested in the model. For the nearshore wave record, the Onslow wind record has shown good validation. As the waves are generated over a larger area, the spatial wind distribution becomes increasingly important further away from the coast. Although the MesoLAPS wind fields do not always fully capture the daily variations (sea/land breeze) – see Appendix M: “Comparison of MesoLAPS wind fields with Monitoring Data”, they have been chosen due to the spatial variability.

Examples of instantaneous MesoLAPS wind fields applied in the wave model are shown in Figure N.12 and Figure N.13 for a summer and a winter condition.

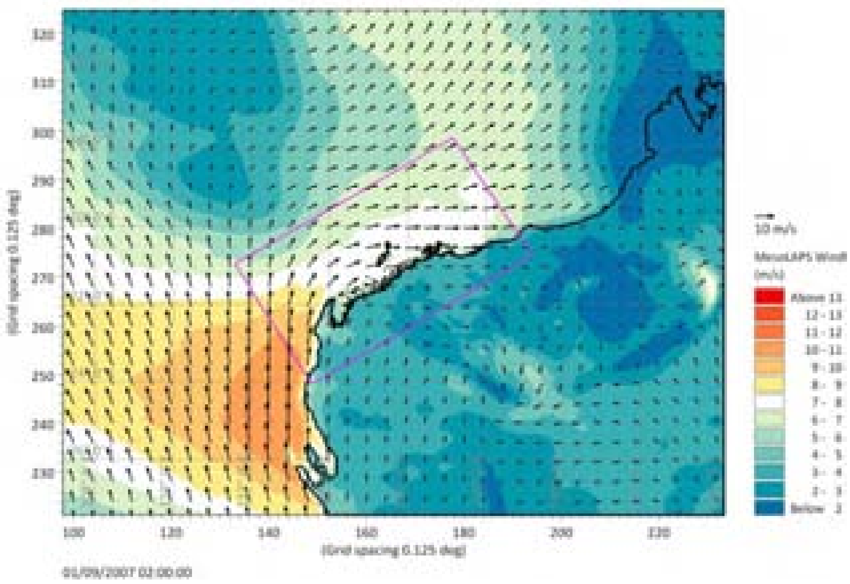


Figure N.12 Sample instantaneous wind field map during summer from MesoLAPS 6-Hourly Winds. The pink box denotes the wave model domain.

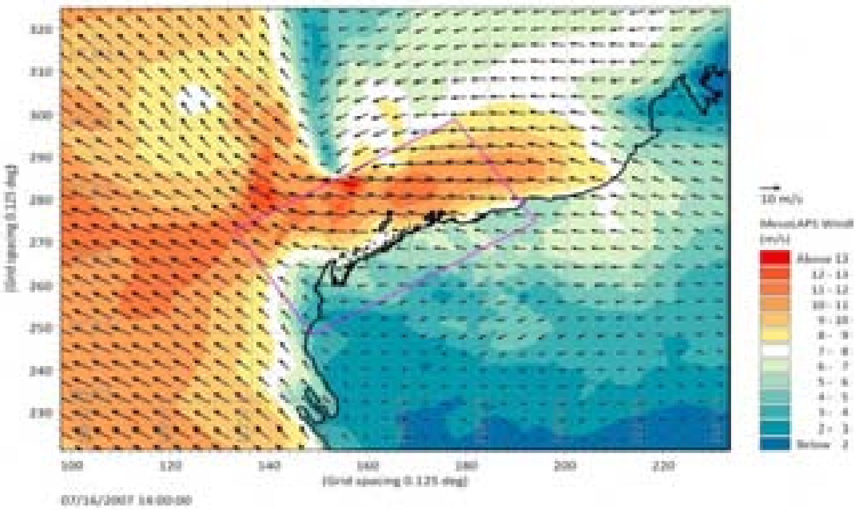


Figure N.13 Sample instantaneous wind field map during winter from MesoLAPS 6-Hourly Winds. The pink box denotes the wave model domain.

N.3 Model Calibration & Validation

N.3.1 Using Offshore Statistics

As outlined in Section N.2.2, the model has been run in two modes. Although the Exmouth wave data were applied on the boundaries of the model used for the dredge spoil modelling, the validation for the model with statistics on the boundaries has also been included in this documentation to illustrate the limited influence of the off-shore boundary data on the nearshore waves.

There is limited overlap between the Exmouth Data and the 13 months data at “Basin DWR”, see Table N.1. The model was calibrated against this data based on the approach with statistically derived boundary conditions (see Section N.2.2). Figure N.14 shows comparison of measured and simulated data at the “Basin DWR” location in Figure N.1, while Figure N.15 compares simulated and measured data at the “Jetty” location.

The model reproduces the overall annual patterns well for both significant wave heights and wave directions. It is noted that the model based on the MesoLAPS winds overestimate the waves during the cyclonic events in March / April of 2006.

In the detailed verification at the Jetty location, the model is seen to reproduce the daily spikes fairly well, demonstrating the strong correlation to the wind fields (as off-shore boundaries are constant values based on the statistics).

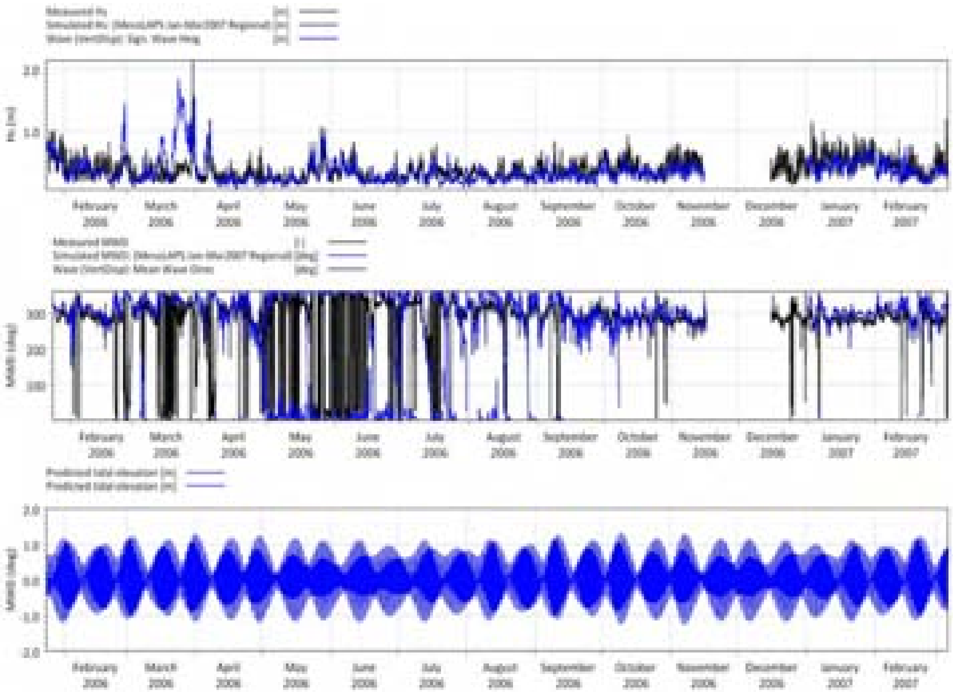


Figure N.14 *Comparison between the measured (black) and simulated (blue) significant wave heights and mean wave directions for the 13 months "Basin DWR" data based on a model setup with statistical wave parameters on the boundary.*

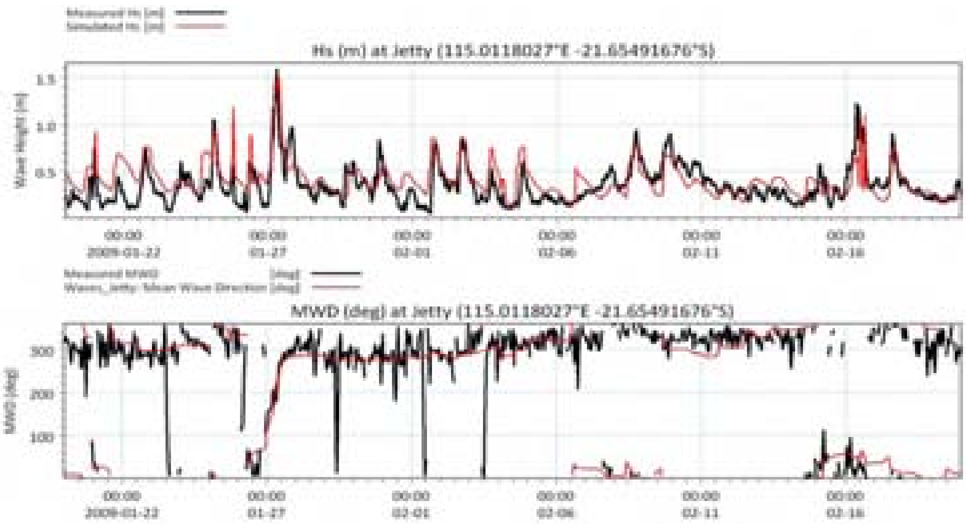


Figure N.15 *Comparison between the measured (black) and simulated (red) significant wave heights and mean wave directions for 1 month data at the "Jetty" based on a model setup with statistical wave parameters on the boundary.*

N.3.2 Verification for Offshore Boundaries based on Exmouth Data

The model setup applied for the dredge plume modelling has been established with the Exmouth Directional Wave data applied as separate sea and swell components on the off-shore boundary. It is noted that there are significant gaps in the off-shore data for this period, and also some gaps in the wind fields. Results are only shown when both off-shore data and wind data are available.

Comparison between simulated and measured data is shown for three locations, the "Jetty" location in relatively shallow water, the "Channel" location at the outer end of the proposed dredged channel, and at the "Spoil Ground" in deep water, see Figure N.1.

Looking at the waves from deeper water and towards the shore, Figure N.16 compares measured and simulated waves at the spoil ground in relatively deep water. A good validation is achieved for both wave heights, directions and periods.

Figure N.17 shows simulated data against measured data at the "Channel" location. The length of the record available at this stage is short, and the boundary and wind data is somewhat scattered, leading to limited data overlap for the validation. The limited data compares well for wave heights, directions and periods.

Finally, Figure N.18 compares simulated and measured data at the "Jetty" location. Overall, the data validates well on heights, directions and periods. The main discrepancy is found on the daily peaks during summer conditions in January. It is noted that the wave conditions are relatively benign, and close to the shore in shallow water, the sea breeze will add significant energy to the waves. As previously mentioned, the MesoLAPS wind model does not fully resolve the daily variations in the nearshore region, and it is therefore not surprising that the wave height peaks are not fully resolved. Previous tests with the winds from Onslow showed that peaks are picked up slightly better in the nearshore region with the measured winds which fully resolve the sea breeze effects.

Although limited data is available at the channel section at this stage, the longer data periods at both the spoil ground and jetty locations clearly indicate a good validation for all seasons, and this can be considered indicative for the channel section. Additional validation will be carried out when more data from the ongoing field campaign becomes available.

This verification is considered fully adequate for the inclusion in the sediment plume modelling where the waves are a secondary effect.

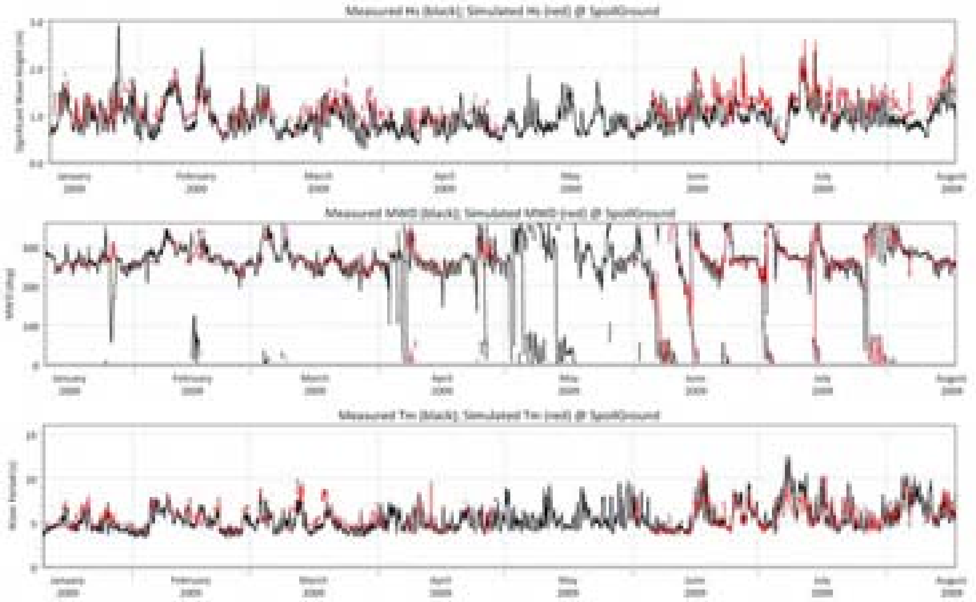


Figure N.16 Comparison between the measured (black) and simulated (red) significant wave heights, mean wave directions and periods at the "Spoil Ground" location based on Exmouth waves on the boundary and MesoLAPS winds.

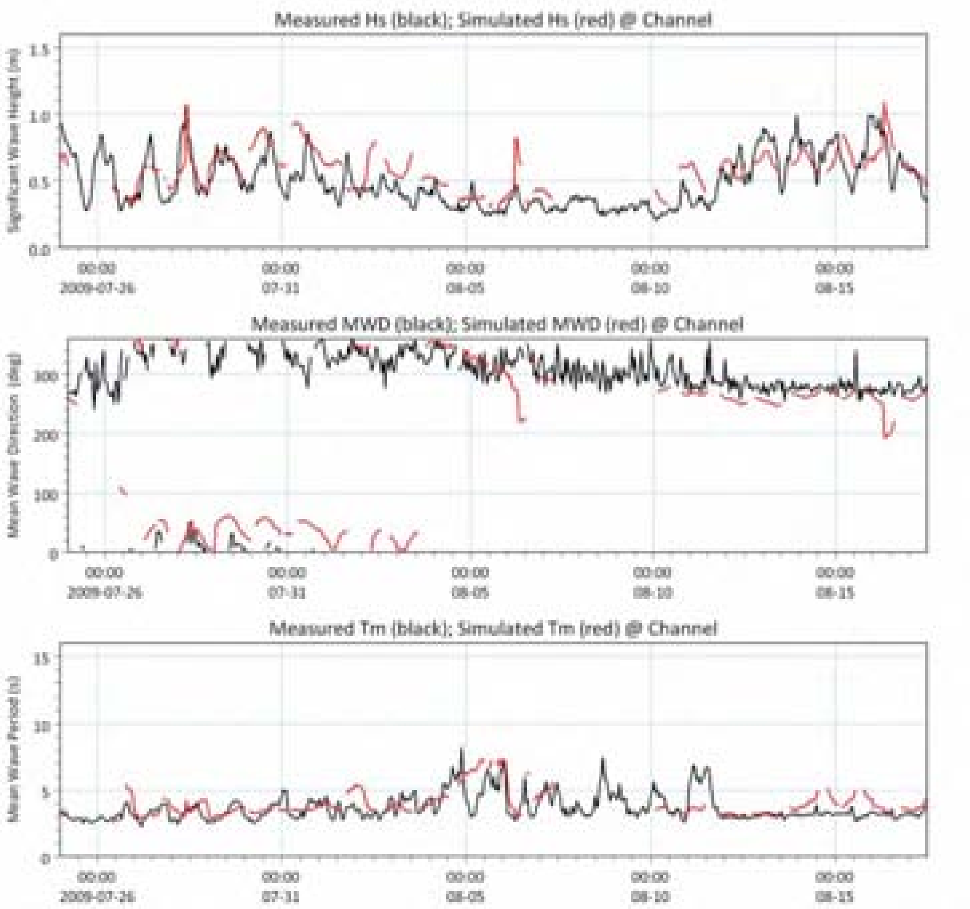


Figure N.17 Comparison between the measured (black) and simulated (red) significant wave heights, mean wave directions and periods at the "channel" location based on Exmouth waves on the boundary and MesoLAPS winds.

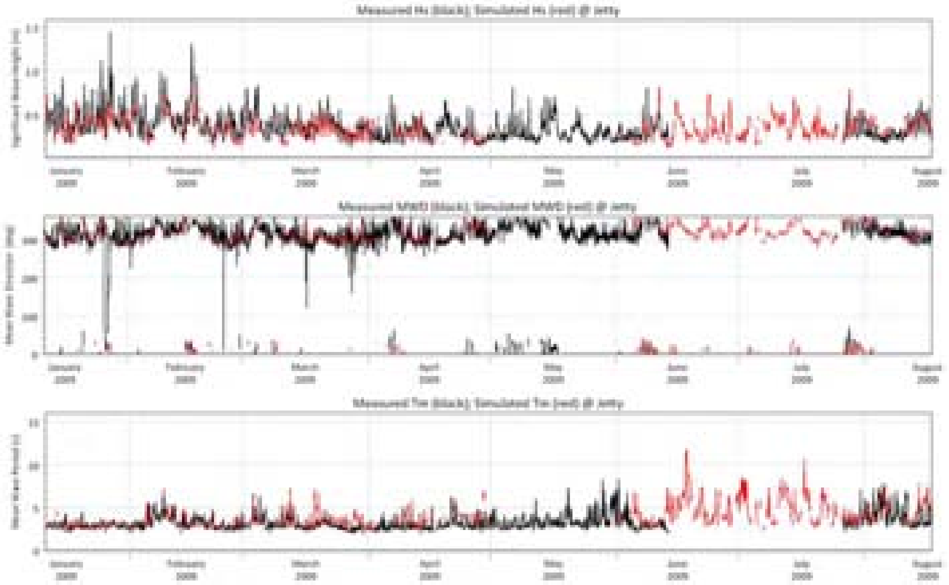


Figure N.18 Comparison between the measured (black) and simulated (red) significant wave heights, mean wave directions and wave periods at the "jetty" location based on Exmouth waves on the boundary and MesoLAPS winds.

N.4 Sample Model Output

Sample 2D wave fields for summer and winter months are shown in Figure N.19 and Figure N.20, respectively. This illustrates the significant loss of energy into shallow water. Although the offshore waves are higher during winter months, the winds are more favourable in terms of generating waves in the nearshore area during the summer months, and the wave climate in the shallow area is similar for the two modelled scenarios. The significant wave height along the navigation channel is in the order of 0.5 m.

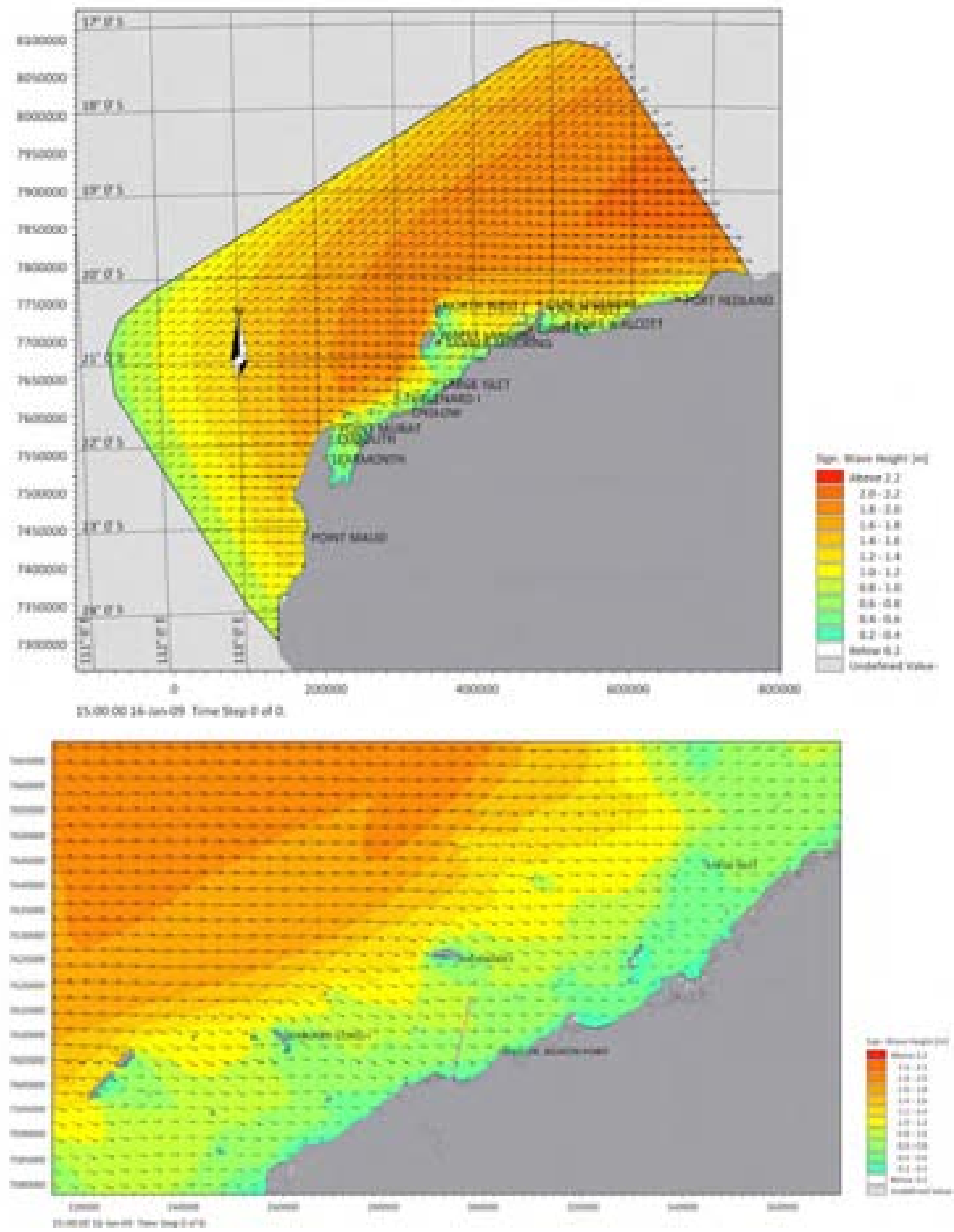


Figure N.19 Sample instantaneous simulated wave field during summer

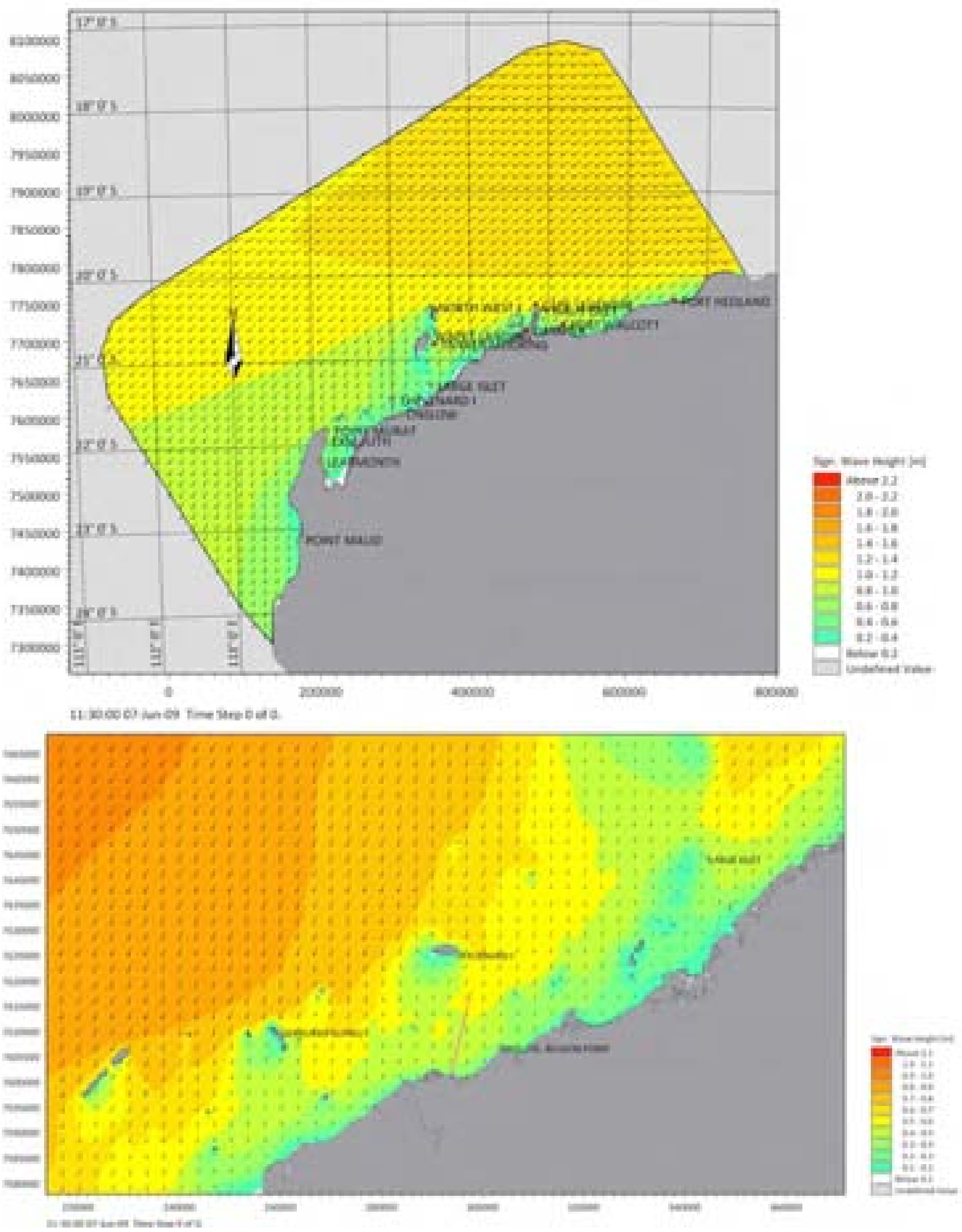


Figure N.20 Sample instantaneous simulated wave field during winter

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Wheatstone Project
Dredge Spoil Modelling

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Results for Dredge Scenario 1 Based on Onslow Winds

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CONTENTS

FIGURES AND TABLES

O RESULTS FOR DREDGE SCENARIO 1 BASED ON ONSLOW WINDS

This appendix presents results from the sediment transport model based on hydrodynamics driven by the Onslow wind fields. The reader is referred to the following sections of the main report and additional appendices for further information;

- Section 4.1.3.2 *Wind Fields*
- Section 6.2 *Results for the Dredging of the Shipping Channel*
- Appendix D *Hydrodynamic Model Validation and Calibration*

O.1 Statistical Plots

The established impact criteria (DHI (2010) *Dredge Plume Impact Assessment Report)* are based on sediment loads, both in terms of excess suspended concentrations and sedimentation rates, over 14 day periods. In terms of exposure and impacts, both the concentrations and the duration of the event is important, which is expressed through the exceedence probability of given limits.

For each simulated case, a set of plots showing the statistical output used in the impact assessment have been produced. All plots are for excess concentrations, i.e. sediments originating from the dredging operations and exclusive of ambient concentrations.

Each mosaic plot comprises:

- Mean excess concentration at two scales
- Exceedence of 5mg/l excess concentration at two scales
- Exceedence of 10mg/l excess concentration
- Exceedence of 25mg/l excess concentration
- Net sedimentation rates at two zoomed levels at the site

Note that all concentrations are presented as depth-averaged values. All values are derived over the assessment period (2^{nd} neap/spring tidal cycle of the month for each climatic scenario), i.e. after at least 14 days warm-up period. Exceedences are expressed in percentage time over the assessment period that the exceedence limit is exceeded.

O.2 Description of Dredge Scenario 1

Nearshore Dredging: Temporary Access Channel

- CSD with pumping to placement site A
- Bathymetry with partly dredged, 75m wide channel to -6m LAT)
- Material available for re-suspension in dredged channel portion and at Placement Site A.

The locations for the various dredge and placement activities are outlined in Figure O.1, while defined low (realistic) and high (worst-case) spill rates for Dredging Scenario 1 are listed in Table 3.2 of the main report.

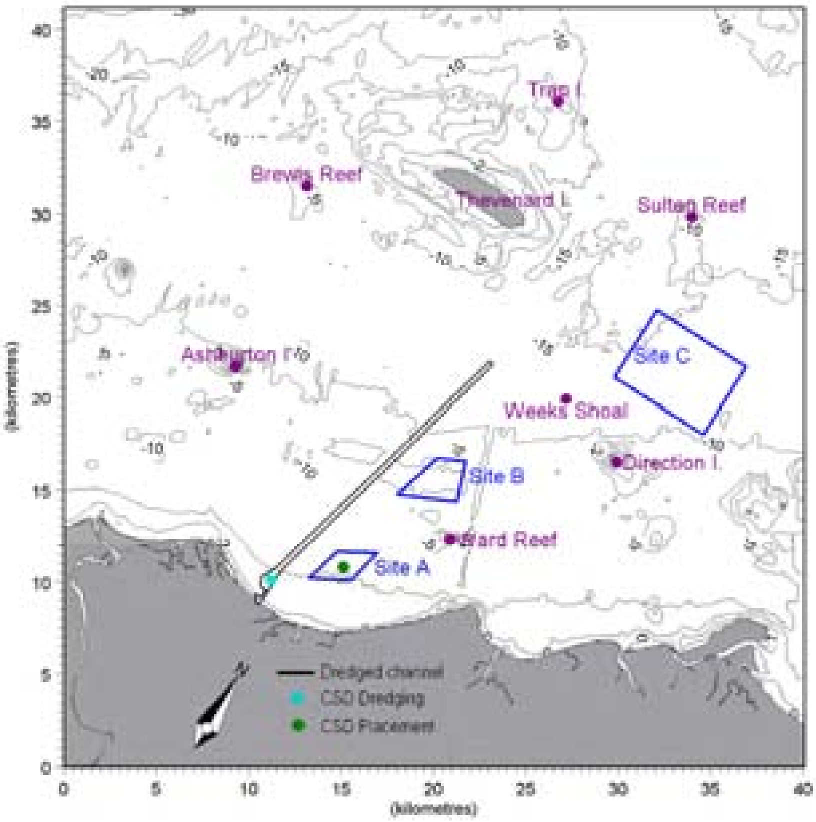

Figure O.1 Sketch of locations for Dredging Scenario 1.

O.3 Summary of Results

Specific observations for Dredge Scenario 1 include:

- The plumes from the nearshore CSD dredging the outer part of the temporary approach channel with pumping to Placement Site A extend primarily parallel to the coastline due to the coastal controlled current patterns and the relatively stationary sources.
- For the strong summer net currents and high (worst case) spill rates, mean excess concentrations up to 5mg/l reach Beadon Point.
- 5mg/l is exceeded 30% of the time more than 40km to the east of the site for the summer, worst case scenario, compared to about 15km for the realistic case.
- Excess concentrations of 10mg/l are exceeded in the order of 10% of the time at Onslow for strong summer conditions.
- For winter conditions, the 5mg/l excess concentration is exceeded more than 5% of the time up to about 20km to the west of the site. Mean excess concentrations in the order of 10mg/l reach Entrance Point.
- The plumes generated by the CSD dredging in the PLF area do not seem to reach Ward Reef at significant levels.

O.4 Results for Low (Realistic) Spill Rates

Dredge Scenario: Scenario 1
Climatic Scenario: Summer A
Spill Rate Estimate: Low ("Realistic") Case

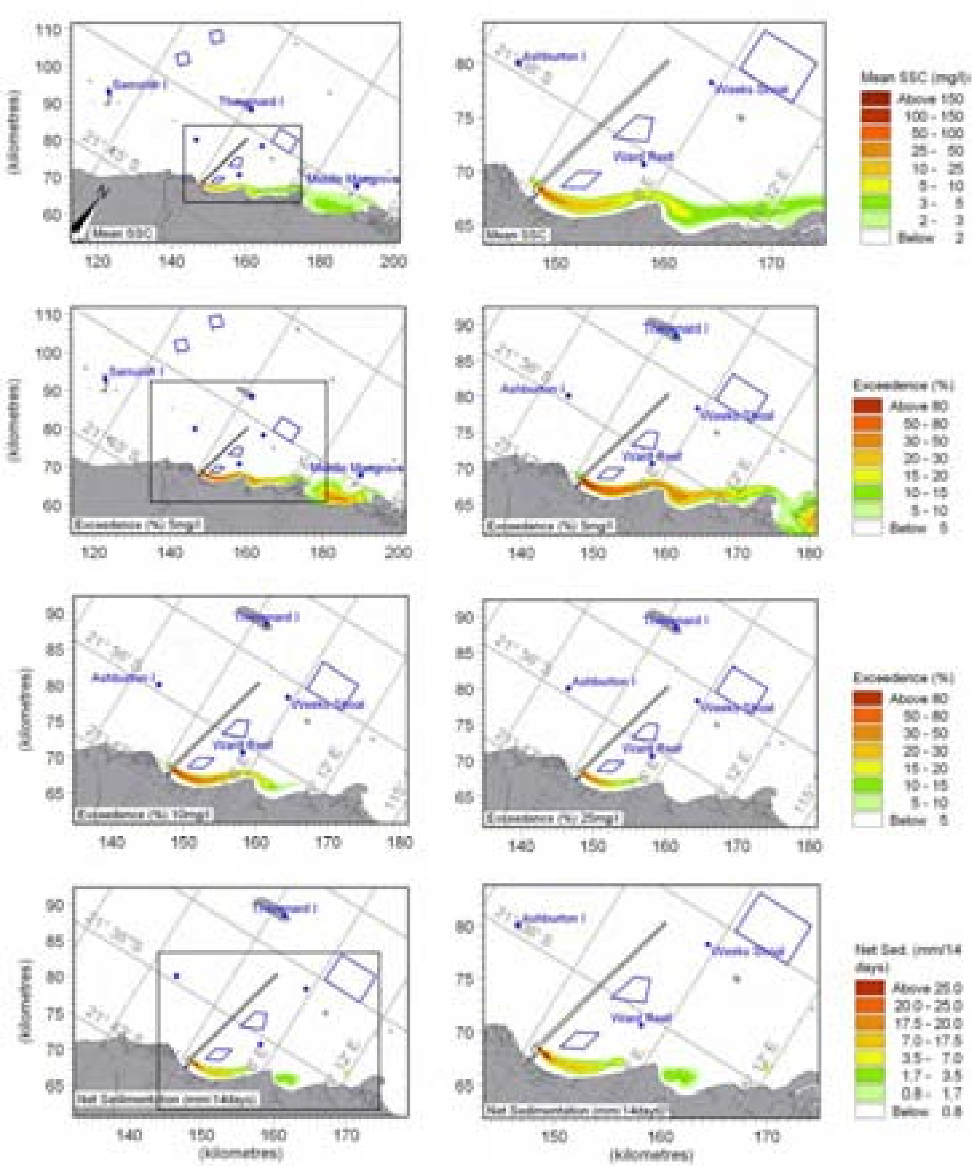

Figure O.2 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 1

O-5

Dredge Scenario: Scenario 1
Climatic Scenario: Summer B
Spill Rate Estimate: Low ("Realistic") Case

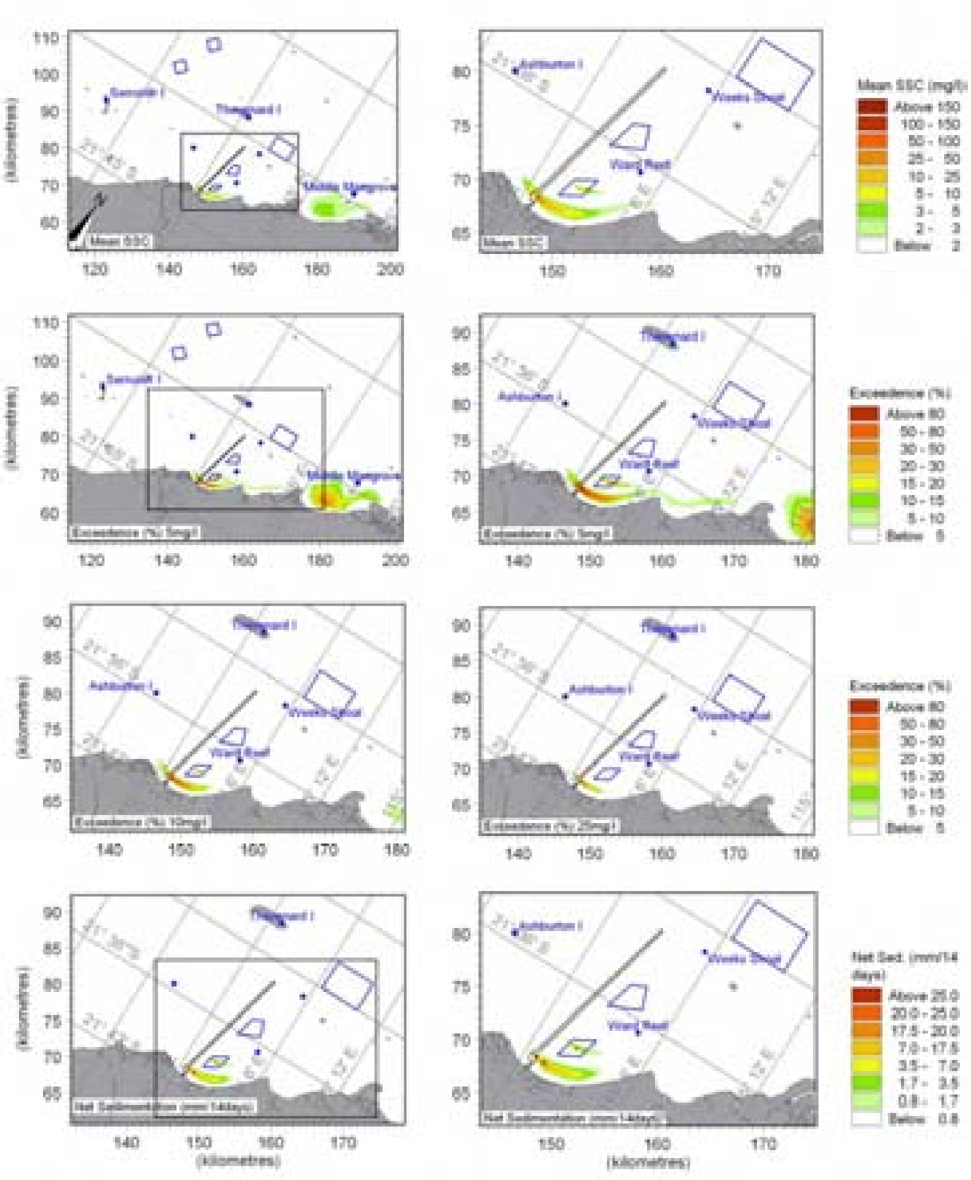

Figure O.3 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 1*

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O-6

Dredge Scenario: Scenario 1
Climatic Scenario: Transitional 1
Spill Rate Estimate: Low (“Realistic”) Case

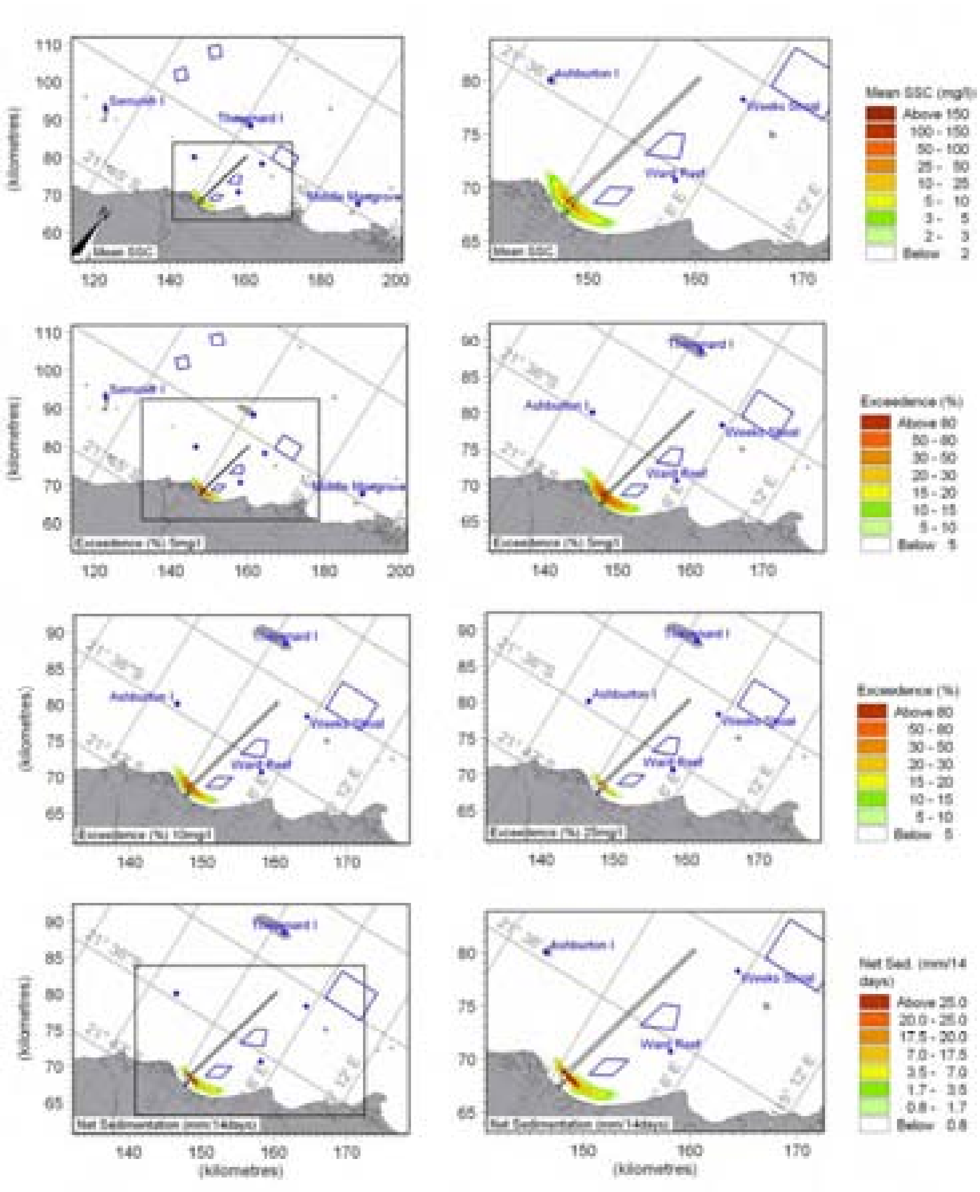

Figure O.4 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 1*

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Dredge Scenario: Scenario 1
Climatic Scenario: Transitional B
Spill Rate Estimate: Low ("Realistic") Case

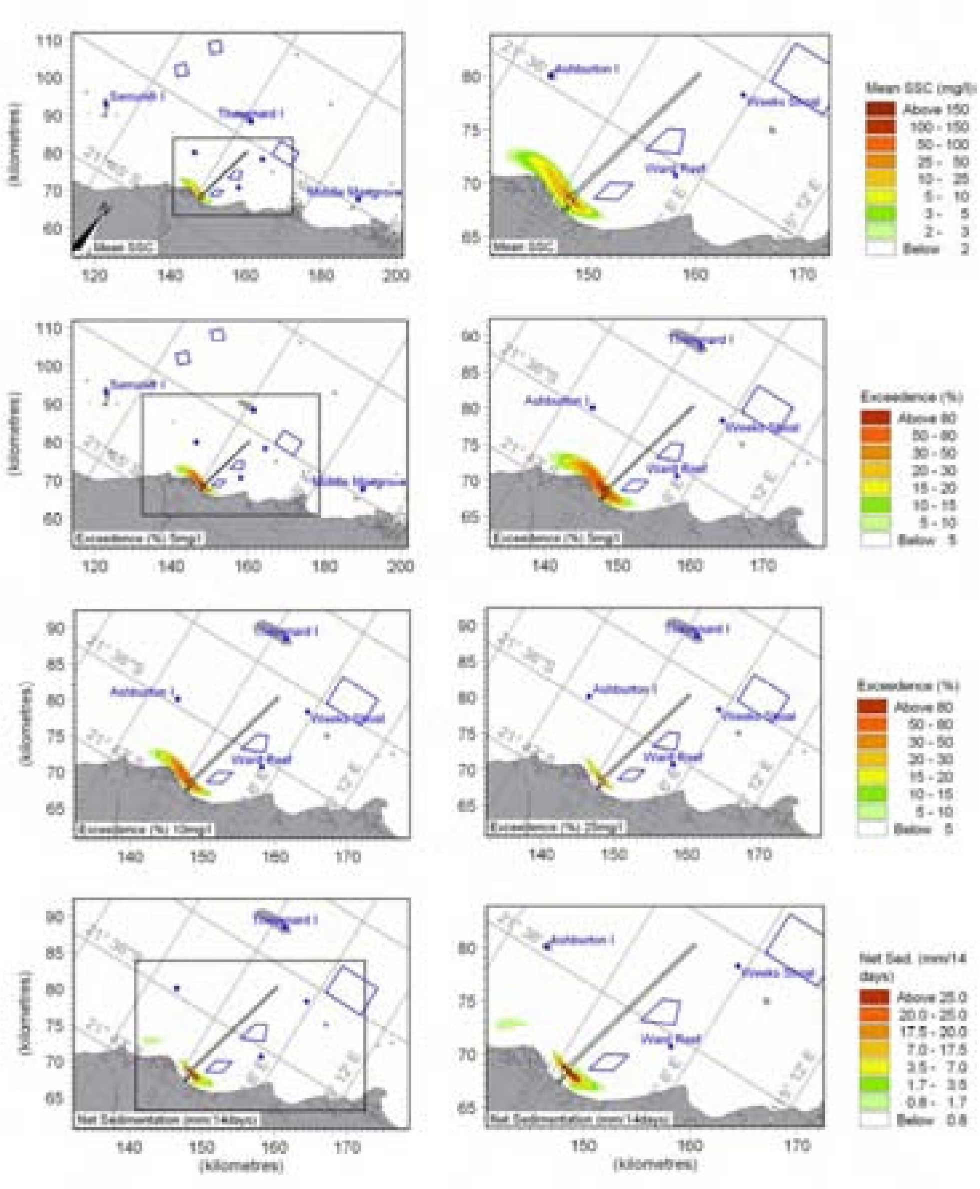

Figure O.5 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 1

O-8

Dredge Scenario: Scenario 1
Climatic Scenario: Winter A
Spill Rate Estimate: Low ("Realistic") Case

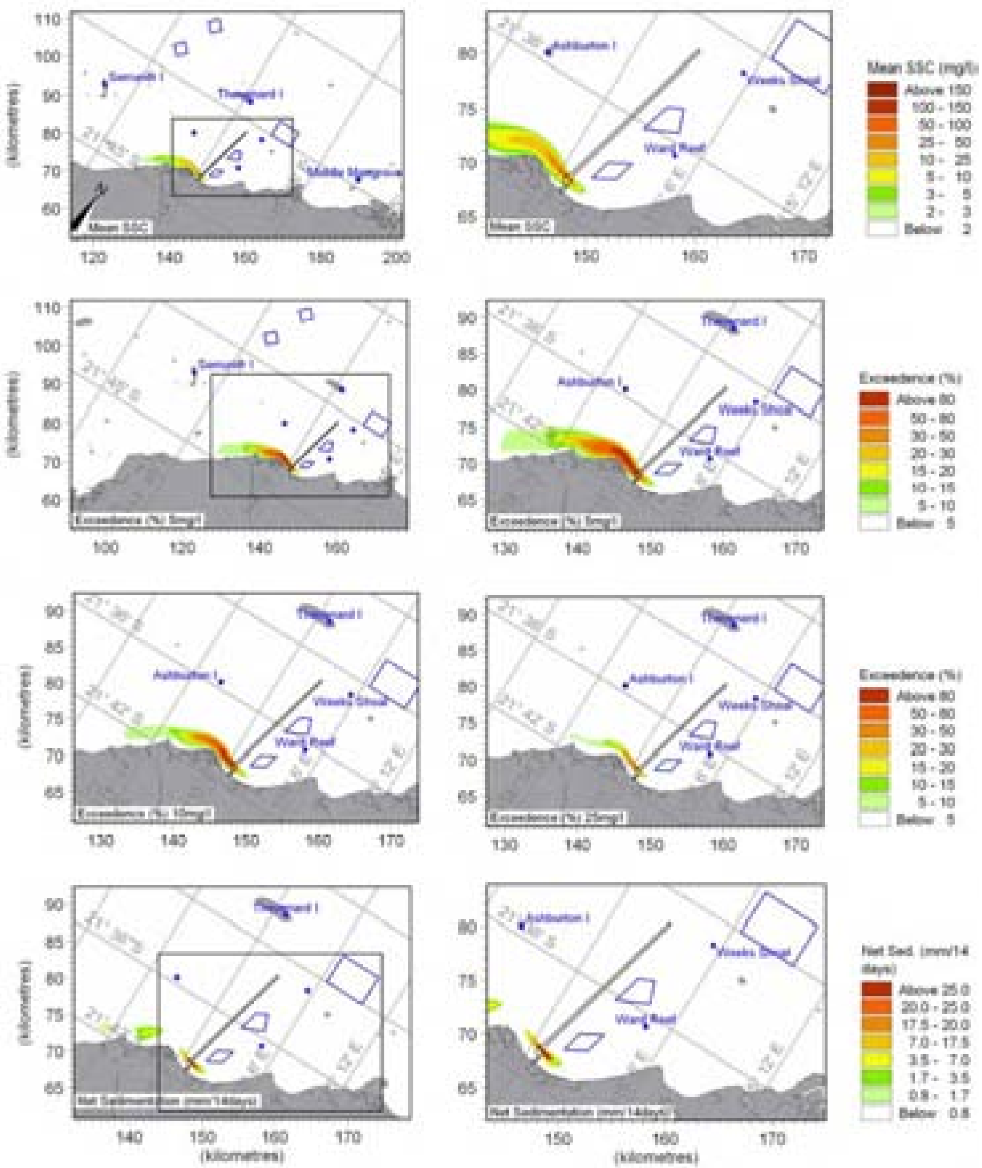

Figure O.6 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 1

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O-9

Dredge Scenario: Scenario 1
Climatic Scenario: Winter B
Spill Rate Estimate: Low ("Realistic") Case

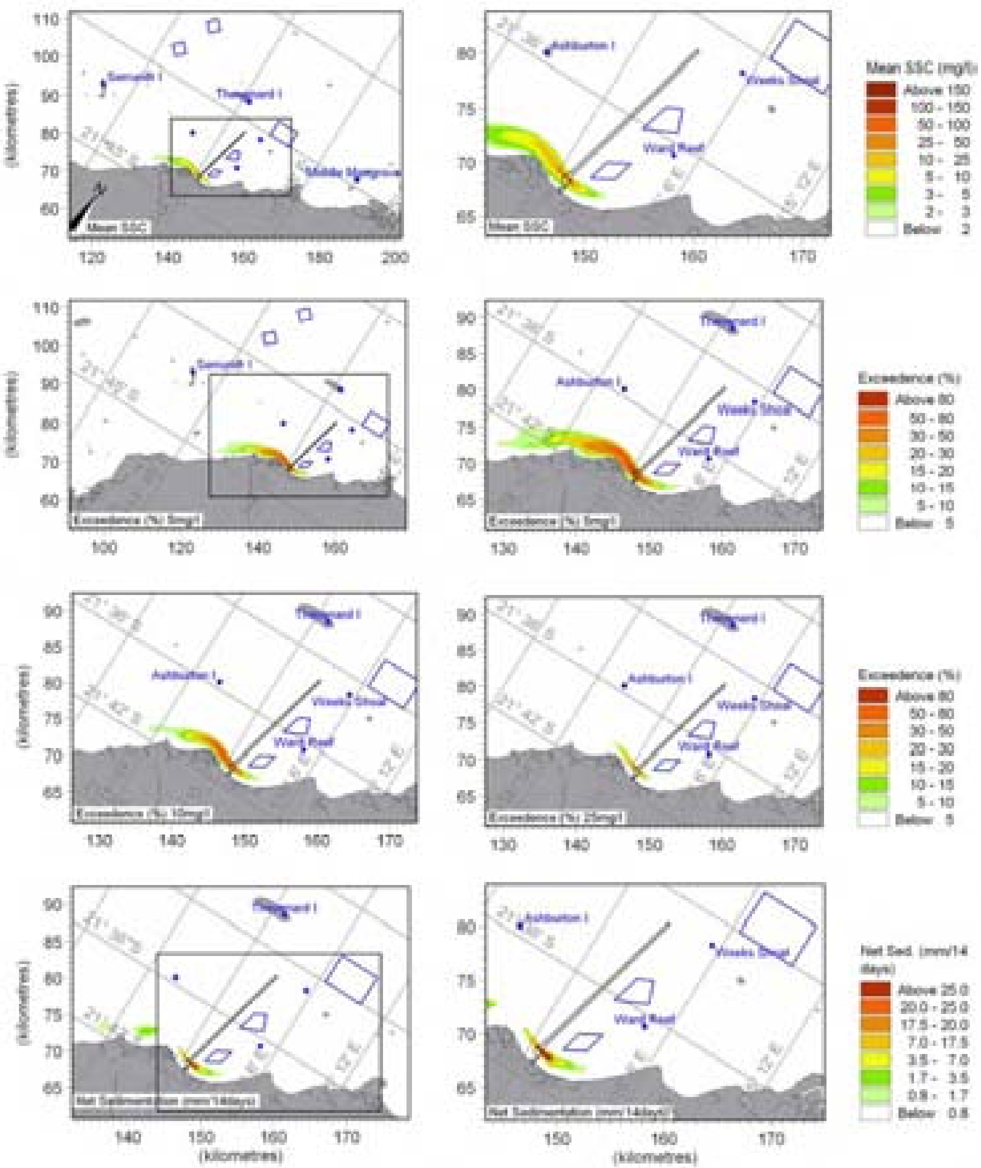

Figure O.7 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 1*

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O.5 Results for High (Worst Case) Spill Rates

Dredge Scenario:	Scenario 1
Climatic Scenario:	Summer A
Spill Rate Estimate:	High ("Worst Case")

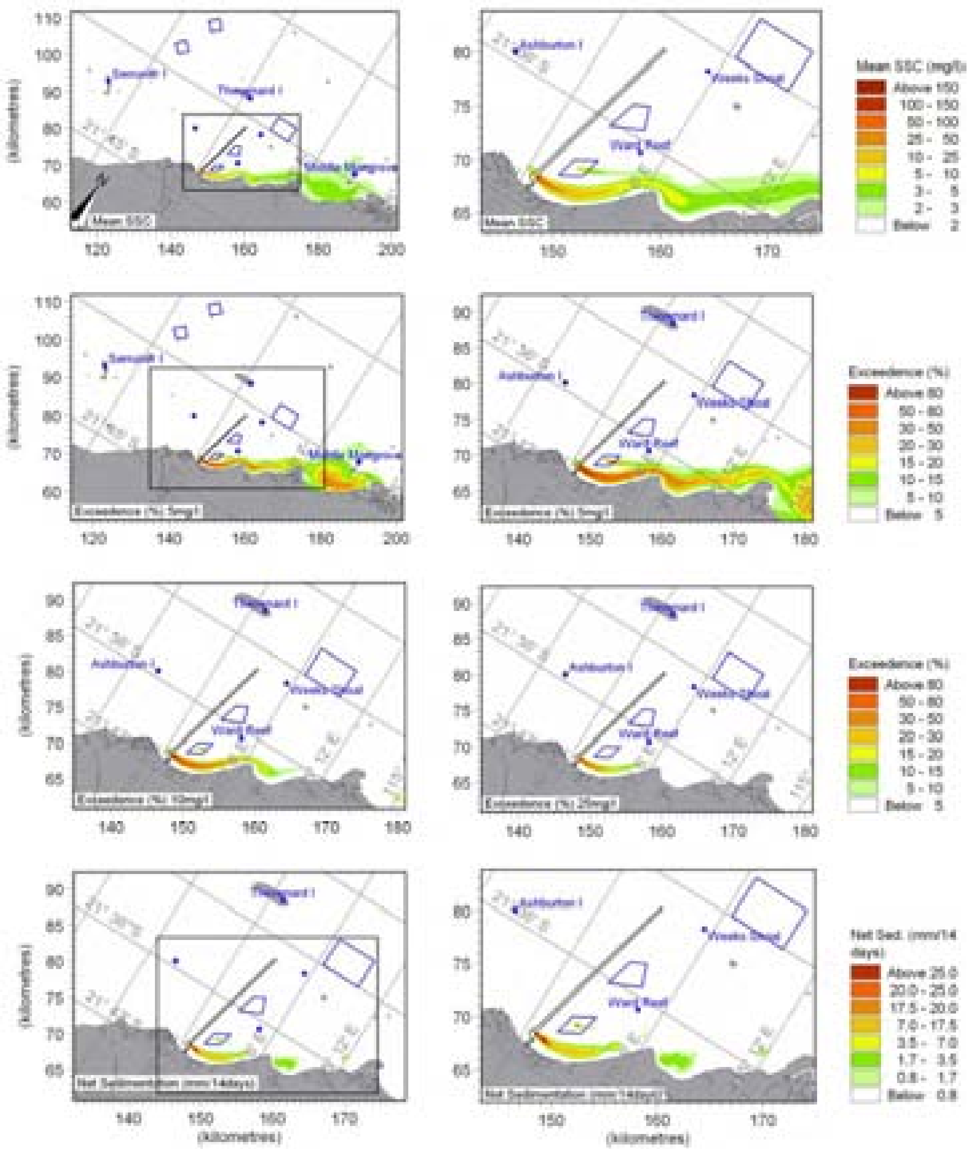

Figure O.8 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/ 14 days) of dredging and disposal works for Scenario 1

Dredge Scenario: Scenario 1
Climatic Scenario: Summer B
Spill Rate Estimate: High ("Worst Case")

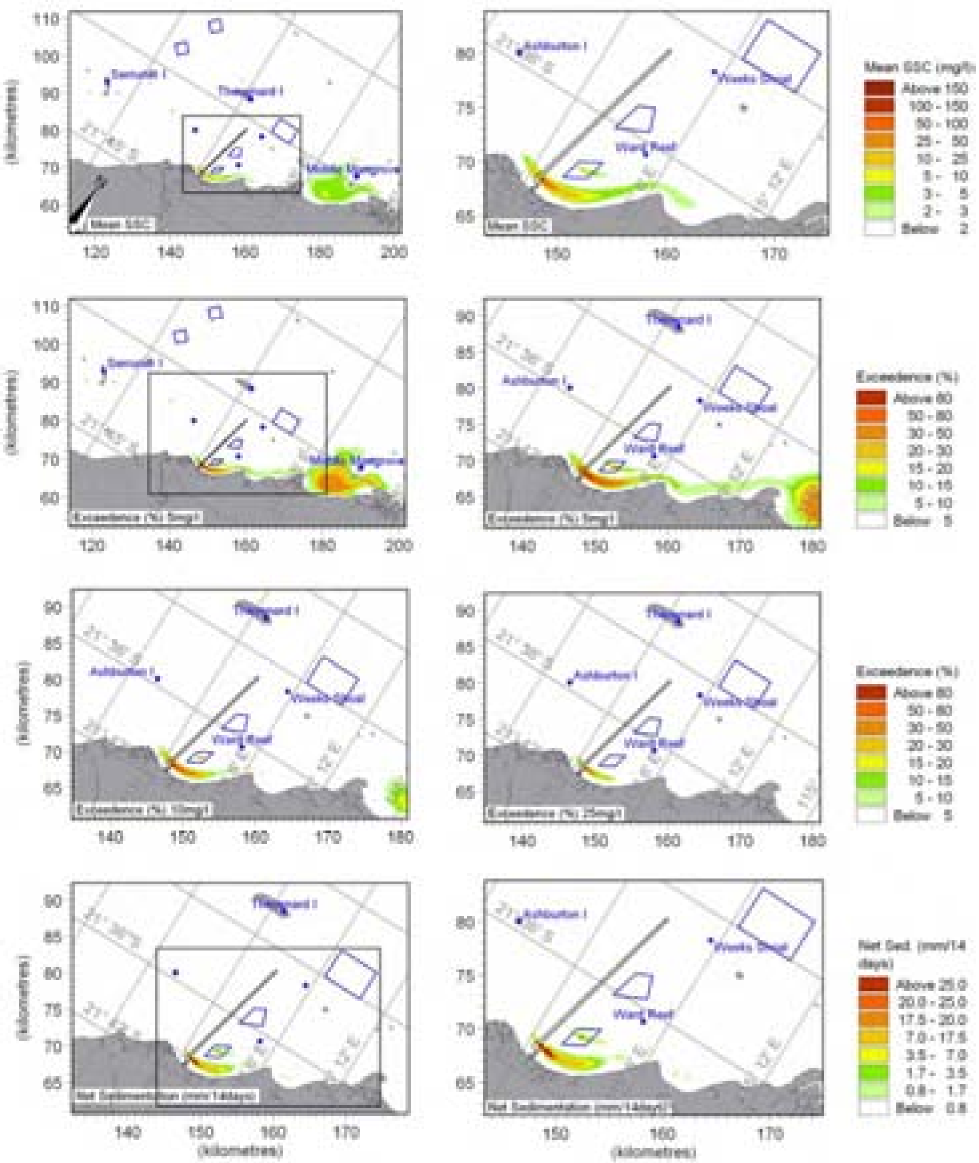

Figure O.9 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/ 14 days) of dredging and disposal works for Scenario 1

O-12

Dredge Scenario: Scenario 1
Climatic Scenario: Transitional A
Spill Rate Estimate: High ("Worst Case")

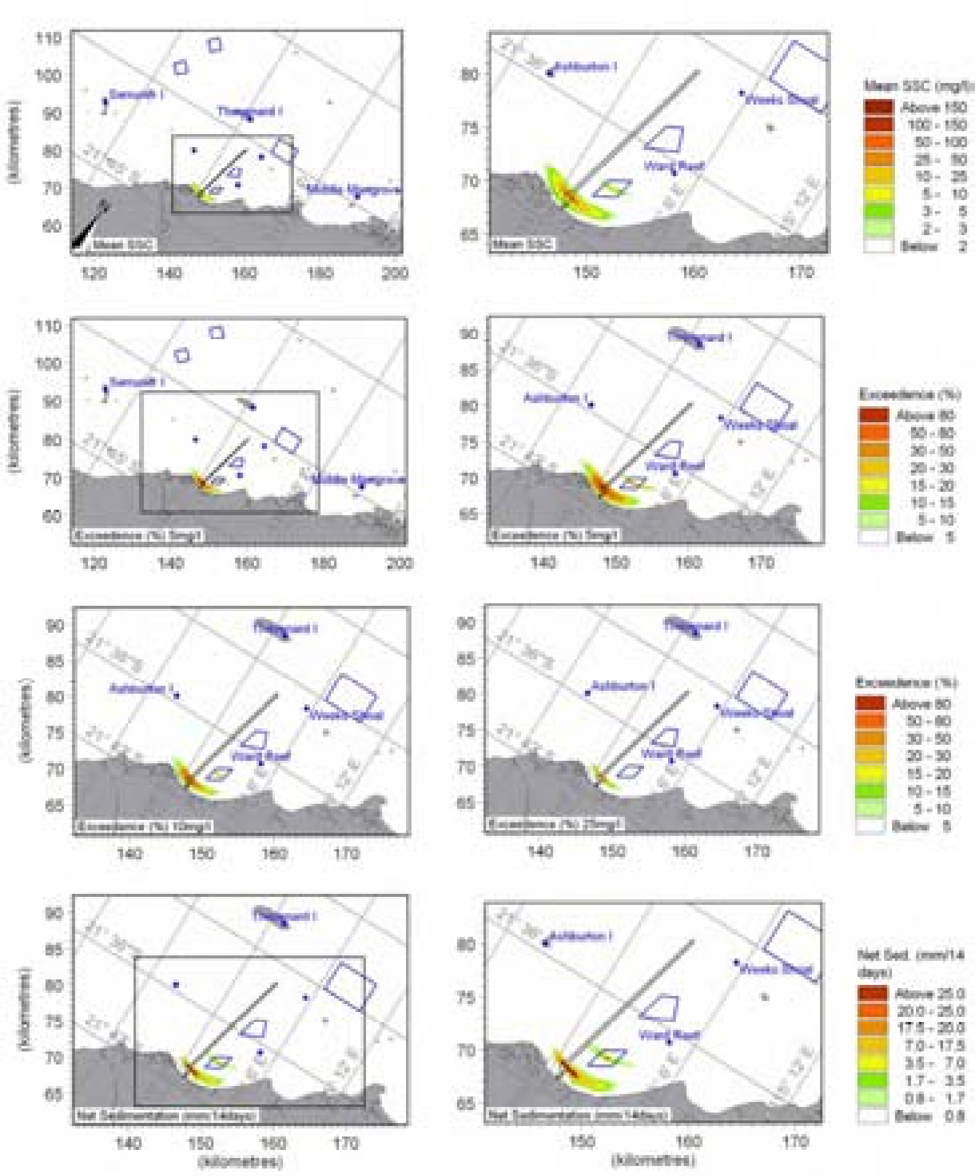

Figure O.10 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/ 14 days) of dredging and disposal works for Scenario 1

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Dredge Scenario: Scenario 1
Climatic Scenario: Transitional B
Spill Rate Estimate: High ("Worst Case")

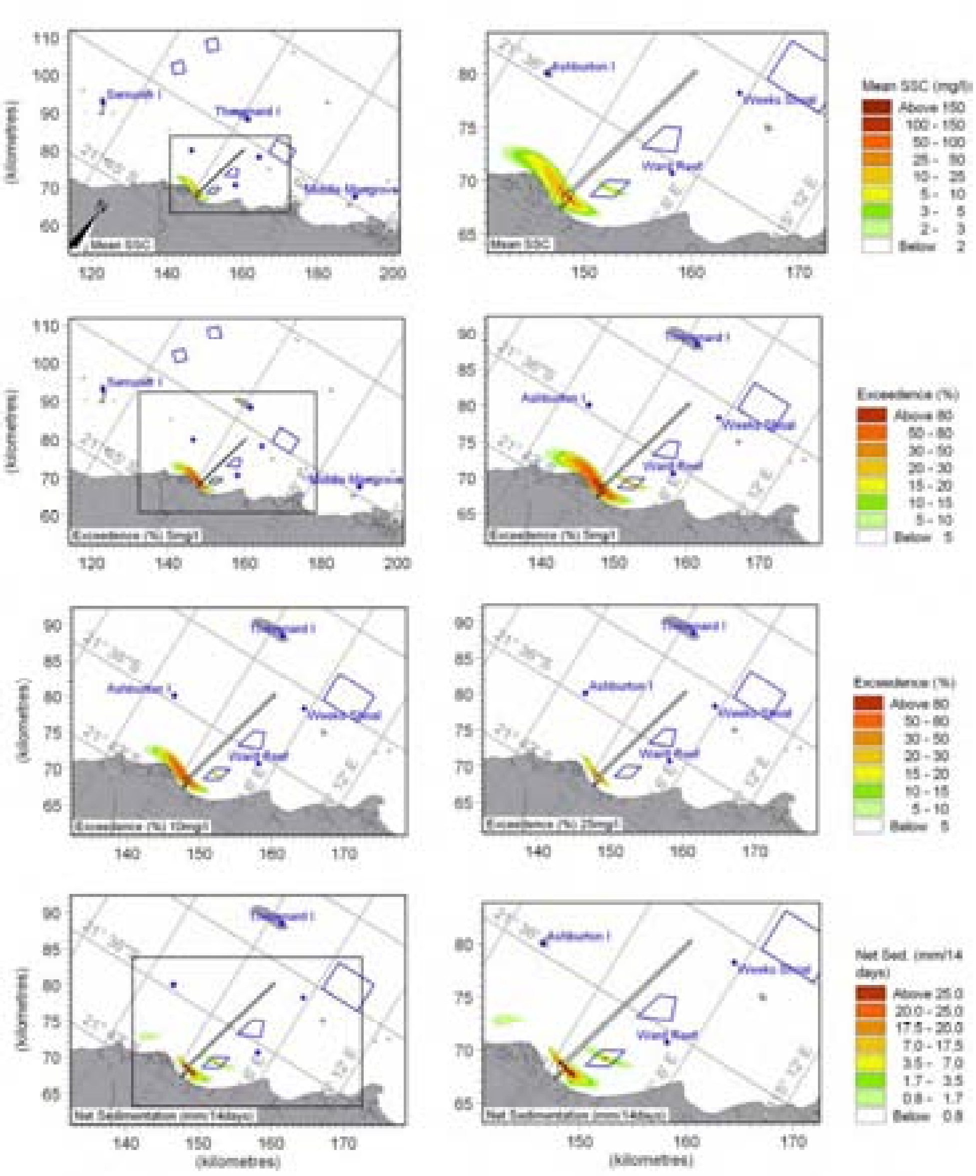

Figure O.11 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/ 14 days) of dredging and disposal works for Scenario 1

O-14

Dredge Scenario: Scenario 1
Climatic Scenario: Winter A
Spill Rate Estimate: High ("Worst Case")

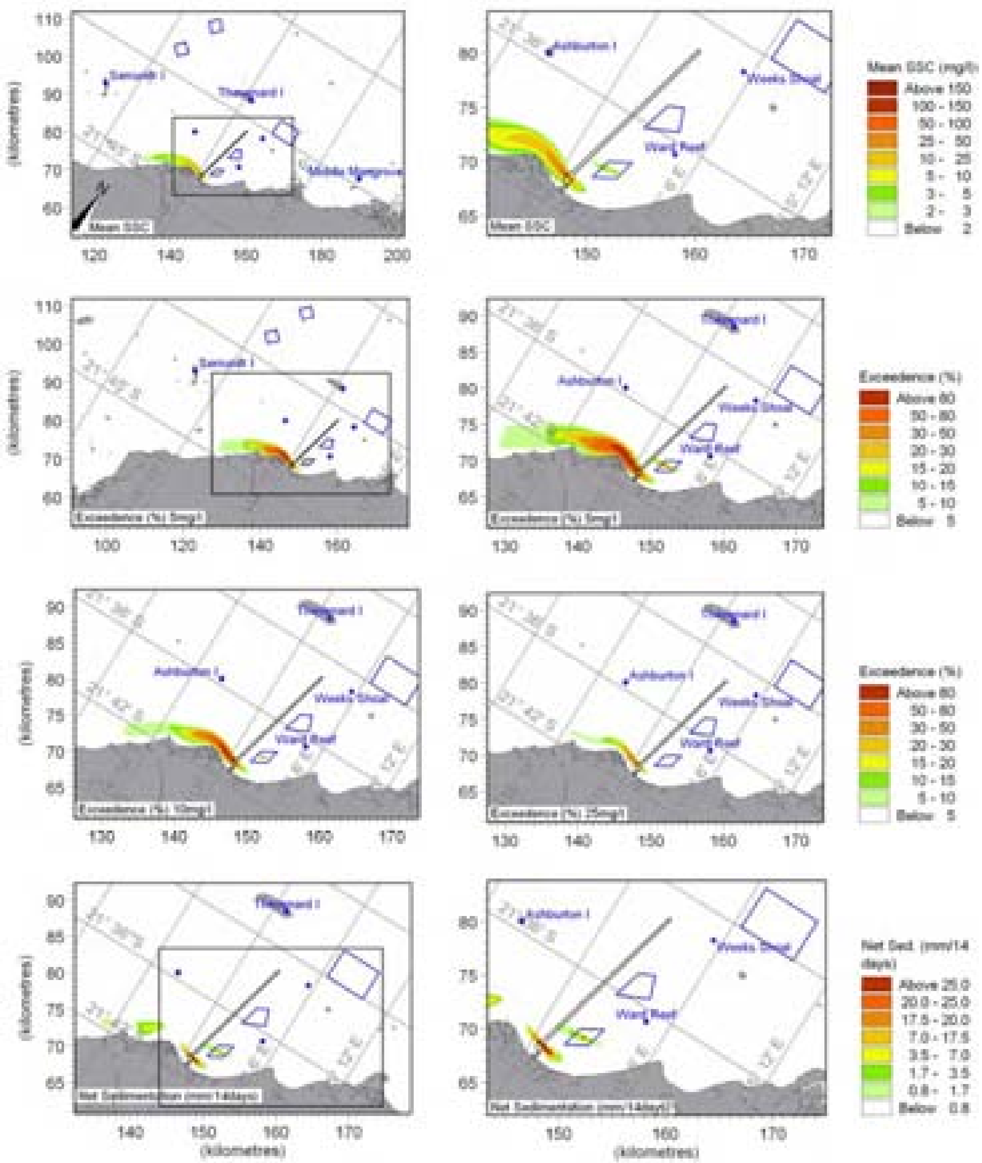

Figure O.12 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/ 14 days) of dredging and disposal works for Scenario 1

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O-15

Dredge Scenario:	Scenario 1
Climatic Scenario:	Winter B
Spill Rate Estimate:	High ("Worst Case")

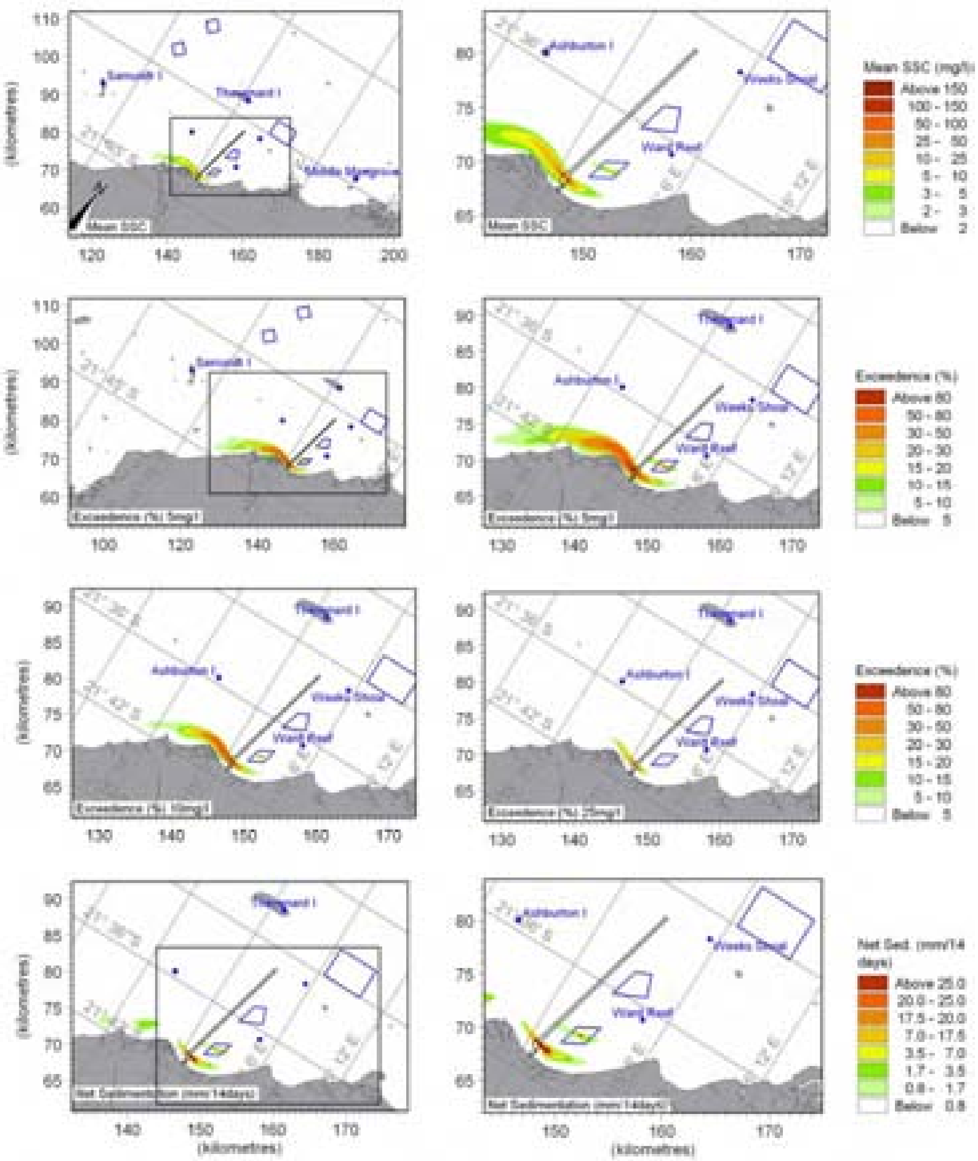

Figure O.13 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 1

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This appendix presents results from the sediment transport model based on hydrodynamics driven by the Onslow wind fields. The reader is referred to the following sections of the main report and additional appendices for further information;

- Section 4.1.3.2 *Wind Fields*
- Section 6.2 *Results for the Dredging of the Shipping Channel*
- Appendix D *Hydrodynamic Model Validation and Calibration*

P.1 Statistical Plots

The established impact criteria (DHI (2010) *Dredge Plume Impact Assessment Report*) are based on sediment loads, both in terms of excess suspended concentrations and sedimentation rates, over 14 day periods. In terms of exposure and impacts, both the concentrations and the duration of the event is important, which is expressed through the exceedence probability of given limits.

For each simulated case, a set of plots showing the statistical output used in the impact assessment have been produced. All plots are for excess concentrations, i.e. sediments originating from the dredging operations and exclusive of ambient concentrations.

Each mosaic plot comprises:

- Mean excess concentration at two scales
- Exceedence of 5mg/l excess concentration at two scales
- Exceedence of 10mg/l excess concentration
- Exceedence of 25mg/l excess concentration
- Net sedimentation rates at two zoomed levels at the site

Note that all concentrations are presented as depth-averaged values. All values are derived over the assessment period (2^{nd} neap/spring tidal cycle of the month for each climatic scenario), i.e. after at least 14 days warm-up period. Exceedences are expressed in percentage time over the assessment period that the exceedence limit is exceeded.

P.2 Description of Dredge Scenario 2

Nearshore Dredging: CSD in PLF basin

- CSD with pumping to barges at -3m LAT for transport to Site C
- Bathymetry with fully dredged access channel to -3m LAT, partly dredged 150m wide channel to -8.3m LAT
- Material available for re-suspension in dredged channel, Site A and Site C
- Includes MOF breakwaters

The locations for the various dredge and placement activities are outlined in Figure P.1, while defined low (realistic) and high (worst-case) spill rates applied in Dredging Scenario 2 are listed in Table 3.2 of the main report.

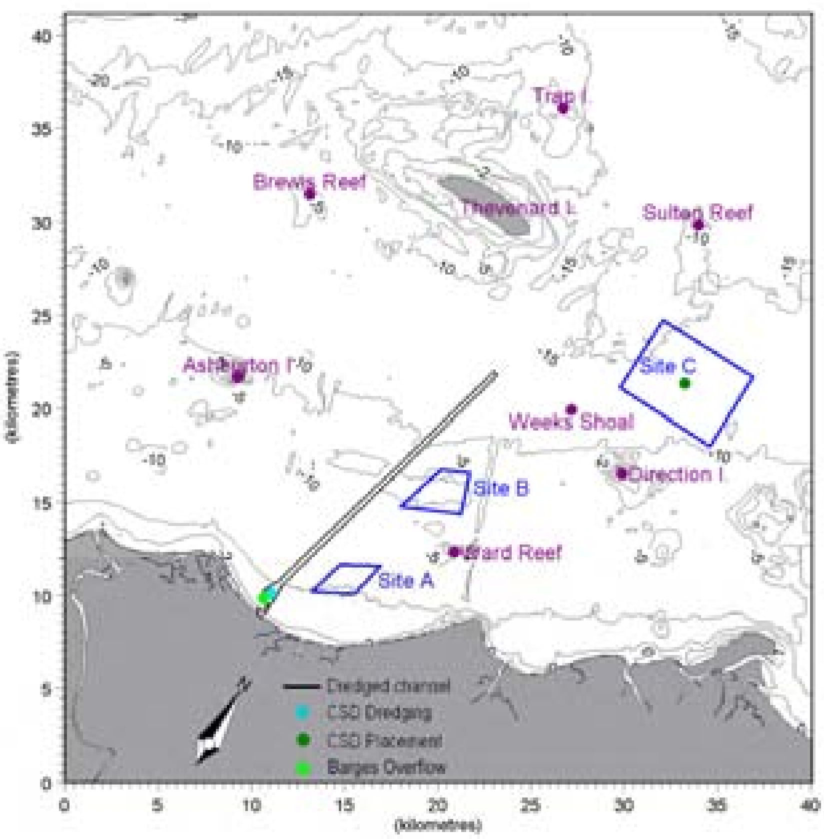

Figure P.1 Sketch of locations for Dredging Scenario 2.

P.3 Summary of Results

Specific observations for Dredge Scenario 2 include:

- The plumes from the CSD dredging of the PLF combined with the overflow of barges at the -3m LAT contour within the PLF leads to a continuous plume running along the coastline – predominantly eastward during summer and westward during winter.
- The plume extends to Beadon Point and Onslow with a mean concentration in the order of 10mg/l during strong summer conditions and to Entrance Point at about 25-50mg/l during winter for "worst case" spill conditions. These values are reduced to 5-10mg/l at Onslow during summer and 10-25mg/l at Entrance Point during winter for the "realistic" spill rates.
- Excess concentrations of 5 mg/l are exceeded more than 80% of the time at Entrance Point during strong winter conditions, and about 50% of the time at Onslow during strong summer conditions.
- The barge filling and overflowing at the -3m LAT contour maintains the plume well landward of Ward Reef.

P.4 Results for Low (Realistic) Spill Rates

Dredge Scenario: Scenario 2
Climatic Scenario: Summer A
Spill Rate Estimate: Low ("Realistic") Case

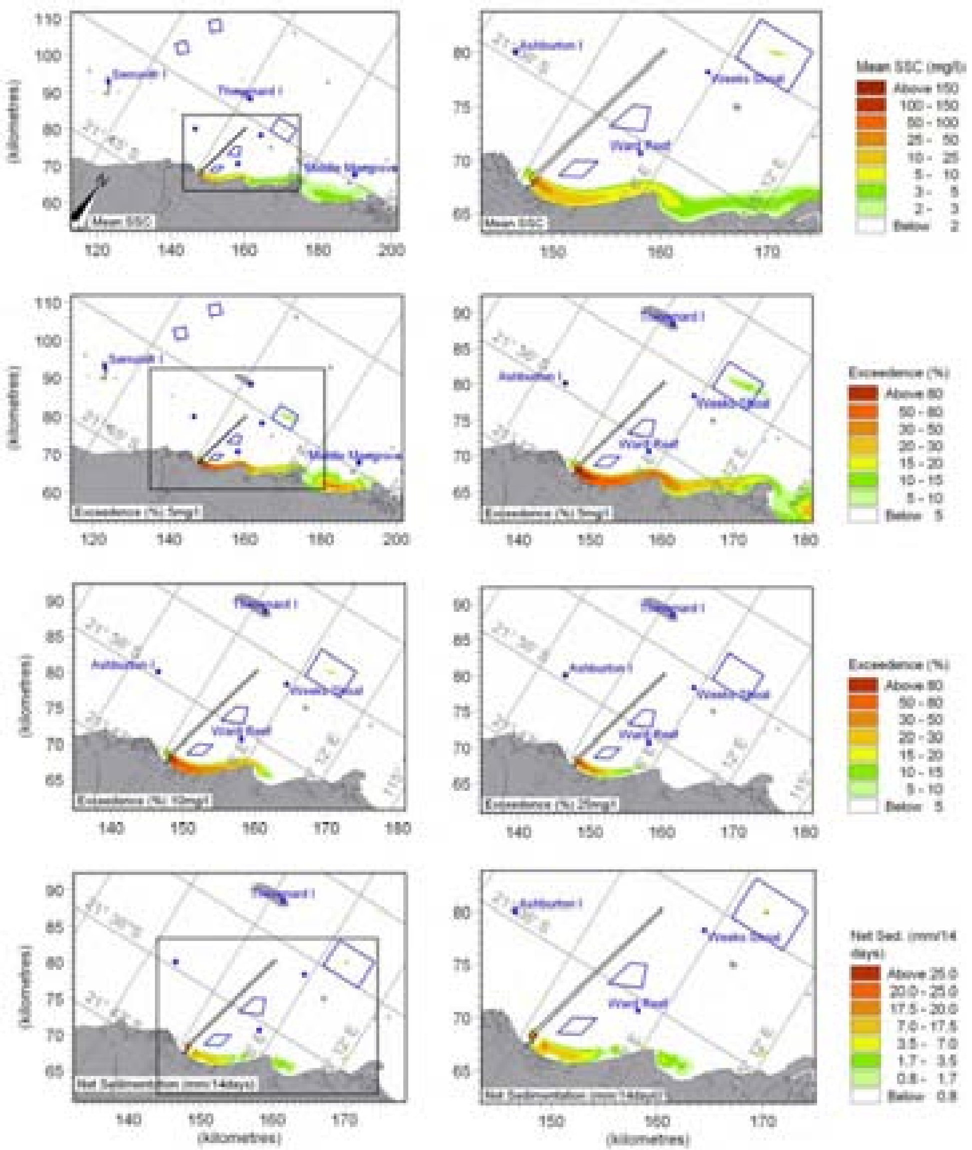

Figure P.2 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 2

Dredge Scenario: Scenario 2
Climatic Scenario: Summer B
Spill Rate Estimate: Low ("Realistic") Case

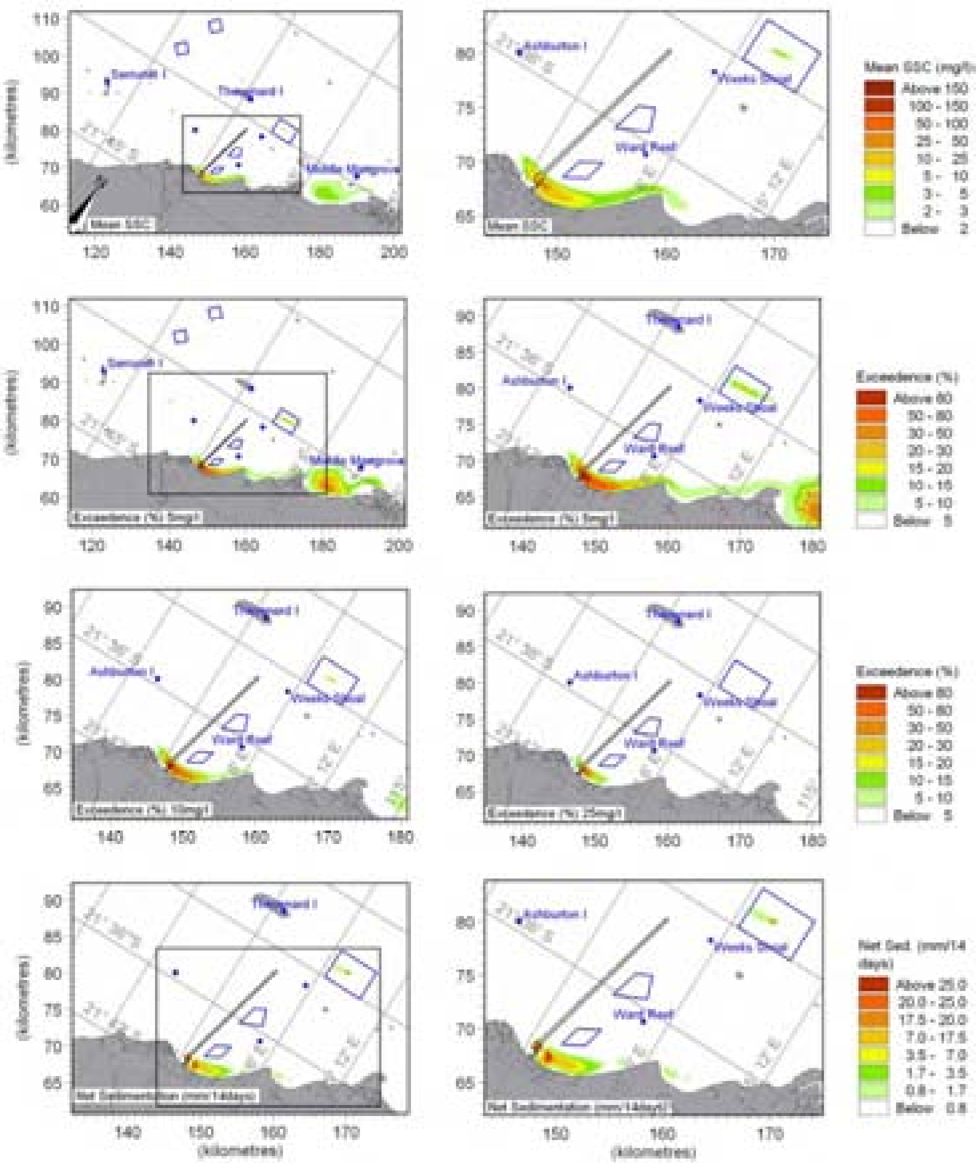

Figure P.3 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 2*

Dredge Scenario: Scenario 2
Climatic Scenario: Transitional A
Spill Rate Estimate: Low (“Realistic”) Case

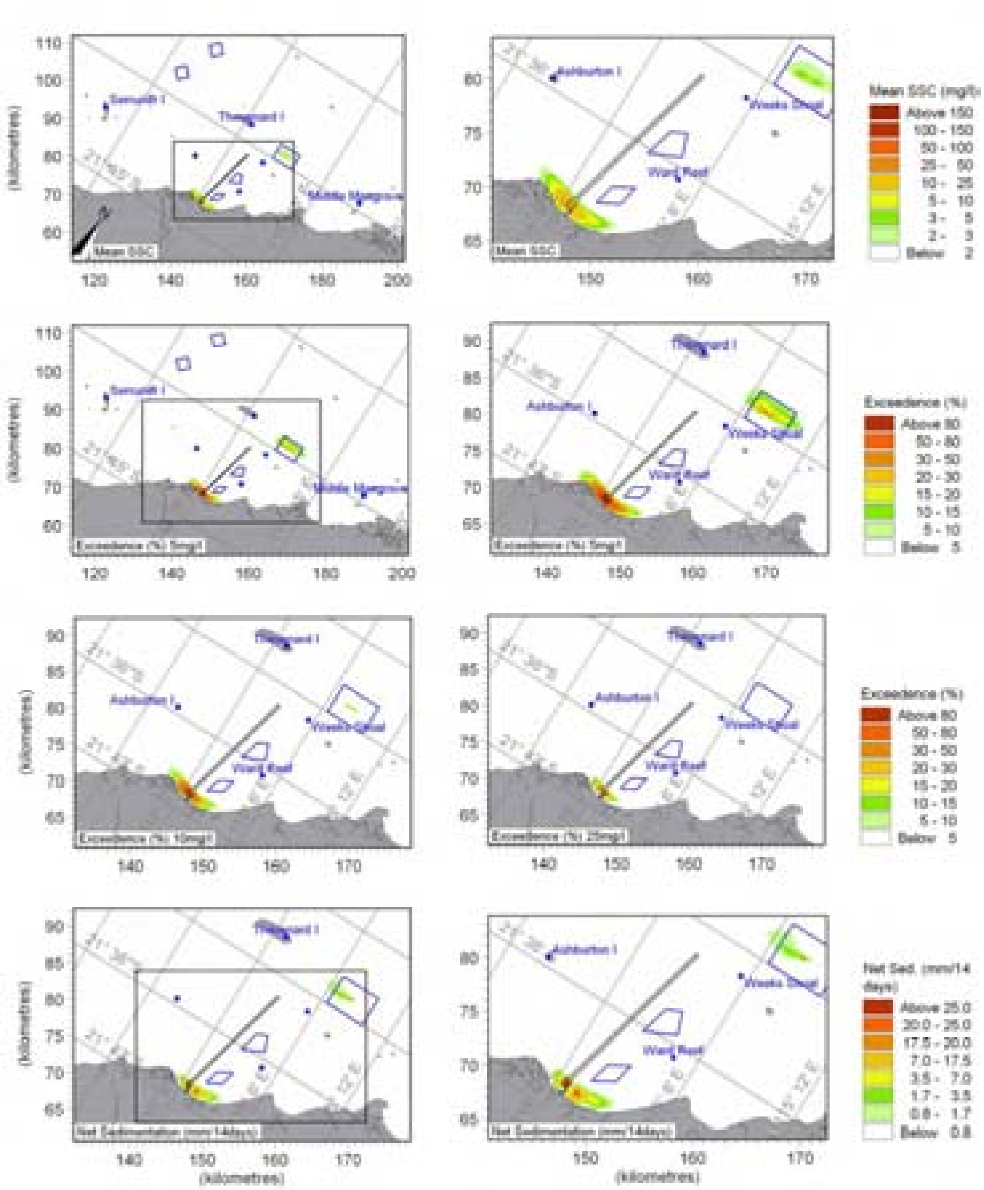

Figure P.4 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 2*

P-6

Dredge Scenario: Scenario 2
Climatic Scenario: Transitional B
Spill Rate Estimate: Low ("Realistic") Case

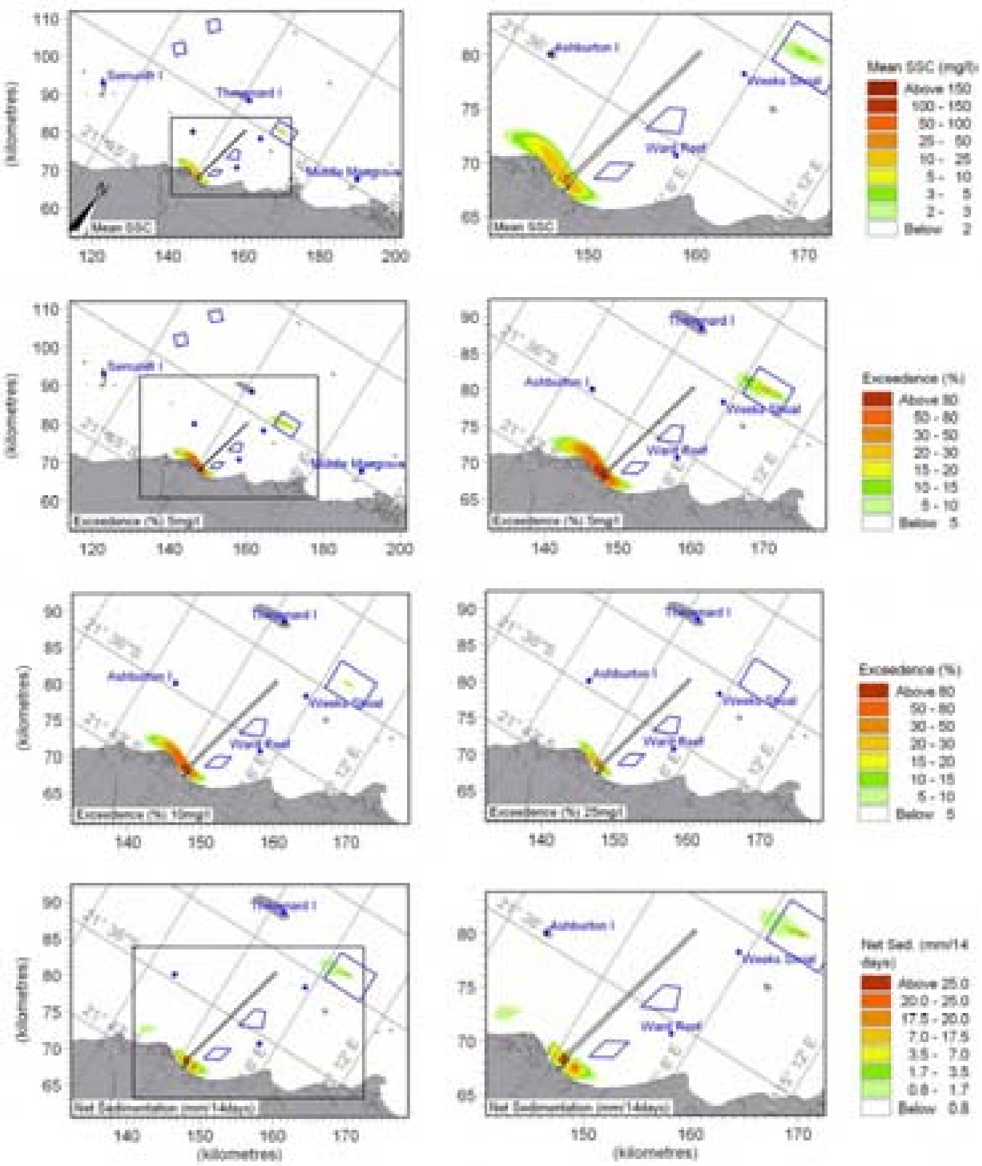

Figure P.5 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 2

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Dredge Scenario:	Scenario 2
Climatic Scenario:	Winter A
Spill Rate Estimate:	Low ("Realistic") Case

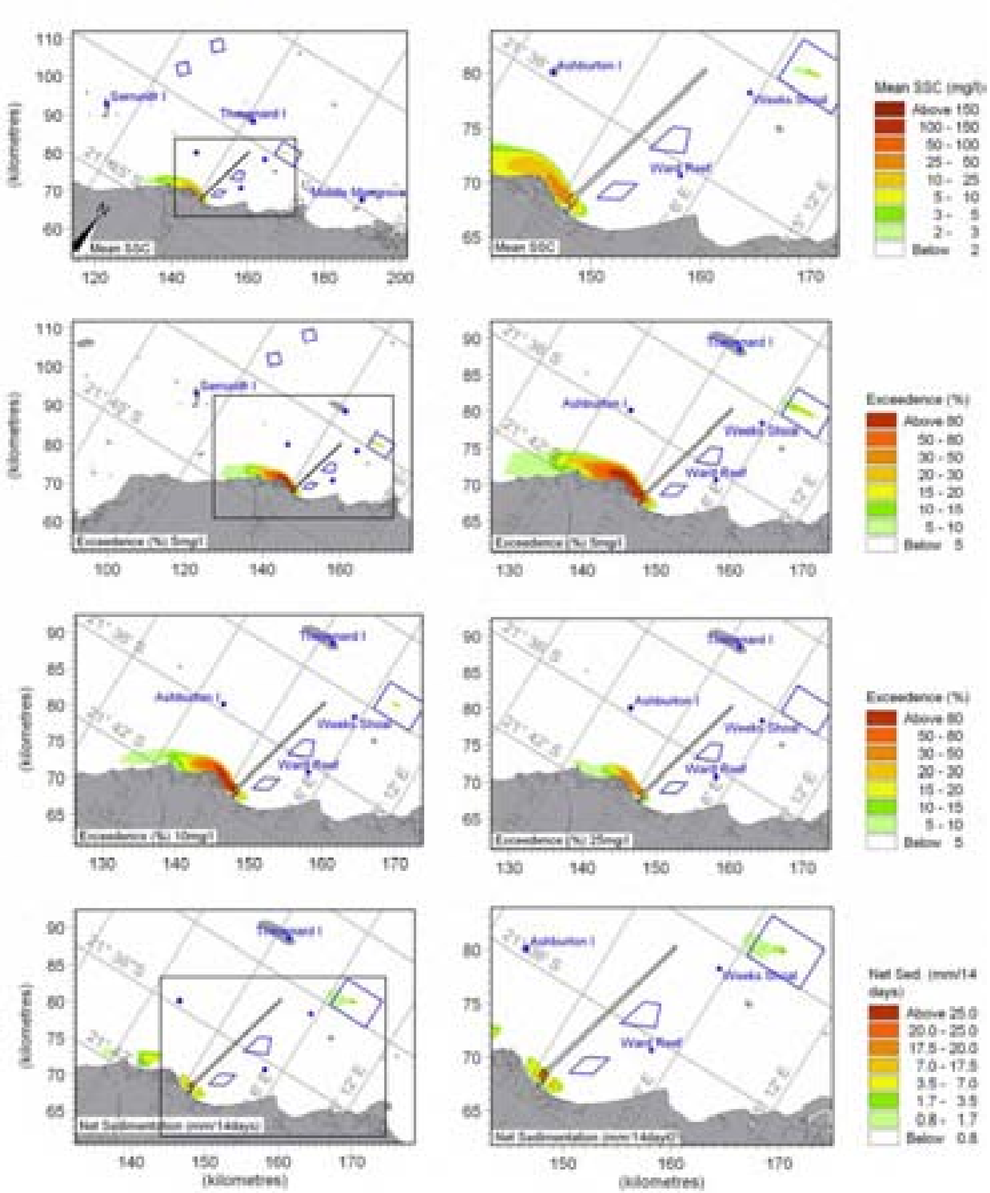

Figure P.6 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 2*

P-8

Dredge Scenario: Scenario 2
Climatic Scenario: Winter B
Spill Rate Estimate: Low ("Realistic") Case

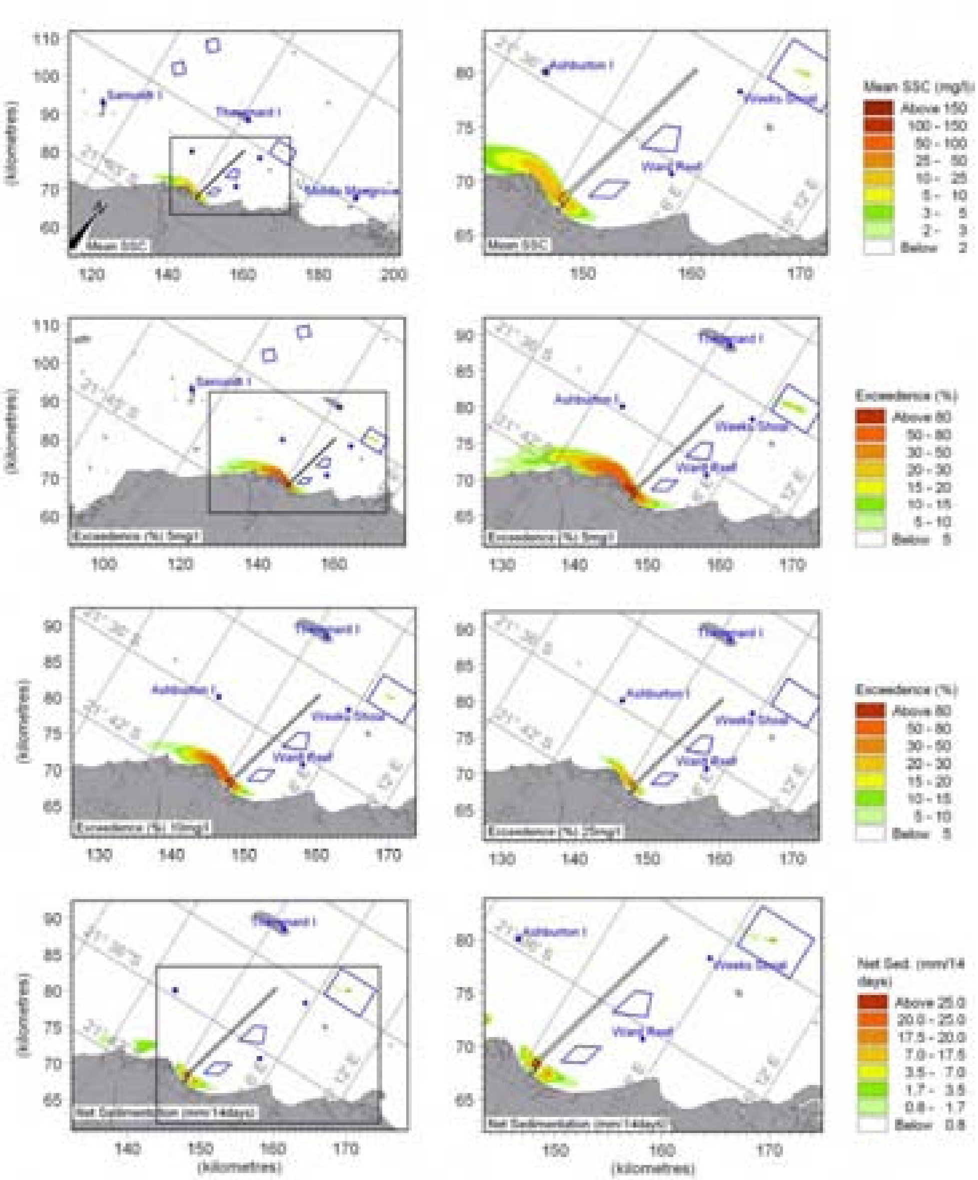

Figure P.7 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 2*

P.5 Results for High (Worst Case) Spill Rates

Dredge Scenario:	Scenario 2
Climatic Scenario:	Summer A
Spill Rate Estimate:	High ("Worst Case")

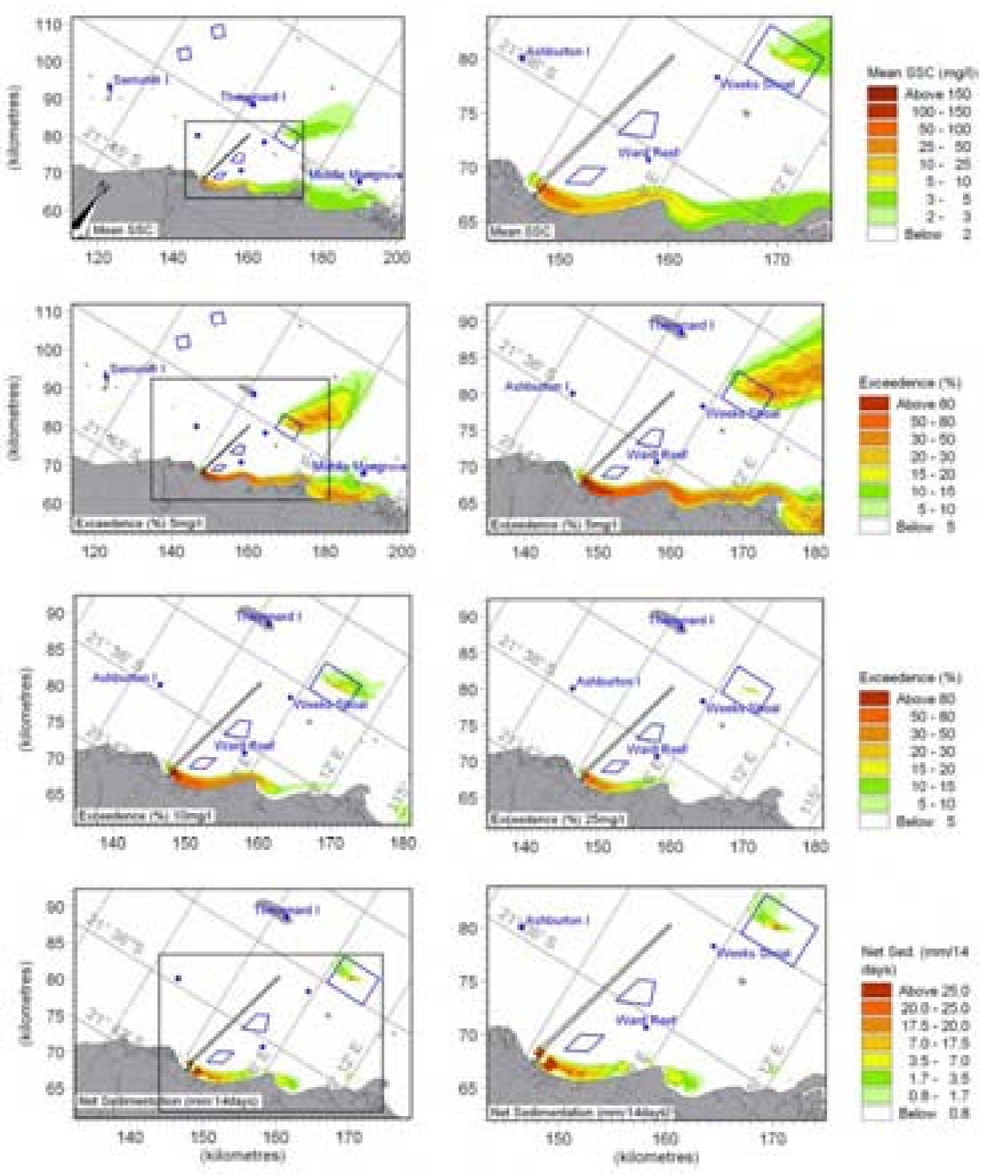

Figure P.8 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 2

Dredge Scenario: Scenario 2
Climatic Scenario: Summer B
Spill Rate Estimate: High ("Worst Case")

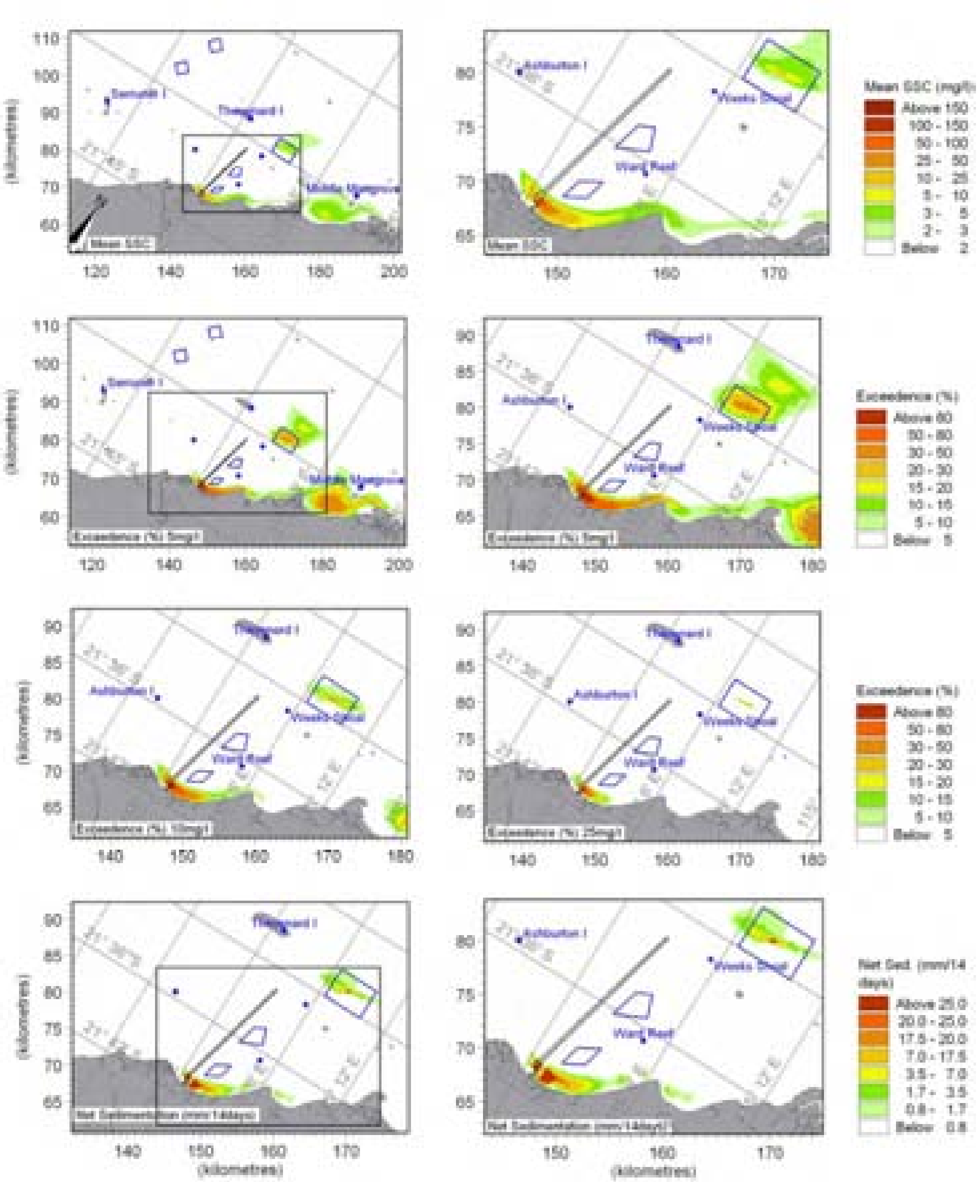

Figure P.9 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 2

P-11

Dredge Scenario:	Scenario 2
Climatic Scenario:	Transitional A
Spill Rate Estimate:	High ("Worst Case")

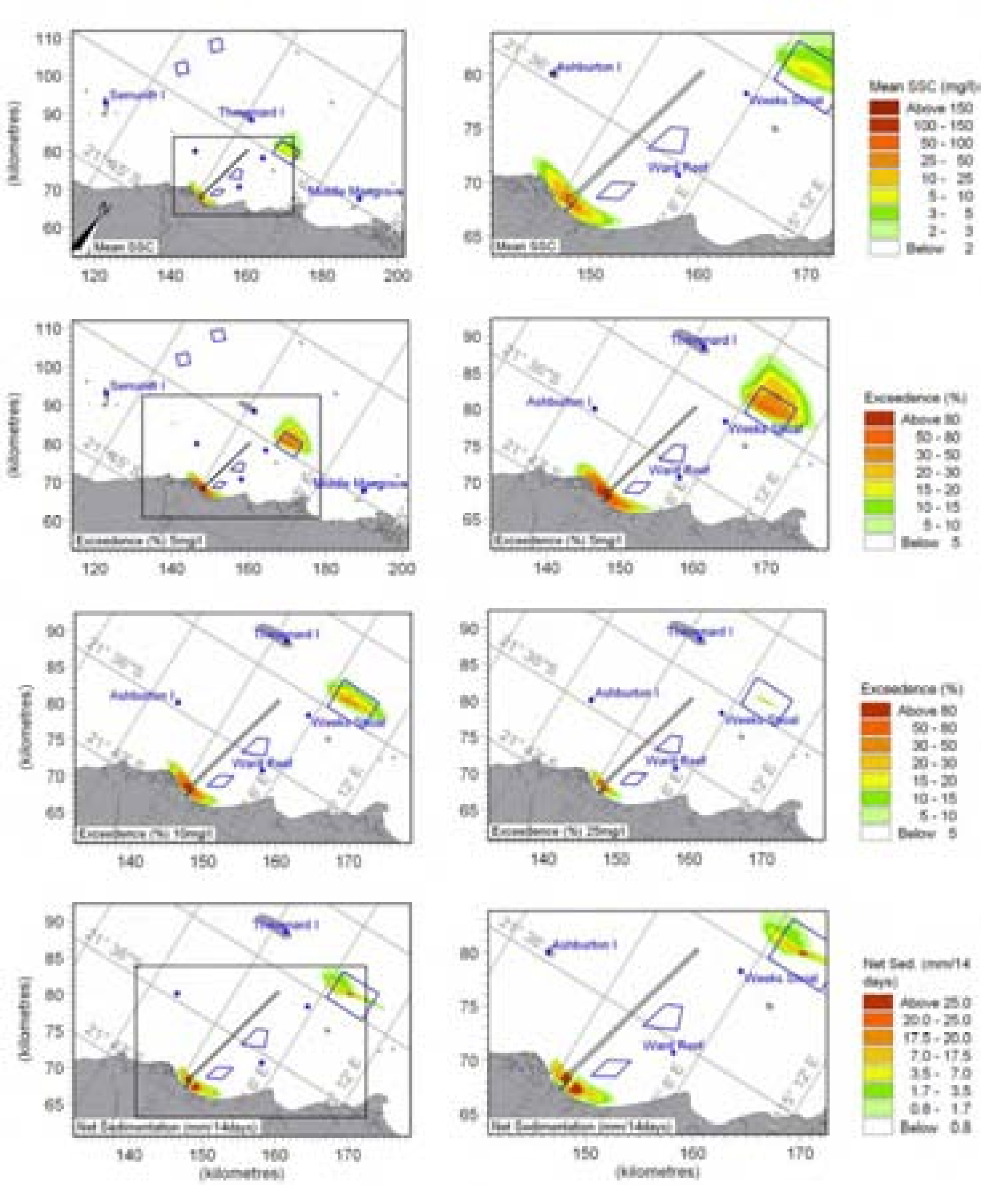

Figure P.10 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 2)

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Dredge Scenario: Scenario 2
Climatic Scenario: Transitional B
Spill Rate Estimate: High ("Worst Case")

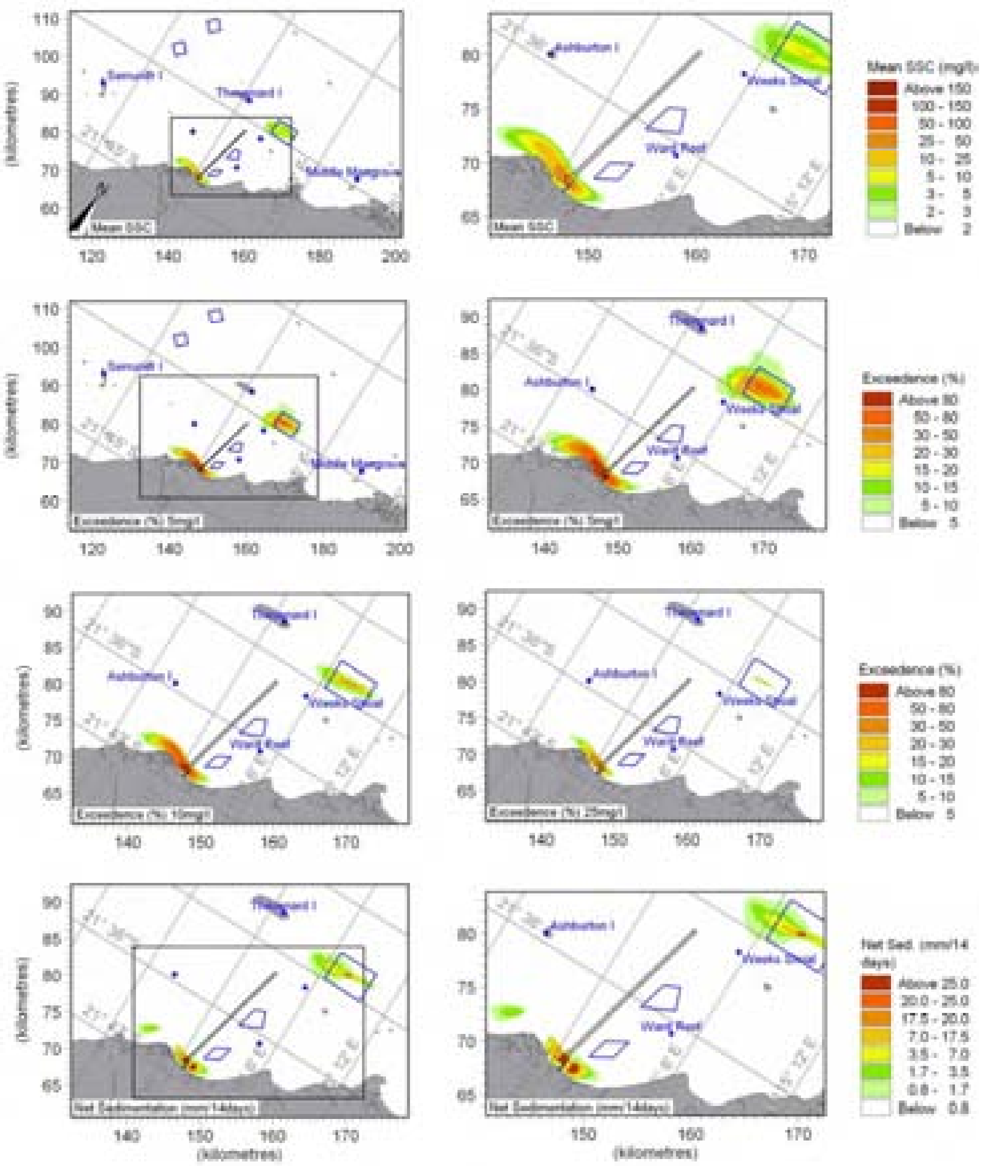

Figure P.11 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 2

Dredge Scenario: Scenario 2
Climatic Scenario: Winter A
Spill Rate Estimate: High ("Worst Case")

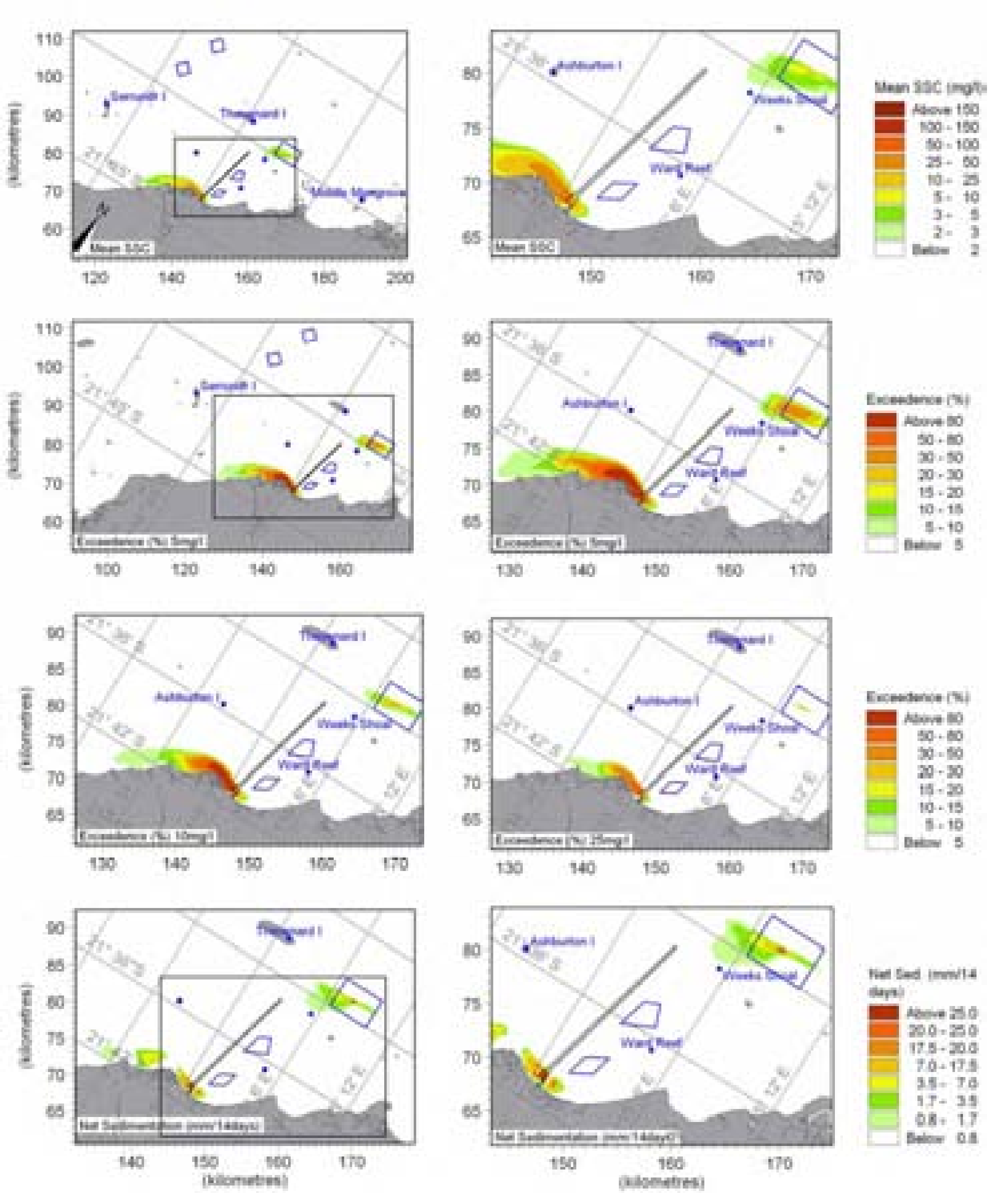

Figure P.12 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 2

Dredge Scenario: Scenario 2
Climatic Scenario: Winter B
Spill Rate Estimate: High ("Worst Case")

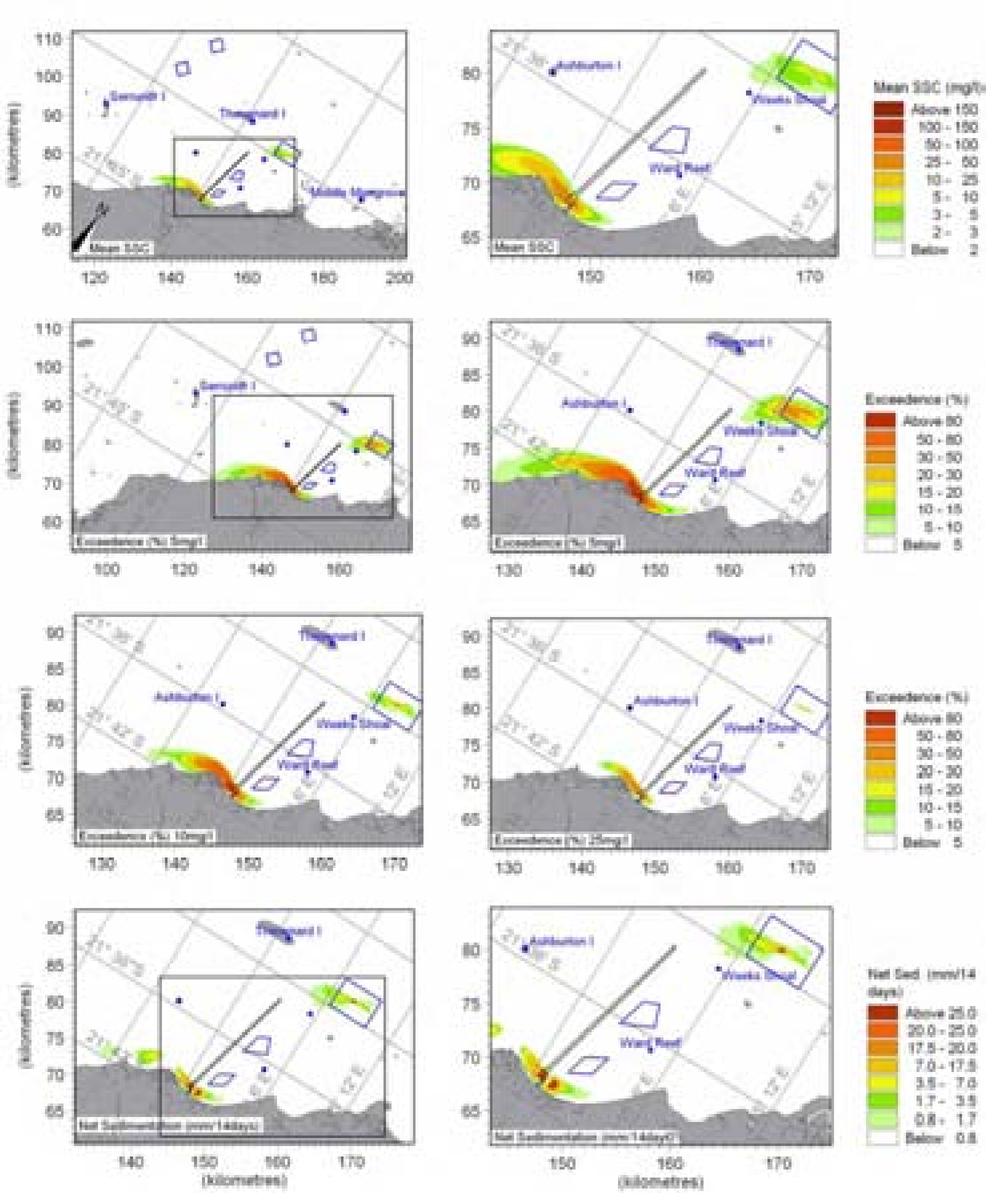

Figure P.13 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 2

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This appendix presents results from the sediment transport model based on hydrodynamics driven by the Onslow wind fields. The reader is referred to the following sections of the main report and additional appendices for further information;

- Section 4.1.3.2 *Wind Fields*
- Section 6.2 *Results for the Dredging of the Shipping Channel*
- Appendix D *Hydrodynamic Model Validation and Calibration*

Q.1 Statistical Plots

The established impact criteria (DHI (2010) *Dredge Plume Impact Assessment Report)* are based on sediment loads, both in terms of excess suspended concentrations and sedimentation rates, over 14 day periods. In terms of exposure and impacts, both the concentrations and the duration of the event is important, which is expressed through the exceedence probability of given limits.

For each simulated case, a set of plots showing the statistical output used in the impact assessment have been produced. All plots are for excess concentrations, i.e. sediments originating from the dredging operations and exclusive of ambient concentrations.

Each mosaic plot comprises:

- Mean excess concentration at two scales
- Exceedence of 5mg/l excess concentration at two scales
- Exceedence of 10mg/l excess concentration
- Exceedence of 25mg/l excess concentration
- Net sedimentation rates at two zoomed levels at the site

Note that all concentrations are presented as depth-averaged values. All values are derived over the assessment period (2nd neap/spring tidal cycle of the month for each climatic scenario), i.e. after at least 14 days warm-up period. Exceedences are expressed in percentage time over the assessment period that the exceedence limit is exceeded.

Q.2 Description of Dredge Scenario 3

Nearshore Dredging: CSD in MOF

- CSD with pumping to barges and transport and disposal at Site C
- Bathymetry with fully dredged, 75m wide channel to -6m LAT and barge access channel.
- Material available for re-suspension in dredged channel, Sites A & C.
- Includes MOF breakwaters

Offshore Dredging: Approach Channel – Section 4 sand

- 5,000m^3 TSHD with disposal at placement Site C
- Dredging along Sections 4 to bring PLF approach channel down to -8m LAT

The locations for the various dredge and placement activities are outlined in Figure Q.1, while defined low (realistic) and high (worst-case) spill rates applied in Dredging Scenario 3 are listed in Table 3.2 of the man report.

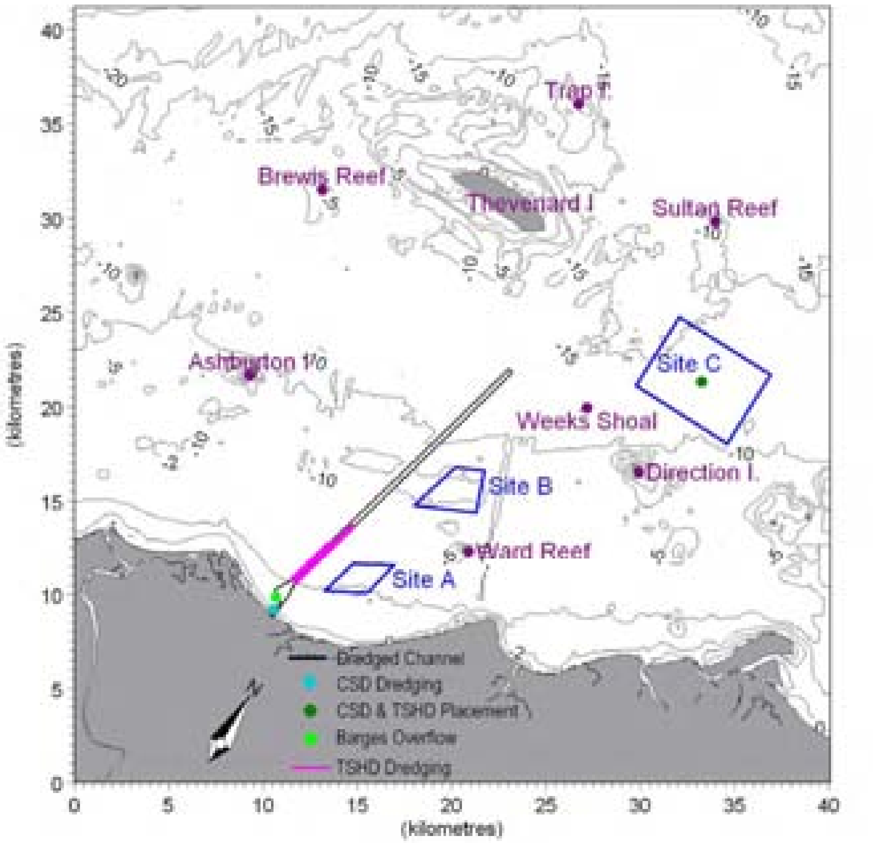

Figure Q.1 Sketch of locations for Dredging Scenario 3.

Q.3 Summary of Results

Specific observations for Dredge Scenario 3 include:

- The plumes from the nearshore CSD dredging of the PLF with pumping ashore leads to an elongated plume "hugging" the coastline in a predominantly easterly direction during summer and westerly direction during winter.
- The 5,000m^3 TSHD operation leads to a lower concentration plume along Section 4 of the channel.
- The combined CSD and TSHD plume creates a wide band along the coastline, just missing Ward Reef.

Q.4 Results for Low (Realistic) Spill Rates

Dredge Scenario: Scenario 3
Climatic Scenario: Summer A
Spill Rate Estimate: Low ("Realistic") Case

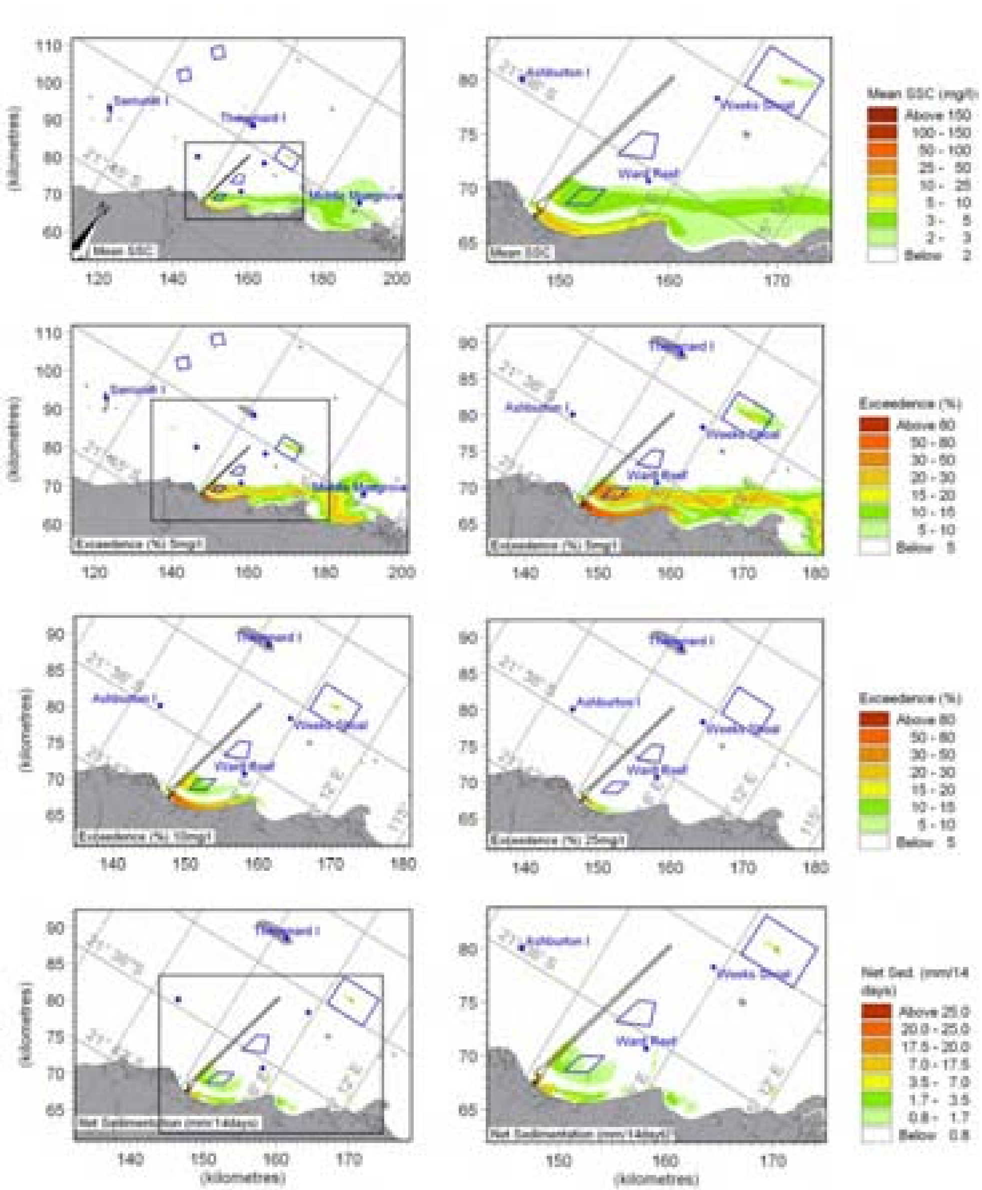

Figure Q.2 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 3

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Dredge Scenario: Scenario 3
Climatic Scenario: Summer B
Spill Rate Estimate: Low ("Realistic") Case

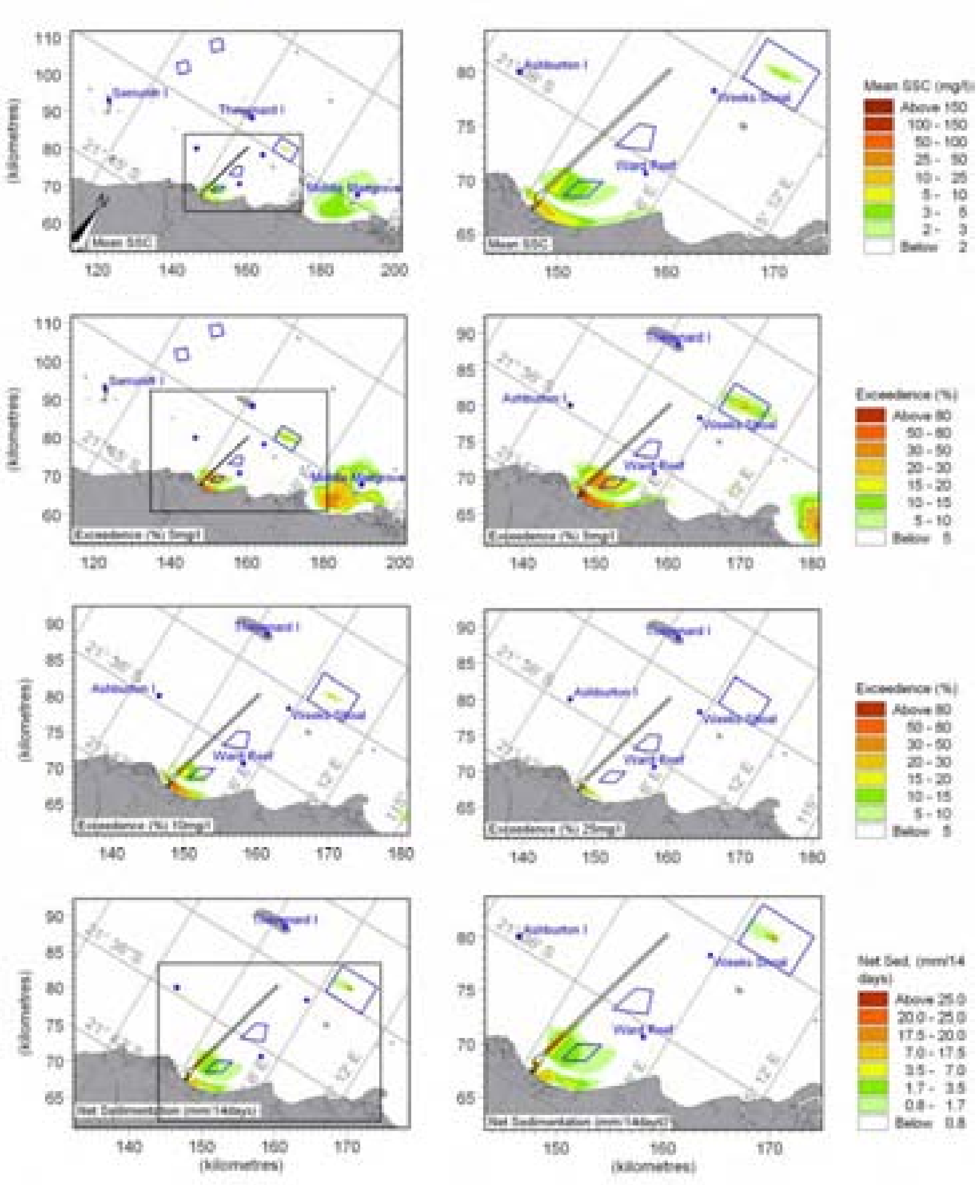

Figure Q.3 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 3

Q-5

Dredge Scenario: Scenario 3
Climatic Scenario: Transitional A
Spill Rate Estimate: Low ("Realistic") Case

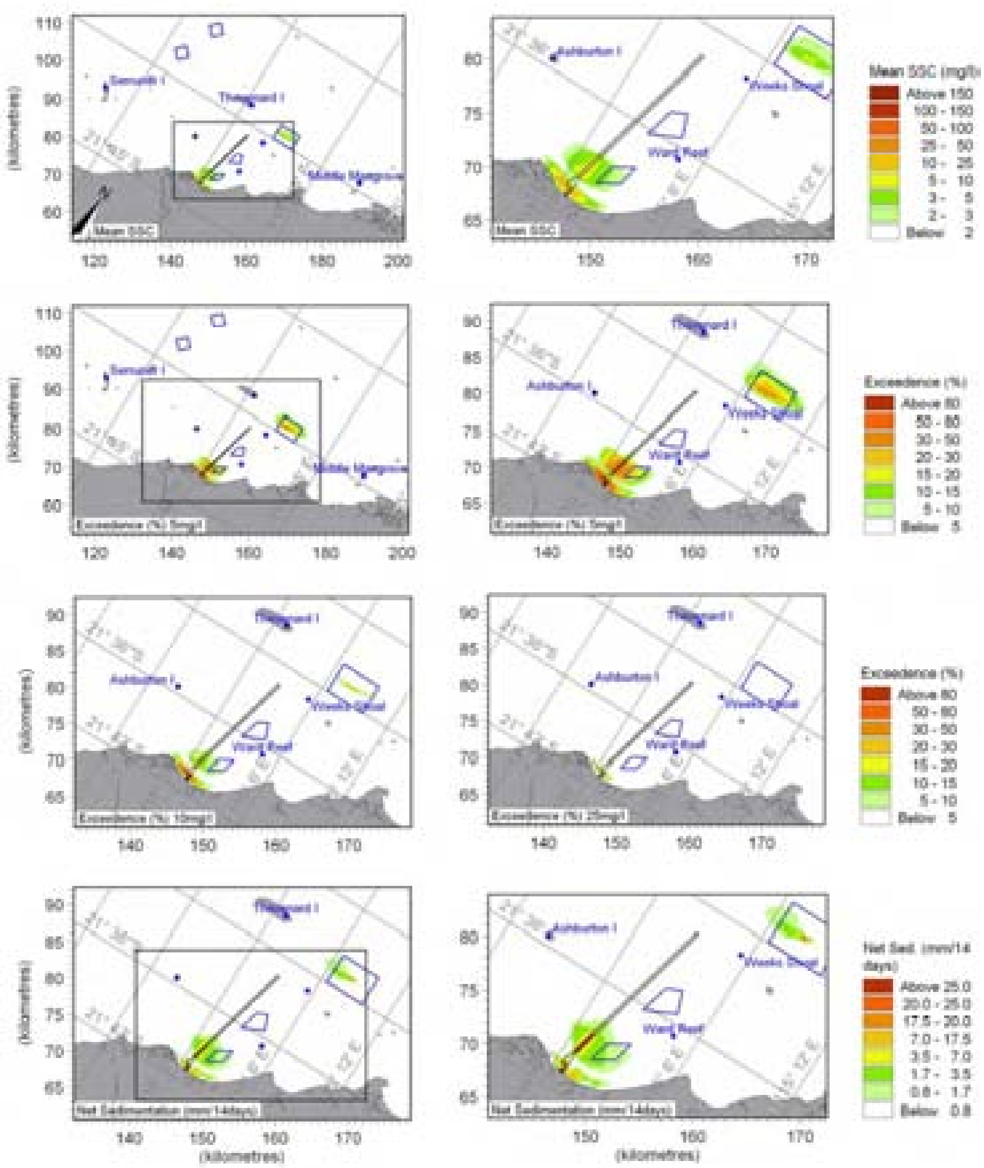

Figure Q.4 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 3)

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Dredge Scenario:	Scenario 3
Climatic Scenario:	Transitional B
Spill Rate Estimate:	Low (“Realistic”) Case

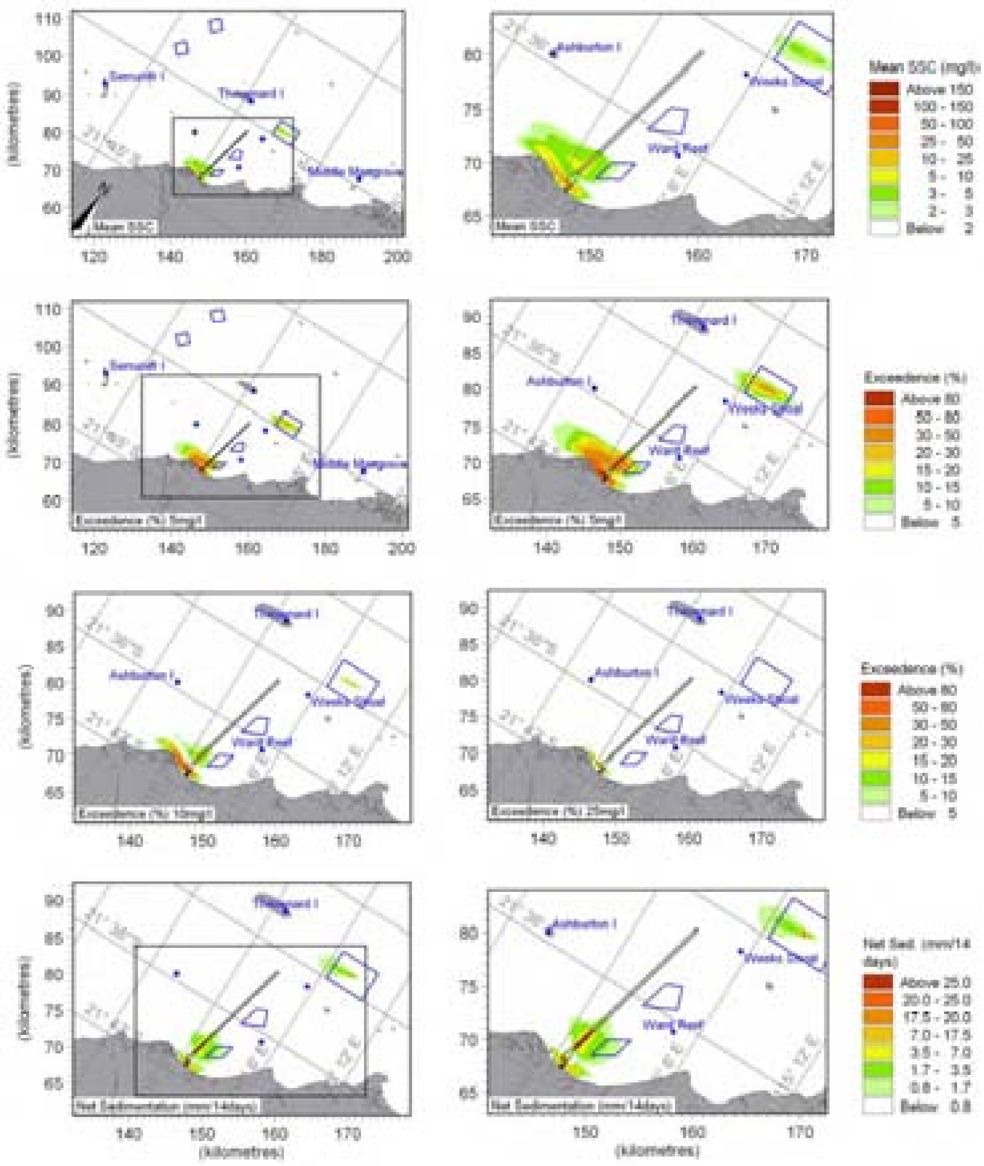

Figure Q.5 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 3

Q-7

Dredge Scenario: Scenario 3
Climatic Scenario: Winter A
Spill Rate Estimate: Low ("Realistic") Case

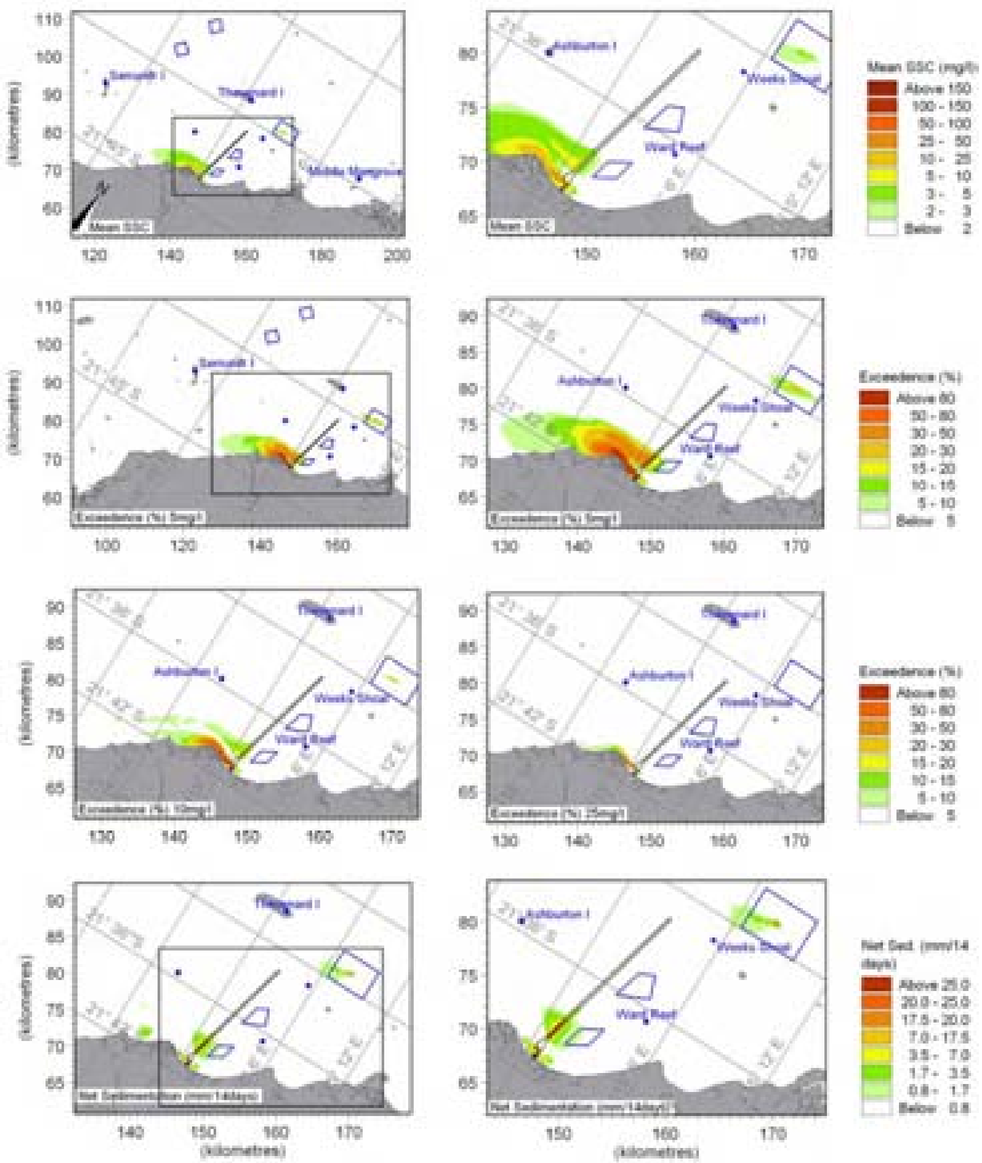

Figure Q.6 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 3*

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Dredge Scenario: Scenario 3
Climatic Scenario: Winter B
Spill Rate Estimate: Low ("Realistic") Case

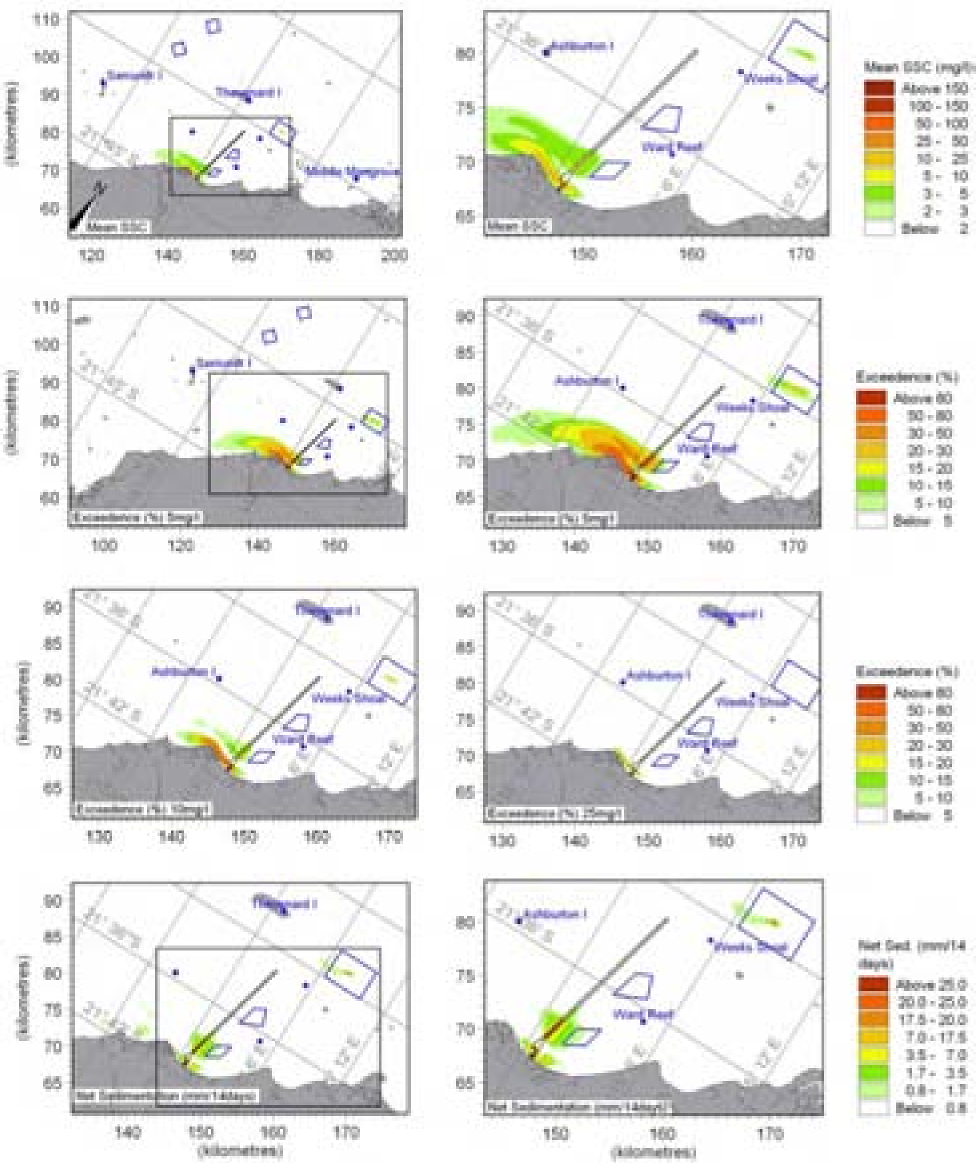

Figure Q.7 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 3*

Q.5 Results for High (Worst Case) Spill Rates

Dredge Scenario: Scenario 3
Climatic Scenario: Summer A
Spill Rate Estimate: High ("Worst Case")

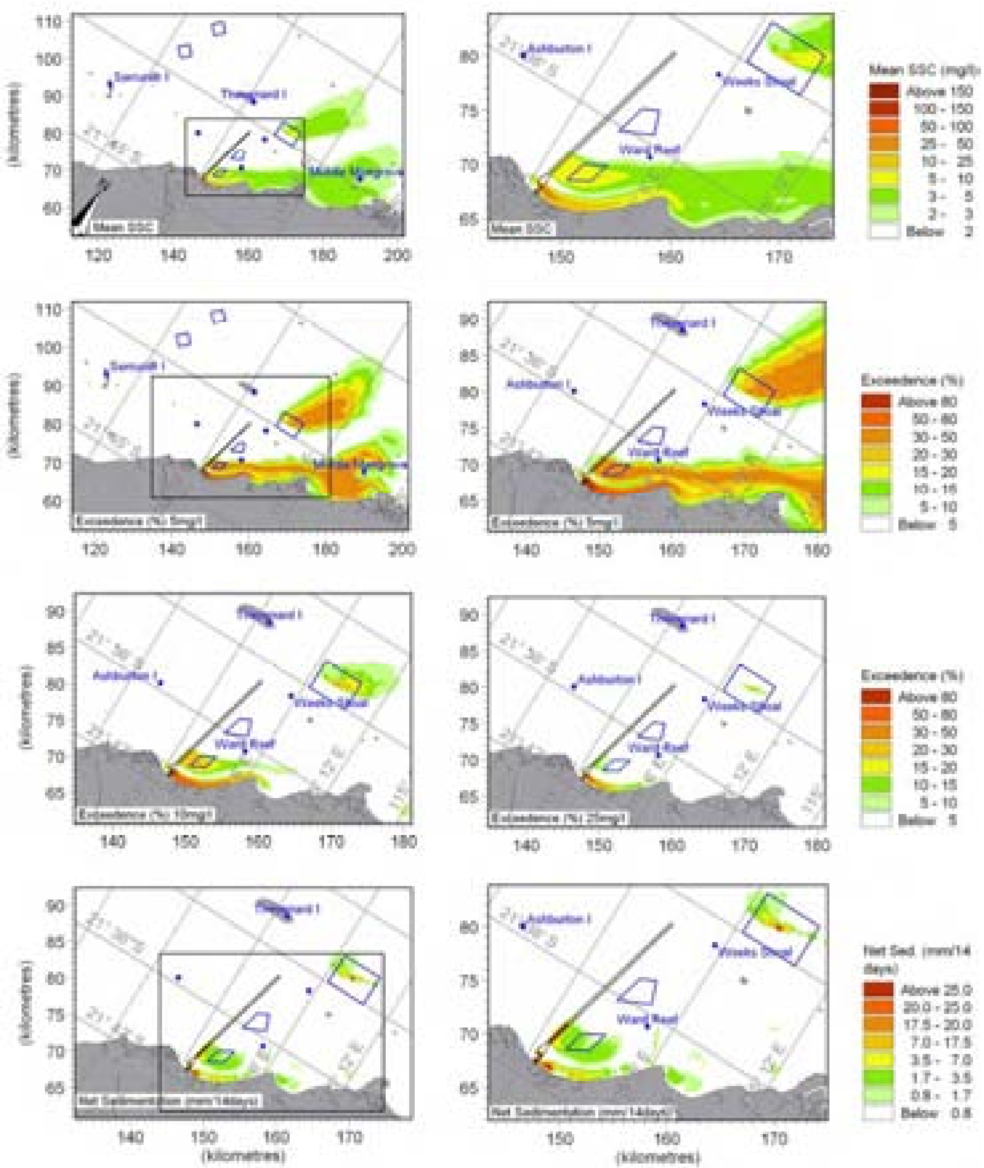

Figure Q.8 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 3*

Dredge Scenario: Scenario 3
Climatic Scenario: Summer B
Spill Rate Estimate: High ("Worst Case")

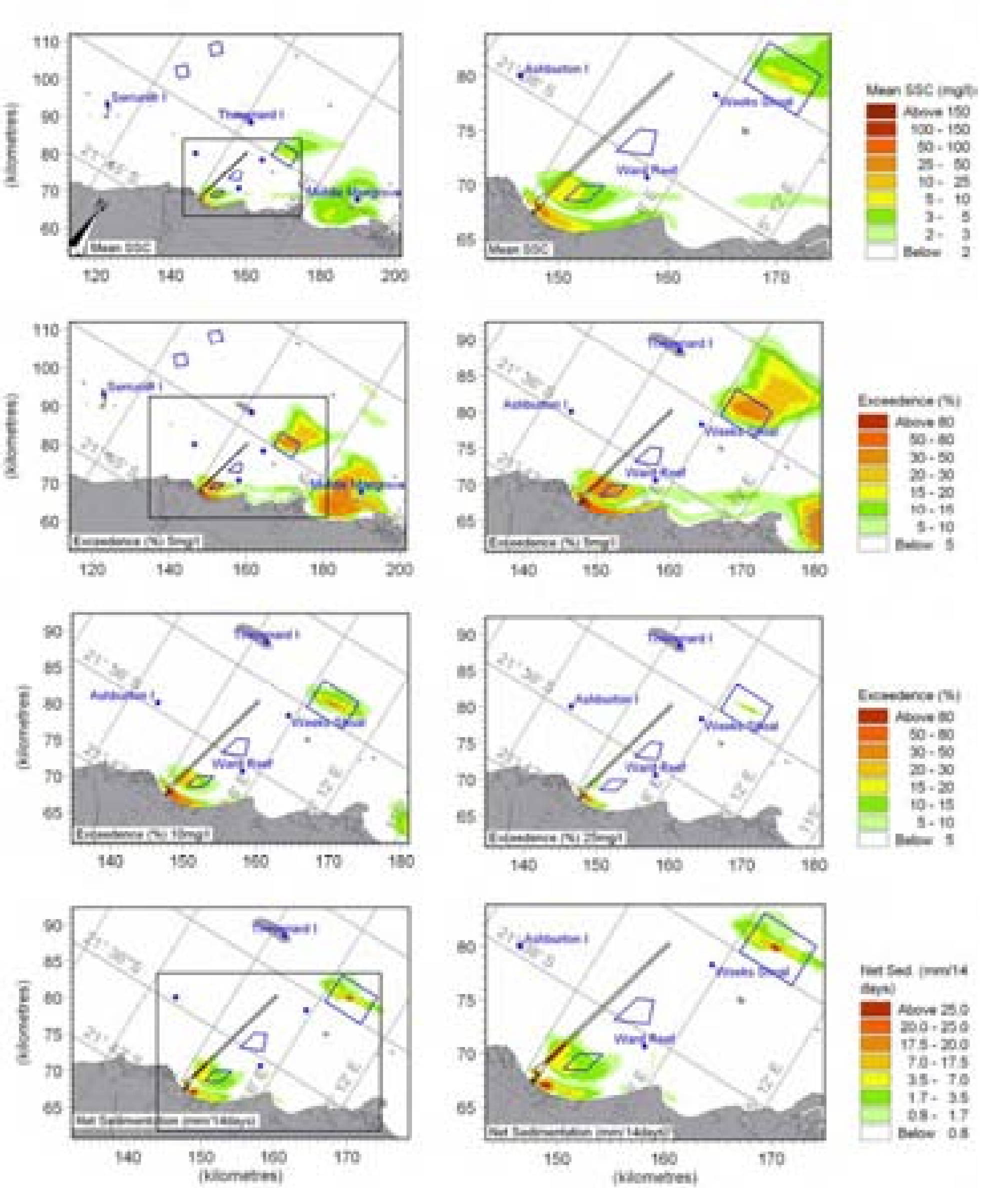

Figure Q.9 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 3*

Q-11

Dredge Scenario: Scenario 3
Climatic Scenario: Transitional A
Spill Rate Estimate: High ("Worst Case")

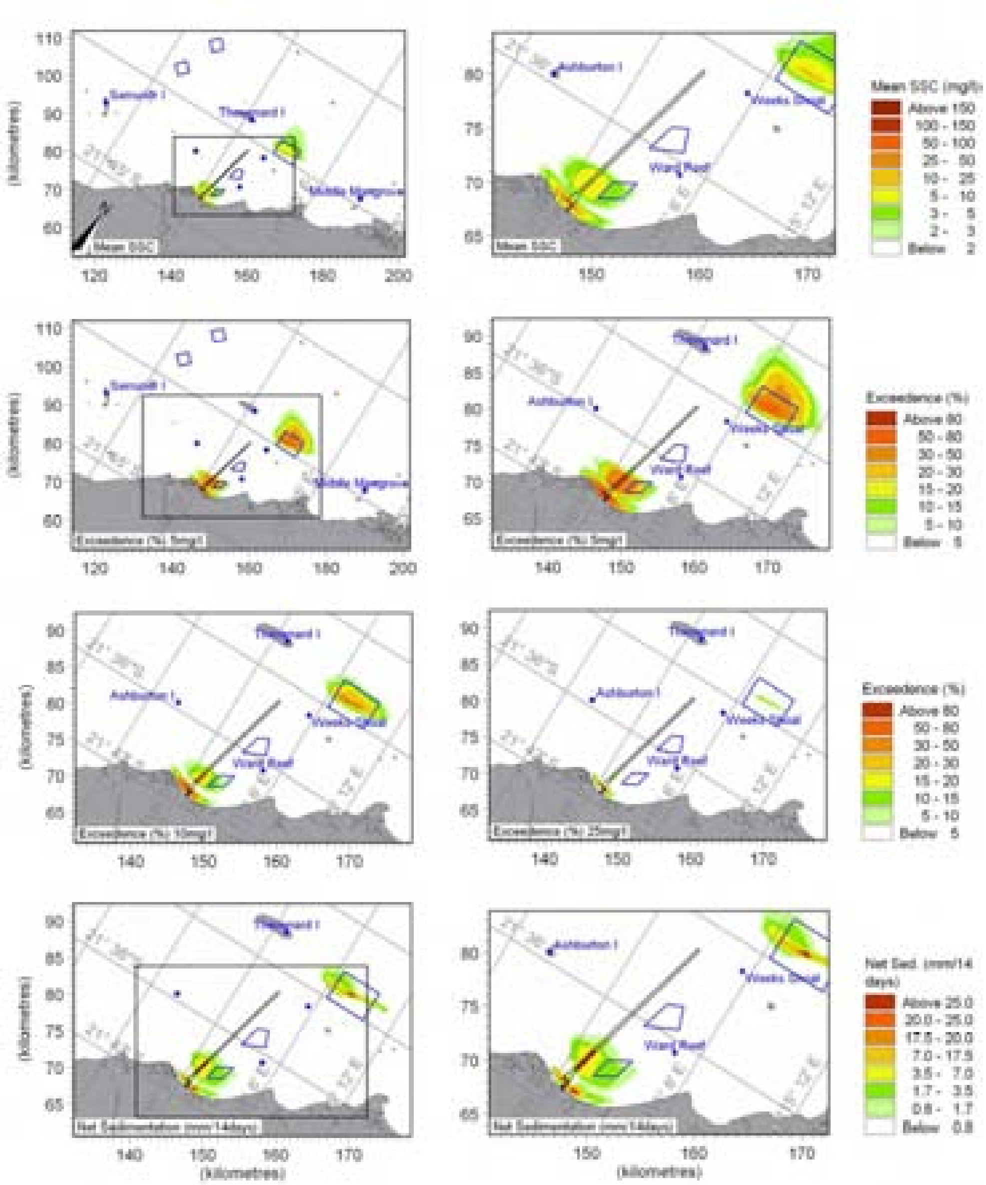

Figure Q.10 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 3

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Dredge Scenario:	Scenario 3
Climatic Scenario:	Transitional B
Spill Rate Estimate:	High ("Worst Case")

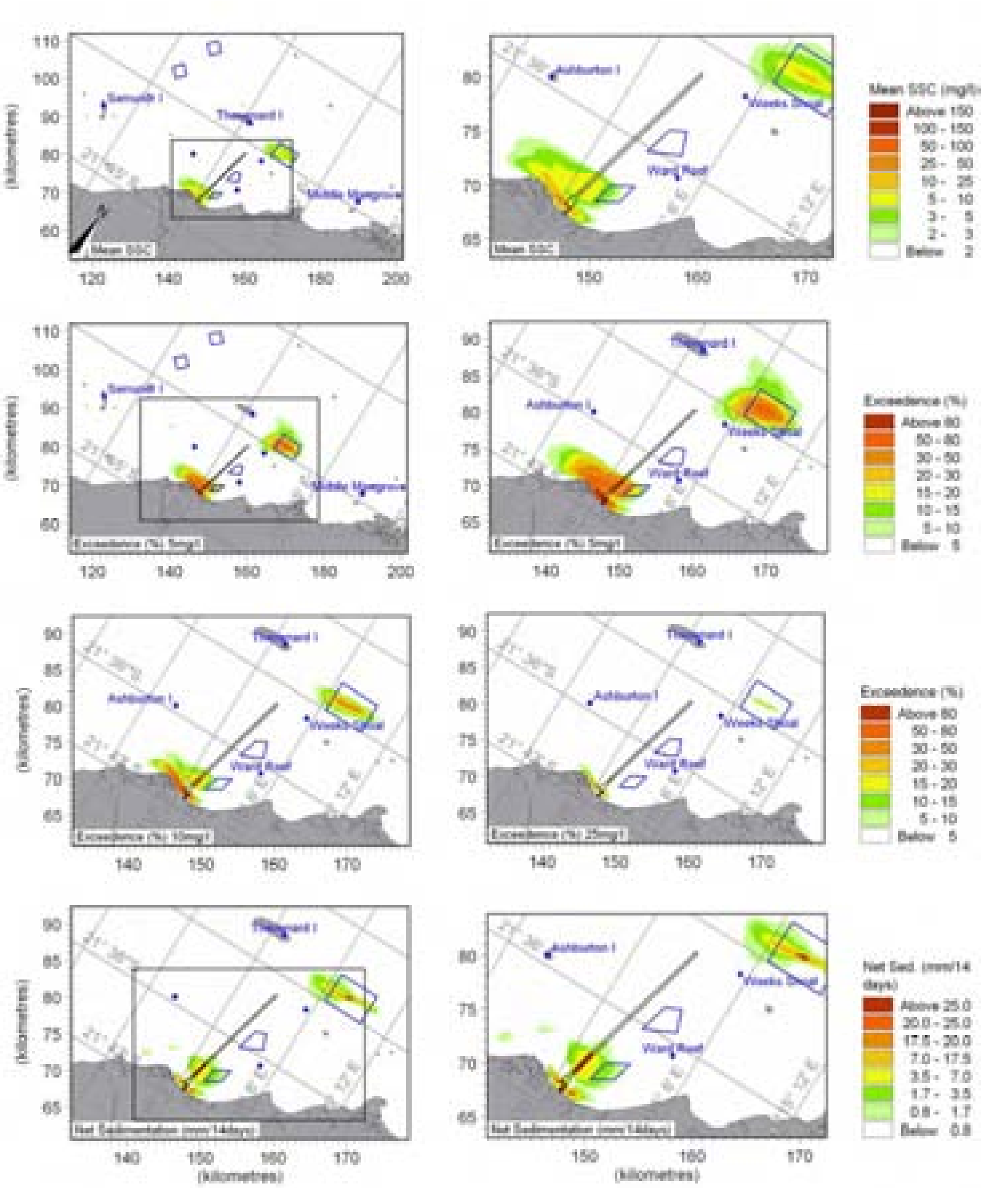

Figure Q.11 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 3

Dredge Scenario: Scenario 3
Climatic Scenario: Winter A
Spill Rate Estimate: High ("Worst Case")

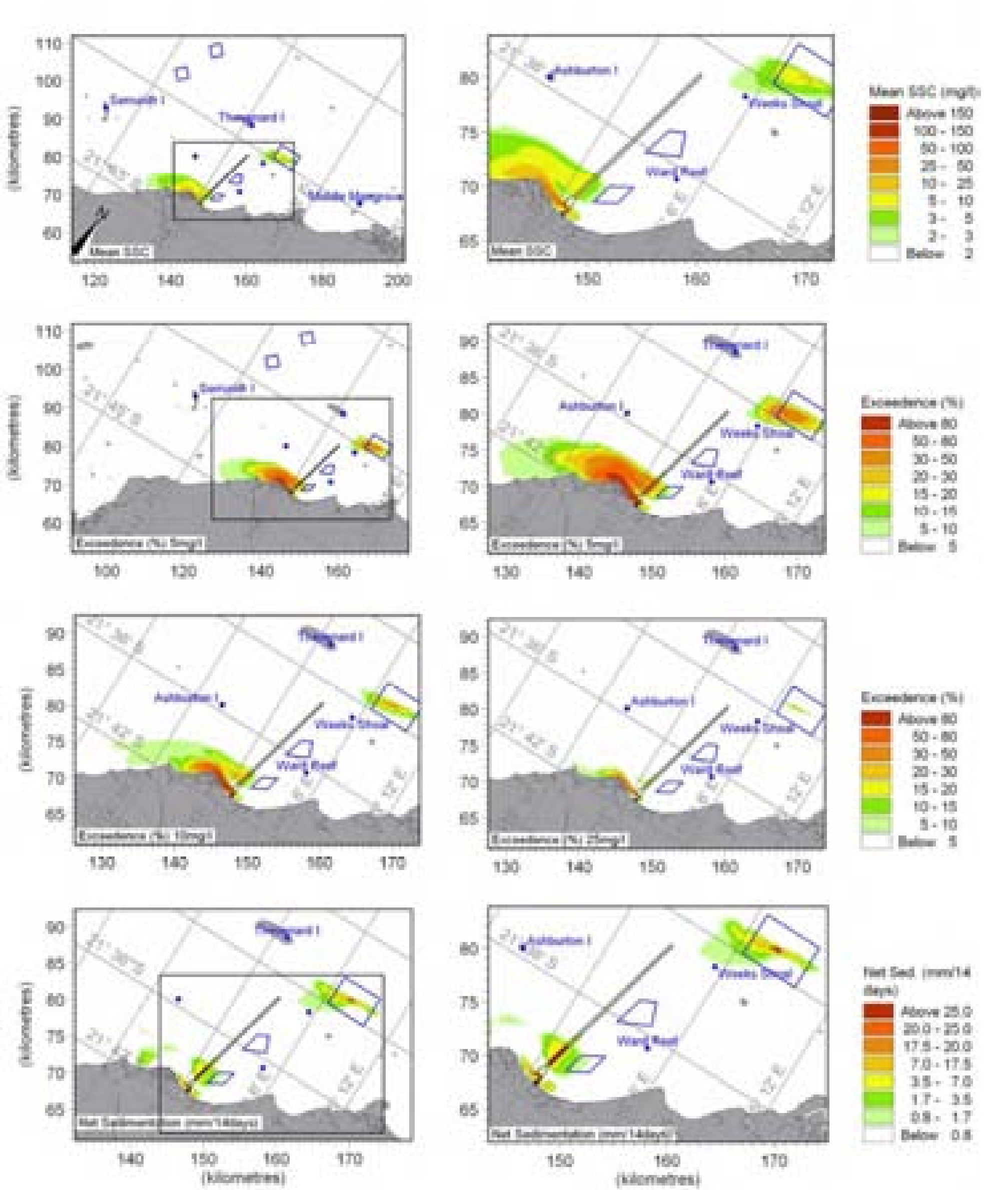

Figure Q.12 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 3

Dredge Scenario: Scenario 3
Climatic Scenario: Winter B
Spill Rate Estimate: High ("Worst Case")

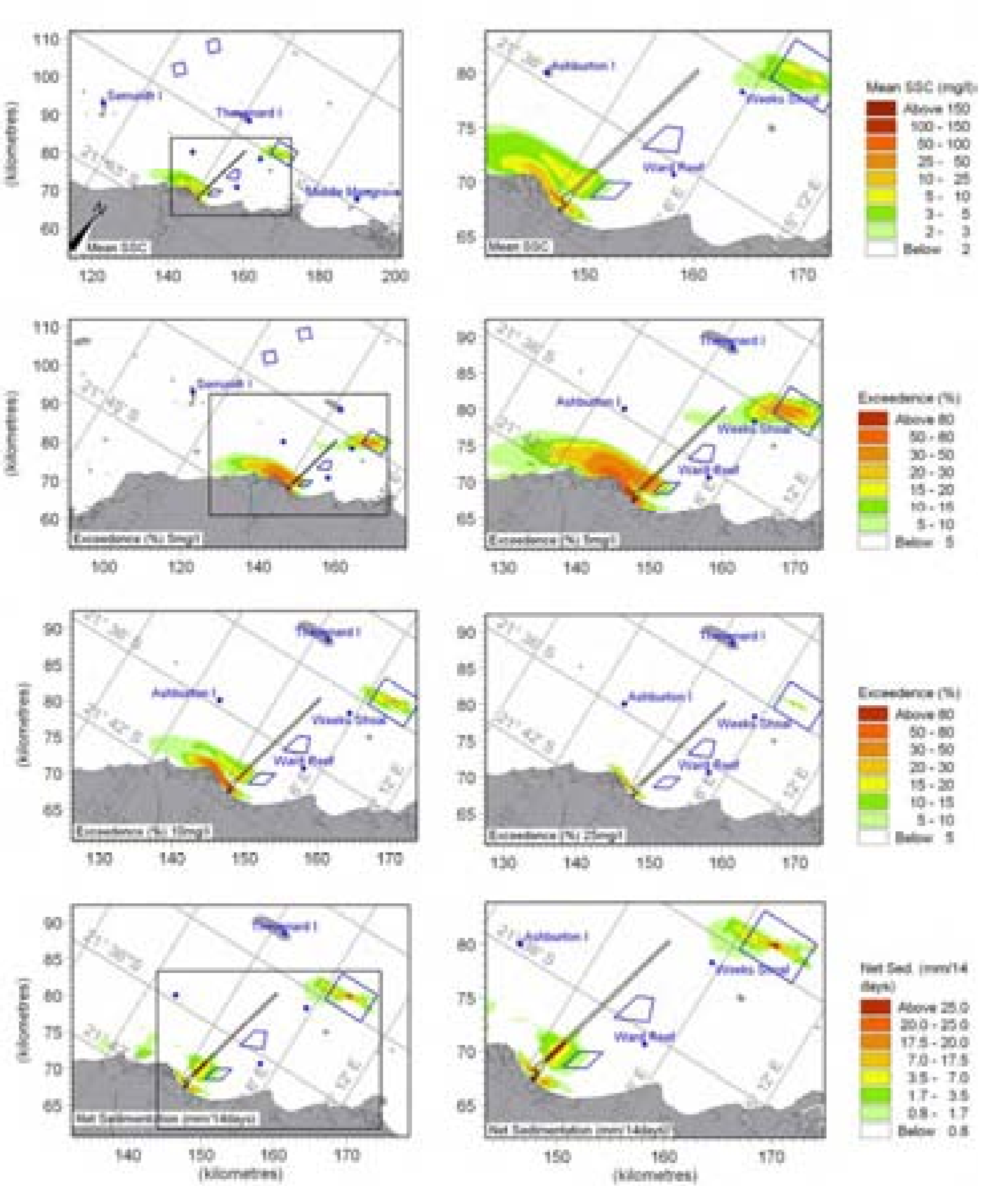

Figure Q.13 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario

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R RESULTS FOR DREDGE SCENARIO 4 BASED ON ONSLOW WINDS

This appendix presents results from the sediment transport model based on hydrodynamics driven by the Onslow wind fields. The reader is referred to the following sections of the main report and additional appendices for further information;

- Section 4.1.3.2 *Wind Fields*
- Section 6.2 *Results for the Dredging of the Shipping Channel*
- Appendix D *Hydrodynamic Model Validation and Calibration*

R.1 Statistical Plots

The established impact criteria (DHI (2010) *Dredge Plume Impact Assessment Report*) are based on sediment loads, both in terms of excess suspended concentrations and sedimentation rates, over 14 day periods. In terms of exposure and impacts, both the concentrations and the duration of the event is important, which is expressed through the exceedence probability of given limits.

For each simulated case, a set of plots showing the statistical output used in the impact assessment have been produced. All plots are for excess concentrations, i.e. sediments originating from the dredging operations and exclusive of ambient concentrations.

Each mosaic plot comprises:

- Mean excess concentration at two scales
- Exceedence of 5mg/l excess concentration at two scales
- Exceedence of 10mg/l excess concentration
- Exceedence of 25mg/l excess concentration
- Net sedimentation rates at two zoomed levels at the site

Note that all concentrations are presented as depth-averaged values. All values are derived over the assessment period (2^{nd} neap/spring tidal cycle of the month for each climatic scenario), i.e. after at least 14 days warm-up period. Exceedences are expressed in percentage time over the assessment period that the exceedence limit is exceeded.

R.2 Description of Dredge Scenario 4

Nearshore Dredging: PLF Basin – weak rock

- 10,000m^3 TSHD in PLF
- Disposal at Site C
- Bathymetry with fully dredged MOF and MOF channel, partly dredged PLF basin to -12m LAT
- Material available for suspension in dredged channel
- Include MOF dredged basin and MOF breakwaters.

Offshore Dredging: Approach Channel – Section 1 sand

- 10,000m^3 TSHD with disposal at placement Site C
- Dredging along Section 1
- Partly dredged approach channel along entire length
- Material available for re-suspension along channel and in placement Sites A and C

The locations for the various dredge and placement activities are outlined in Figure R.1, while defined low (realistic) and high (worst-case) spill rates applied in Dredging Scenario 3 are listed in Table 3.2 of the man report.

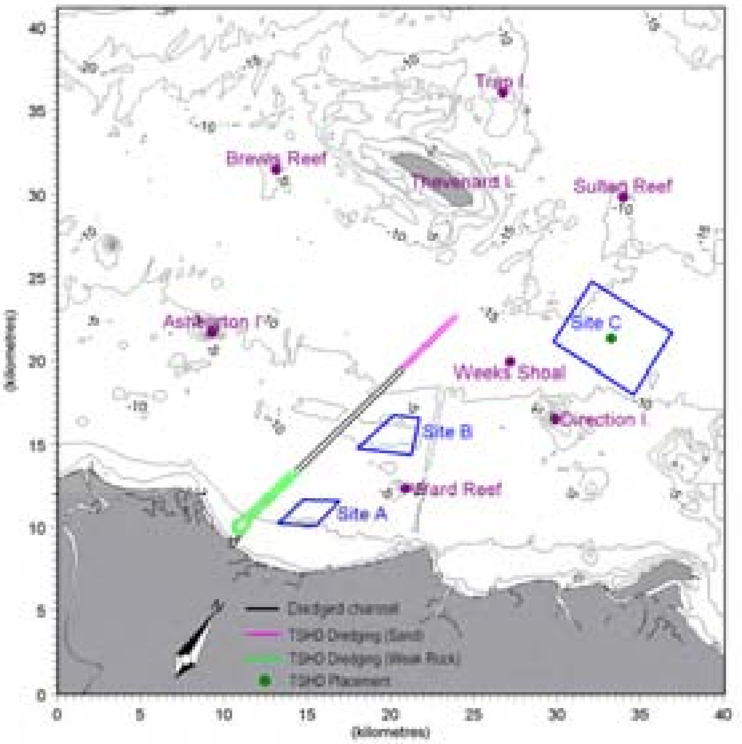

Figure R.1 Sketch of locations for Dredging Scenario 4.

R.3 Summary of Results

Specific observations for Dredge Scenario 4 include:

- The plumes from the 10,000m^3 TSHD dredging weak rock in the PLF are much lower in concentration than the corresponding plume dredging in sand at Section 1.
- The plumes from the TSHD dredging at Section 1 combines with the plumes generated from the placement at Site C.
- The plumes from Placement Site C are much less intense than for Scenario 4 due to the lower total production (and dumping) rates.
- The PLF dredging generates a plume that runs along the coastline in a predominantly easterly direction during summer and westerly direction during winter.
- As the weak rock dredging stretches out into Section 4, the nearshore plume tends to split into a component running along the coastline and a component separating from the coastline.
- The plume generated from Section 5 of the PLF / PLF Approach channel skirts Ward Reef to the south.

R.4 Results for Low (Realistic) Spill Rates

Dredge Scenario:	Scenario 4
Climatic Scenario:	Summer A
Spill Rate Estimate:	Low ("Realistic") Case

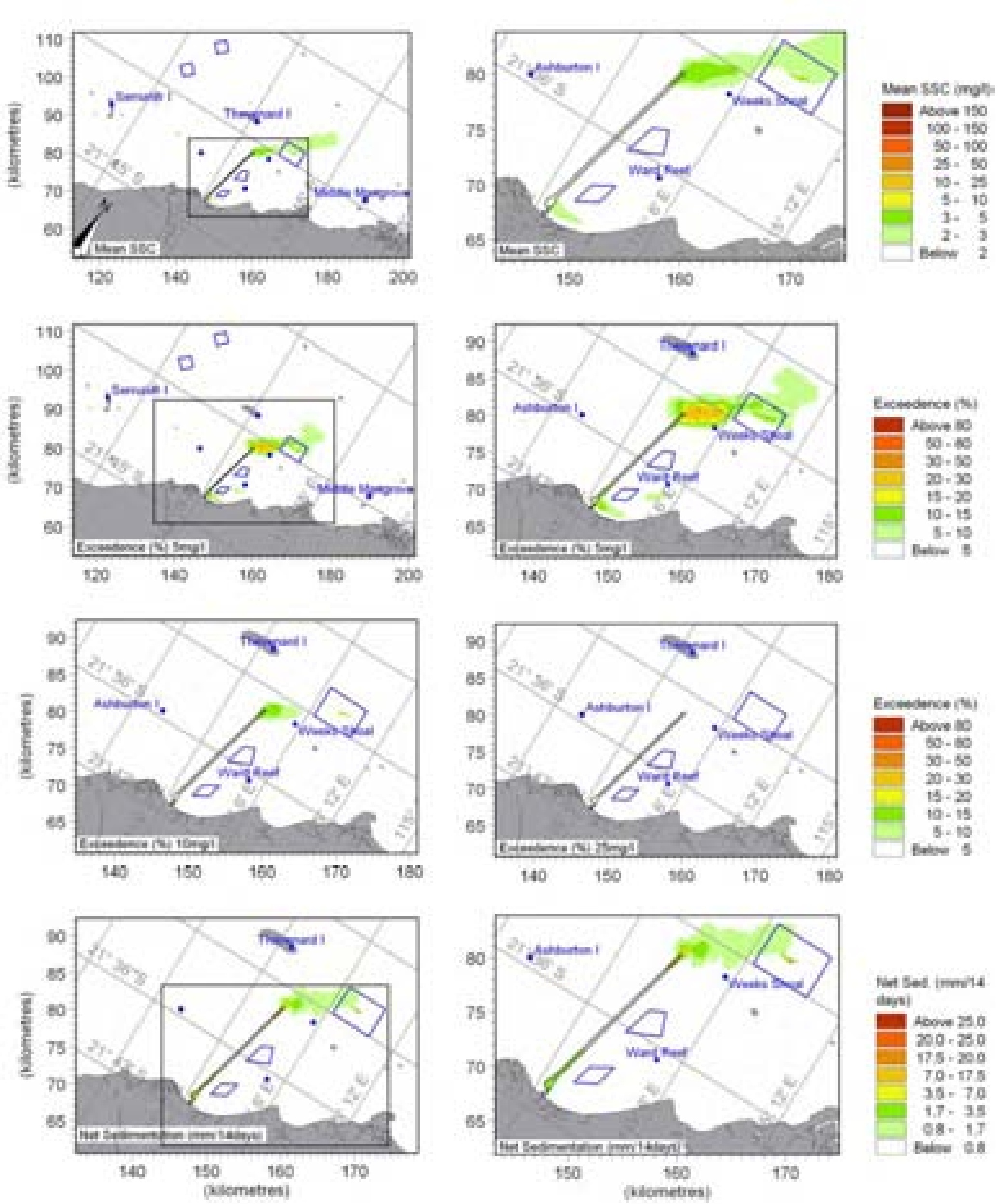

Figure R.2 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 4

R-4

Dredge Scenario: Scenario 4
Climatic Scenario: Summer B
Spill Rate Estimate: Low ("Realistic") Case

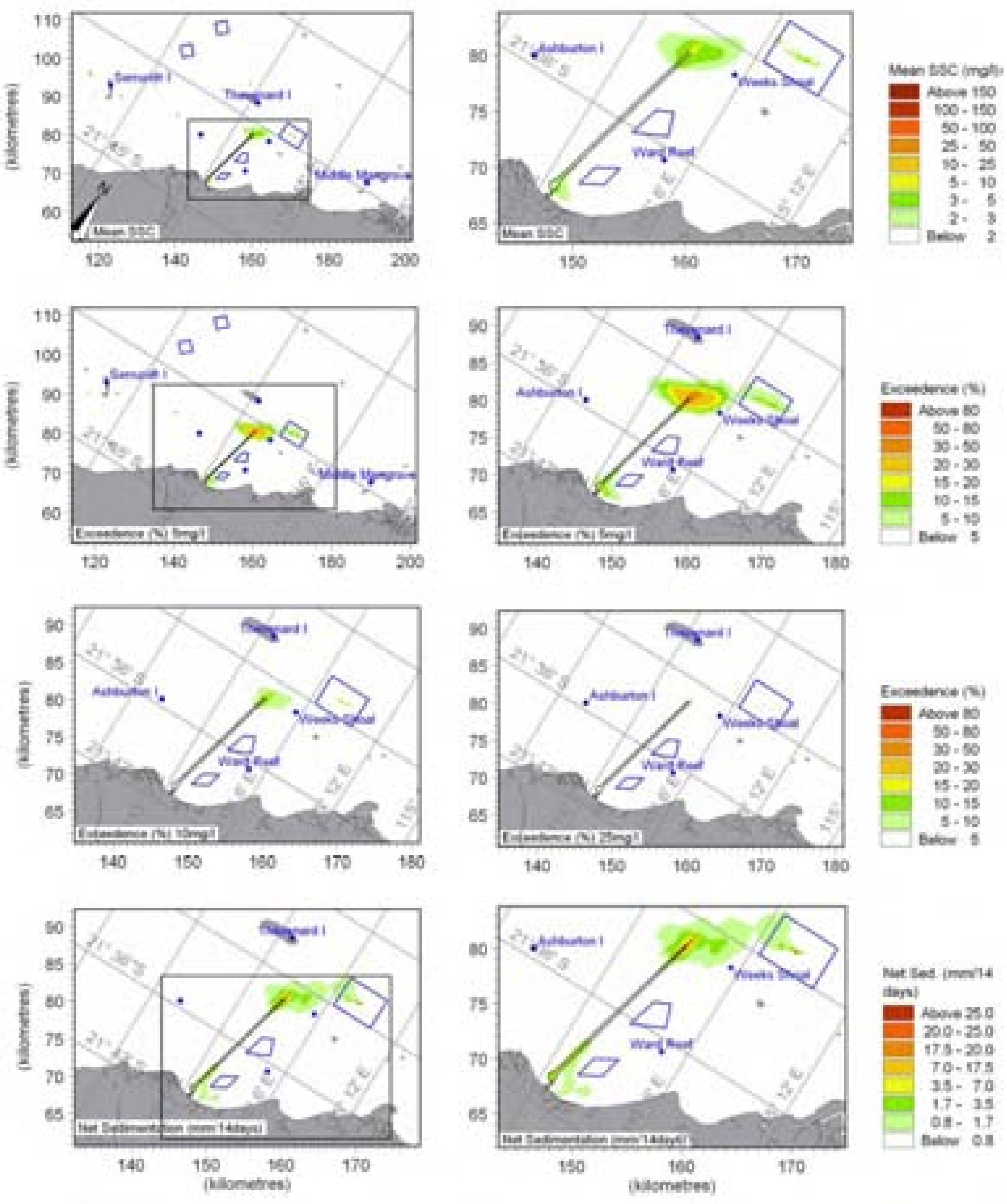

Figure R.3 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 4*

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Dredge Scenario: Scenario 4
Climatic Scenario: Transitional A
Spill Rate Estimate: Low ("Realistic") Case

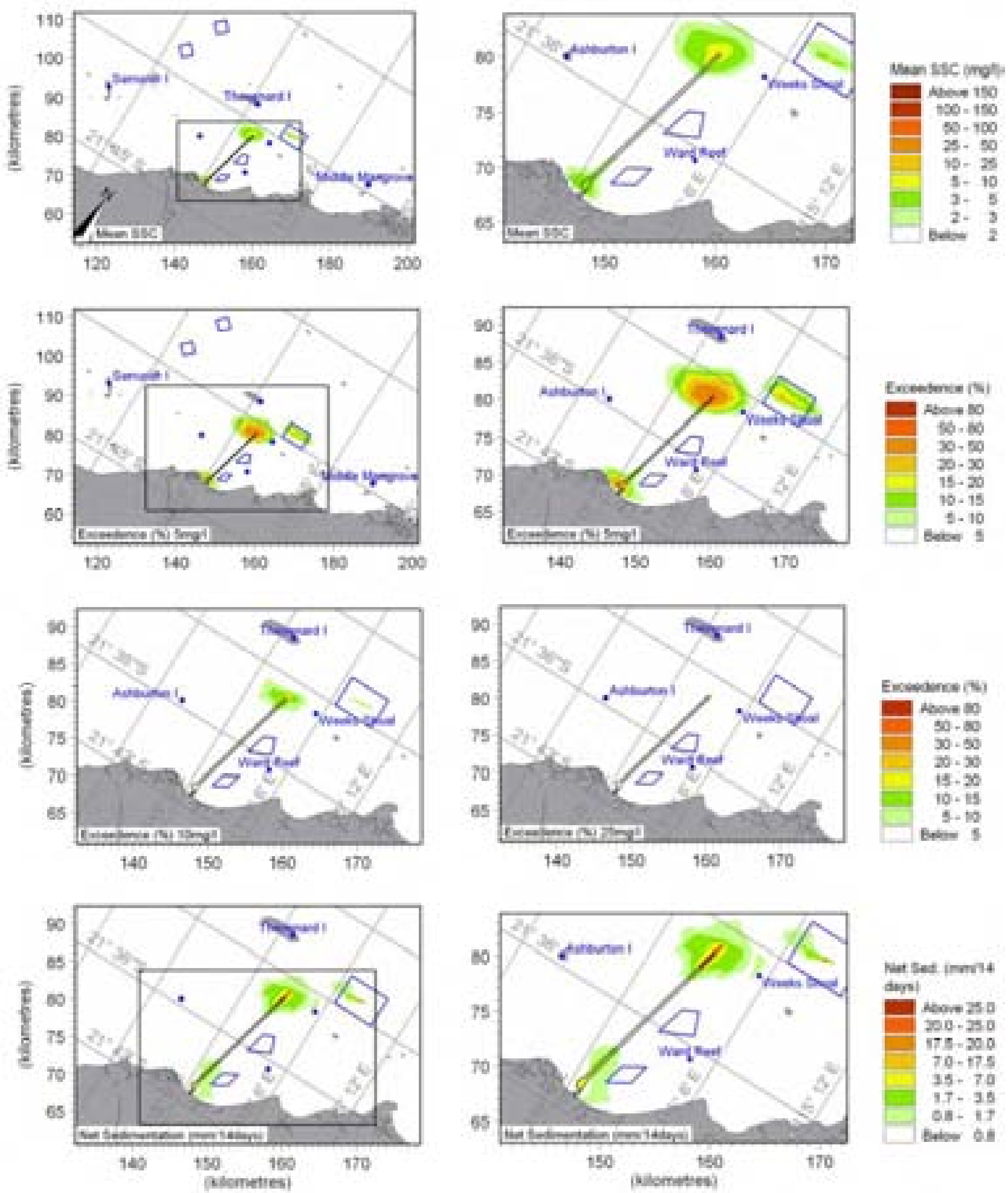

Figure R.4 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 4*

Dredge Scenario: Scenario 4
Climatic Scenario: Transitional B
Spill Rate Estimate: Low ("Realistic") Case

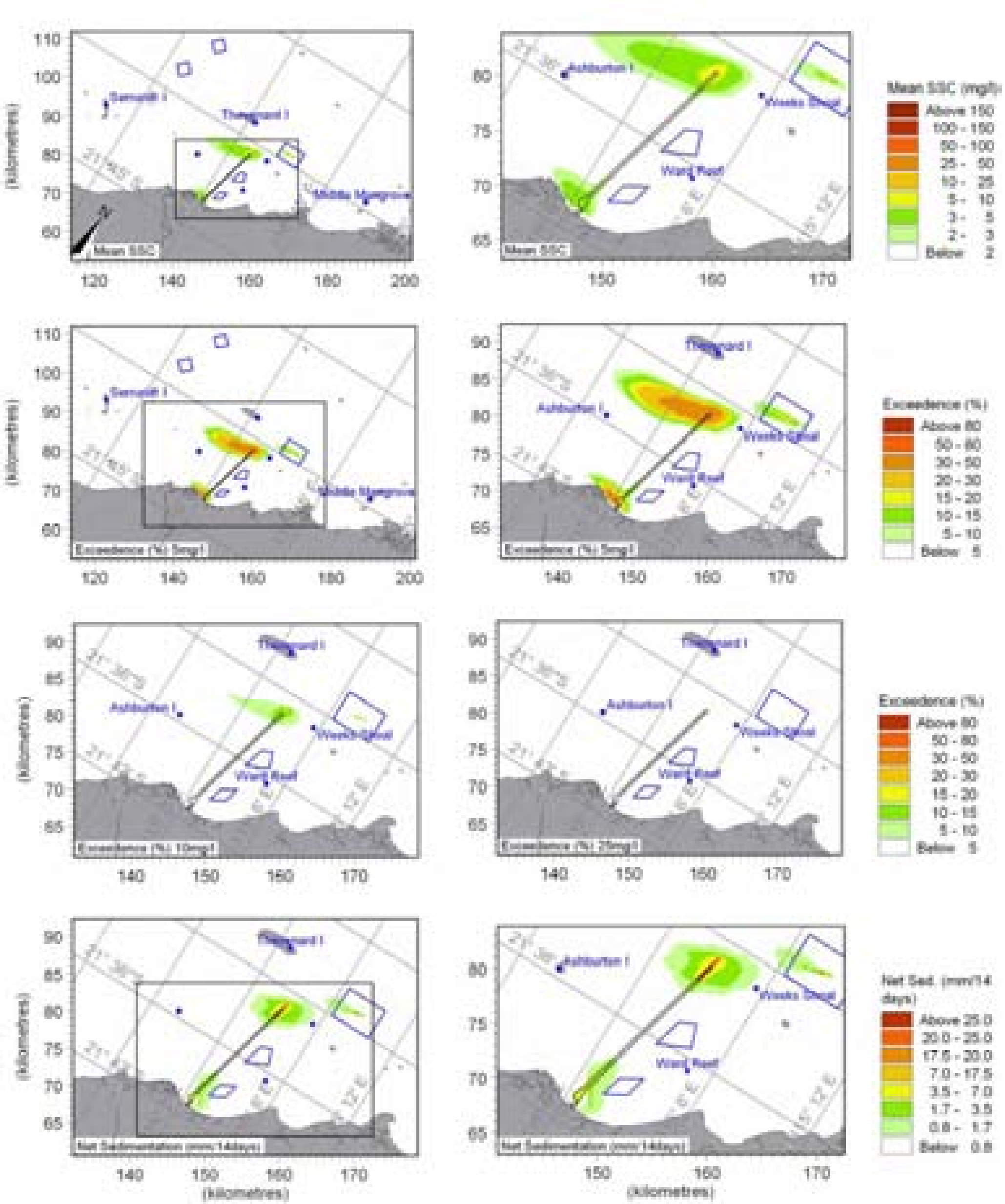

Figure R.5 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 4*

R-7

Dredge Scenario: Scenario 4
Climatic Scenario: Winter A
Spill Rate Estimate: Low ("Realistic") Case

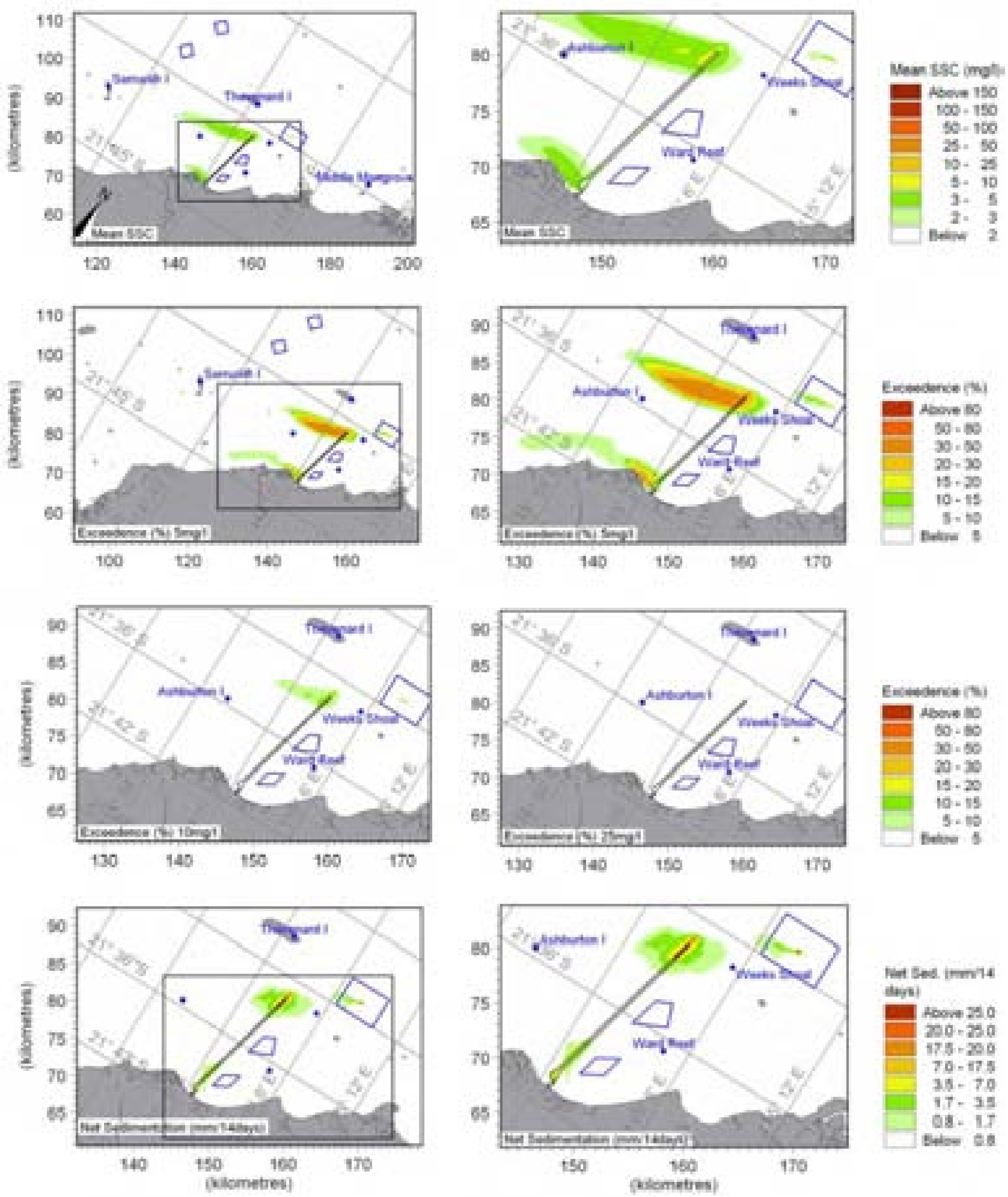

Figure R.6 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 4*

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R-8

Dredge Scenario: Scenario 4
Climatic Scenario: Winter B
Spill Rate Estimate: Low ("Realistic") Case

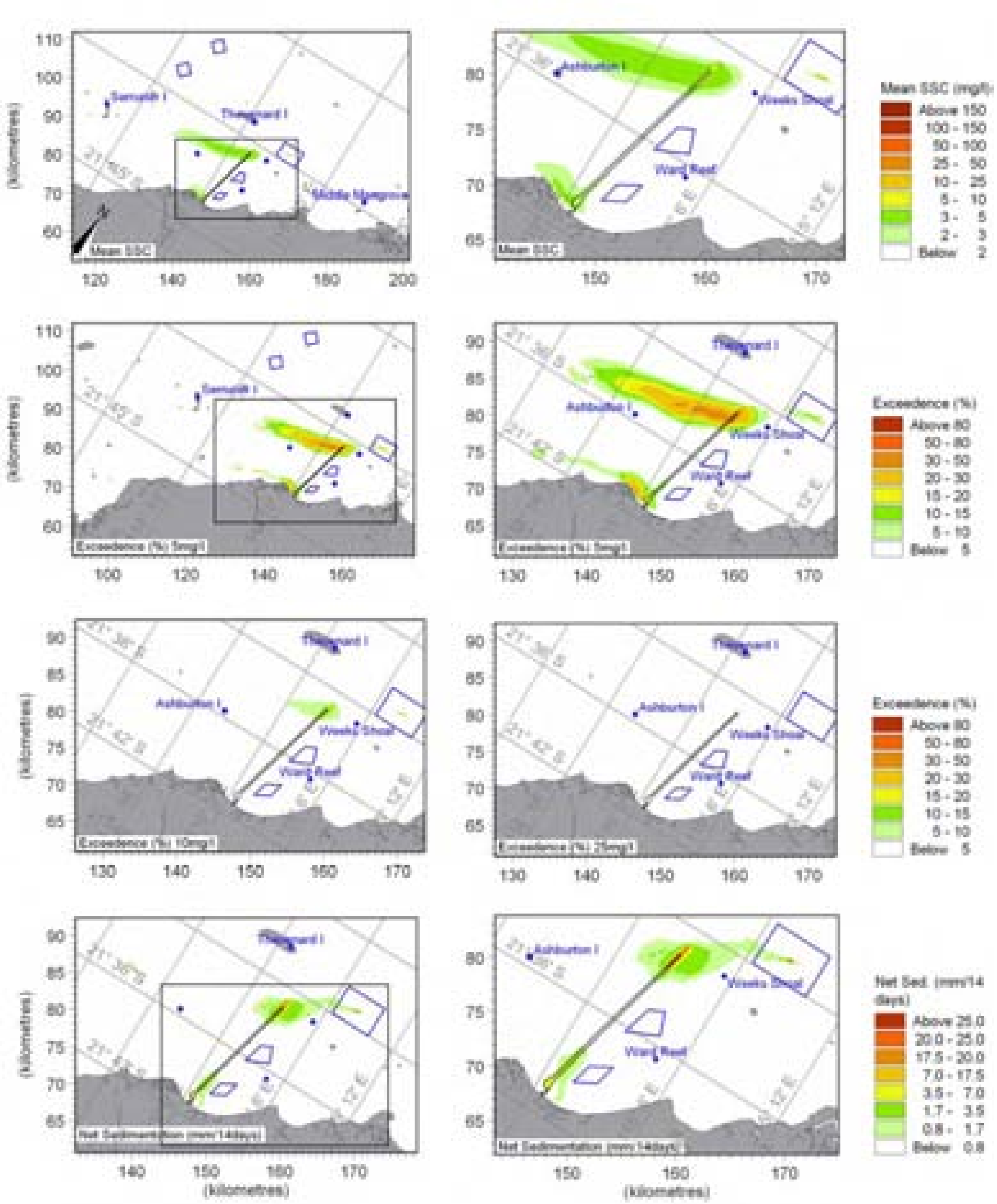

Figure R.7 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 4*

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R.5 Results for High (Worst-Case) Spill Rates

Dredge Scenario:	Scenario 4
Climatic Scenario:	Summer A
Spill Rate Estimate:	High (“Worst Case”)

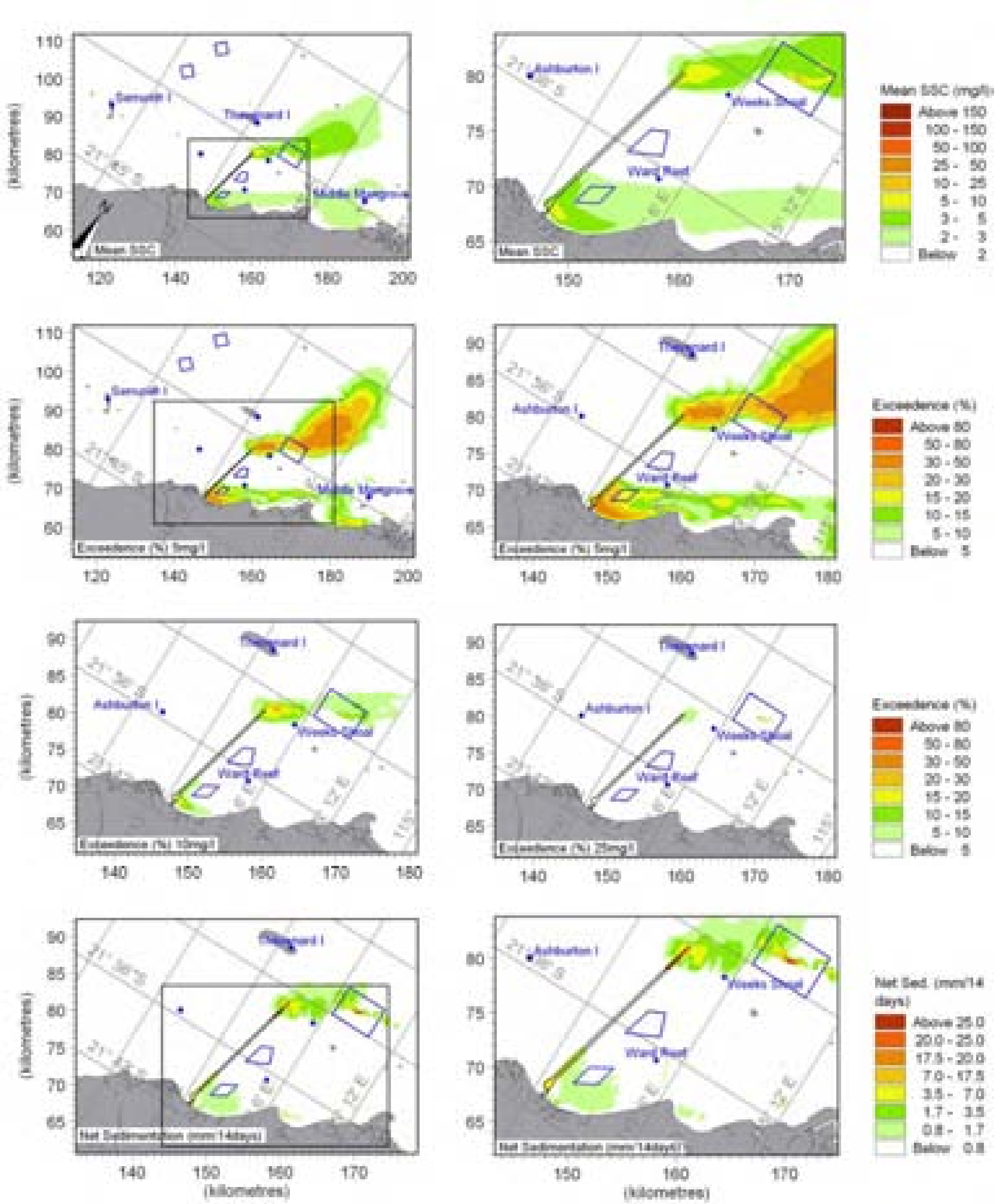

Figure R.8 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 4

R-10

Dredge Scenario: Scenario 4
Climatic Scenario: Summer B
Spill Rate Estimate: High ("Worst Case")

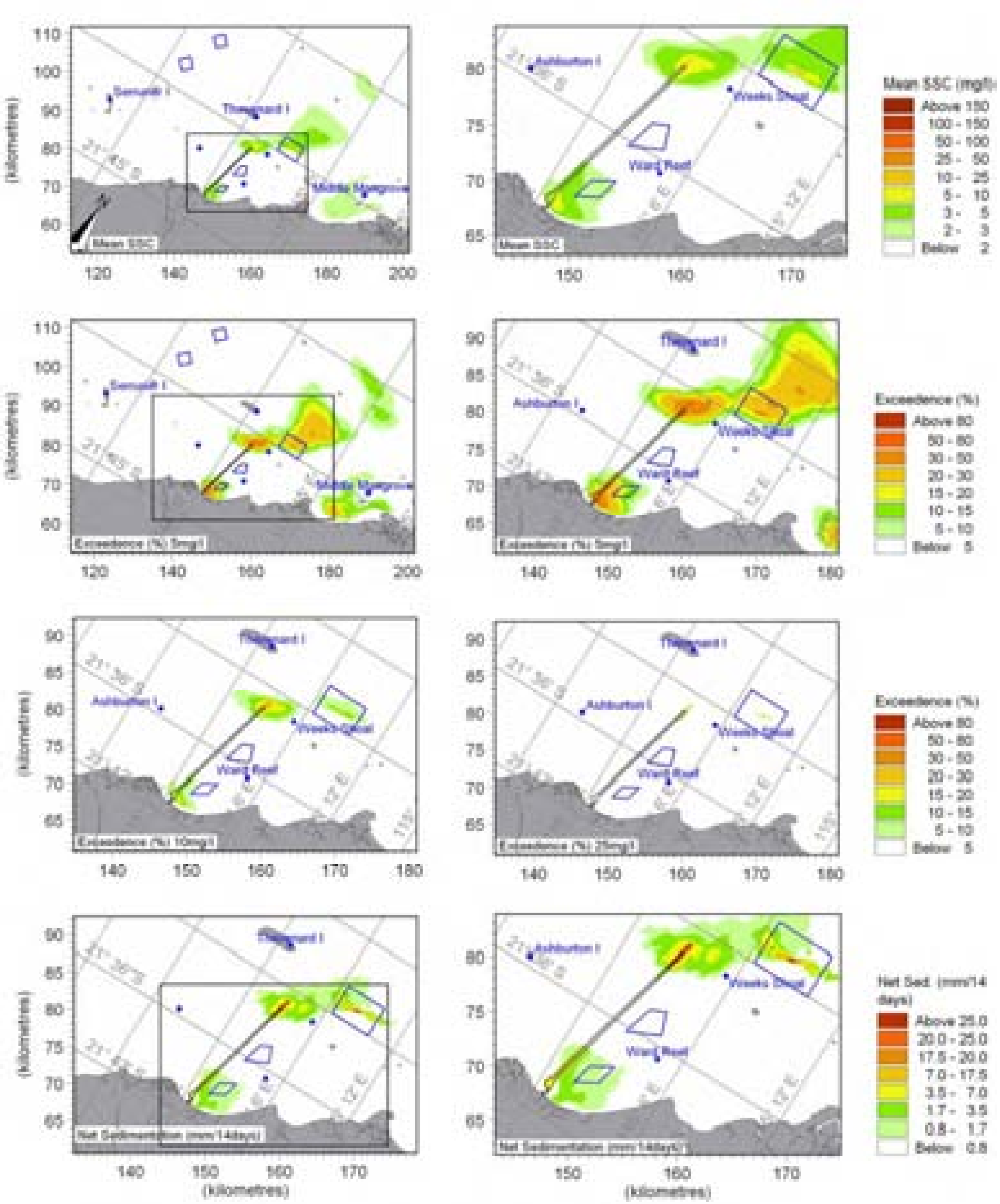

Figure R.9 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 4*

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R-11

Dredge Scenario: Scenario 4
Climatic Scenario: Transitional A
Spill Rate Estimate: High ("Worst Case")

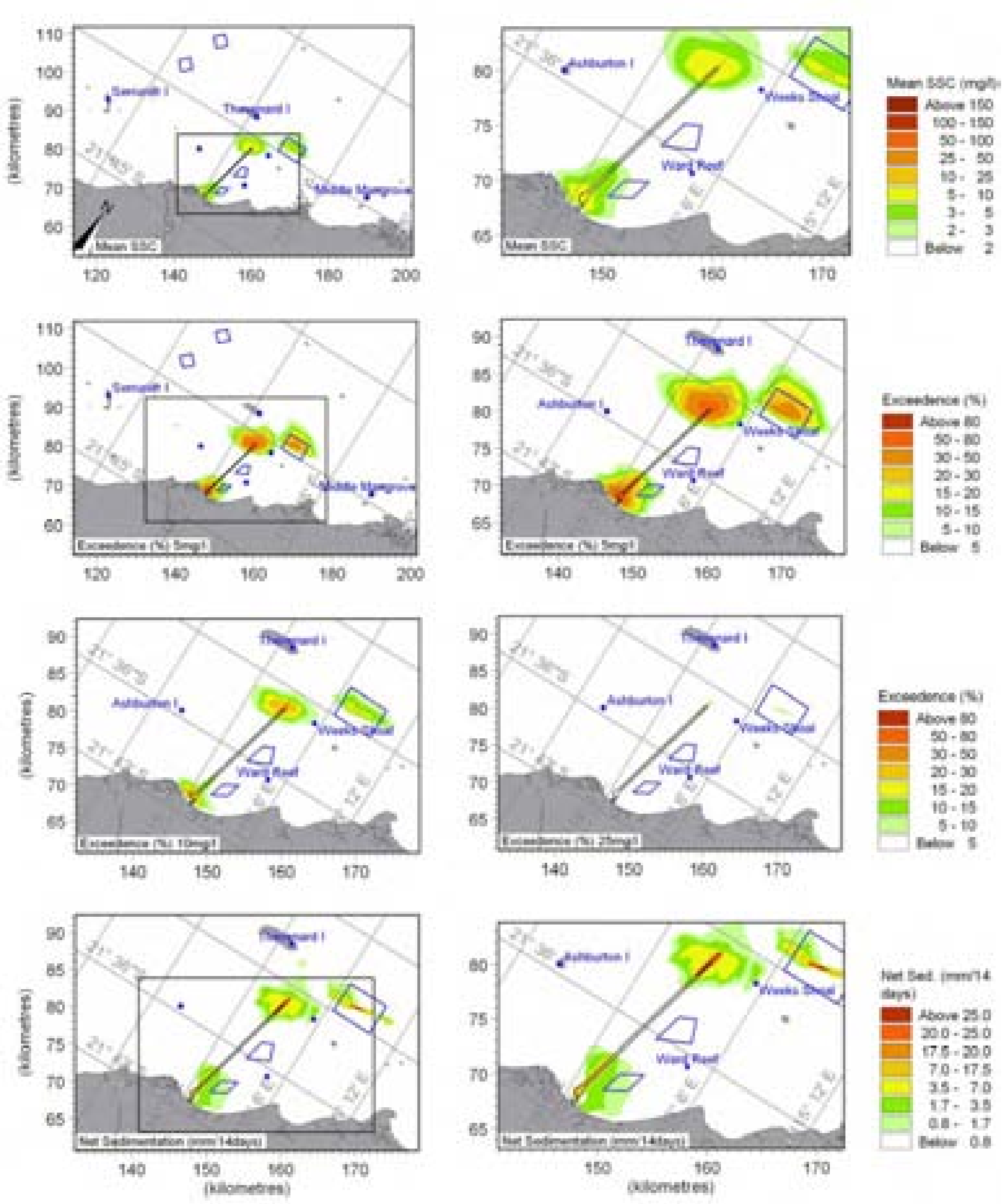

Figure R.10 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 4

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Dredge Scenario:	Scenario 4
Climatic Scenario:	Transitional B
Spill Rate Estimate:	High ("Worst Case")

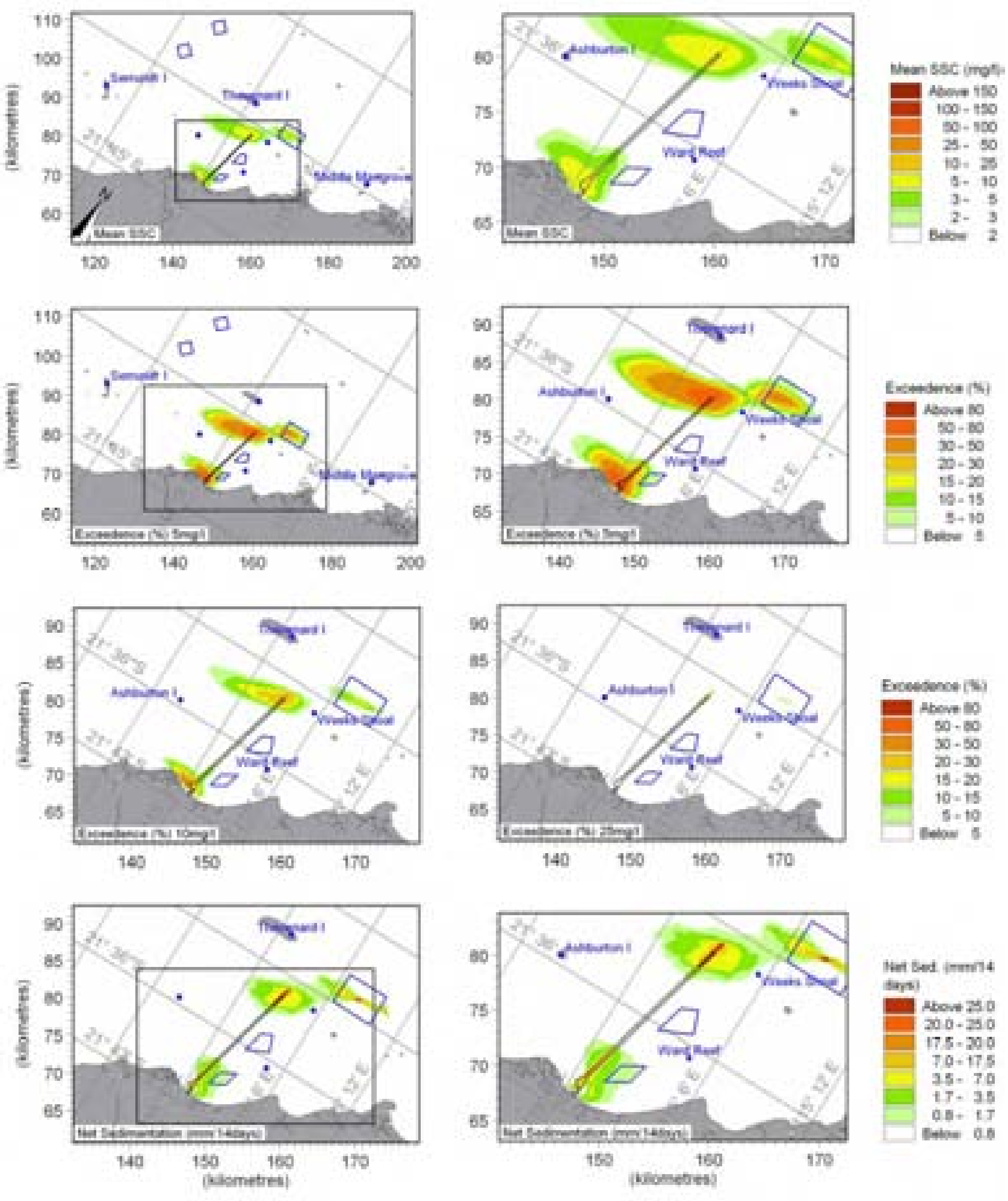

Figure R.11 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 4

R-13

Dredge Scenario: Scenario 4
Climatic Scenario: Winter A
Spill Rate Estimate: High ("Worst Case")

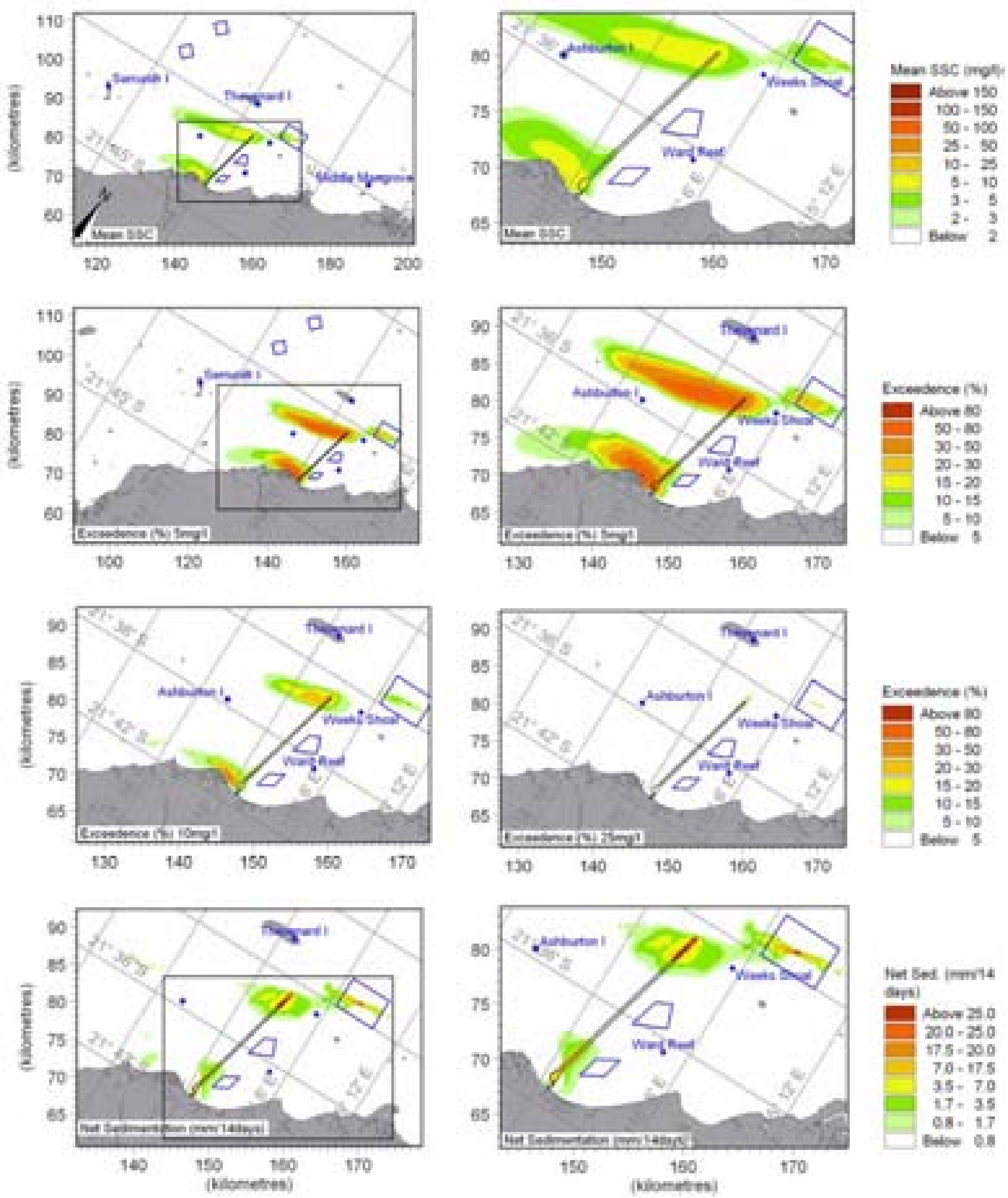

Figure R.12 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 4

DHI Water & Environment

Dredge Scenario: Scenario 4
Climatic Scenario: Winter B
Spill Rate Estimate: High ("Worst Case")

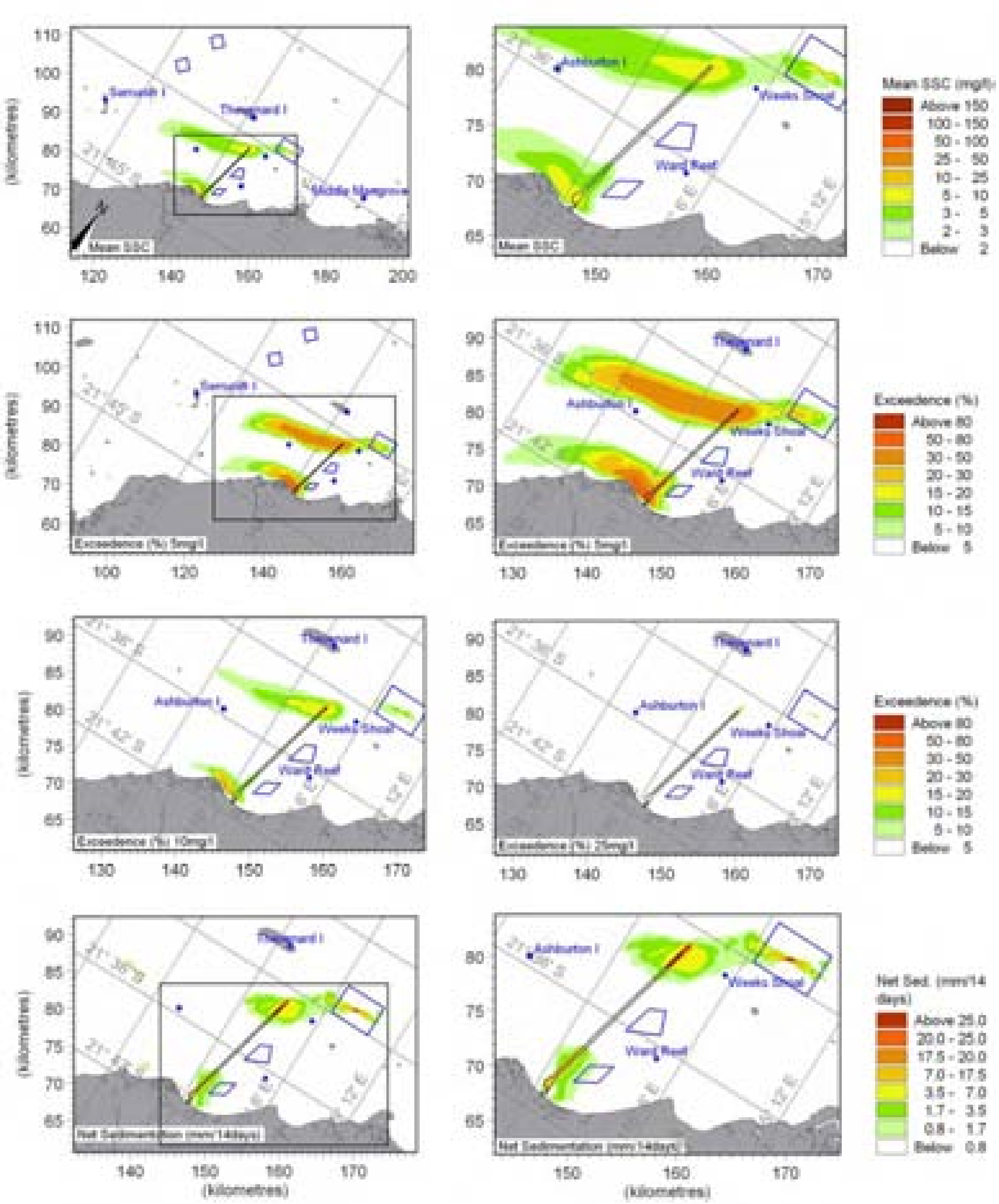

Figure R.13 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 4

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Wheatstone Project
Dredge Spoil Modelling

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Results for Dredge Scenario 5 Based on Onslow Winds

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S RESULTS FOR DREDGE SCENARIO 5 BASED ON ONSLOW WINDS

This appendix presents results from the sediment transport model based on hydrodynamics driven by the Onslow wind fields. The reader is referred to the following sections of the main report and additional appendices for further information;

- Section 4.1.3.2 *Wind Fields*
- Section 6.2 *Results for the Dredging of the Shipping Channel*
- Appendix D *Hydrodynamic Model Validation and Calibration*

S.1 Statistical Plots

The established impact criteria (DHI (2010) *Dredge Plume Impact Assessment Report)* are based on sediment loads, both in terms of excess suspended concentrations and sedimentation rates, over 14 day periods. In terms of exposure and impacts, both the concentrations and the duration of the event is important, which is expressed through the exceedence probability of given limits.

For each simulated case, a set of plots showing the statistical output used in the impact assessment have been produced. All plots are for excess concentrations, i.e. sediments originating from the dredging operations and exclusive of ambient concentrations.

Each mosaic plot comprises:

- Mean excess concentration at two scales
- Exceedence of 5mg/l excess concentration at two scales
- Exceedence of 10mg/l excess concentration
- Exceedence of 25mg/l excess concentration
- Net sedimentation rates at two zoomed levels at the site

Note that all concentrations are presented as depth-averaged values. All values are derived over the assessment period (2^{nd} neap/spring tidal cycle of the month for each climatic scenario), i.e. after at least 14 days warm-up period. Exceedences are expressed in percentage time over the assessment period that the exceedence limit is exceeded.

S.2 Description of Dredge Scenario 5

General

- Bathymetry with fully dredged MOF, MOF channel and PLF basin. Partly dredged approach channel along entire length
- Material available for resuspension along all dredged areas and in placement Sites A and C
- Include MOF dredged basin and MOF breakwaters.

Offshore Dredging 1: Approach Channel – Section 3 sand

- 10,000 m^3 TSHD with disposal at placement Site C
- Dredging along Section 3

Offshore Dredging 2: Approach Channel – weak rock

- 10,000 m^3 TSHD with disposal at placement Site C

- Dredging along Sections 1 & 2

The locations for the various dredge and placement activities are outlined in Figure S.1, while defined low (realistic) and high (worst-case) spill rates applied in Dredging Scenario 3 are listed in Table 3.2 of the man report.

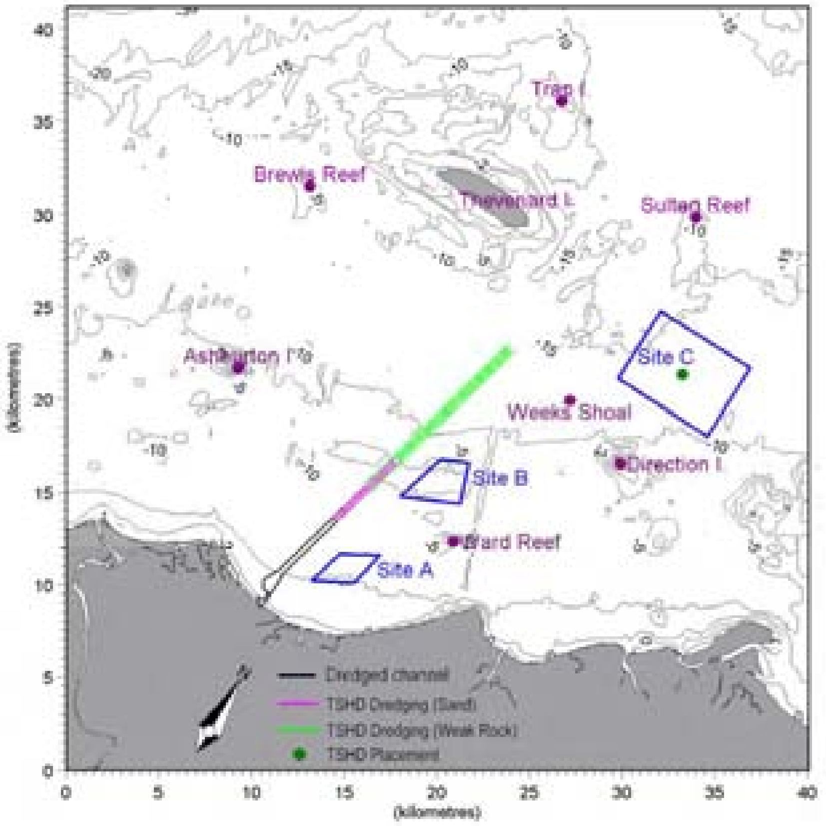

Figure S.1 Sketch of locations for Dredging Scenario 5.

S.3 Summary of Results

Specific observations for Dredge Scenario 5 include:

- The plumes from the 10,000m^3 TSHD dredging weak rock in the PLF channel are much lower in concentration than the corresponding plume dredging in sand at Section 3.
- The (lower concentration) plumes from the TSHD dredging at Sections 1 and 2 combine with the plumes generated from the sand dredging at Section 3 as well as the plumes from placement at Site C.
- The plume generated from Section 3 of the PLF Approach channel skirts Ward Reef on the northern side.
- The plume generated from Section 3 of the PLF Approach channel runs across Placement Site B.
- Ashburton Island is exposed to low concentration plumes during winter and some transitional conditions.

S.4 Results for Low (Realistic) Spill Rates

Dredge Scenario: Scenario 5
Climatic Scenario: Summer A
Spill Rate Estimate: Low ("Realistic") Case

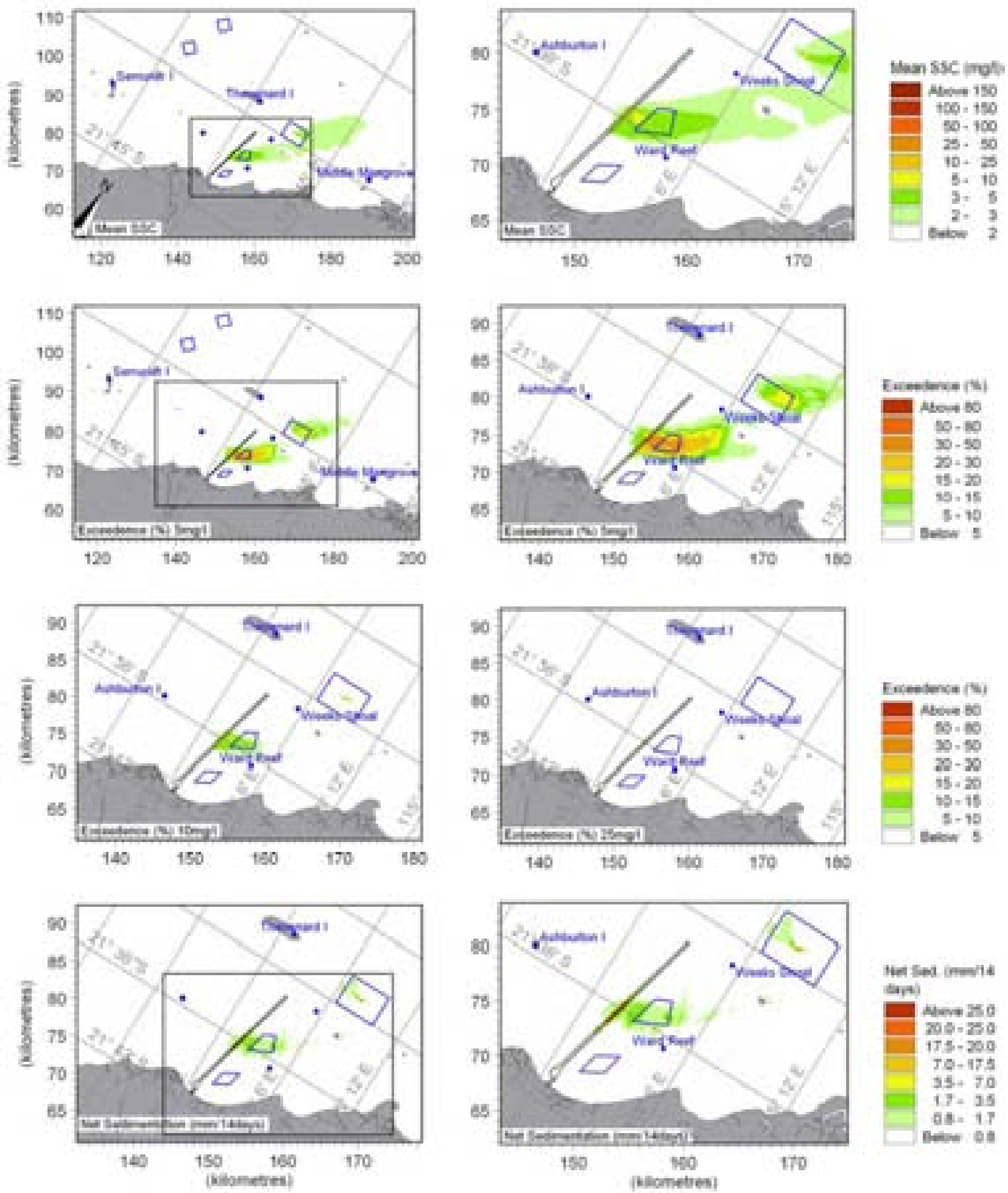

Figure S.2 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 5

S-4

Dredge Scenario: Scenario 5
Climatic Scenario: Summer B
Spill Rate Estimate: Low (“Realistic”) Case

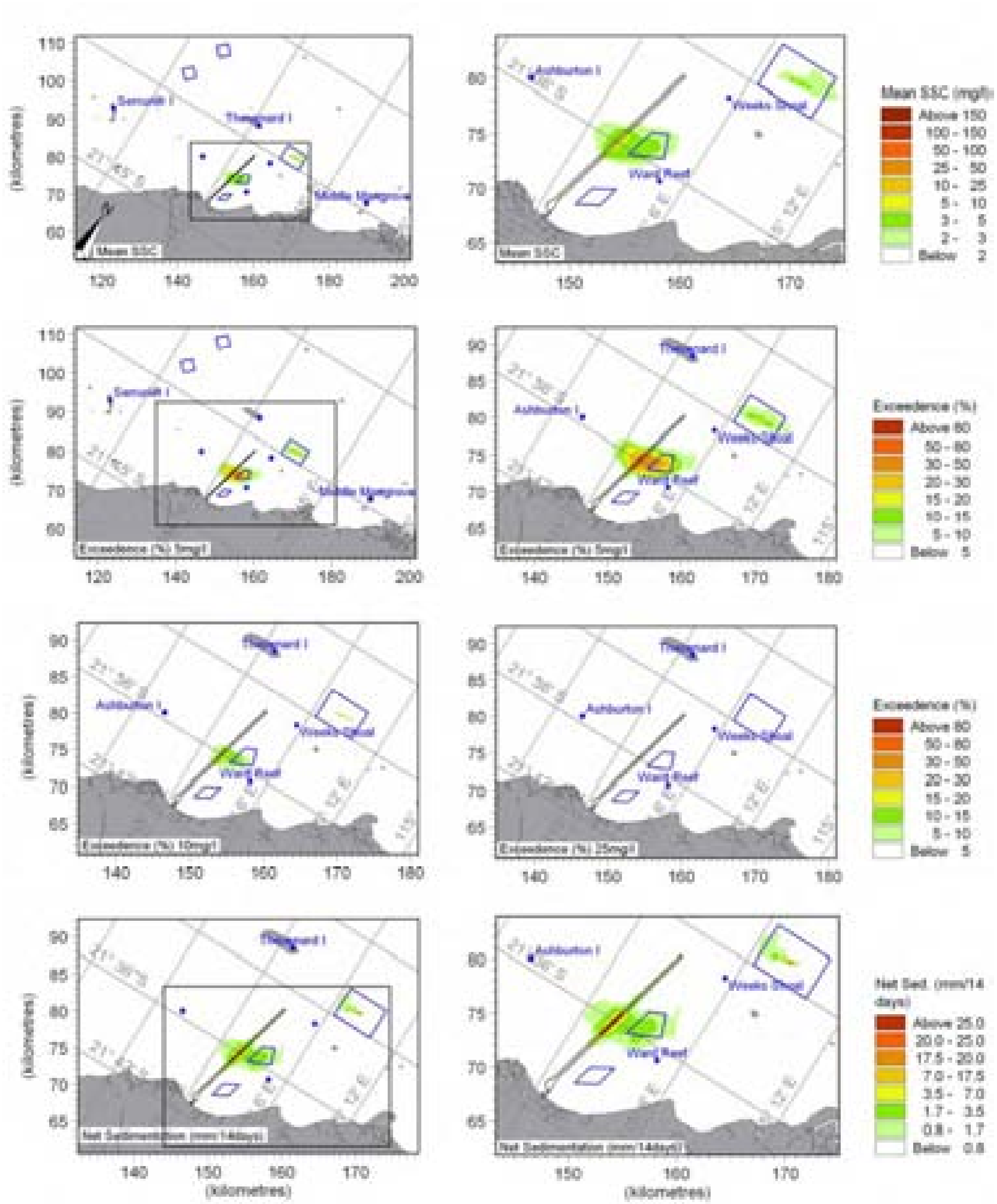

Figure S.3 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 5*

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S-5

Dredge Scenario: Scenario 5
Climatic Scenario: Transitional A
Spill Rate Estimate: Low ("Realistic") Case

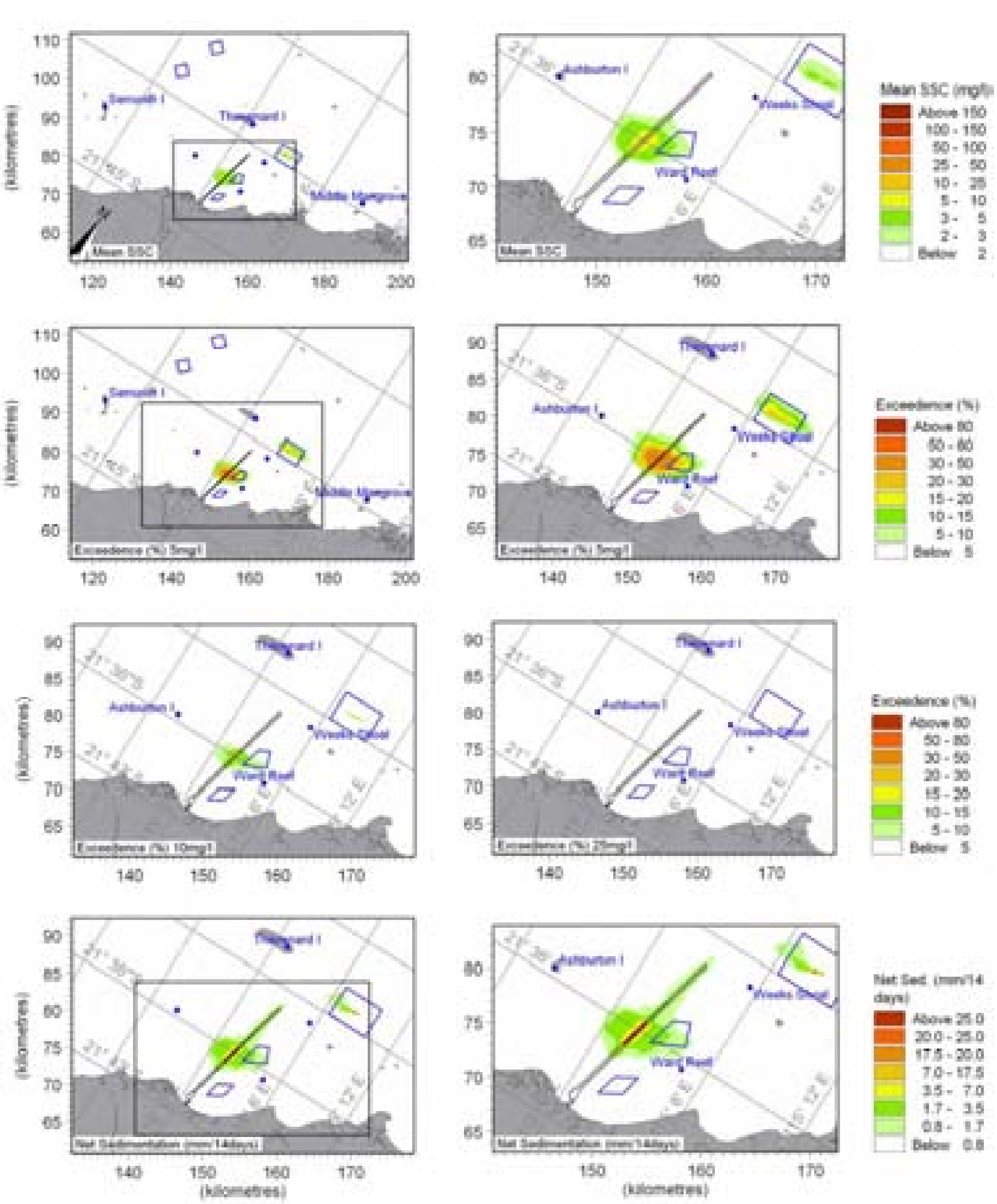

Figure S.4 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 5

DHI Water & Environment

Dredge Scenario: Scenario 5
Climatic Scenario: Transitional B
Spill Rate Estimate: Low (“Realistic”) Case

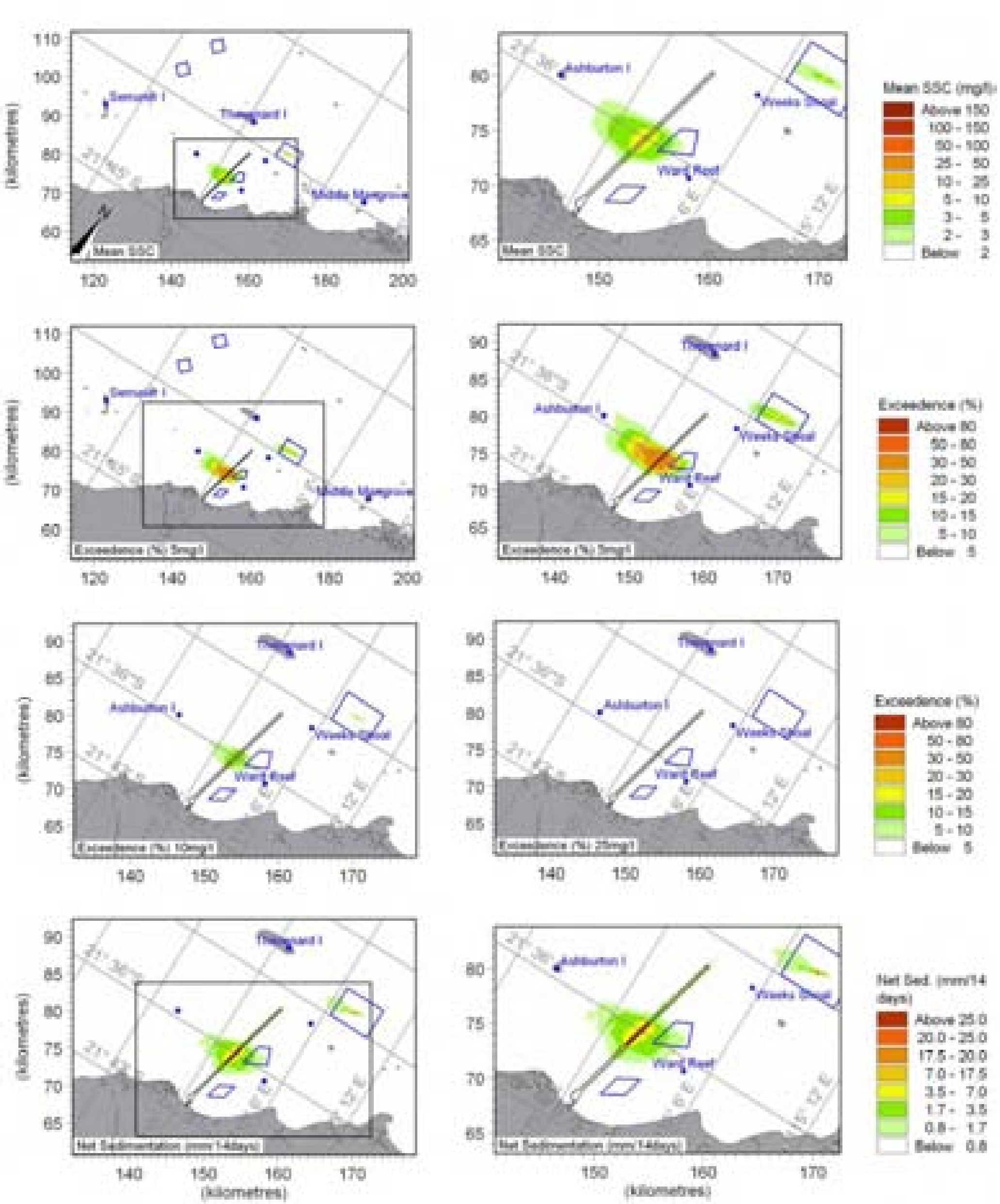

Figure S.5 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 5*

S-7

Dredge Scenario: Scenario 5
Climatic Scenario: Winter A
Spill Rate Estimate: Low ("Realistic") Case

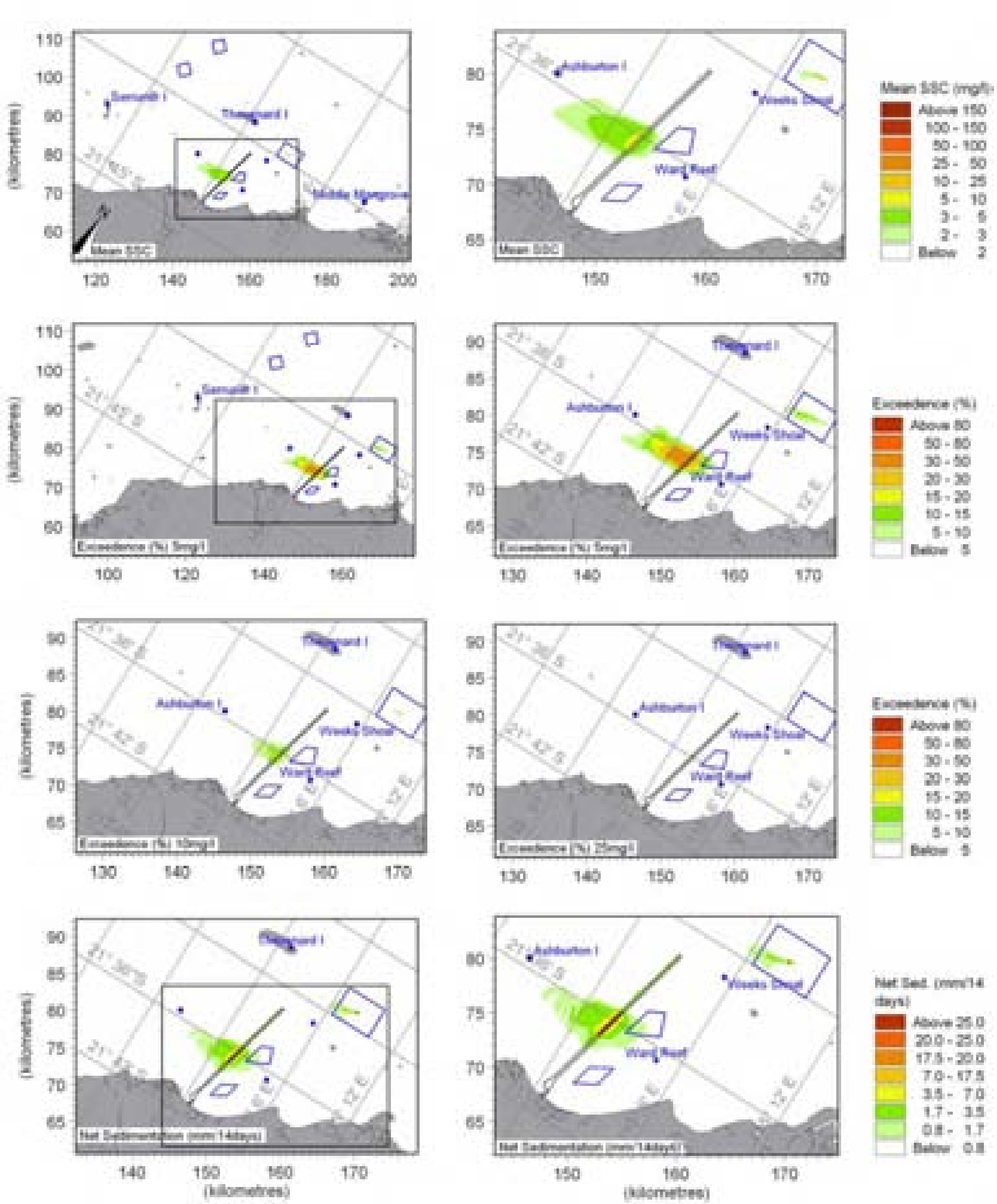

Figure S.6 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 5

DHI Water & Environment

S-8

Dredge Scenario: Scenario 5
Climatic Scenario: Winter B
Spill Rate Estimate: Low (“Realistic”) Case

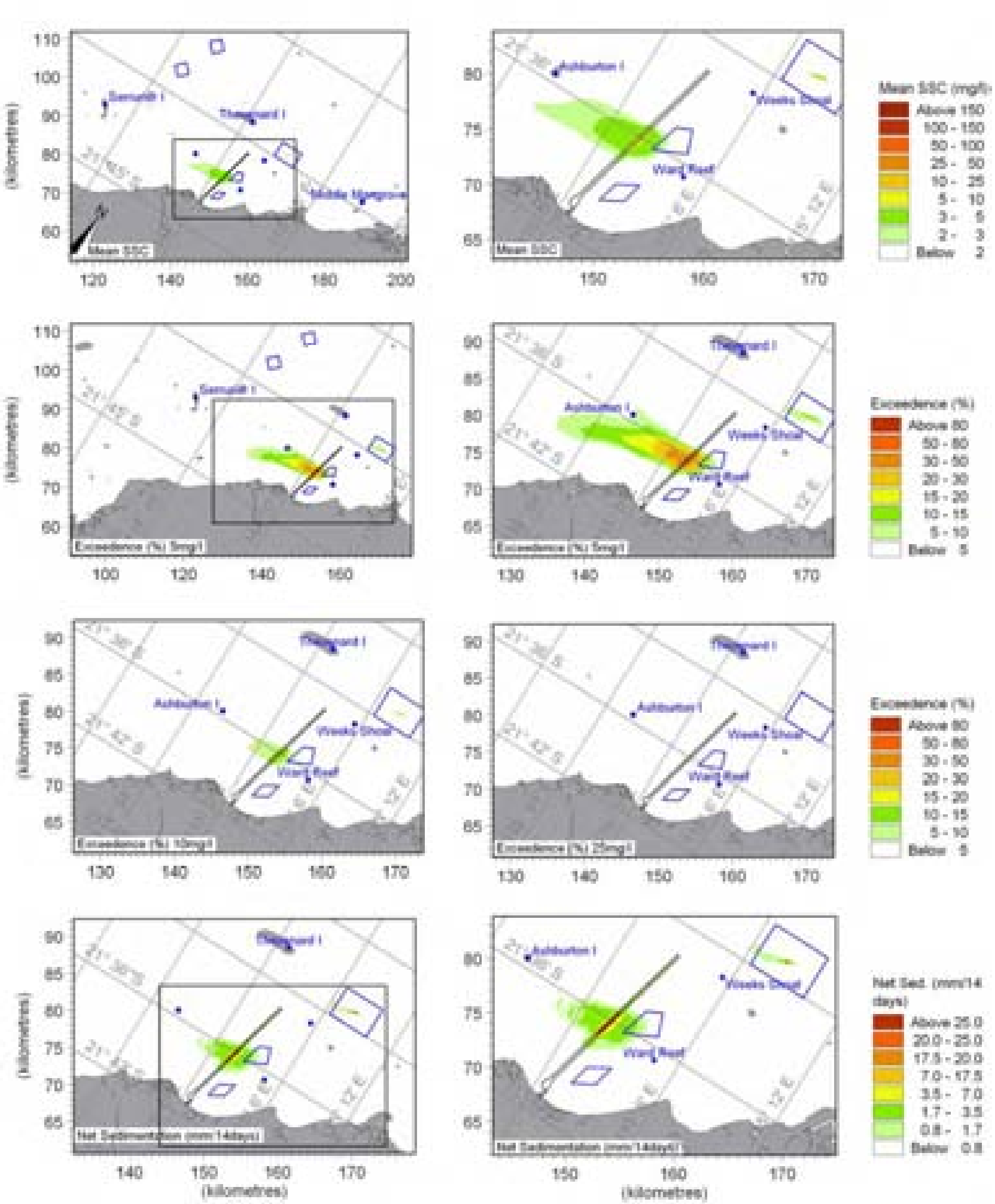

Figure S.7 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 5

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S.5 Results for High (Worst-Case) Spill Rates

Dredge Scenario:	Scenario 5
Climatic Scenario:	Summer A
Spill Rate Estimate:	High ("Worst Case")

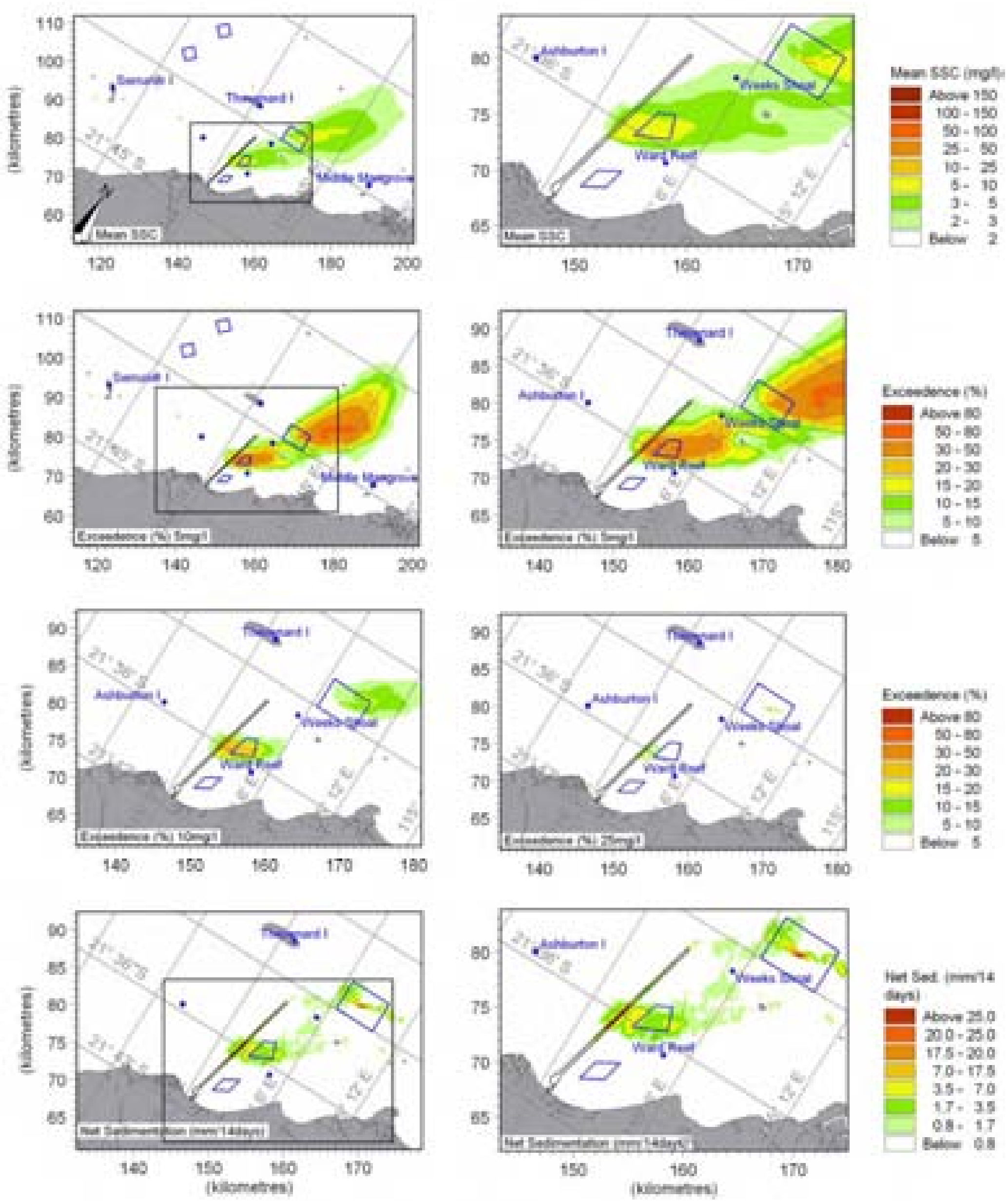

Figure S.8 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 5

S-10

Dredge Scenario: Scenario 5
Climatic Scenario: Summer B
Spill Rate Estimate: High ("Worst Case")

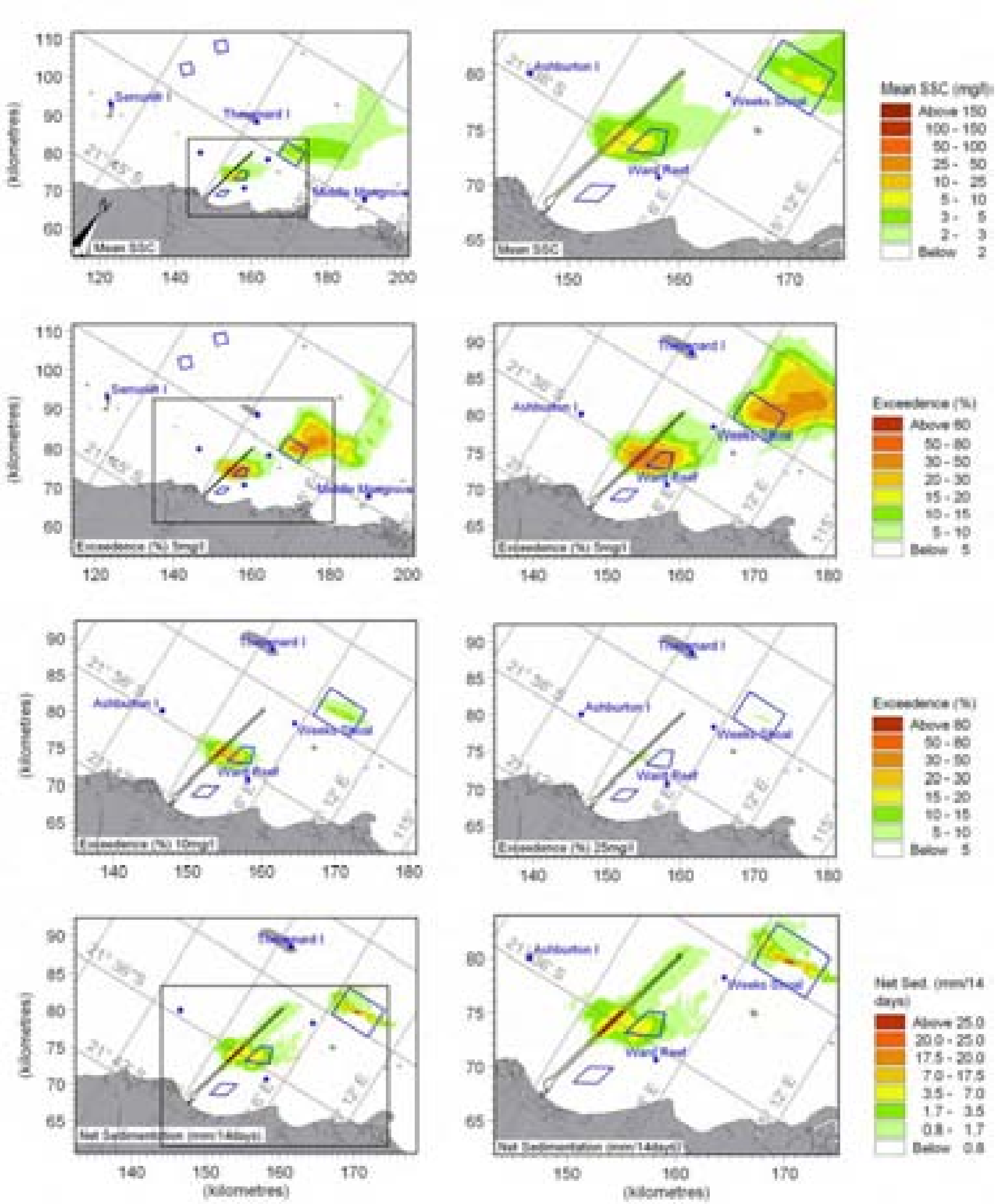

Figure S.9 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 5

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Dredge Scenario: Scenario 5
Climatic Scenario: Transitional A
Spill Rate Estimate: High ("Worst Case")

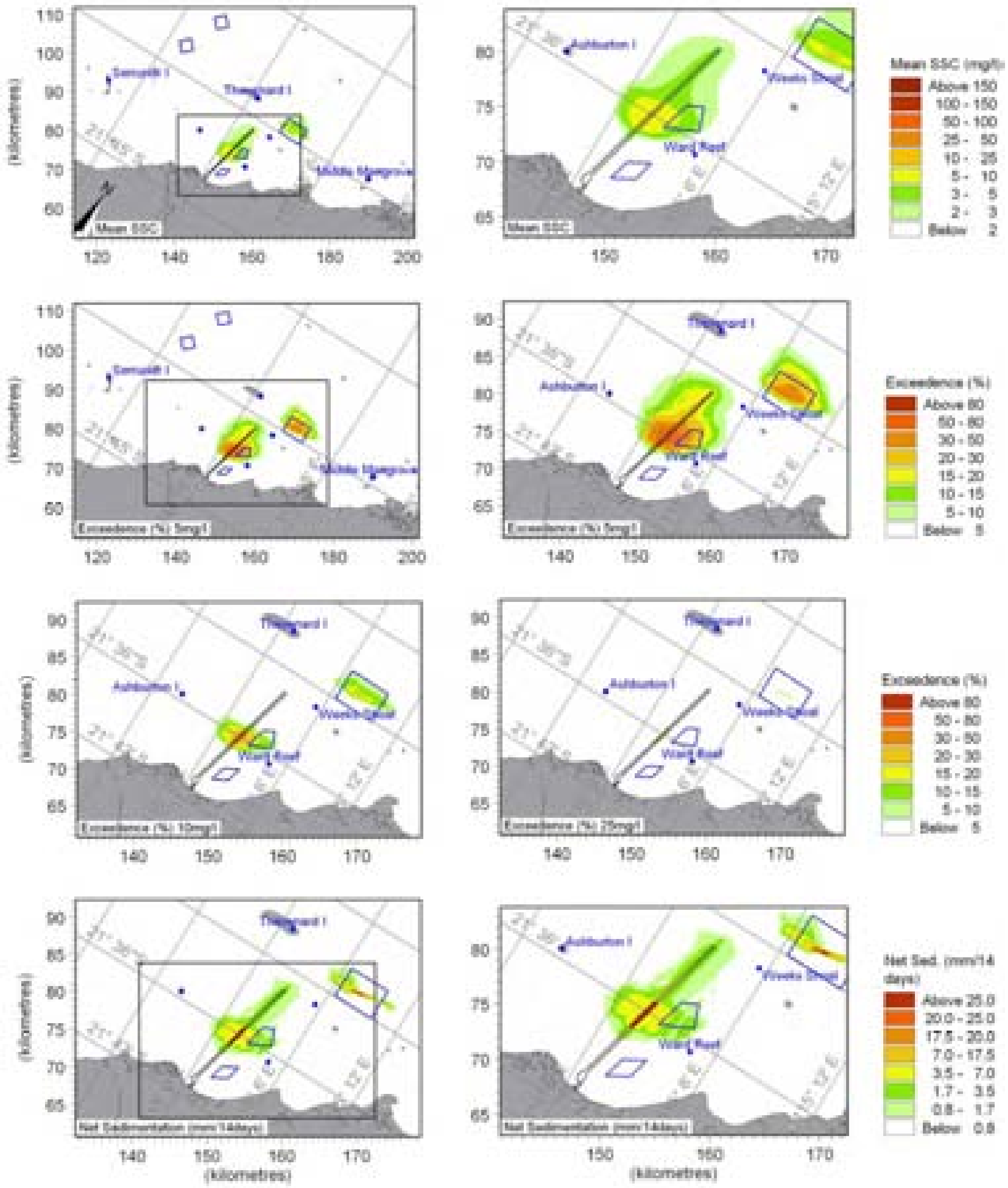

Figure S.10 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 5

Dredge Scenario: Scenario 5
Climatic Scenario: Transitional B
Spill Rate Estimate: High ("Worst Case")

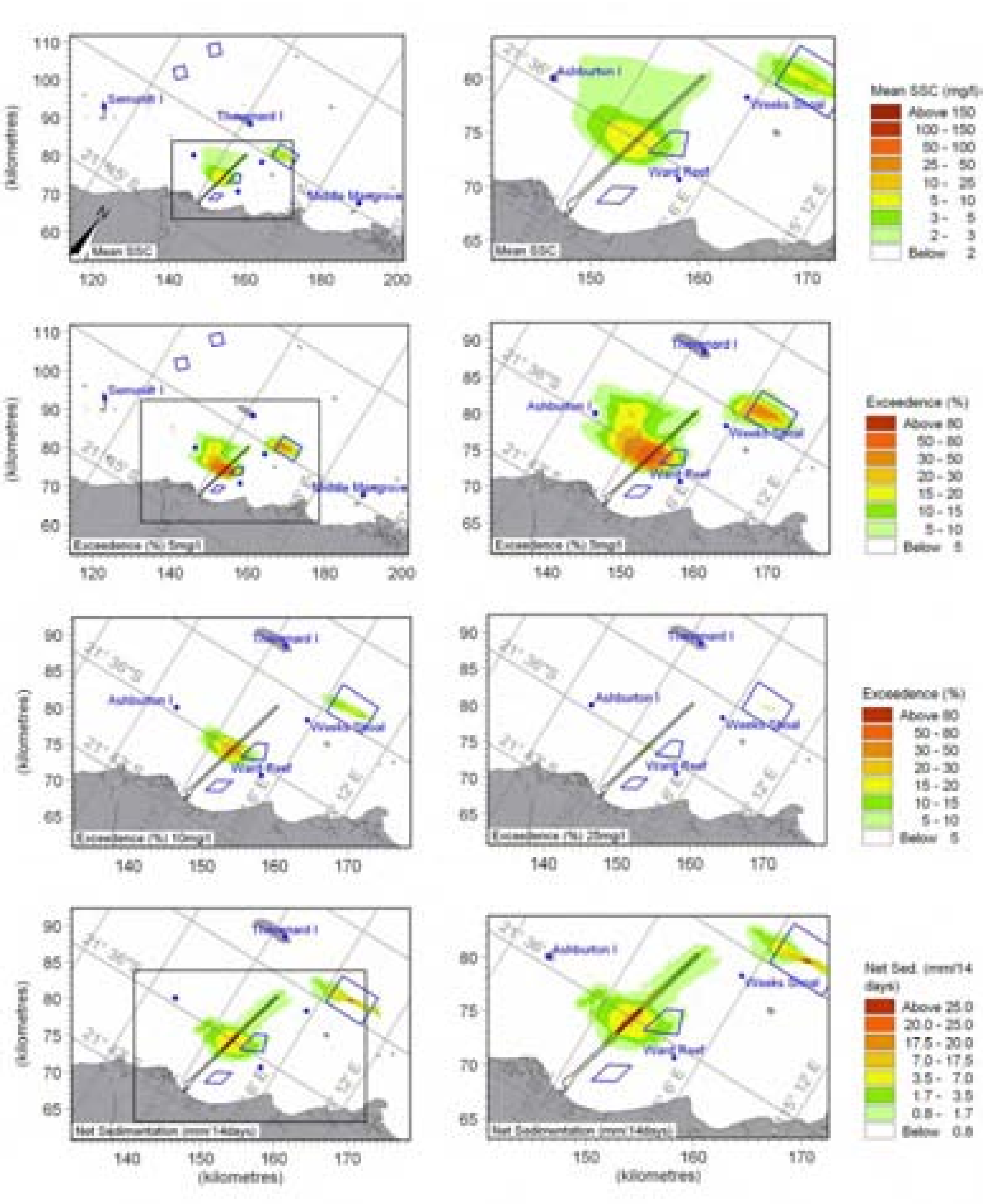

Figure S.11 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 5

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S-13

Dredge Scenario: Scenario 5
Climatic Scenario: Winter A
Spill Rate Estimate: High ("Worst Case")

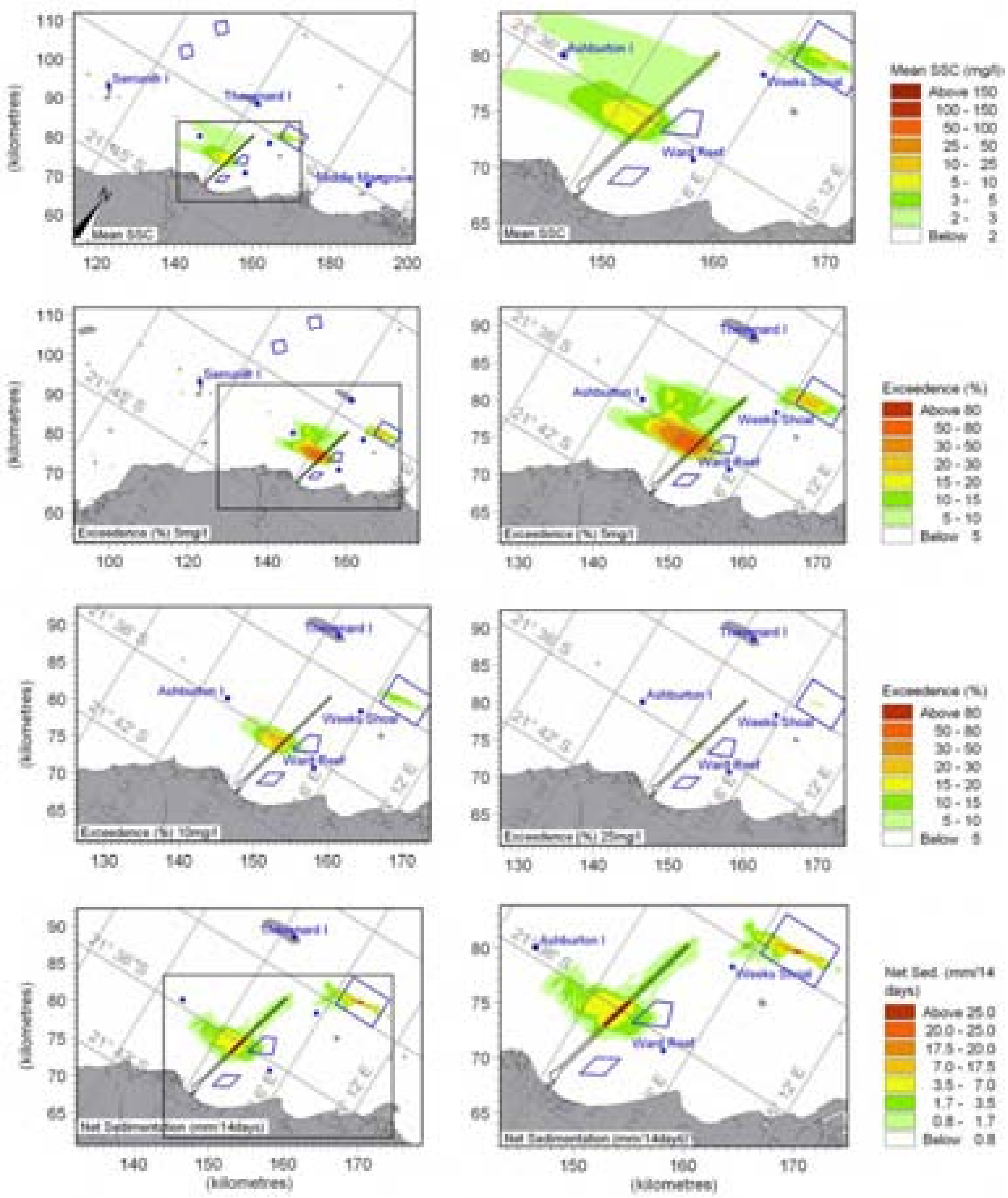

Figure S.12 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 5

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S-14

Dredge Scenario:	Scenario 5
Climatic Scenario:	Winter B
Spill Rate Estimate:	High ("Worst Case") missing plot

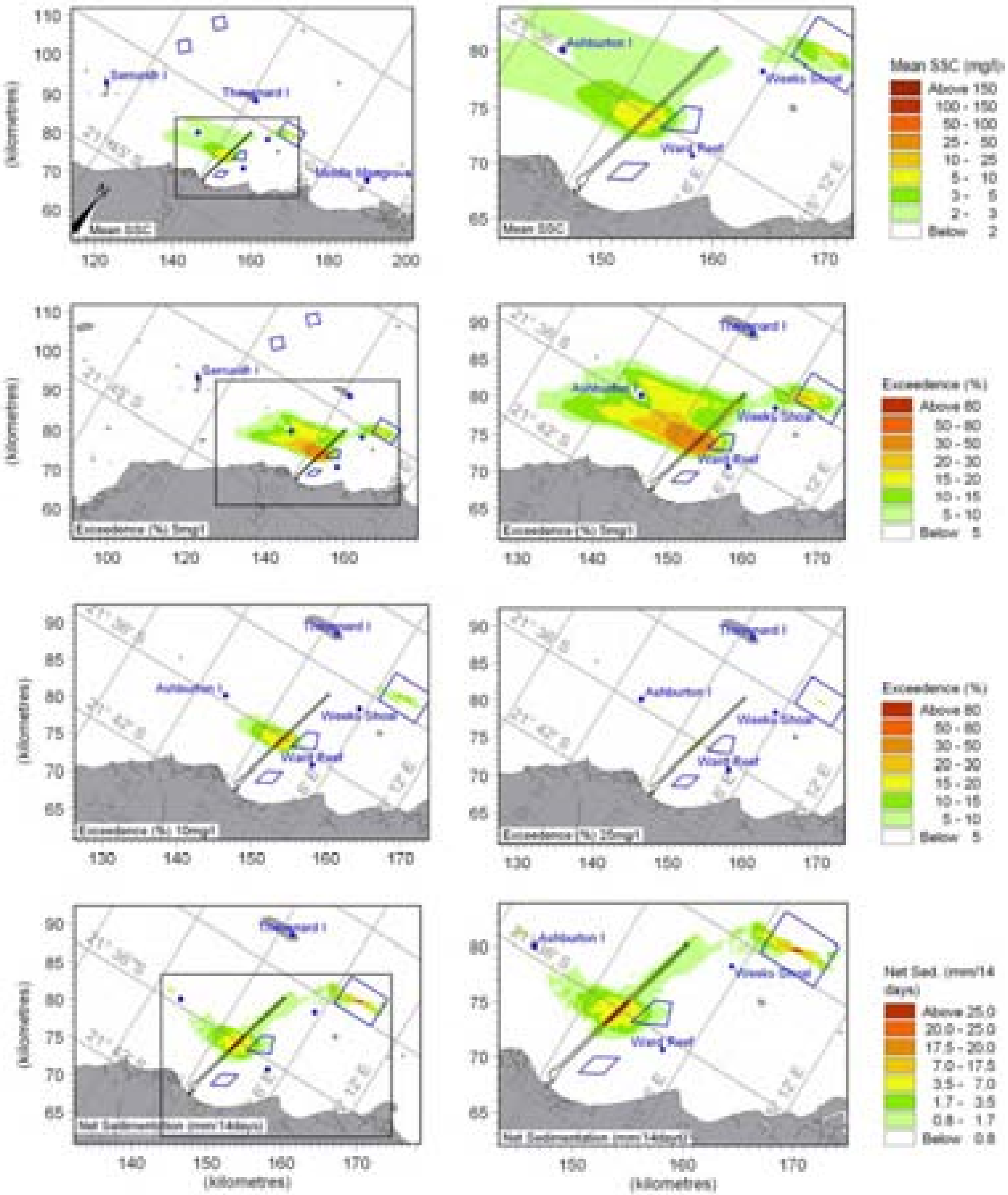

Figure S.13 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 5

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T RESULTS FOR DREDGE SCENARIO 6 BASED ON ONSLOW WINDS

This appendix presents results from the sediment transport model based on hydrodynamics driven by the Onslow wind fields. The reader is referred to the following sections of the main report and additional appendices for further information;

- Section 4.1.3.2 *Wind Fields*
- Section 6.2 *Results for the Dredging of the Shipping Channel*
- Appendix D *Hydrodynamic Model Validation and Calibration*

T.1 Statistical Plots

The established impact criteria (DHI (2010) *Dredge Plume Impact Assessment Report)* are based on sediment loads, both in terms of excess suspended concentrations and sedimentation rates, over 14 day periods. In terms of exposure and impacts, both the concentrations and the duration of the event is important, which is expressed through the exceedence probability of given limits.

For each simulated case, a set of plots showing the statistical output used in the impact assessment have been produced. All plots are for excess concentrations, i.e. sediments originating from the dredging operations and exclusive of ambient concentrations.

Each mosaic plot comprises:

- Mean excess concentration at two scales
- Exceedence of 5mg/l excess concentration at two scales
- Exceedence of 10mg/l excess concentration
- Exceedence of 25mg/l excess concentration
- Net sedimentation rates at two zoomed levels at the site

Note that all concentrations are presented as depth-averaged values. All values are derived over the assessment period (2^{nd} neap/spring tidal cycle of the month for each climatic scenario), i.e. after at least 14 days warm-up period. Exceedences are expressed in percentage time over the assessment period that the exceedence limit is exceeded.

T.2 Description of Dredge scenario 6

General

- Bathymetry with fully dredged MOF, MOF channel and PLF basin. Partly dredged approach channel along entire length
- Material available for re-suspension along all dredged areas and in placement Sites A and C
- Include MOF dredged basin and MOF breakwaters.

Offshore Dredging 1: Approach Channel – Section 4 sand

- 10,000m^3 TSHD with disposal at placement Site C
- Dredging along Section 4

Offshore Dredging 2: Approach Channel – weak rock

- 10,000m^3 TSHD with disposal at placement Site C
- Dredging along Sections 3 & 4

The locations for the various dredge and placement activities are outlined in Figure T.1, while defined "realistic" and "worst case" spill rates for Dredging Scenario 6 are listed in Table 3.2 of the main report.

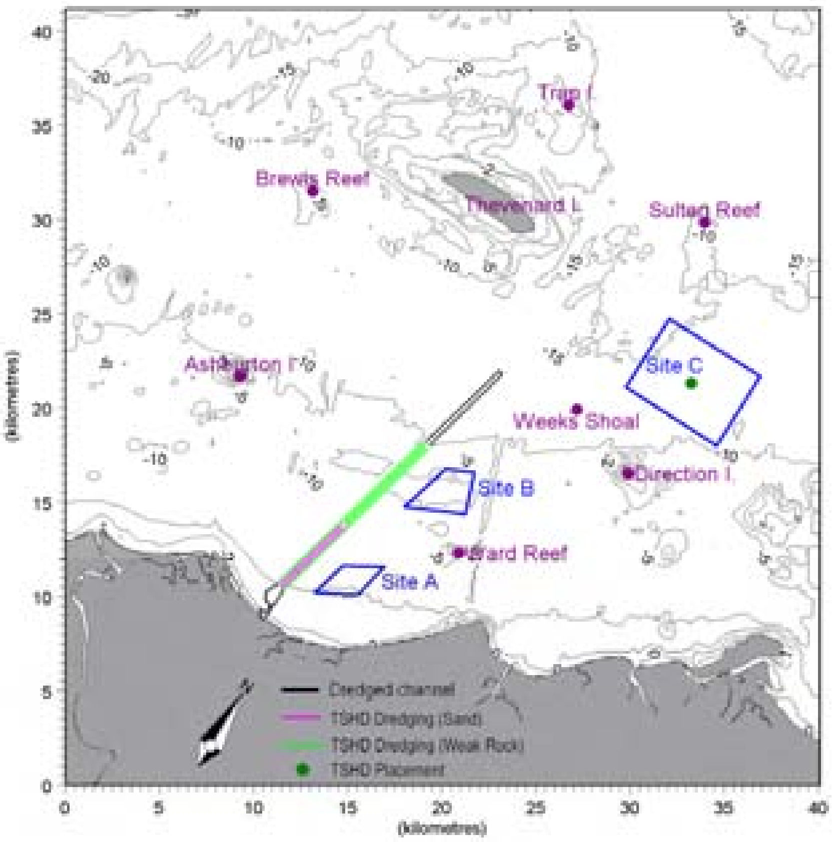

Figure T.1 Sketch of locations for Dredging Scenario 6.

T.3 Summary of Results

Specific observations for Dredge Scenario 6 include:

- The (lower concentration) plumes from the TSHD dredging at Sections 3 and 4 combine with the plumes generated from the sand dredging at Section 4 to generate a higher concentration plume.
- Mean excess concentrations of 10mg/l extends up to 25km to the east during strong summer conditions and up to 10km to the west during strong winter conditions for worst case spill rates.
- The plume generated from Section 4 of the PLF Approach channel overlaps Ward Reef during summer conditions

T.4 Results for Low (Realistic) Spill Rates

Dredge Scenario: Scenario 6
Climatic Scenario: Summer A
Spill Rate Estimate: Low ("Realistic") Case

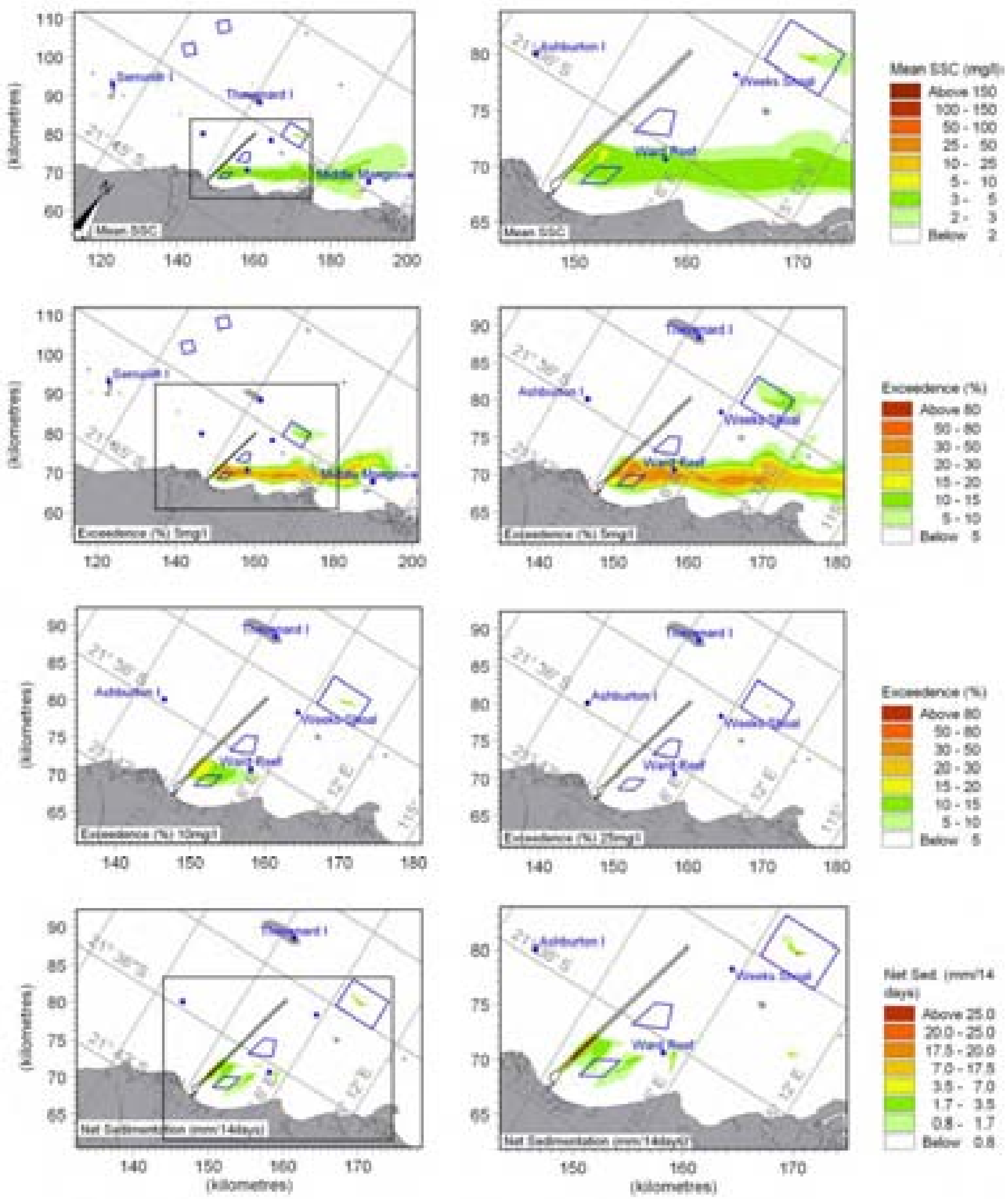

Figure T.2 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 6

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T-4

Dredge Scenario: Scenario 6
Climatic Scenario: Summer B
Spill Rate Estimate: Low ("Realistic") Case

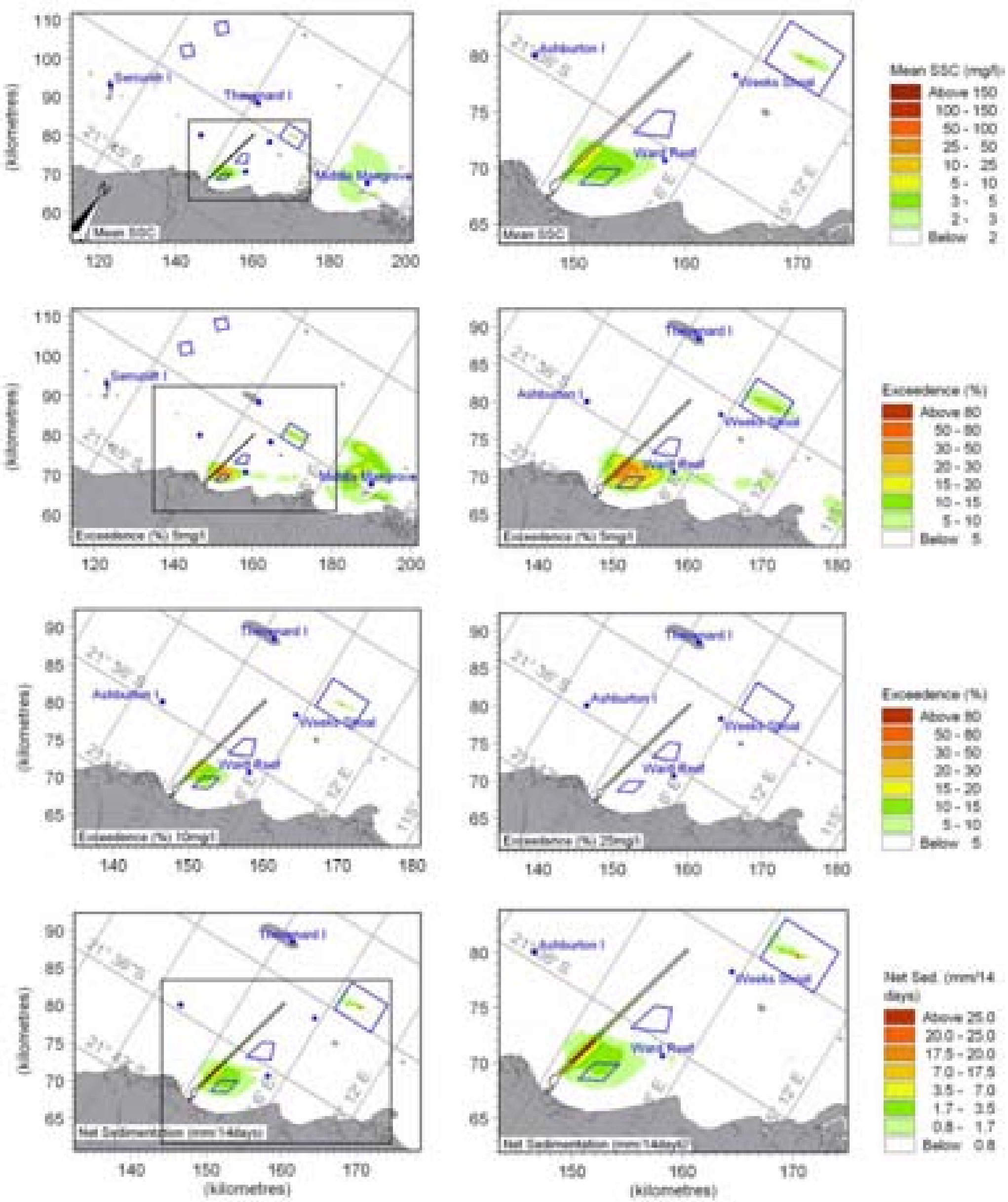

Figure T.3 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 6*

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T-5

Dredge Scenario:	Scenario 6
Climatic Scenario:	Transitional A
Spill Rate Estimate:	Low ("Realistic") Case

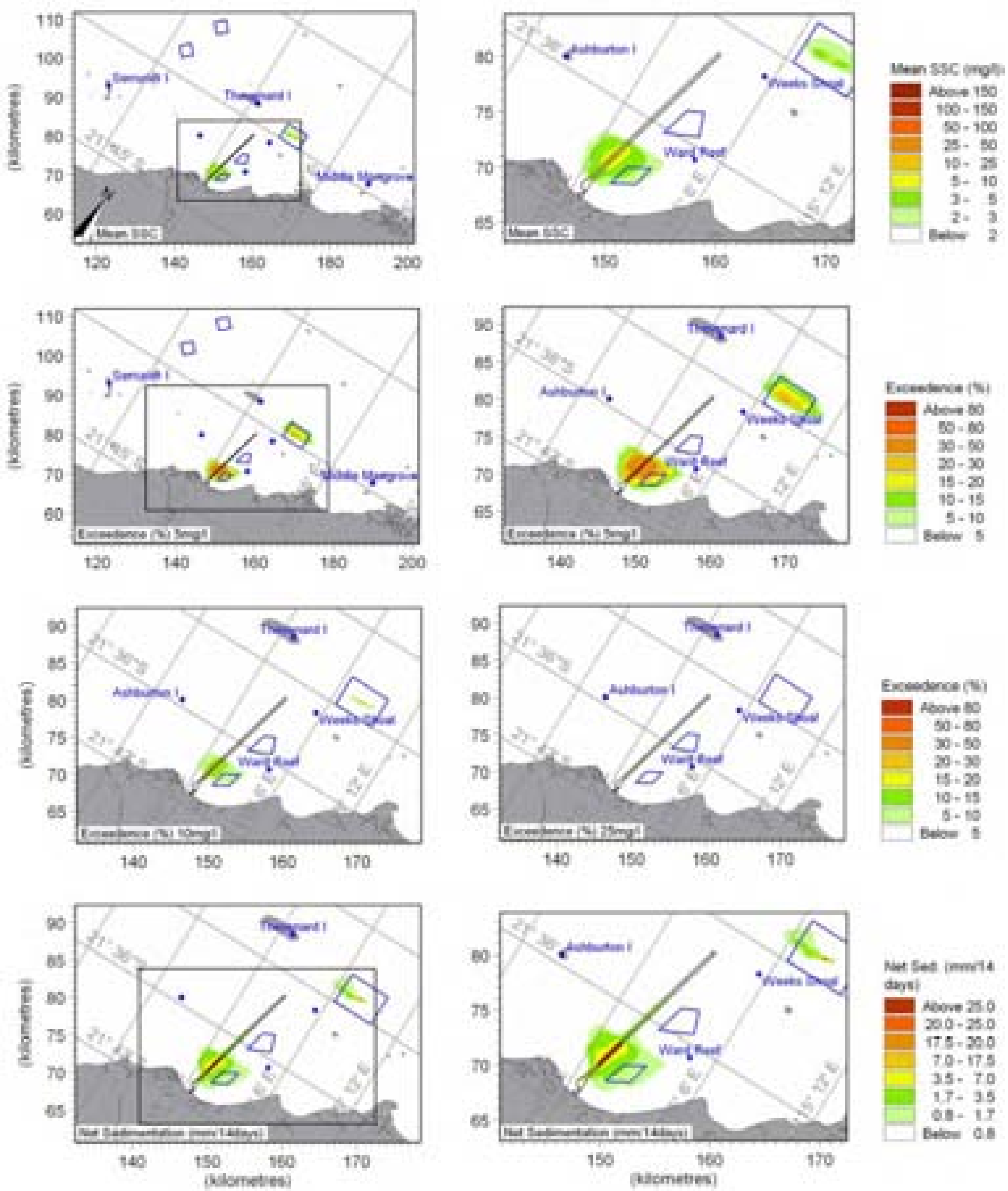

Figure T.4 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 6*

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T-6

Dredge Scenario: Scenario 6
Climatic Scenario: Transitional B
Spill Rate Estimate: Low ("Realistic") Case

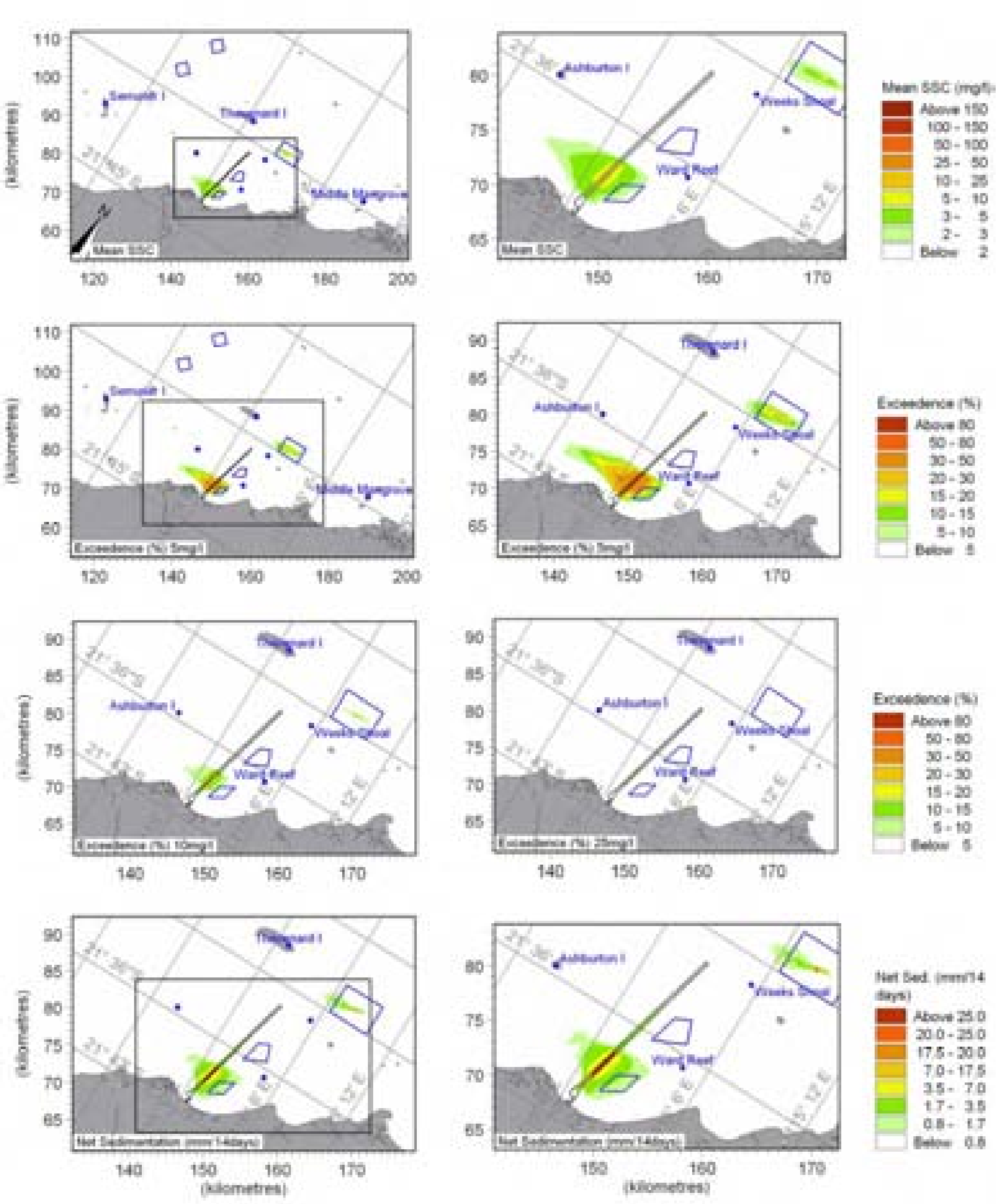

Figure T.5 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 6*

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T-7

Dredge Scenario: Scenario 6
Climatic Scenario: Winter A
Spill Rate Estimate: Low (“Realistic”) Case

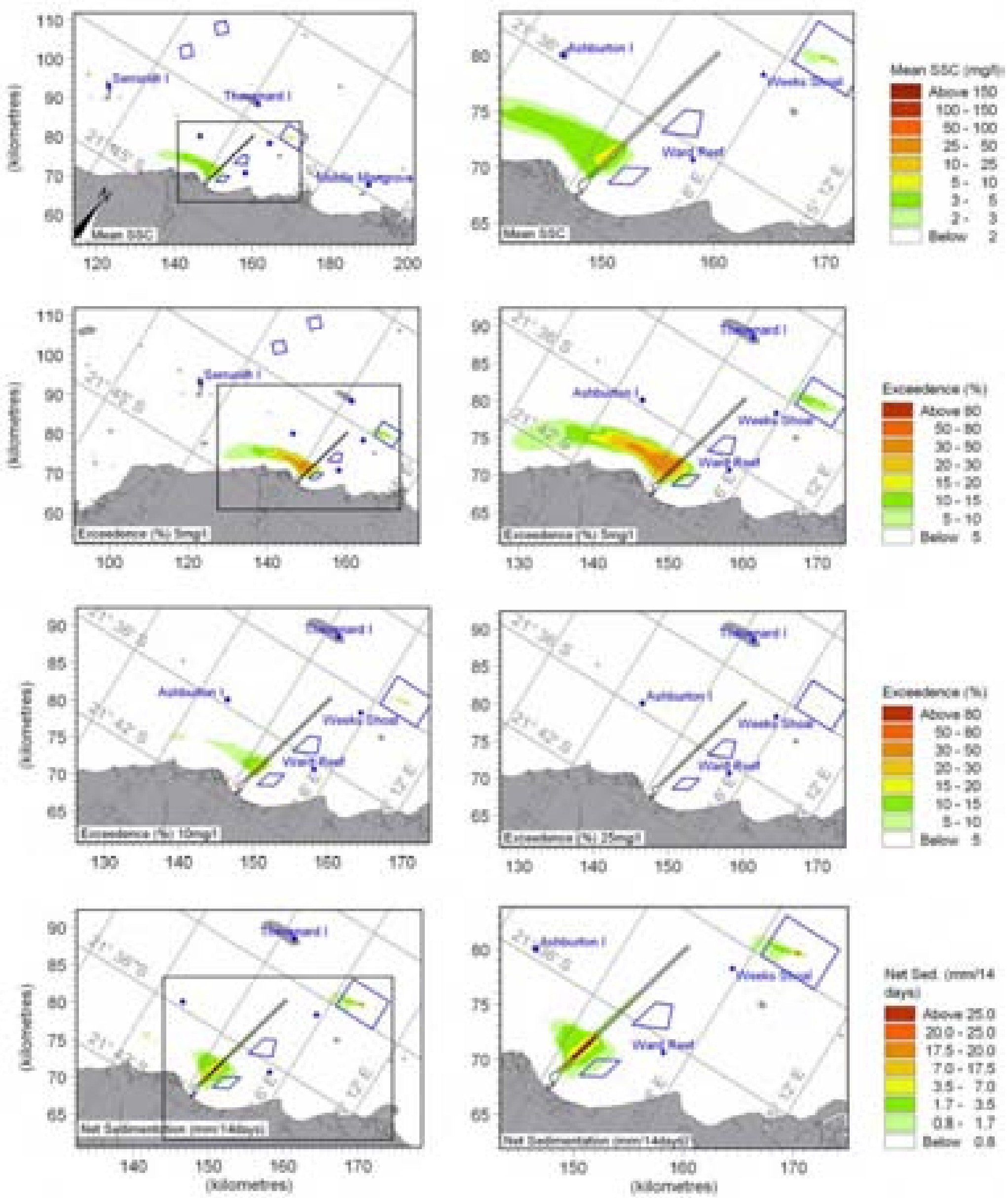

Figure T.6 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 6*

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T-8

Dredge Scenario: Scenario 6
Climatic Scenario: Winter B
Spill Rate Estimate: Low ("Realistic") Case

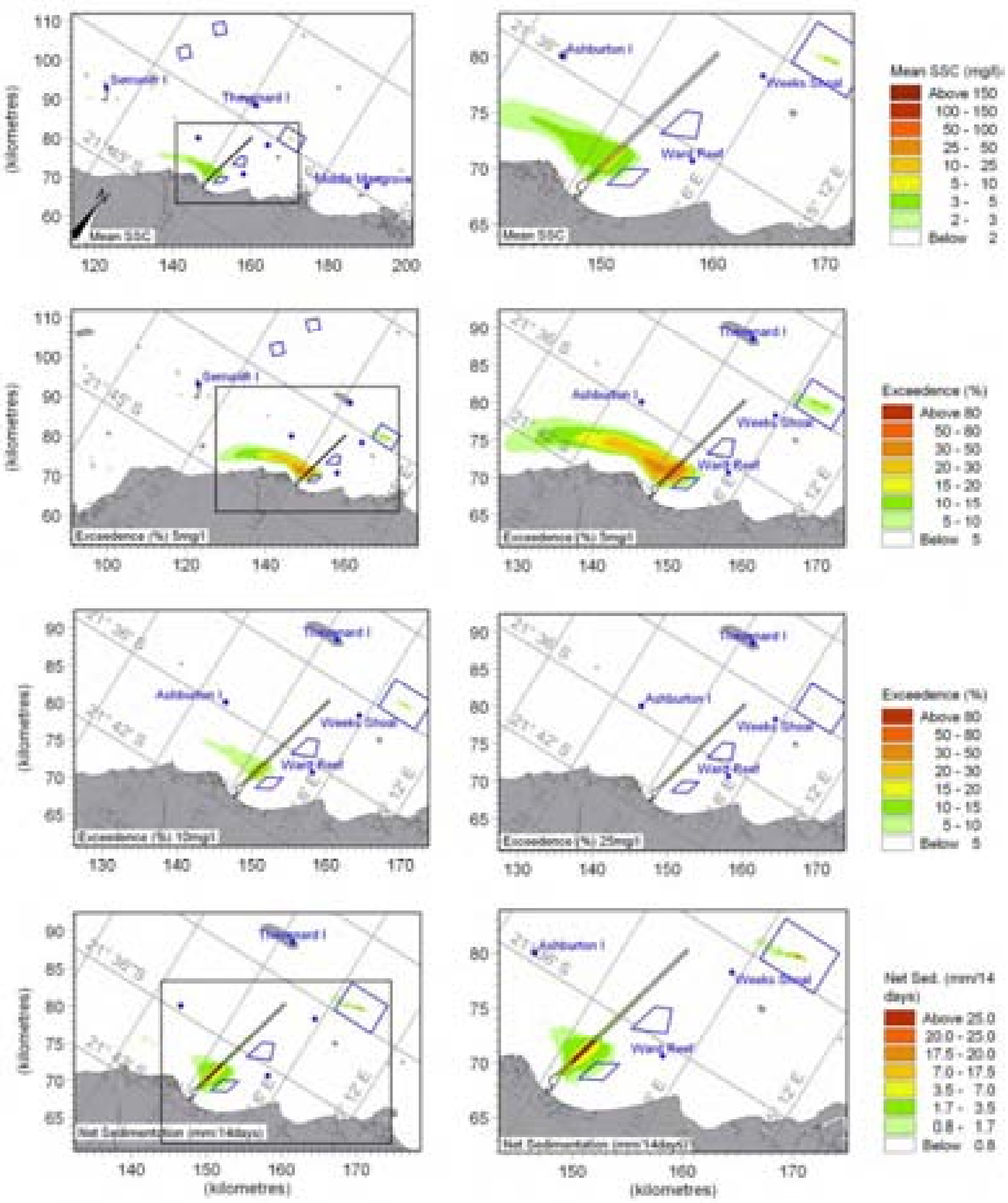

Figure T.7 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 6*

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T.5 Results for High (Worst-Case) Spill Rates

Dredge Scenario: Scenario 6
Climatic Scenario: Summer A
Spill Rate Estimate: High ("Worst Case")

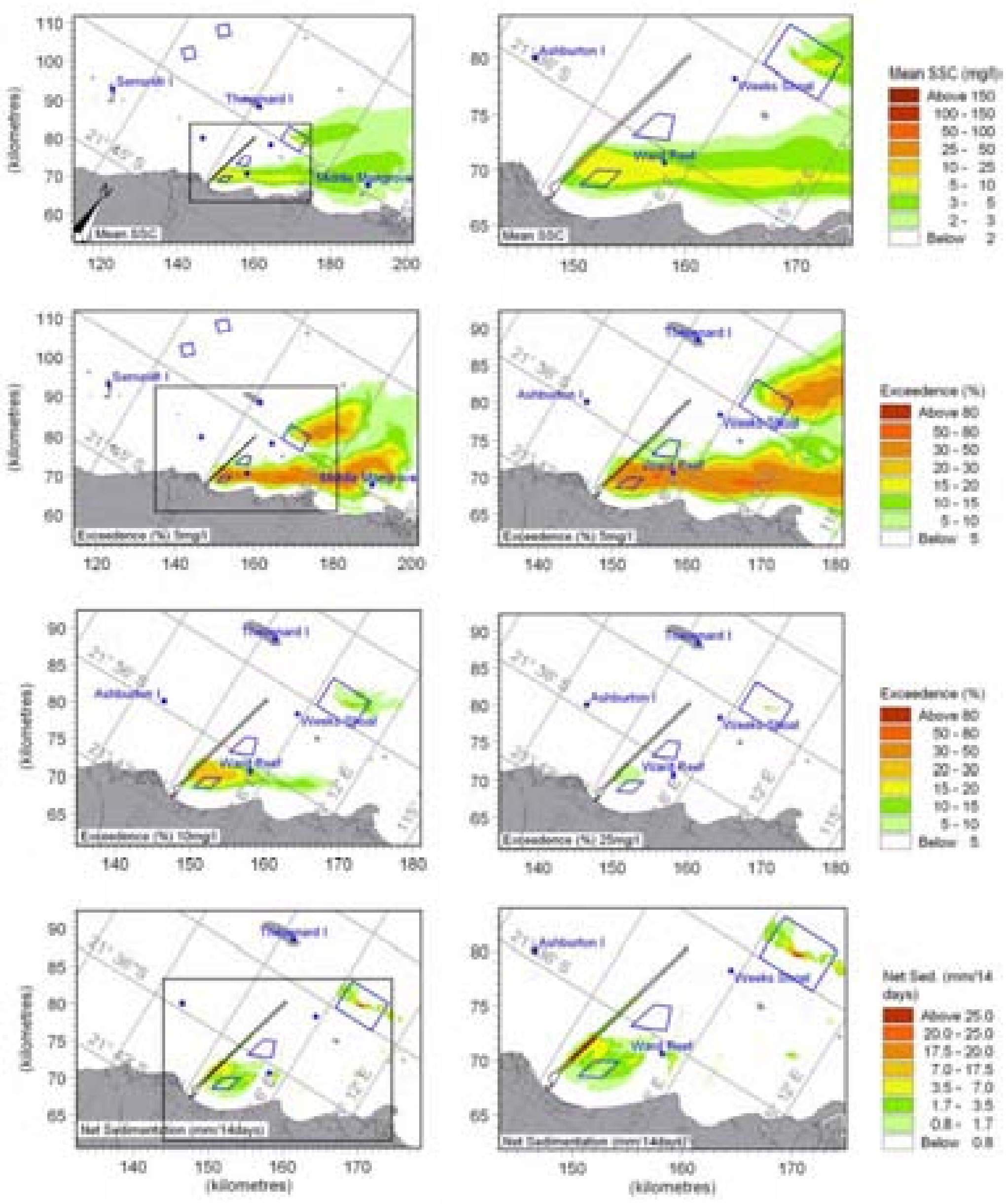

Figure T.8 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 6

T-10

Dredge Scenario: Scenario 6
Climatic Scenario: Summer B
Spill Rate Estimate: High ("Worst Case")

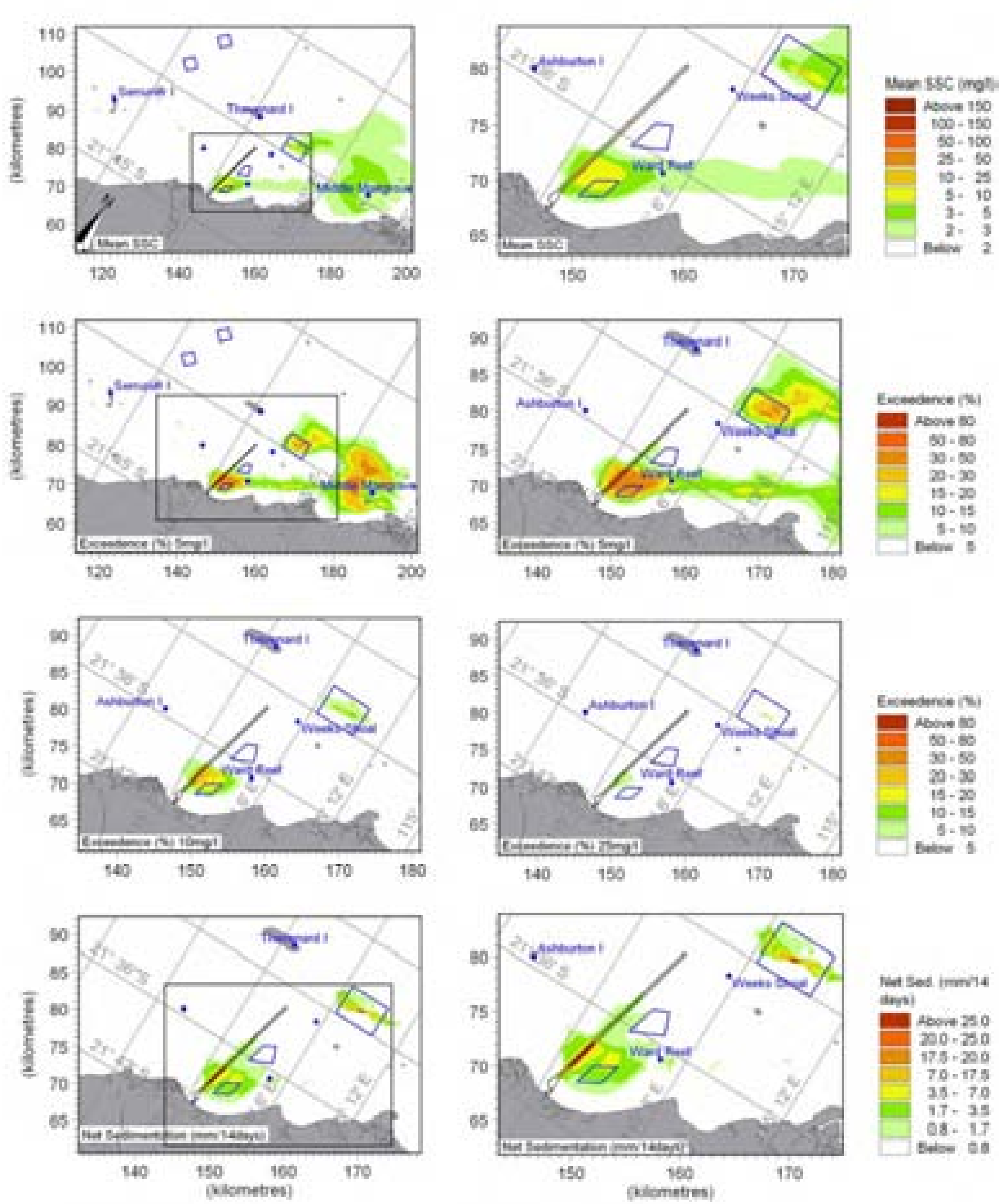

Figure T.9 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 6*

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T-11

Dredge Scenario: Scenario 6
Climatic Scenario: Transitional A
Spill Rate Estimate: High (“Worst Case”)

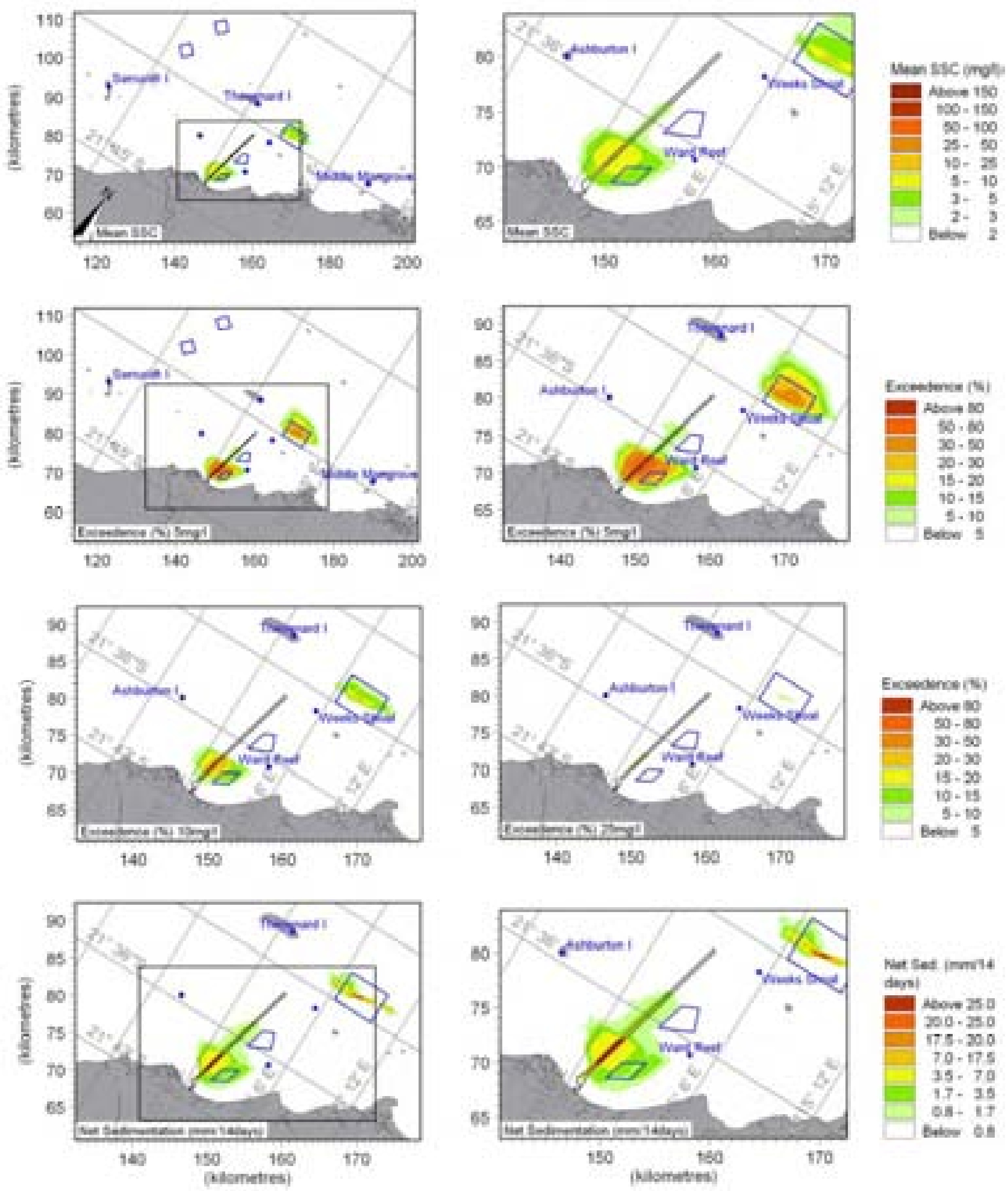

Figure T.10 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 6*

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T-12

Dredge Scenario: Scenario 6
Climatic Scenario: Transitional B
Spill Rate Estimate: High ("Worst Case")

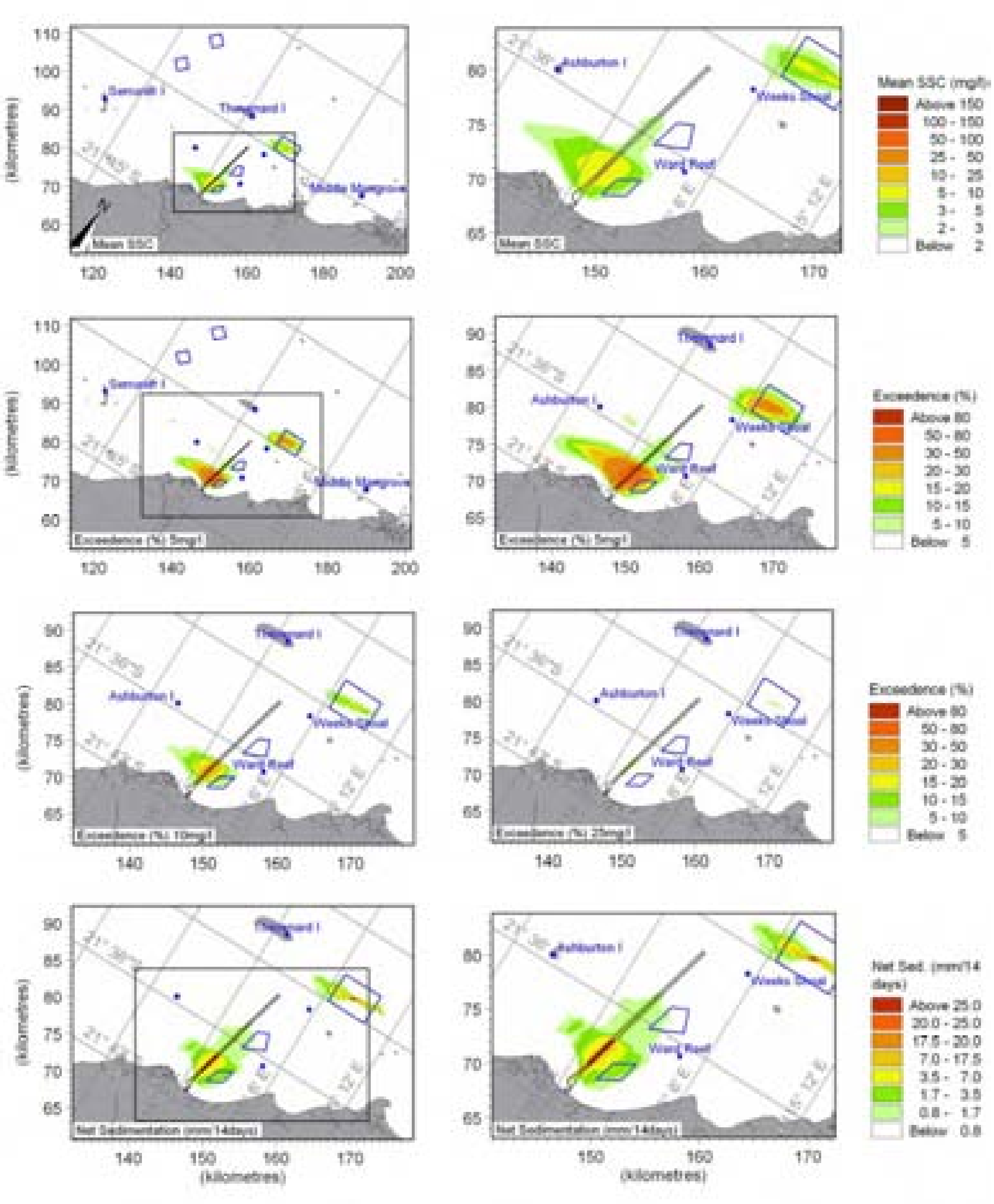

Figure T.11 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 6

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T-13

Dredge Scenario: Scenario 6
Climatic Scenario: Winter A
Spill Rate Estimate: High ("Worst Case")

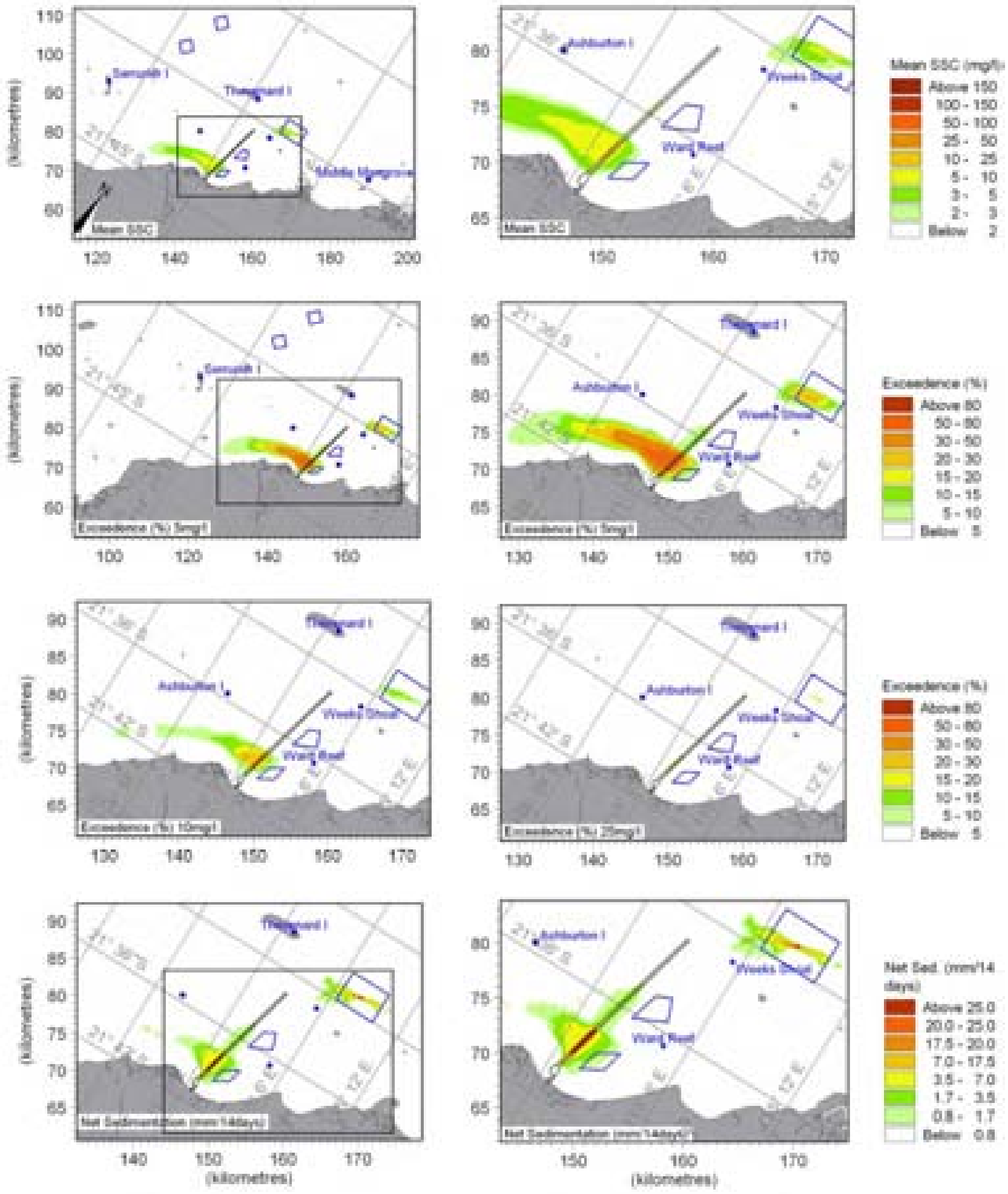

Figure T.12 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 6

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T-14

Dredge Scenario: Scenario 6
Climatic Scenario: Winter B
Spill Rate Estimate: High ("Worst Case")

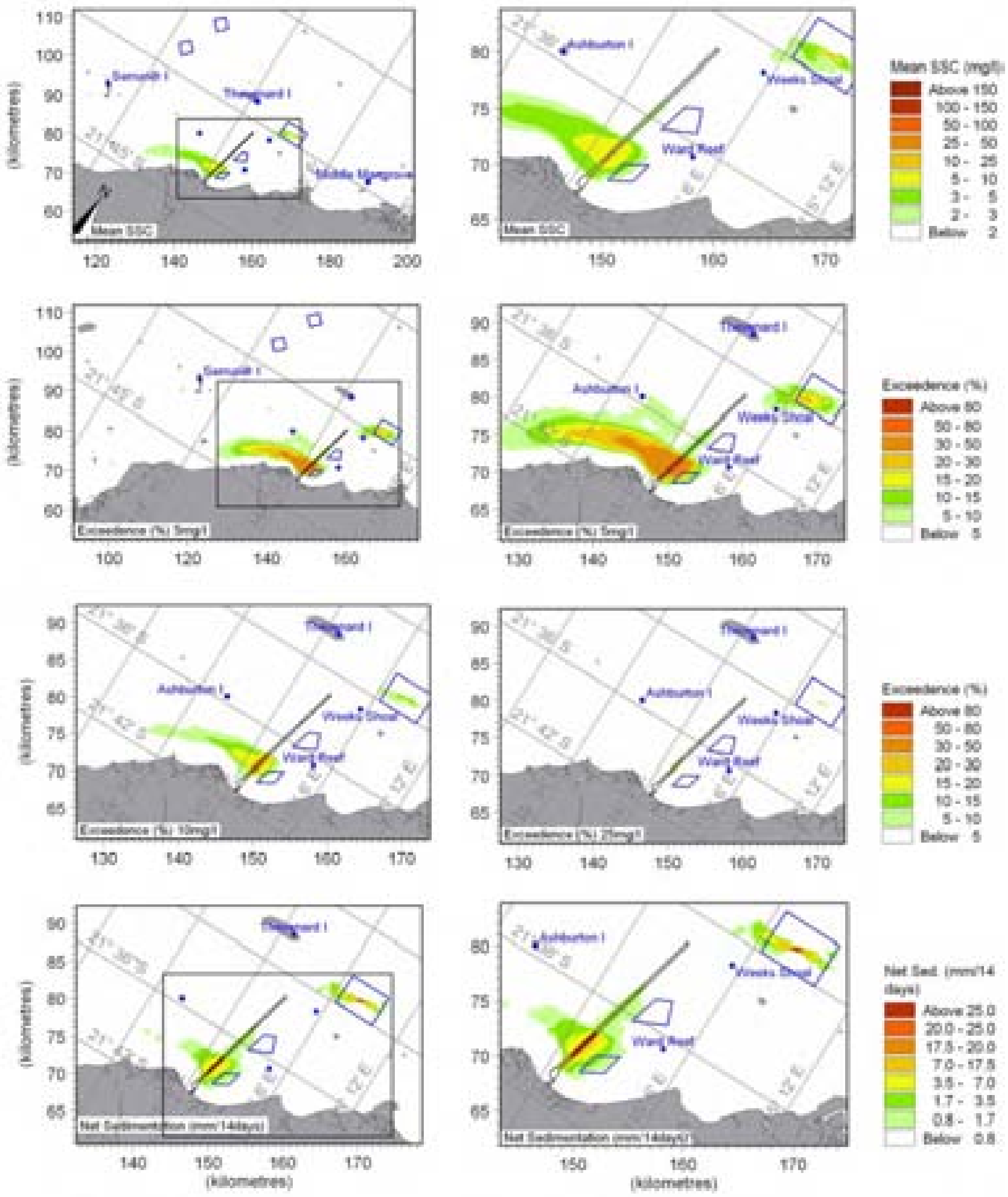

Figure T.13 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 6

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U RESULTS FOR DREDGE SCENARIO 7 BASED ON ONSLOW WINDS

This appendix presents results from the sediment transport model based on hydrodynamics driven by the Onslow wind fields. The reader is referred to the following sections of the main report and additional appendices for further information;

- Section 4.1.3.2 *Wind Fields*
- Section 6.2 *Results for the Dredging of the Shipping Channel*
- Appendix D *Hydrodynamic Model Validation and Calibration*

U.1 Statistical Plots

The established impact criteria (DHI (2010) *Dredge Plume Impact Assessment Report)* are based on sediment loads, both in terms of excess suspended concentrations and sedimentation rates, over 14 day periods. In terms of exposure and impacts, both the concentrations and the duration of the event is important, which is expressed through the exceedence probability of given limits.

For each simulated case, a set of plots showing the statistical output used in the impact assessment have been produced. All plots are for excess concentrations, i.e. sediments originating from the dredging operations and exclusive of ambient concentrations.

Each mosaic plot comprises:

- Mean excess concentration at two scales
- Exceedence of 5mg/l excess concentration at two scales
- Exceedence of 10mg/l excess concentration
- Exceedence of 25mg/l excess concentration
- Net sedimentation rates at two zoomed levels at the site

Note that all concentrations are presented as depth-averaged values. All values are derived over the assessment period (2nd neap/spring tidal cycle of the month for each climatic scenario), i.e. after at least 14 days warm-up period. Exceedences are expressed in percentage time over the assessment period that the exceedence limit is exceeded.

U.2 Description of Dredge scenario 7A

General

- Bathymetry with fully dredged MOF, MOF channel and PLF basin. Partly dredged approach channel along entire length
- Material available for re-suspension along all dredged areas and in placement Sites A and C
- Include MOF dredged basin and MOF breakwaters.

Offshore Dredging: Approach Channel – Section 2 sand

- 10,000m^3 TSHD with disposal at placement Site C
- Dredging along Section 2

The locations for the various dredge and placement activities are outlined in Figure U.1, while defined "realistic" and "worst case" spill rates for Dredging Scenario 7 are listed in Table 3.2 of the main report.

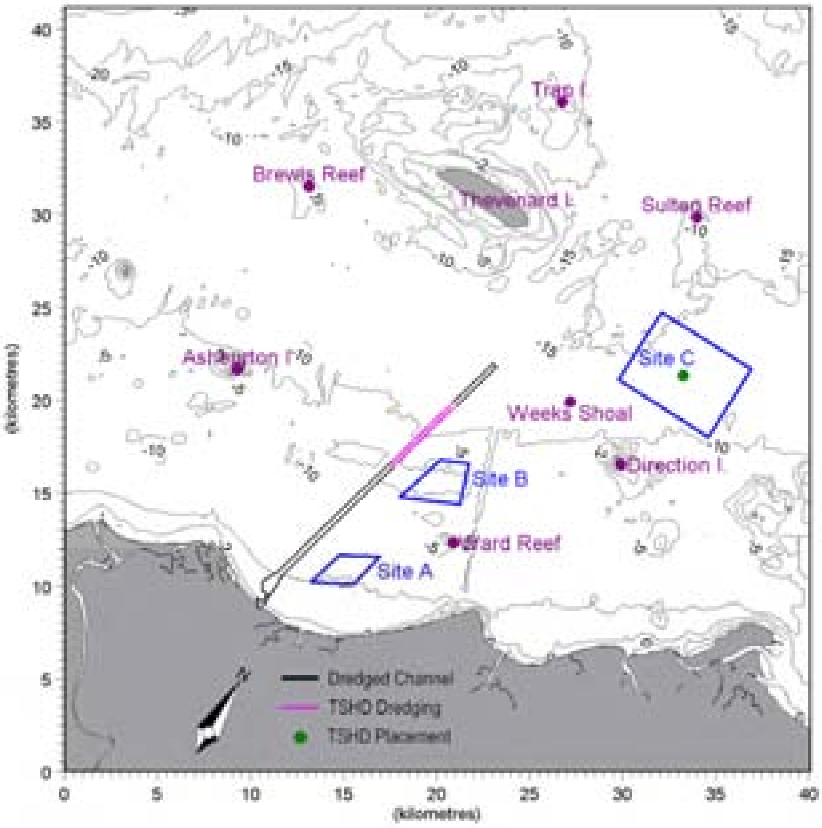

Figure U.1 Sketch of locations for Dredging Scenario 7.

U.3 Summary of Results

Specific observations for Dredge Scenario 7 include:

- During summer conditions, the plumes emitted from dredging in Section 2 combine with the plumes from Site C to form a larger plume.
- The plumes generated from Section 2 overlap several reefs found along the 10m contour area.

U.4 Results for Low (Realistic) Spill Rates

Dredge Scenario: Scenario 7
Climatic Scenario: Summer A
Spill Rate Estimate: Low ("Realistic") Case

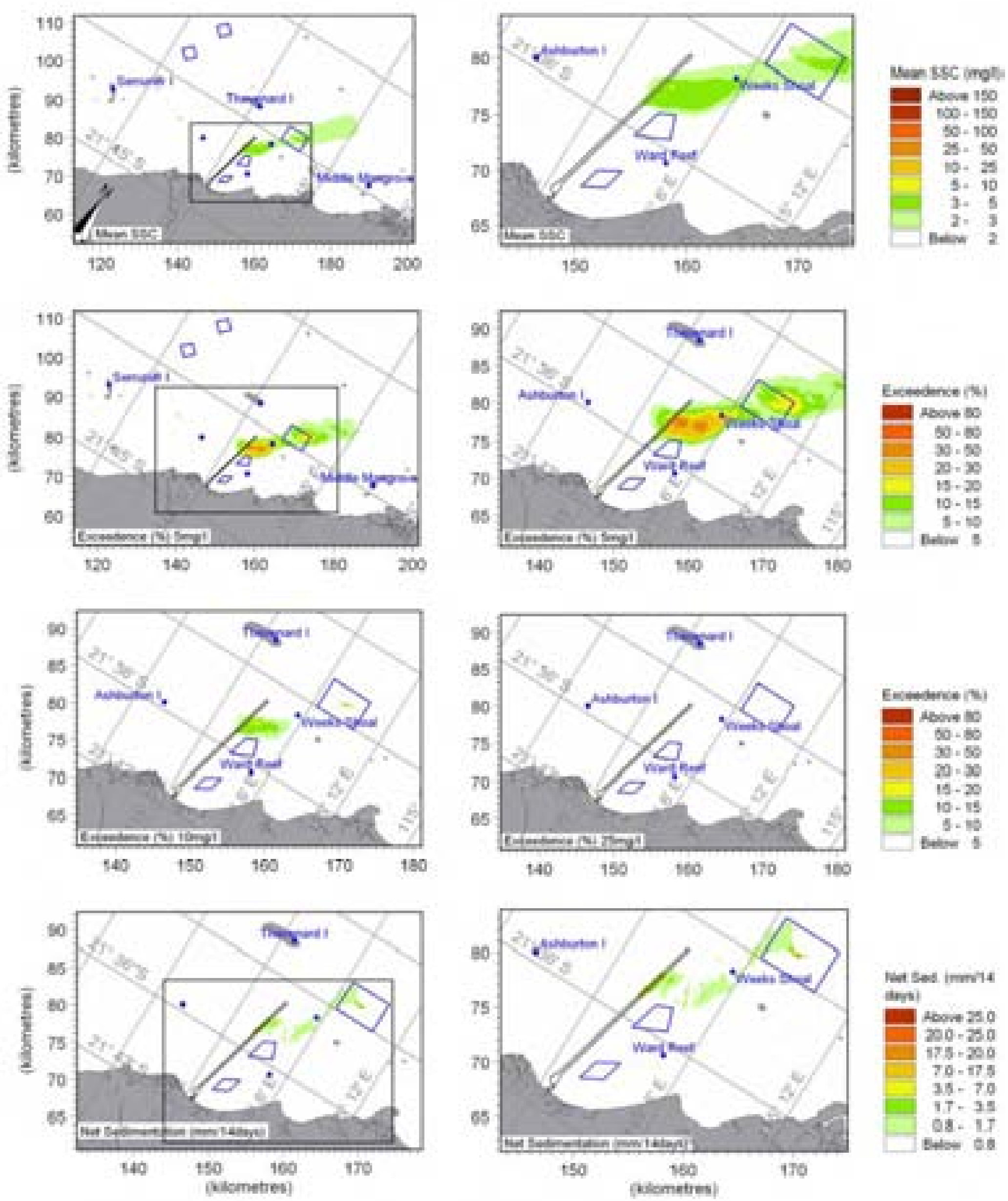

Figure U.2 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7

U-4

Dredge Scenario: Scenario 7
Climatic Scenario: Summer B
Spill Rate Estimate: Low ("Realistic") Case

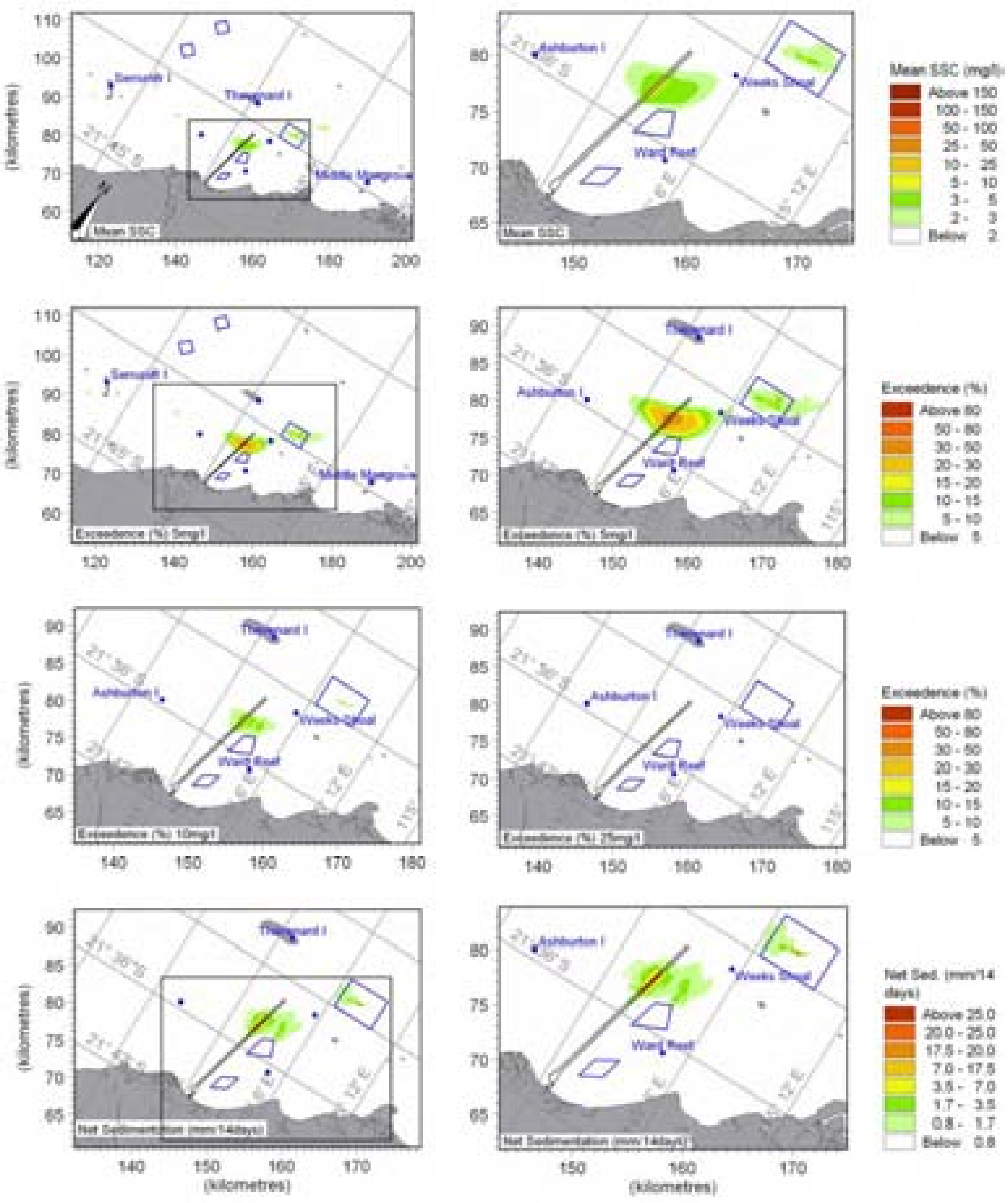

Figure U.3 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7

DHI Water & Environment

U-5

Dredge Scenario: Scenario 7
Climatic Scenario: Transitional A
Spill Rate Estimate: Low ("Realistic") Case

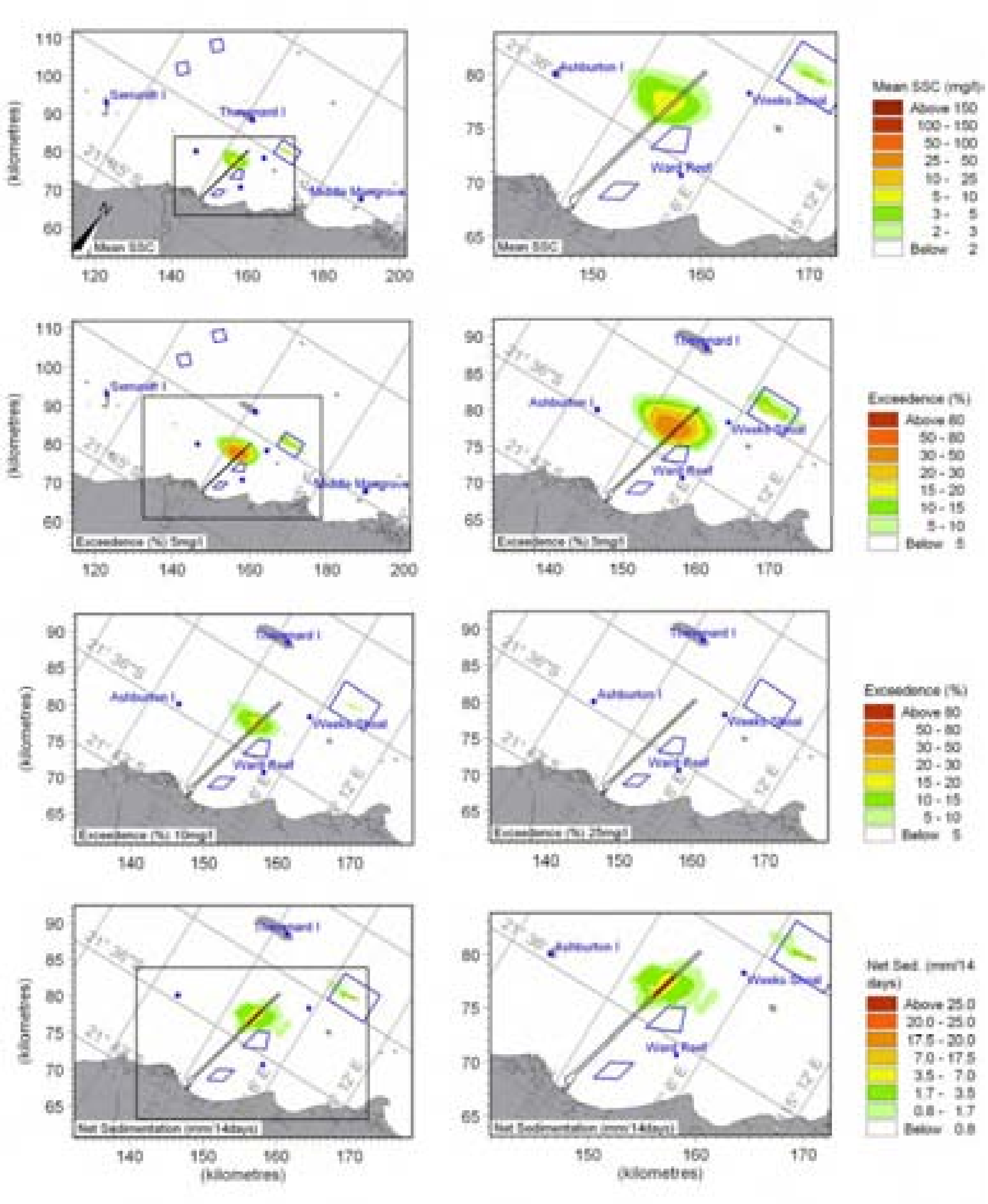

Figure U.4 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7

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U-6

Dredge Scenario: Scenario 7
Climatic Scenario: Transitional B
Spill Rate Estimate: Low ("Realistic") Case

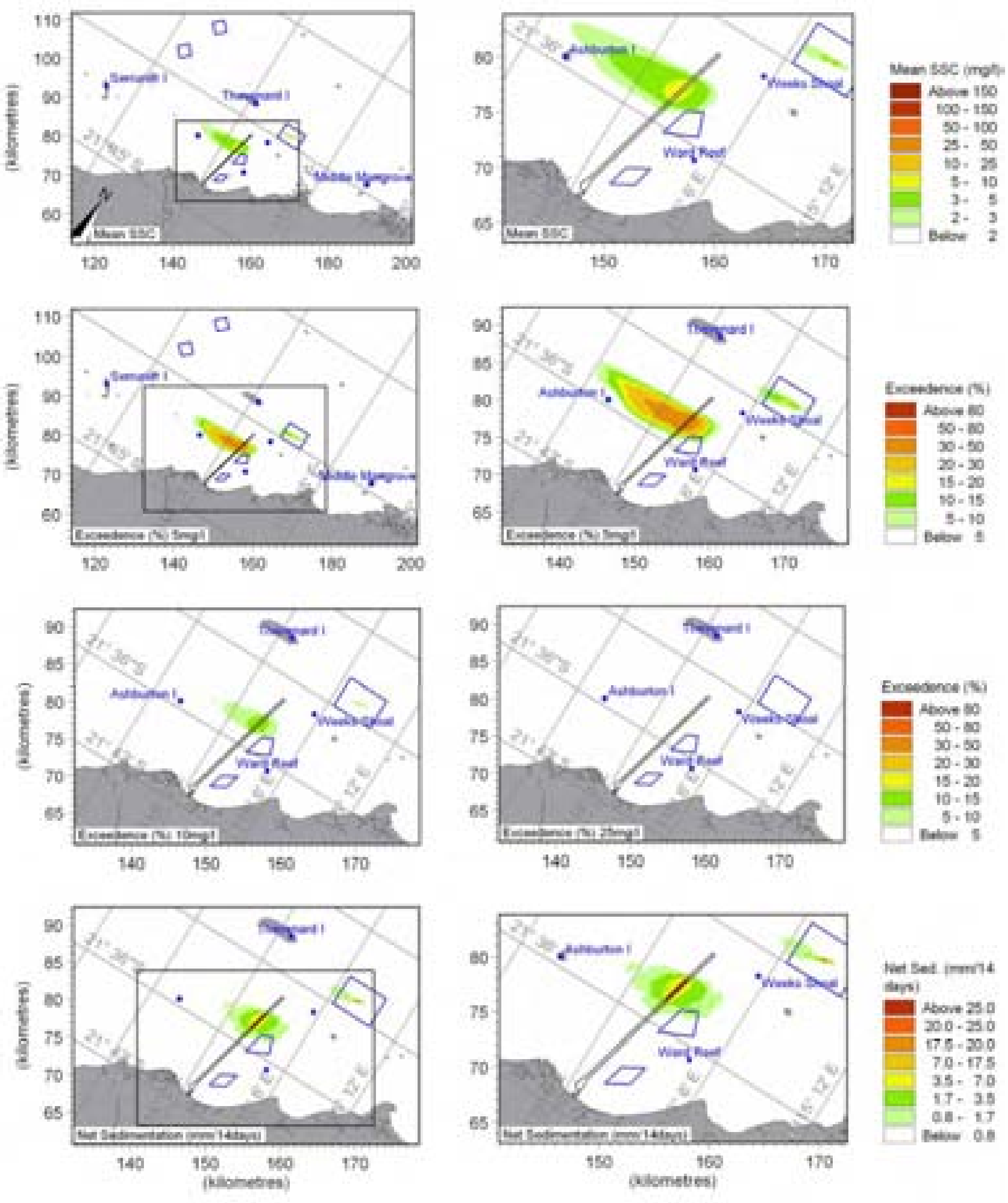

Figure U.5 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7*

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U-7

Dredge Scenario: Scenario 7
Climatic Scenario: Winter A
Spill Rate Estimate: Low ("Realistic") Case

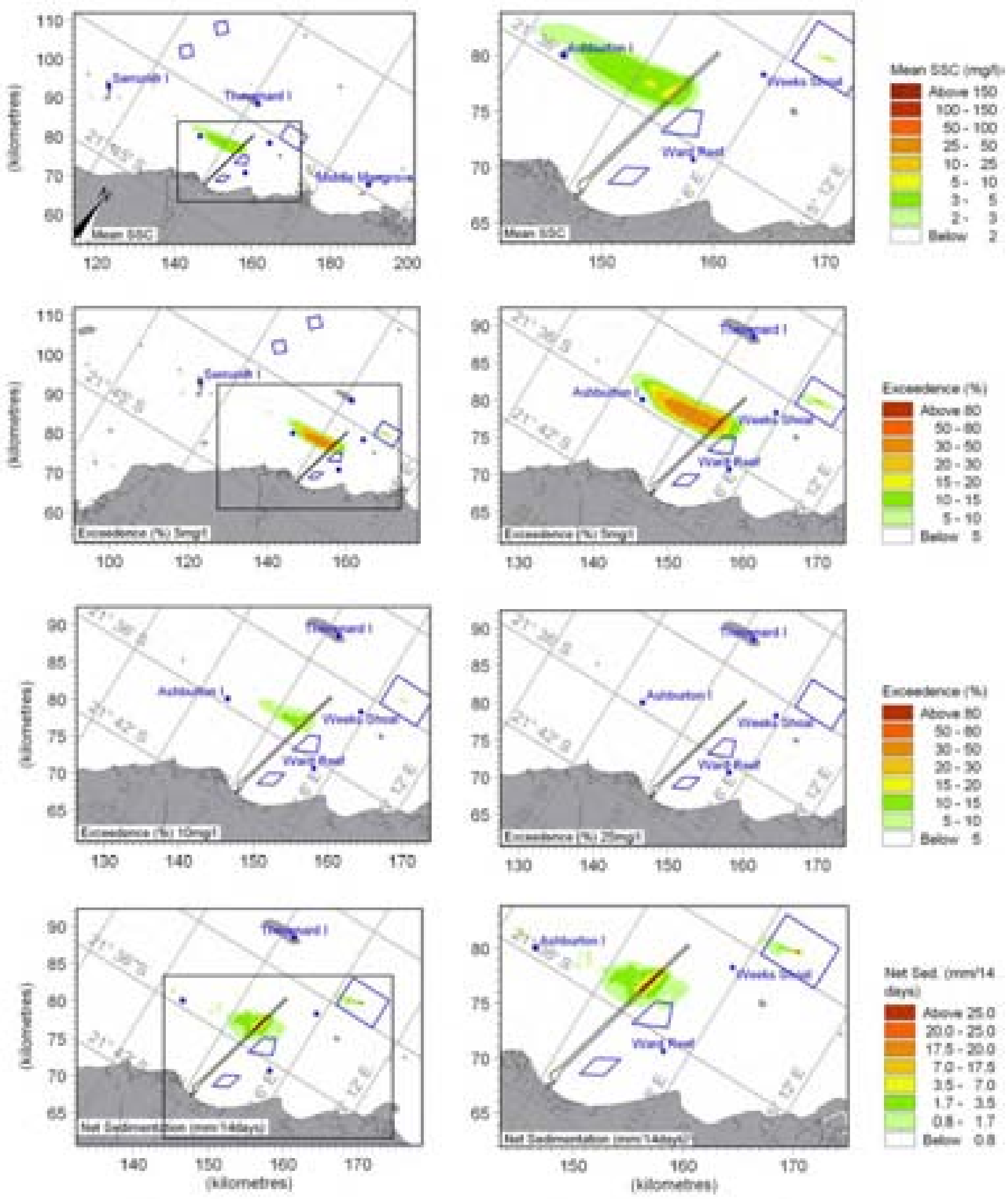

Figure U.6 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7

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U-8

Dredge Scenario: Scenario 7
Climatic Scenario: Winter B
Spill Rate Estimate: Low ("Realistic") Case

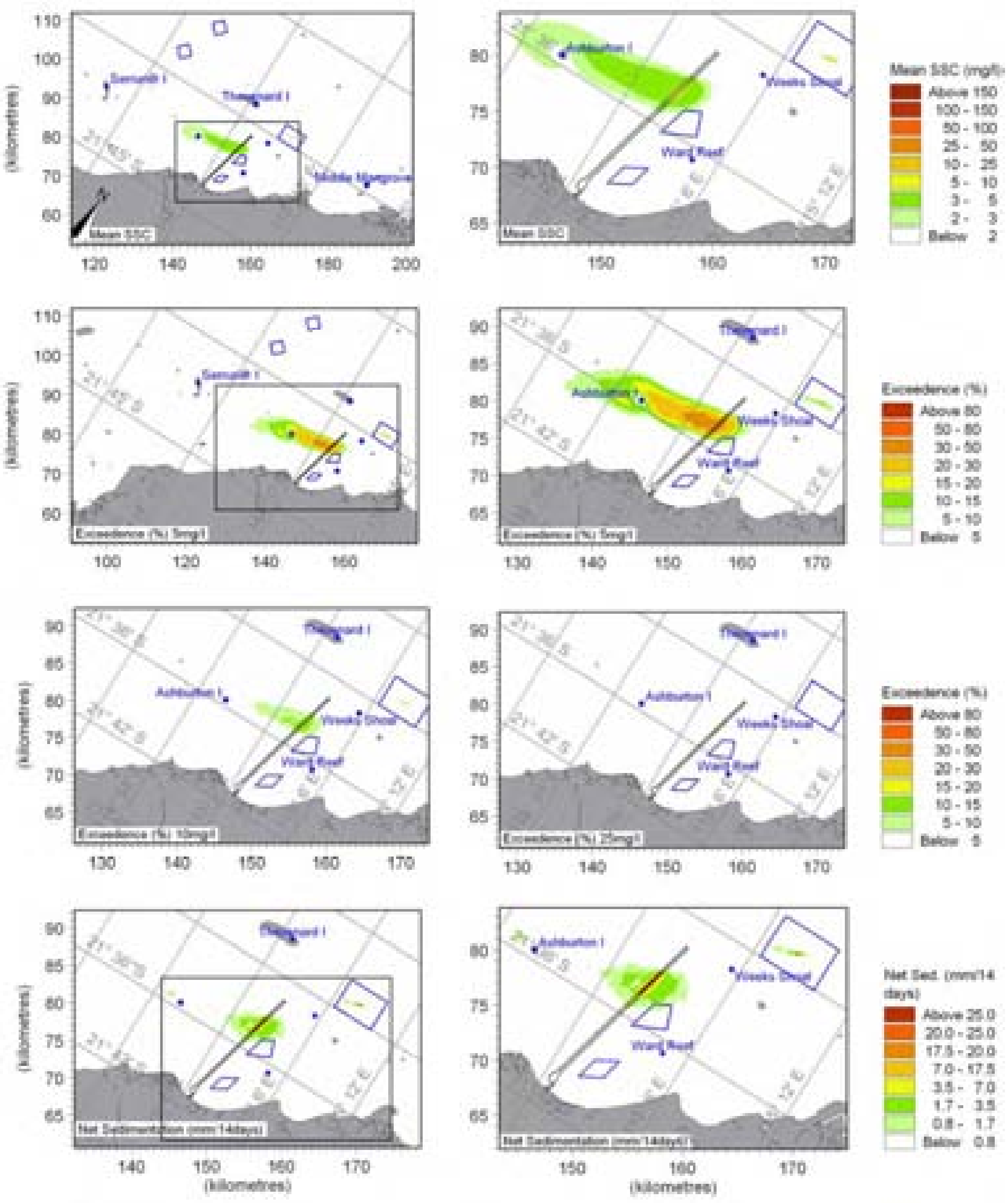

Figure U.7 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7*

U.5 Results for High (Worst-Case) Spill Rates

Dredge Scenario: Scenario 7
Climatic Scenario: Summer A
Spill Rate Estimate: High ("Worst Case")

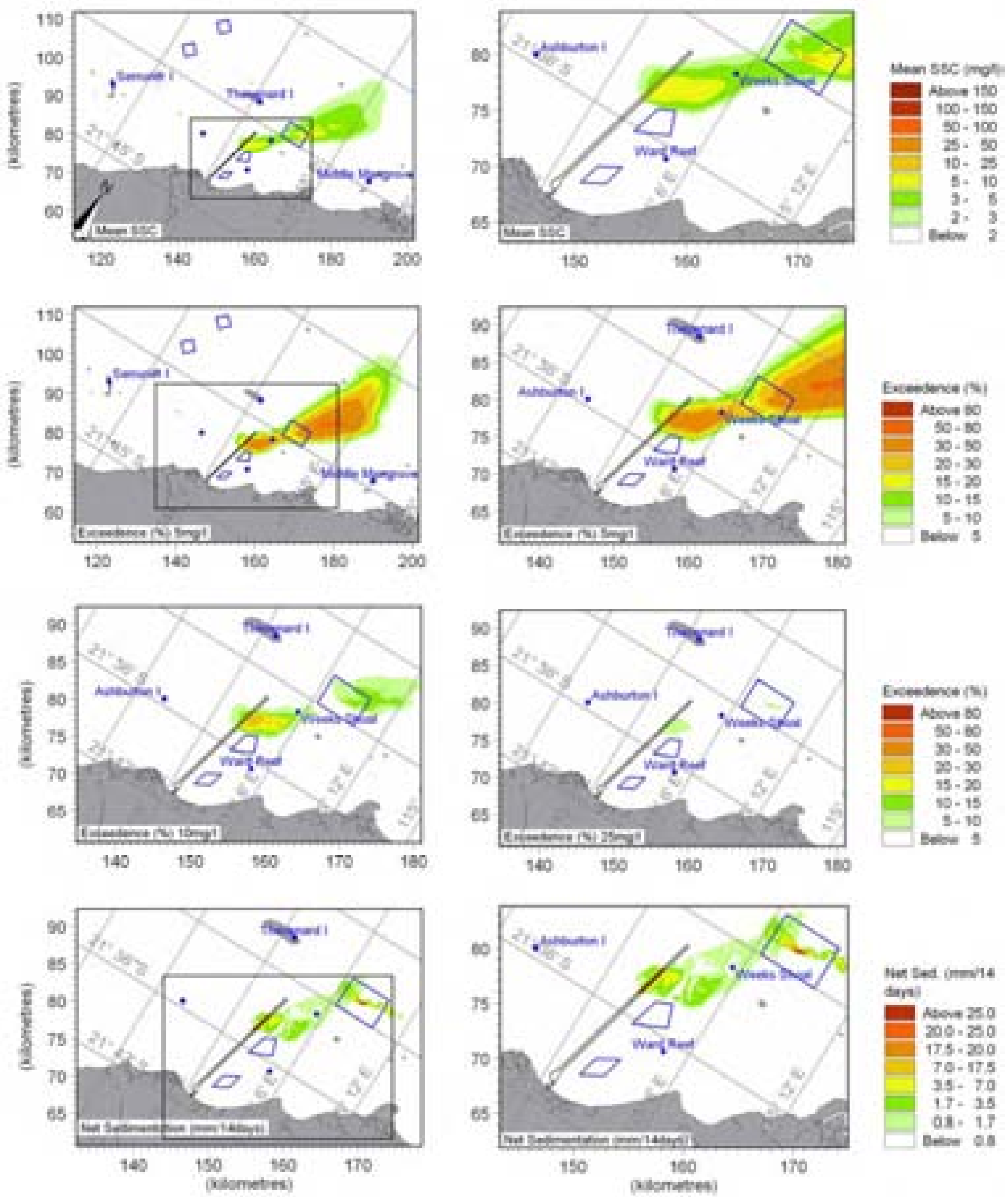

Figure U.8 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7

Dredge Scenario: Scenario 7
Climatic Scenario: Summer B
Spill Rate Estimate: High ("Worst Case")

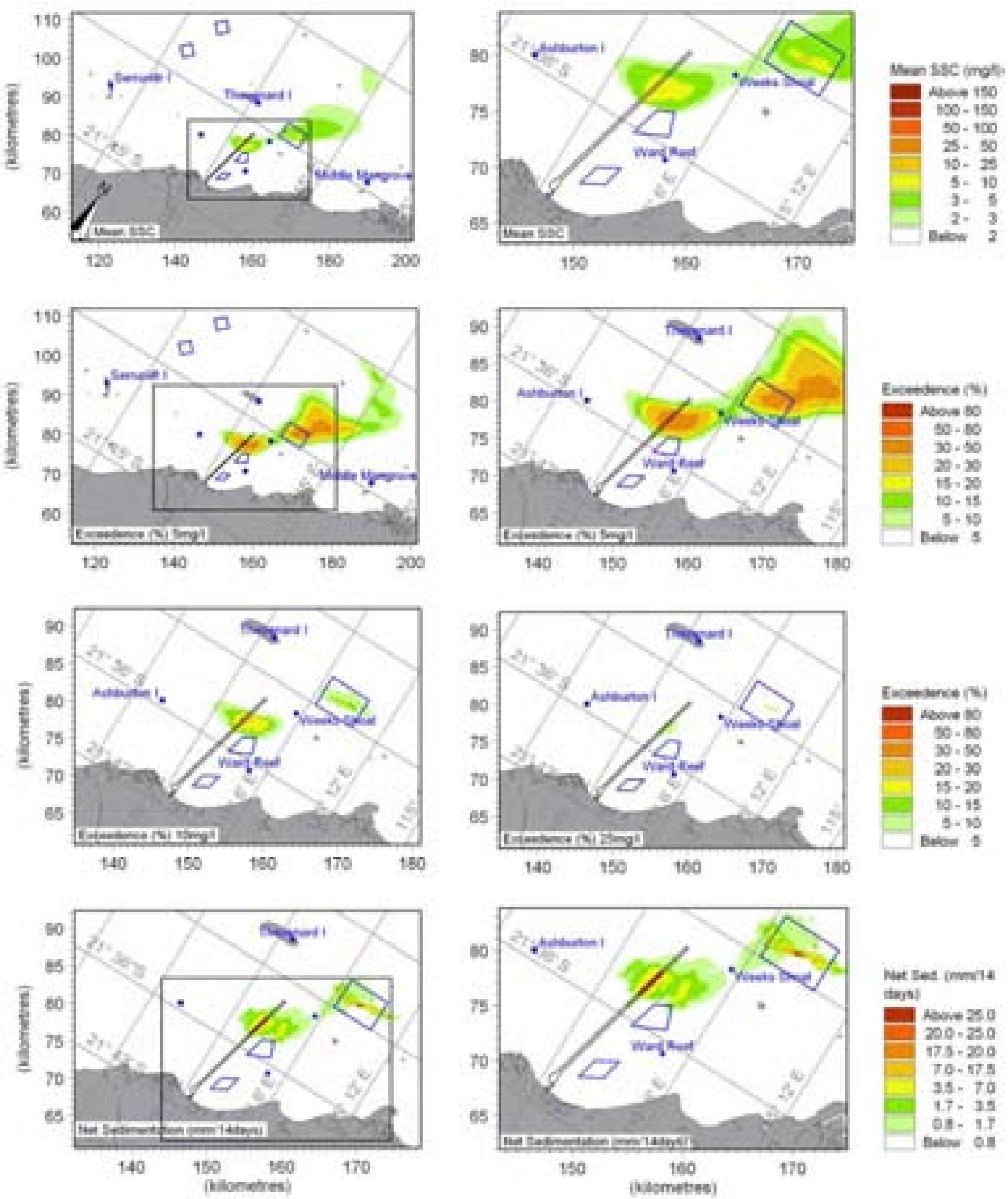

Figure U.9 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7*

U-11

Dredge Scenario: Scenario 7
Climatic Scenario: Transitional A
Spill Rate Estimate: High ("Worst Case")

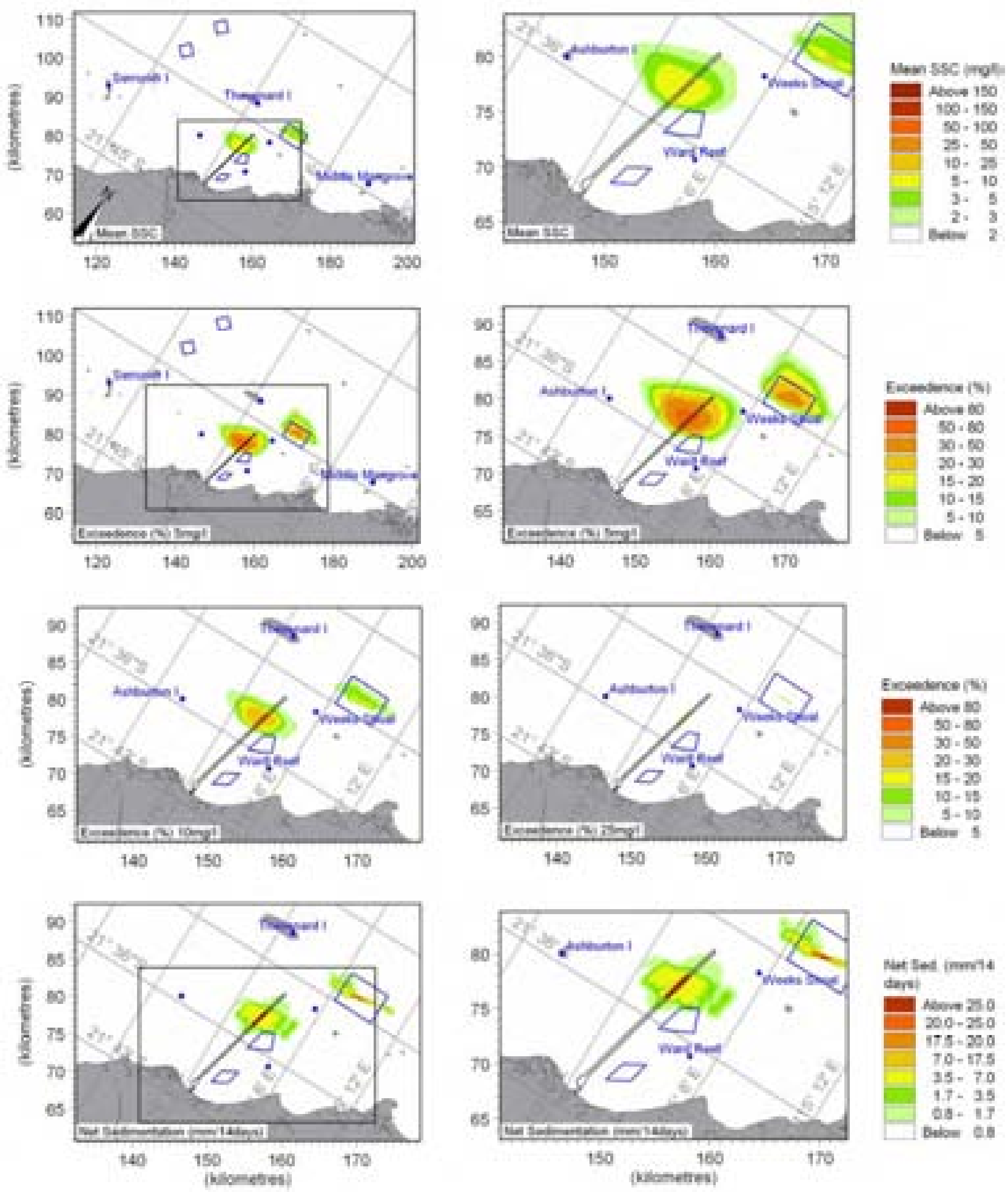

Figure U.10 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7

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U-12

Dredge Scenario: Scenario 7
Climatic Scenario: Transitional B
Spill Rate Estimate: High ("Worst Case")

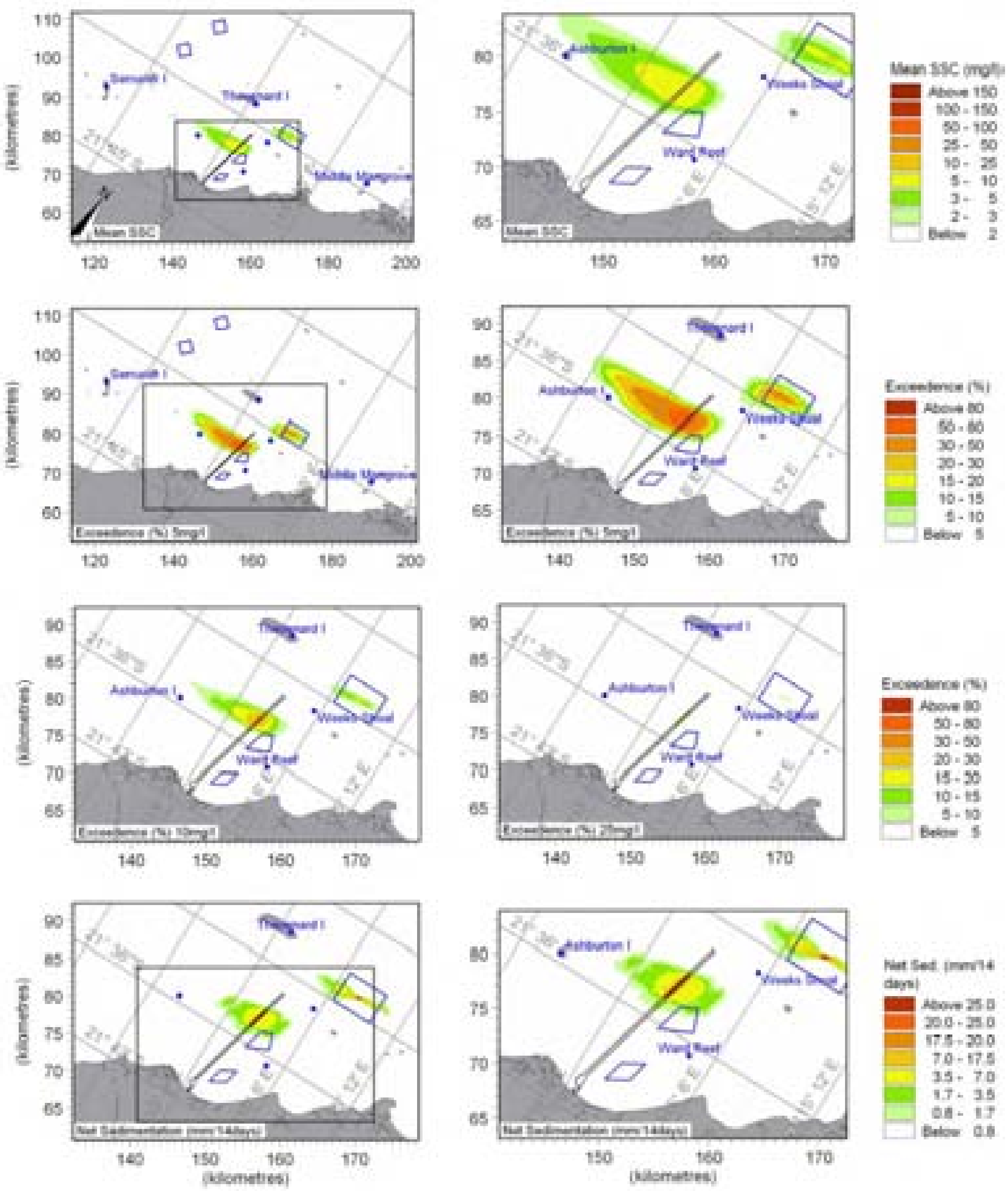

Figure U.11 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7

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U-13

Dredge Scenario: Scenario 7
Climatic Scenario: Winter A
Spill Rate Estimate: High ("Worst Case")

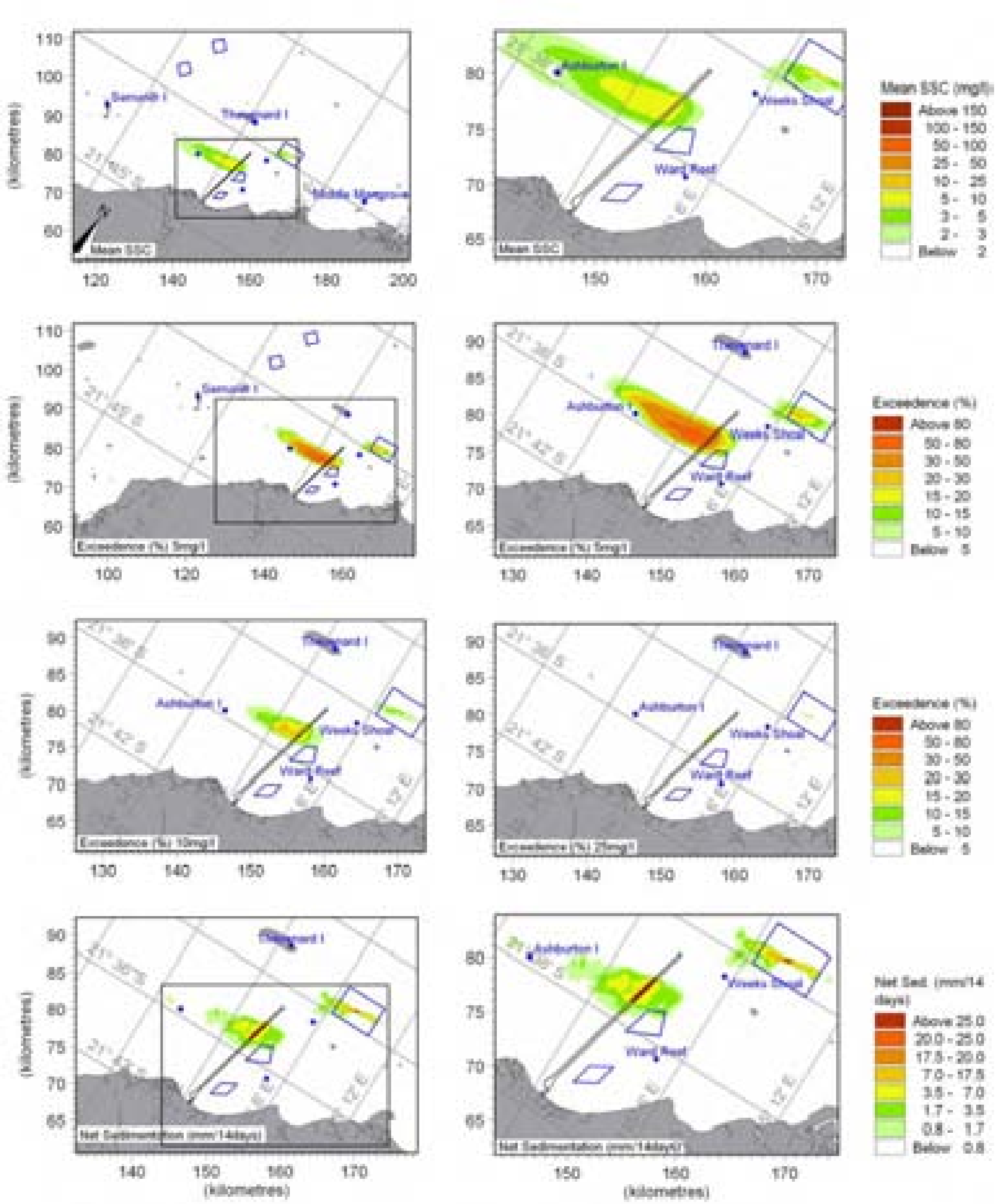

Figure U.12 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7

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U-14

Dredge Scenario: Scenario 7
Climatic Scenario: Winter B
Spill Rate Estimate: High ("Worst Case")

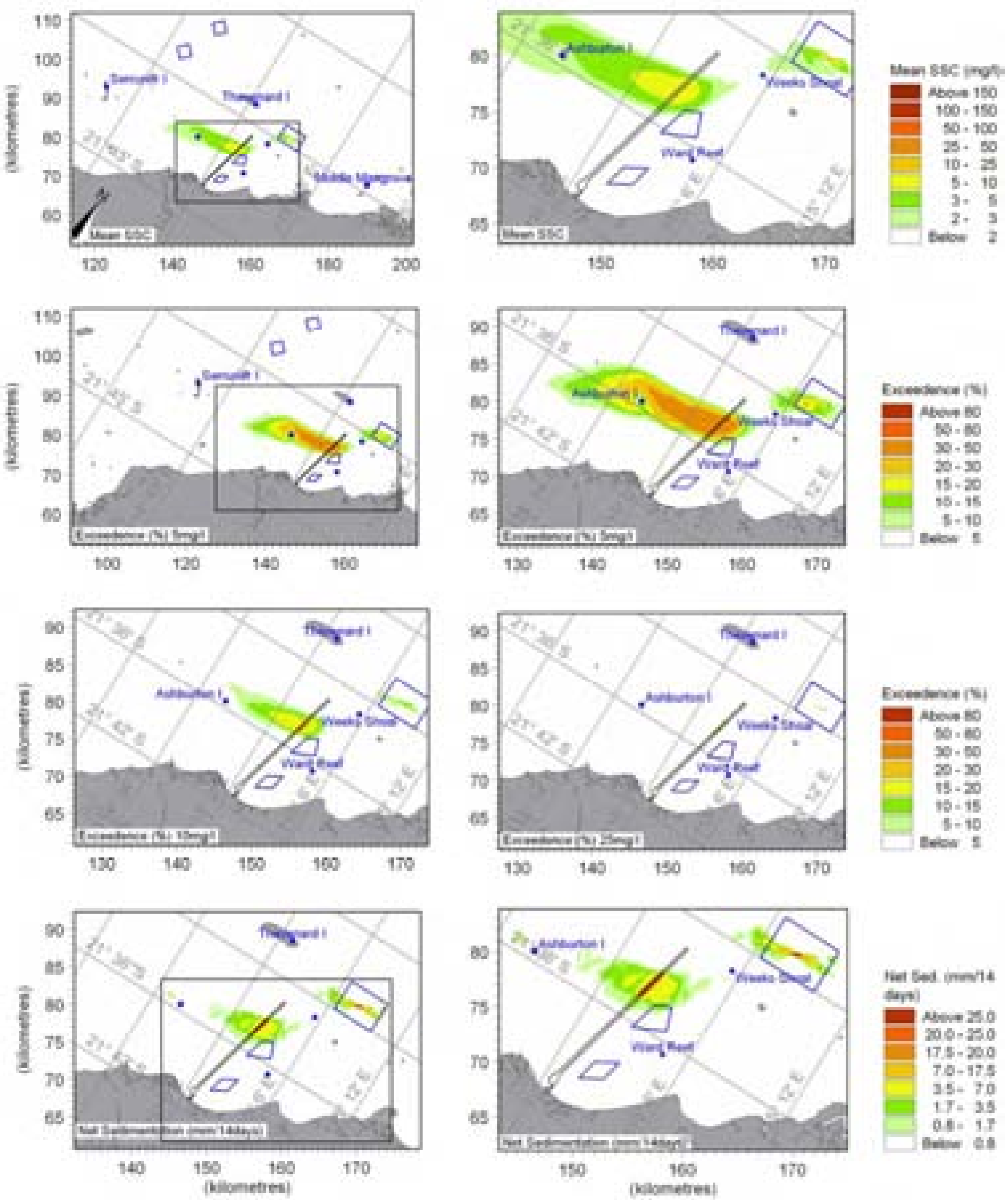

Figure U.13 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7

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V RESULTS FOR DREDGE SCENARIO 7A BASED ON ONSLOW WINDS

This appendix presents results from the sediment transport model based on hydrodynamics driven by the Onslow wind fields. The reader is referred to the following sections of the main report and additional appendices for further information;

- Section 4.1.3.2 *Wind Fields*
- Section 6.2 *Results for the Dredging of the Shipping Channel*
- Appendix D *Hydrodynamic Model Validation and Calibration*

V.1 Statistical Plots

The established impact criteria (DHI (2010) *Dredge Plume Impact Assessment Report)* are based on sediment loads, both in terms of excess suspended concentrations and sedimentation rates, over 14 day periods. In terms of exposure and impacts, both the concentrations and the duration of the event is important, which is expressed through the exceedence probability of given limits.

For each simulated case, a set of plots showing the statistical output used in the impact assessment have been produced. All plots are for excess concentrations, i.e. sediments originating from the dredging operations and exclusive of ambient concentrations.

Each mosaic plot comprises:

- Mean excess concentration at two scales
- Exceedence of 5mg/l excess concentration at two scales
- Exceedence of 10mg/l excess concentration
- Exceedence of 25mg/l excess concentration
- Net sedimentation rates at two zoomed levels at the site

Note that all concentrations are presented as depth-averaged values. All values are derived over the assessment period (2^{nd} neap/spring tidal cycle of the month for each climatic scenario), i.e. after at least 14 days warm-up period. Exceedences are expressed in percentage time over the assessment period that the exceedence limit is exceeded.

V.2 Description of Dredge scenario 7A

General

- Scenario 7A is a mitigated version of Scenario 7 to avoid overflow in critical zone.

Offshore Dredging: Approach Channel – Section 2 sand with operational mitigation

- 10,000m^3 TSHD with disposal at placement Site C
- Dredging along Section 2 and parts of Sections 1 and 3 with operational mitigation to avoid overflow in “no overflow” zone.

For each dredge cycle, the TSHD starts dredging at the centre of the “no overflow” zone within Section 2. It takes 25 minutes, corresponding to a sailing distance of 1.5km for a speed of 1m/s (app. 2knots) before overflow starts. The dredger keeps dredging for another 3km with overflow. The dredger dredges towards south and north, respectively, on alternate trips. This leads to a 3 km section with no overflow with 3km with overflow on each side, i.e. the total channel section being dredged is 9km.

The locations for the various dredge and placement activities are outlined in Figure V.1, while defined low (realistic) and high (worst case) spill rates applied in Dredge Scenario 7A are listed in Table 3.2 of the main report.

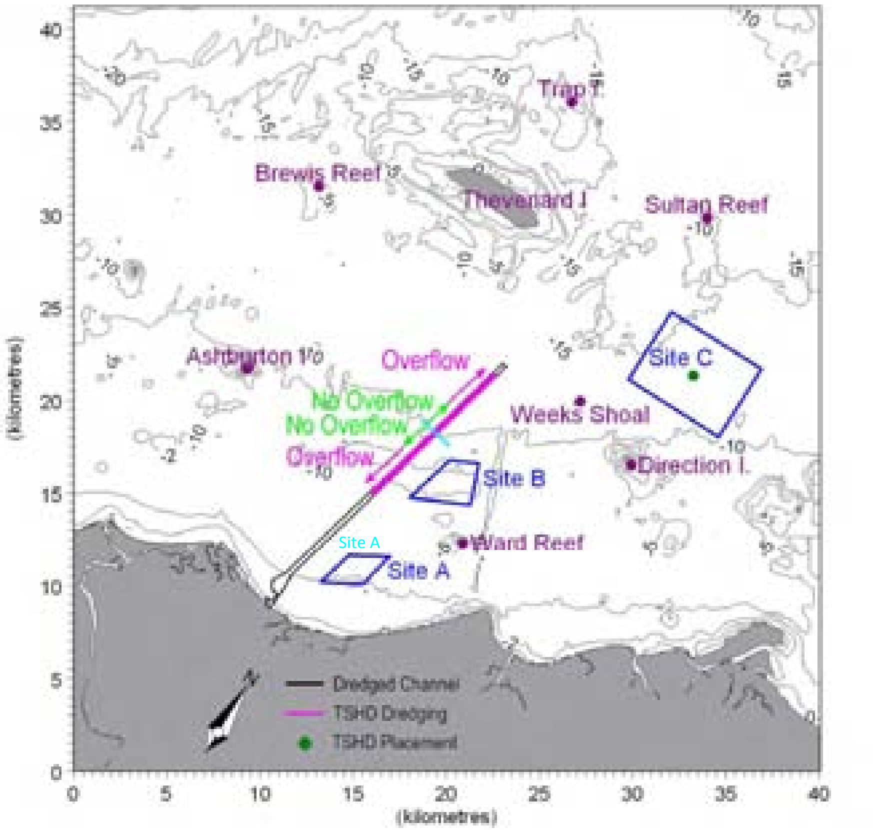

Figure V.1 Sketch of locations for Dredge Scenario 7A.

V.3 Summary of Results

Specific observations for Dredge Scenario 7A include:

- The no overflow zone is clearly distinguishable in the plots.
- The alternate dredging in two adjacent areas leads to much lower mean excess concentrations and exceedence values (the spill in tonnes/day along each section is only half compared to Section 2 in Scenario 7).
- Overall, the scenario leads to a larger area affected, but at much lower exceedences.
- The Mitigation is considered effective in reducing the impacts at the critical receptors adjacent to this sector of channel.

V.4 Results for Low (Realistic) Spill Rates

Dredge Scenario:	Scenario 7A
Climatic Scenario:	Summer A
Spill Rate Estimate:	Low ("Realistic") Case

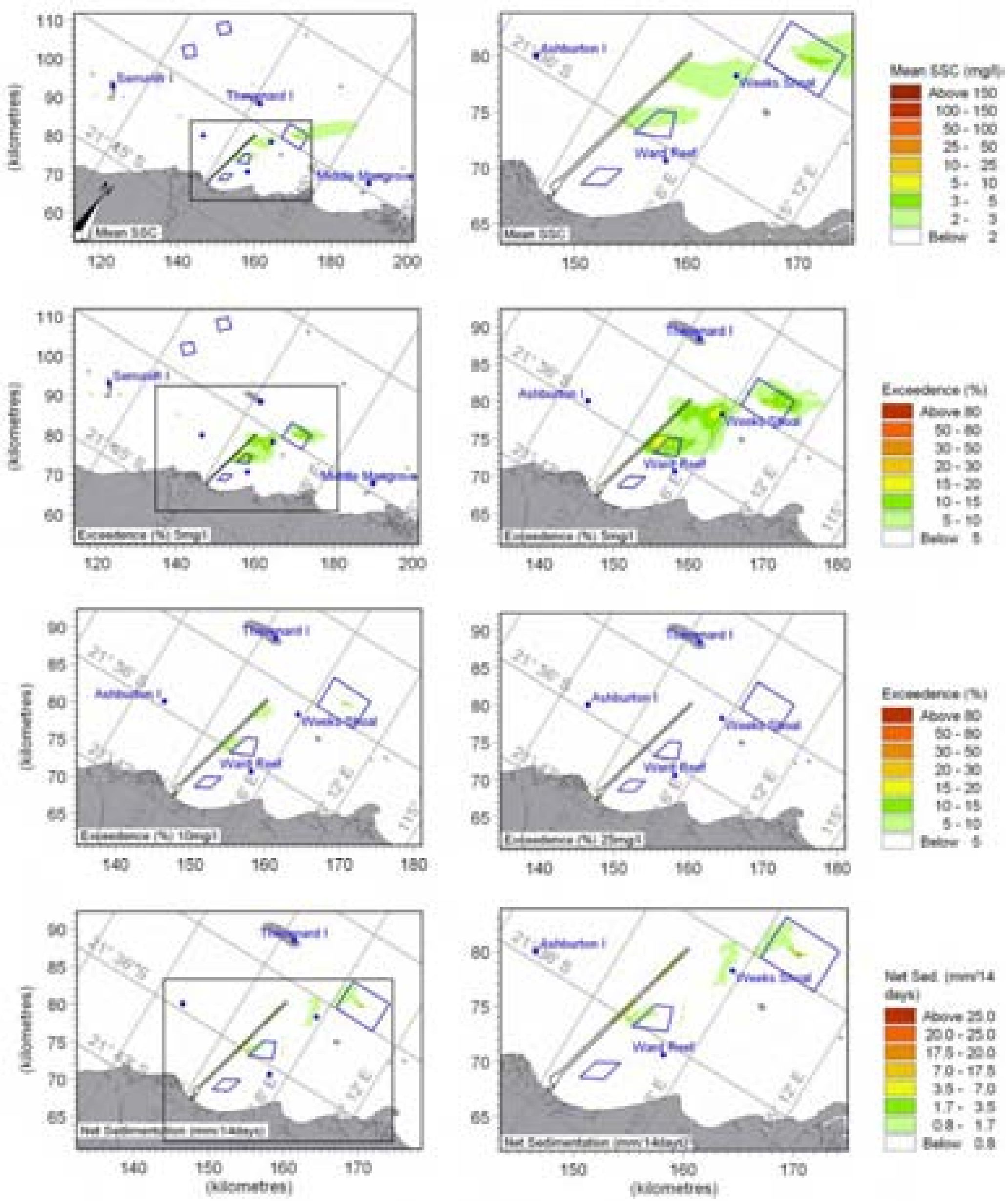

Figure V.2 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7A

V-4

Dredge Scenario: Scenario 7A
Climatic Scenario: Summer B
Spill Rate Estimate: Low ("Realistic") Case

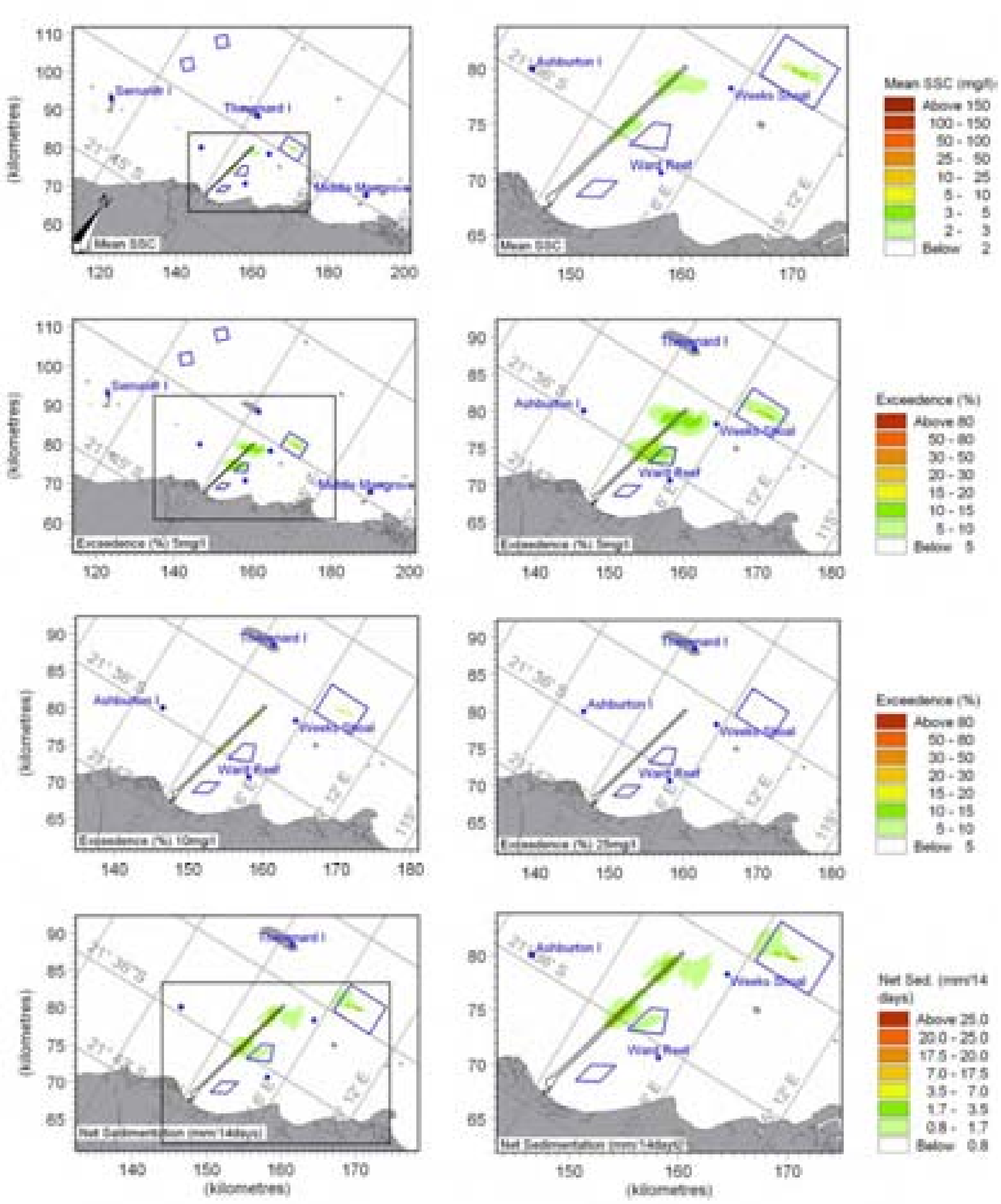

Figure V.3 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7A*

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V-5

Dredge Scenario:	Scenario 7A
Climatic Scenario:	Transitional A
Spill Rate Estimate:	Low ("Realistic") Case

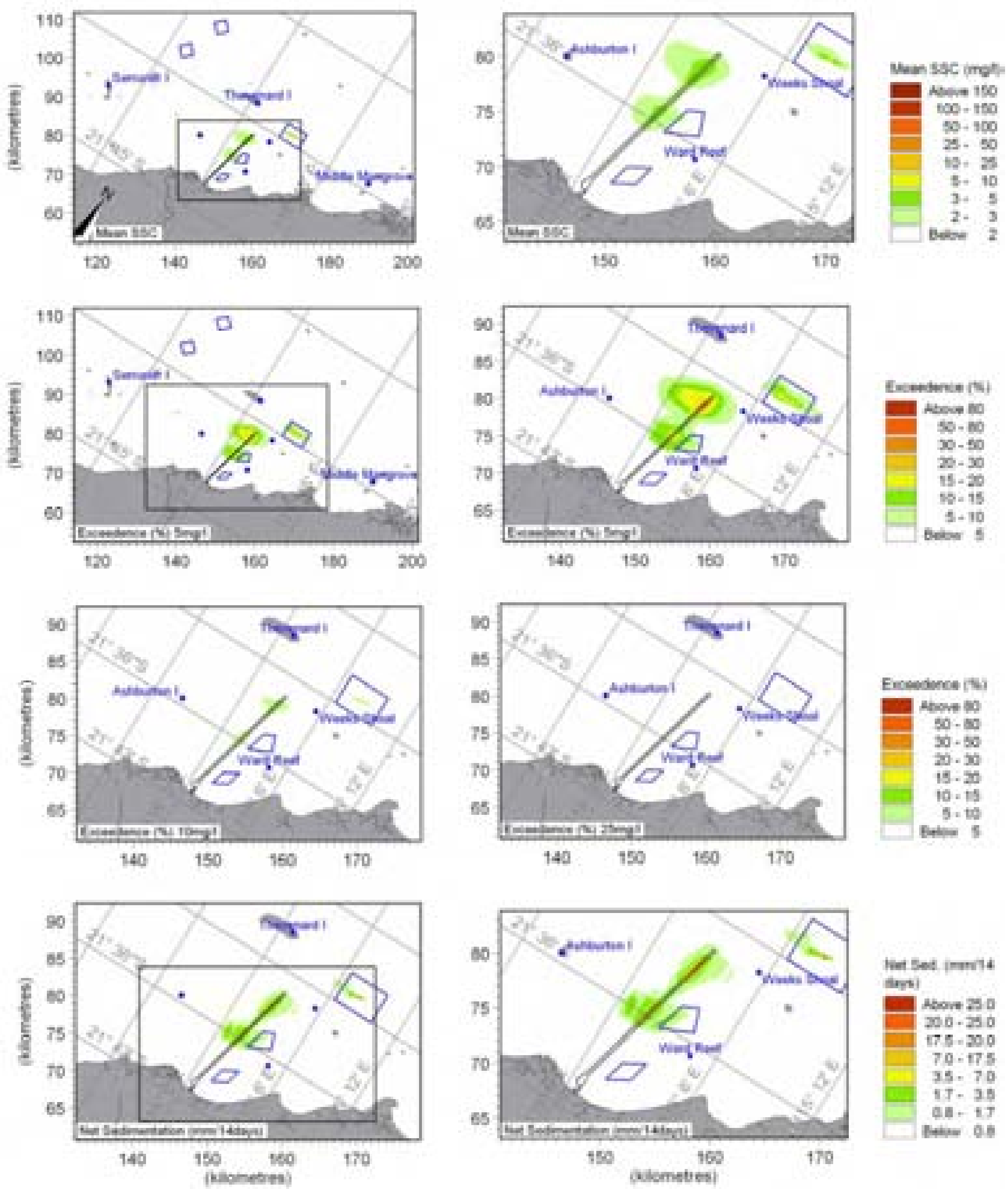

Figure V.4 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7A*

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Dredge Scenario:	Scenario 7A
Climatic Scenario:	Transitional B
Spill Rate Estimate:	Low ("Realistic") Case

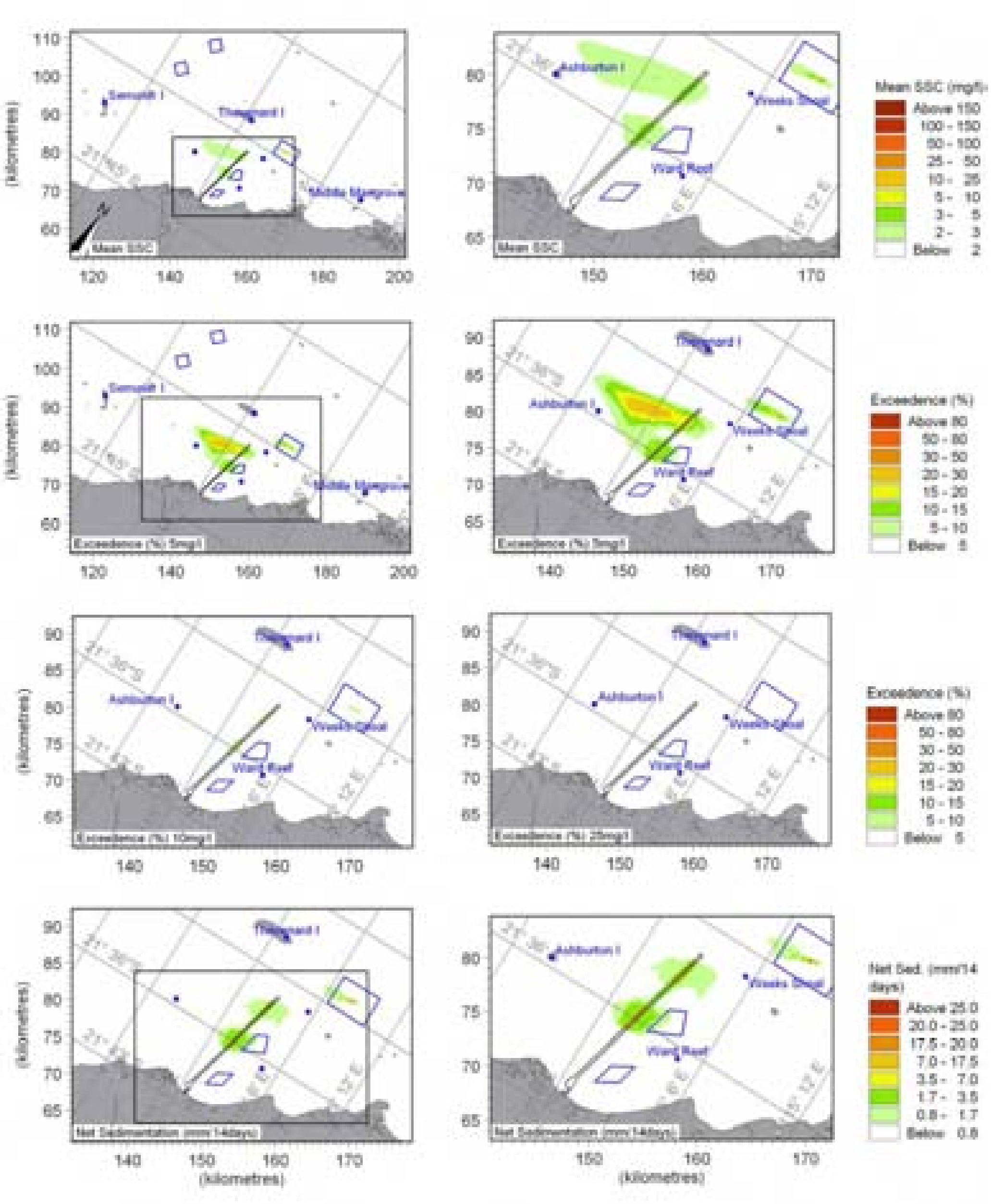

Figure V.5 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7A*

V-7

Dredge Scenario: Scenario 7A
Climatic Scenario: Winter A
Spill Rate Estimate: Low ("Realistic") Case

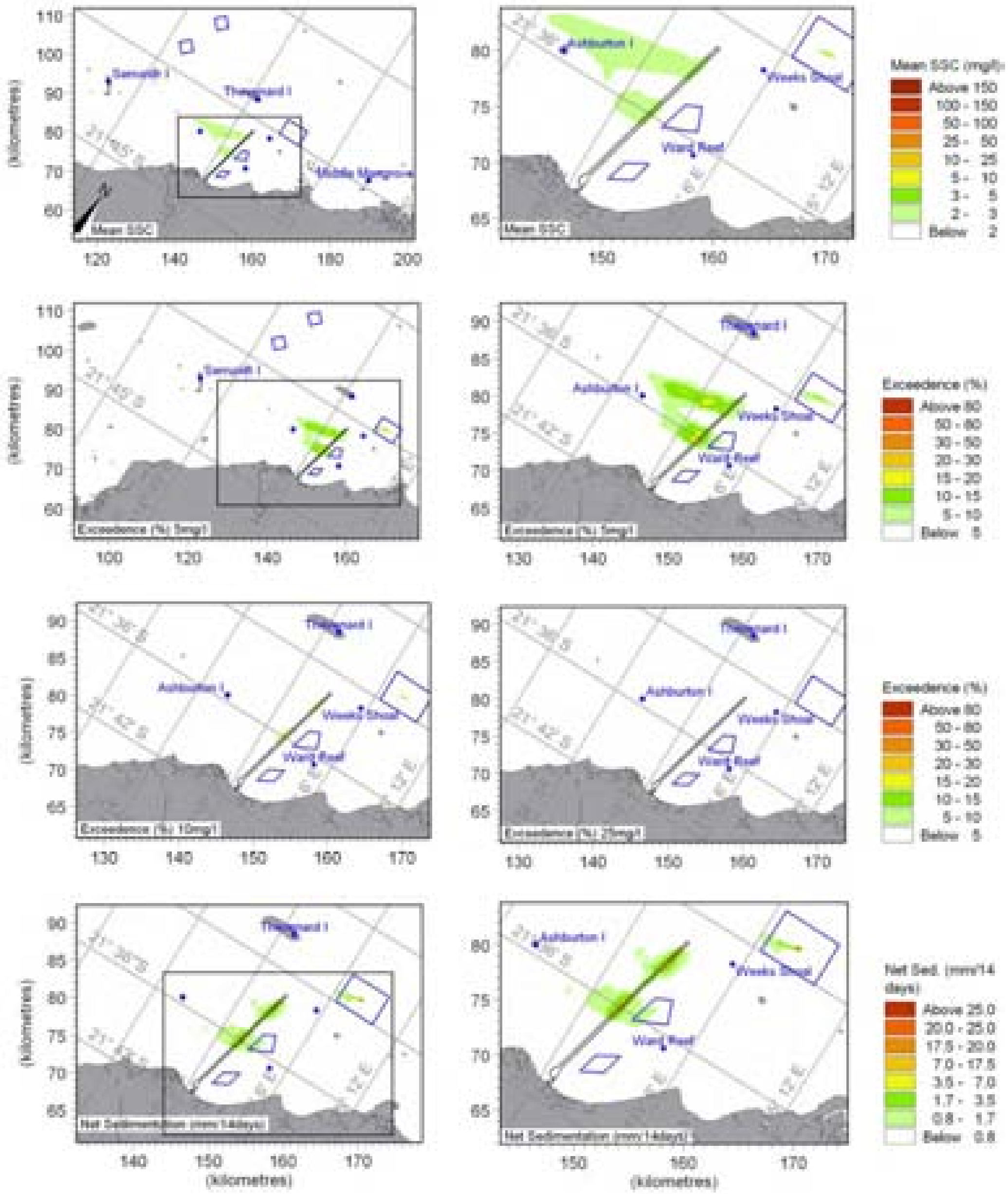

Figure V.6 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7A

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V-8

Dredge Scenario: Scenario 7A
Climatic Scenario: Winter B
Spill Rate Estimate: Low ("Realistic") Case

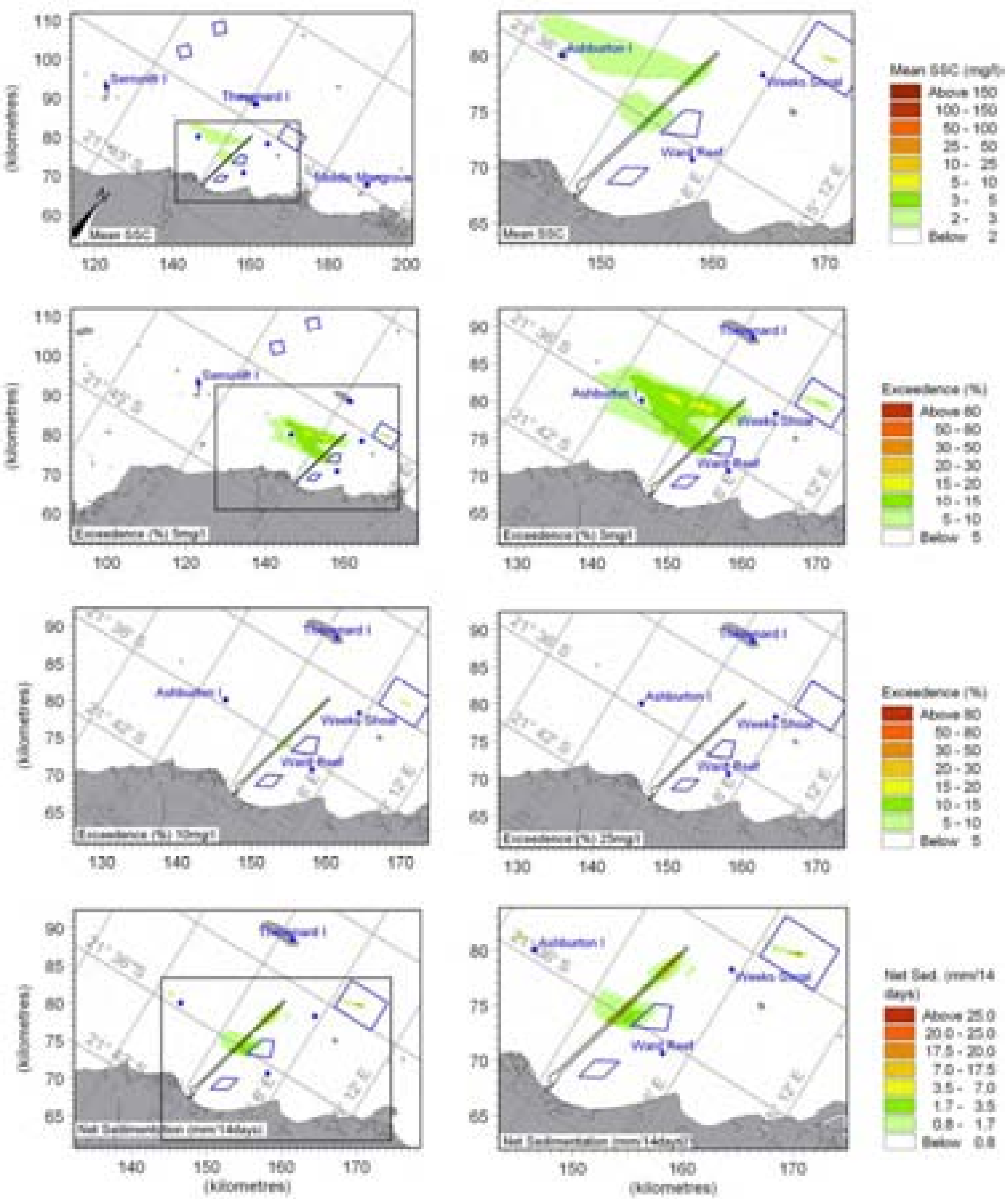

Figure V.7 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7A

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V.5 Results for High (Worst-Case) Spill Rates

Dredge Scenario: Scenario 7A
Climatic Scenario: Summer A
Spill Rate Estimate: High ("Worst Case")

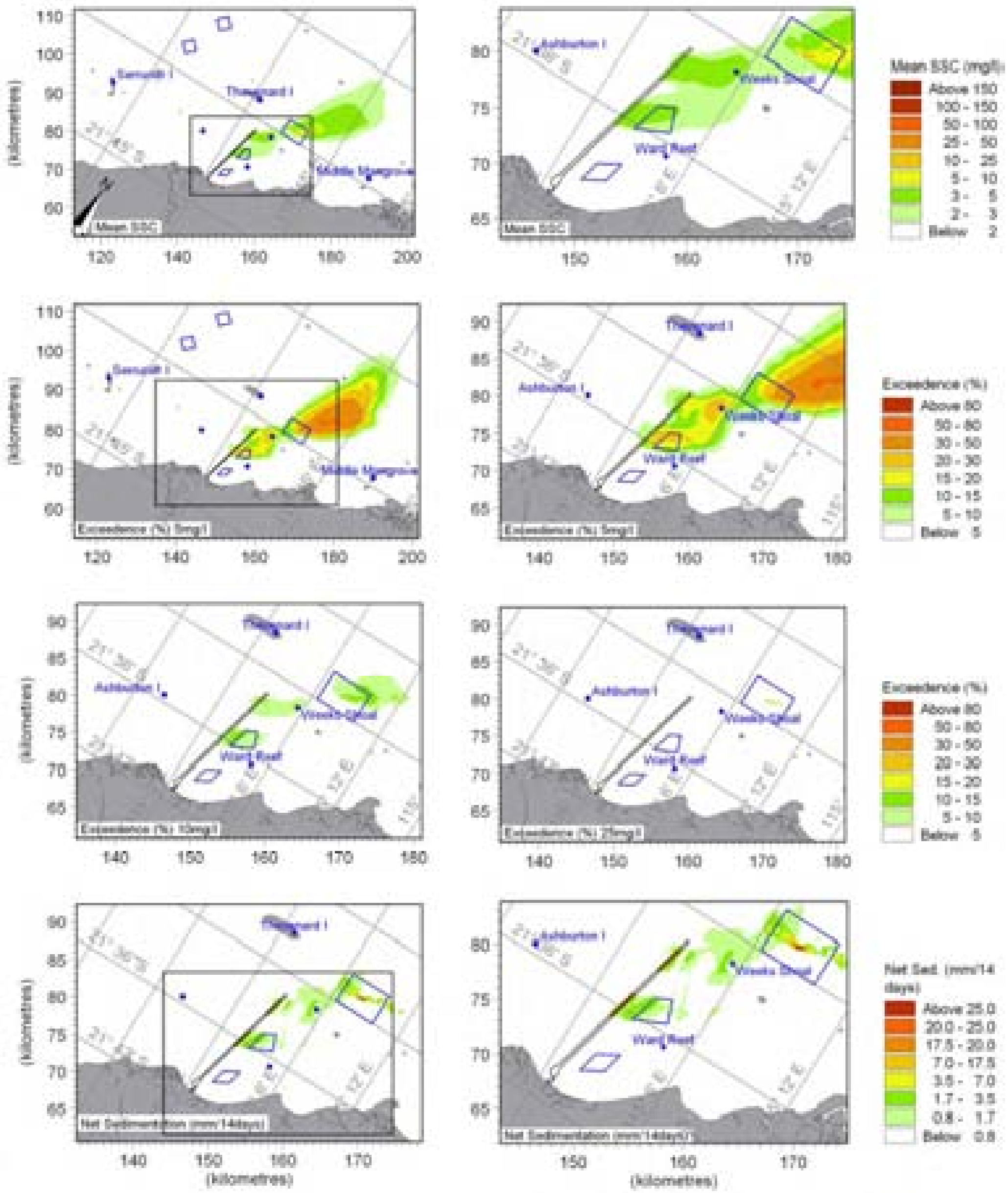

Figure V.8 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7A.

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V-10

Dredge Scenario: Scenario 7A
Climatic Scenario: Summer B
Spill Rate Estimate: High ("Worst Case")

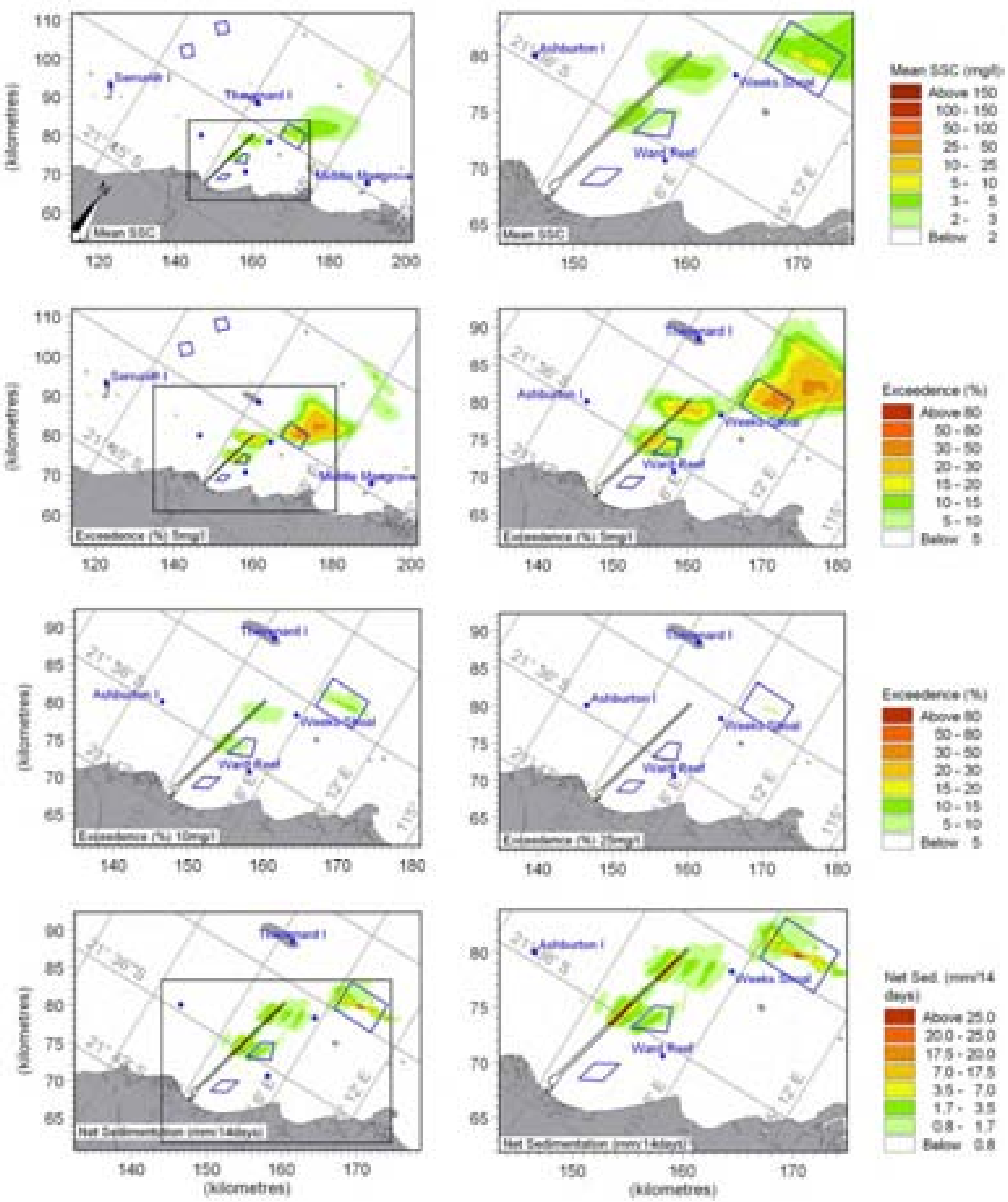

Figure V.9 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7A.

V-11

Dredge Scenario: Scenario 7A
Climatic Scenario: Transitional A
Spill Rate Estimate: High ("Worst Case")

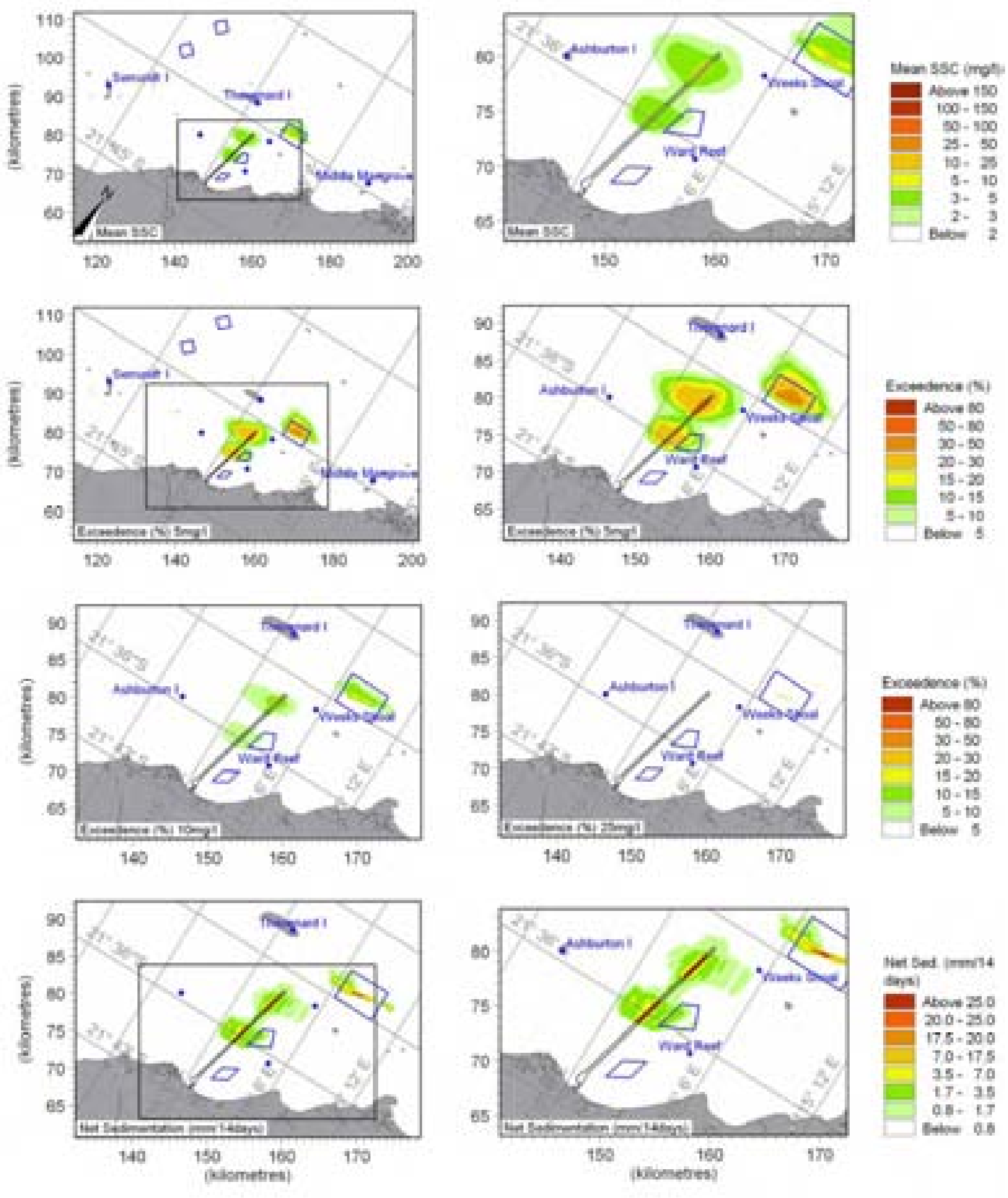

Figure V.10 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7A

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V-12

Dredge Scenario: Scenario 7A
Climatic Scenario: Transitional B
Spill Rate Estimate: High ("Worst Case")

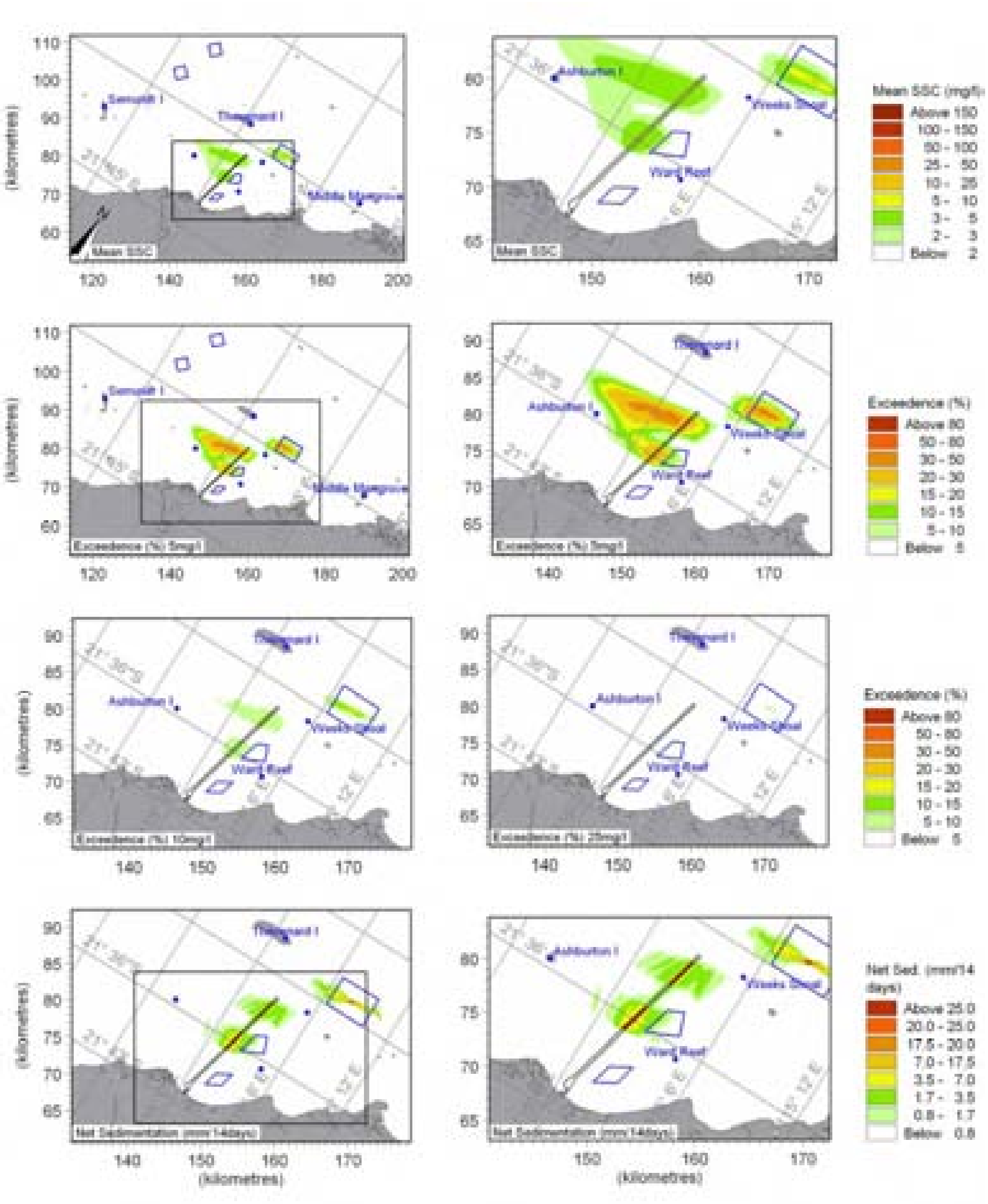

Figure V.11 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7A

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V-13

Dredge Scenario: Scenario 7A
Climatic Scenario: Winter A
Spill Rate Estimate: High ("Worst Case")

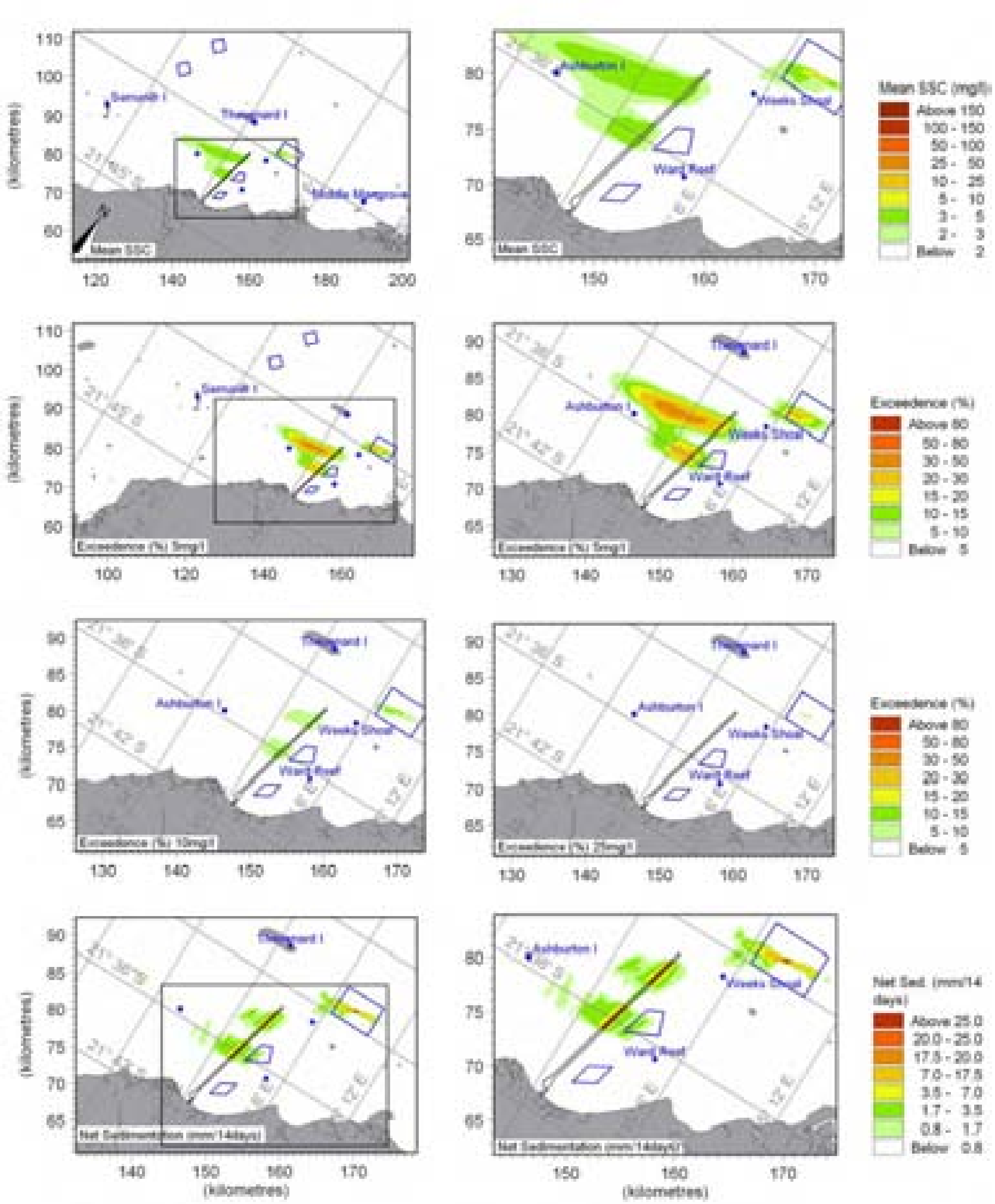

Figure V.12 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7A

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Dredge Scenario: Scenario 7A
Climatic Scenario: Winter - representative
Spill Rate Estimate: High ("Worst Case")

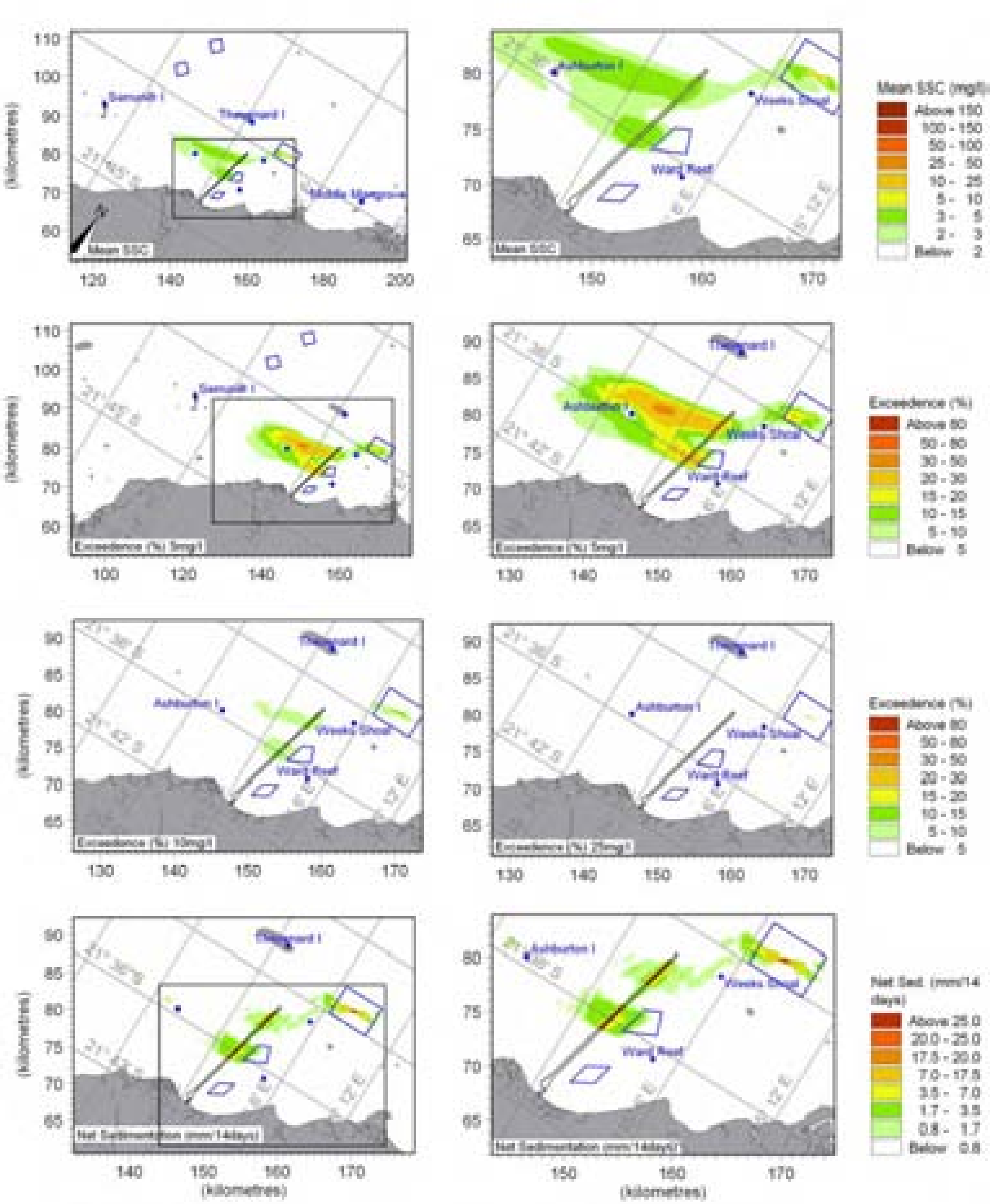

Figure V.13 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7A.

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Results for Dredge Scenario 1 Based on MesoLAPS Winds

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W RESULTS FOR DREDGE SCENARIO 1 BASED ON MESOLAPS WINDS

This appendix presents results from the sediment transport model based on hydrodynamics driven by the MesoLAPS wind fields. The reader is referred to the following sections of the main report and additional appendices for further information;

- Section 4.1.3.2 *Wind Fields*
- Section 6.2 *Results for the Dredging of the Shipping Channel*
- Appendix D *Hydrodynamic Model Validation and Calibration*

W.1 Statistical Plots

The established impact criteria (DHI (2010) *Dredge Plume Impact Assessment Report)* are based on sediment loads, both in terms of excess suspended concentrations and sedimentation rates, over 14 day periods. In terms of exposure and impacts, both the concentrations and the duration of the event is important, which is expressed through the exceedence probability of given limits.

For each simulated case, a set of plots showing the statistical output used in the impact assessment have been produced. All plots are for excess concentrations, i.e. sediments originating from the dredging operations and exclusive of ambient concentrations.

Each mosaic plot comprises:

- Mean excess concentration at two scales
- Exceedence of 5mg/l excess concentration at two scales
- Exceedence of 10mg/l excess concentration
- Exceedence of 25mg/l excess concentration
- Net sedimentation rates at two zoomed levels at the site

Note that all concentrations are presented as depth-averaged values. All values are derived over the assessment period (2nd neap/spring tidal cycle of the month for each climatic scenario), i.e. after at least 14 days warm-up period. Exceedences are expressed in percentage time over the assessment period that the exceedence limit is exceeded.

W.2 Description of Dredge Scenario 1

Nearshore Dredging: Temporary Access Channel

- CSD with pumping to placement site A
- Bathymetry with partly dredged, 75m wide channel to -6m LAT)
- Material available for resuspension in dredged channel portion and at Placement Site A.

The locations for the various dredge and placement activities are outlined in Figure W.1, while defined low (realistic) and high (worst-case) spill rates for Dredging Scenario 1 are listed in Table 3.2 of the main report.

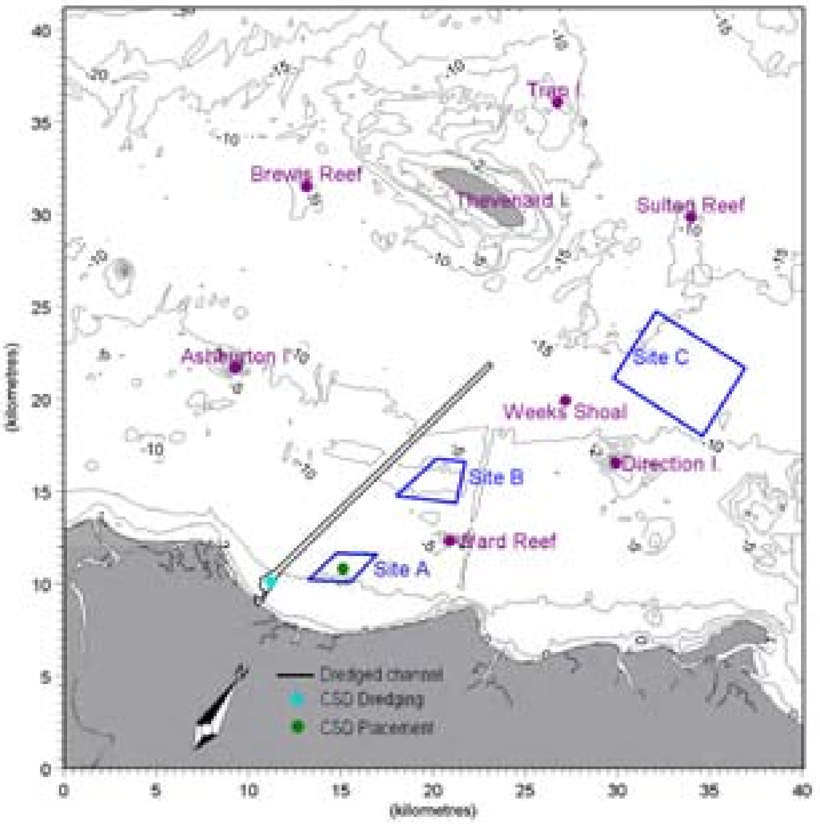

Figure W.1 Sketch of locations for Dredging Scenario 1.

W.3 Summary of Results

Specific observations for Dredge Scenario 1 include:

- The plumes from the nearshore CSD dredging the outer part of the temporary approach channel with pumping to Placement Site A extend primarily parallel to the coastline due to the coastal controlled current patterns and the relatively stationary sources.
- For the strong summer net currents and high (worst case) spill rates, mean excess concentrations up to 5mg/l reach Beadon Point.
- 5mg/l is exceeded 30% of the time more than 40km to the east of the site for the summer, worst case scenario, compared to about 15km for the realistic case.
- Excess concentrations of 10mg/l are exceeded in the order of 10% of the time at Onslow for strong summer conditions.
- For winter conditions, the 5mg/l excess concentration is exceeded more than 5% of the time up to about 20km to the west of the site. Mean excess concentrations in the order of 10mg/l reach Entrance Point.
- The plumes generated by the CSD dredging in the PLF area do not seem to reach Ward Reef at significant levels.

W.4 Results for Low (Realistic) Spill Rates

Dredge Scenario: Scenario 1
Climatic Scenario: Summer A
Spill Rate Estimate: Low ("Realistic") Case

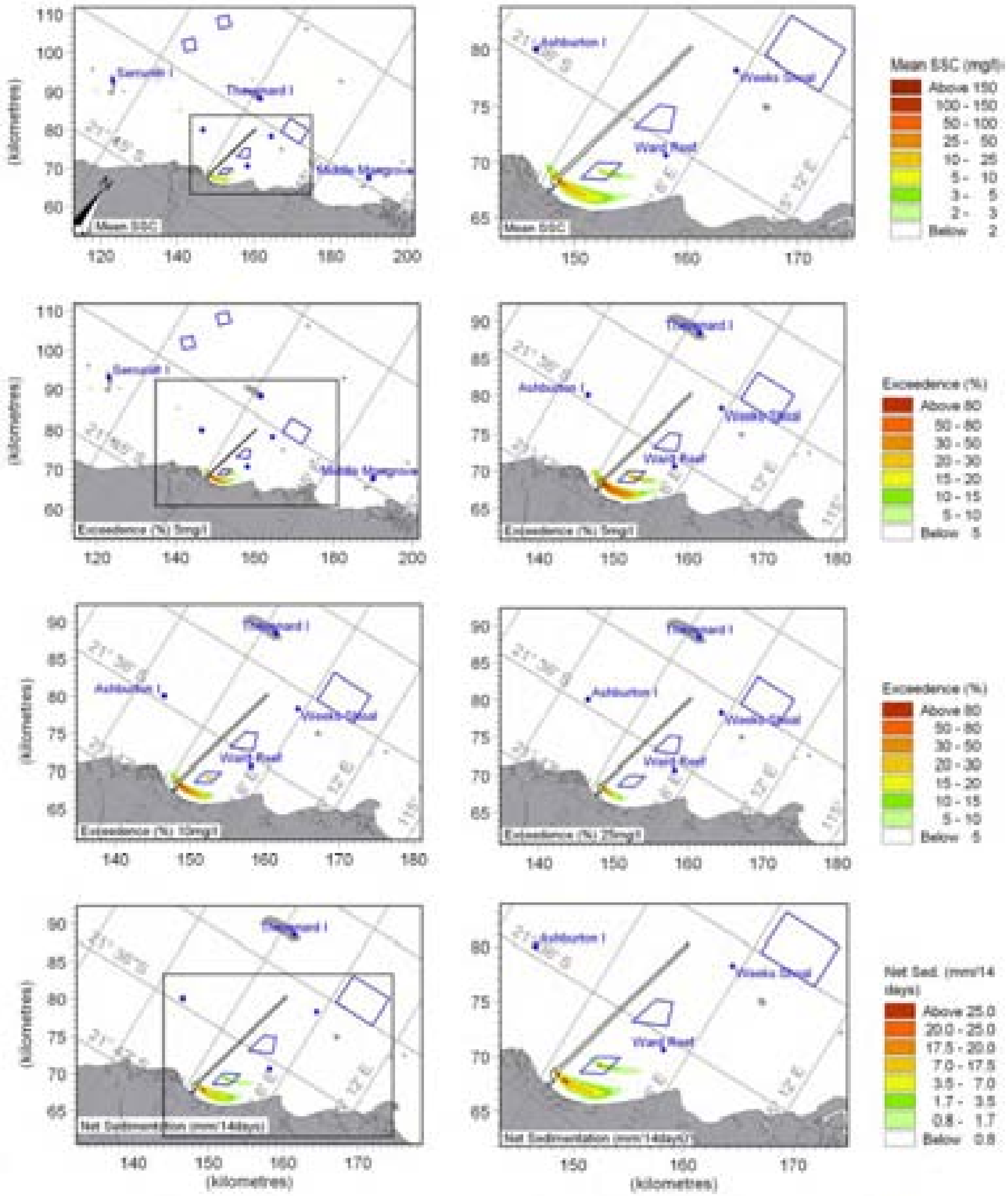

Figure W.2 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 1

W-5

Dredge Scenario: Scenario 1
Climatic Scenario: Summer B
Spill Rate Estimate: Low ("Realistic") Case

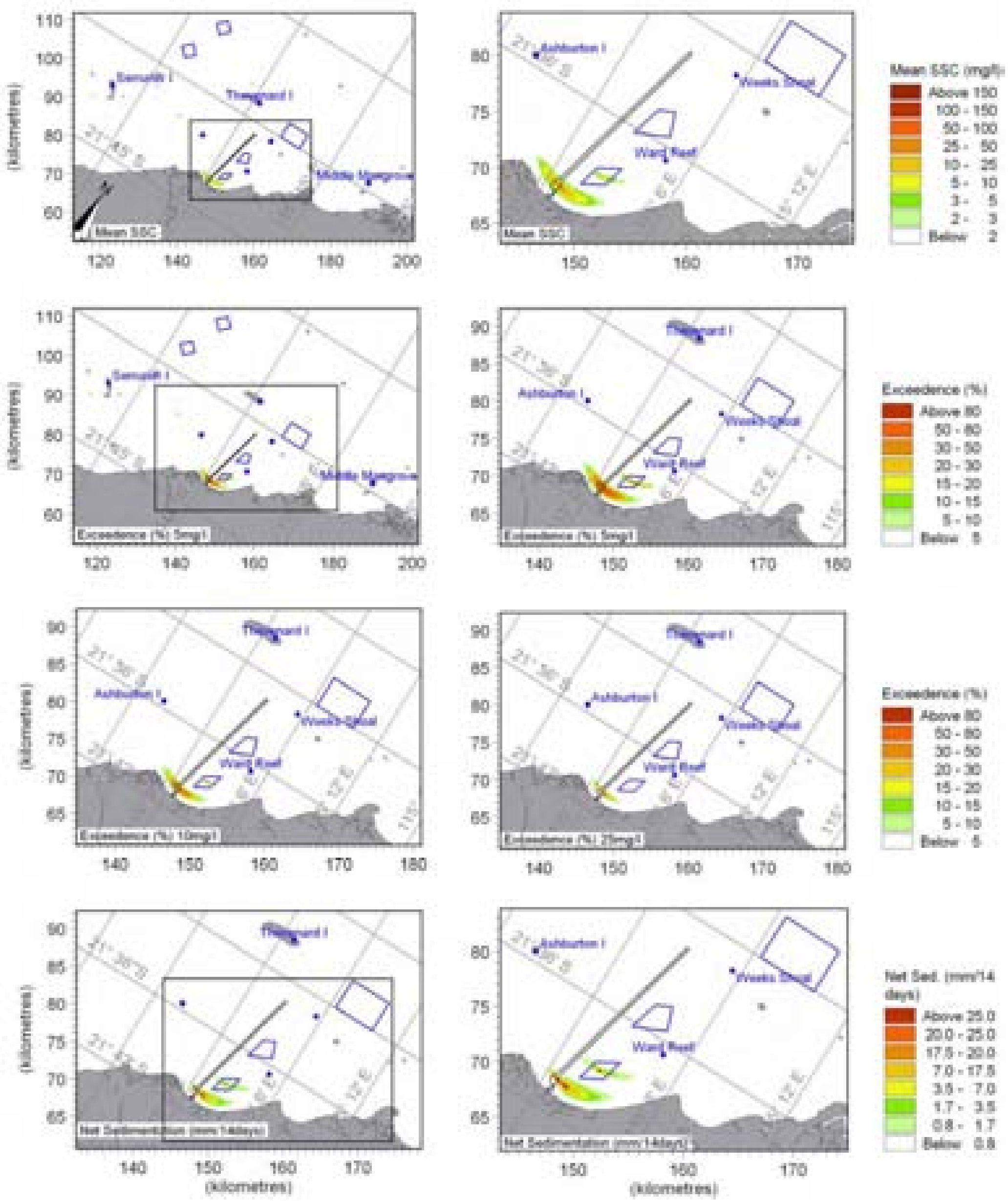

Figure W.3 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 1

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W-6

Dredge Scenario: Scenario 1
Climatic Scenario: Transitional 1
Spill Rate Estimate: Low ("Realistic") Case

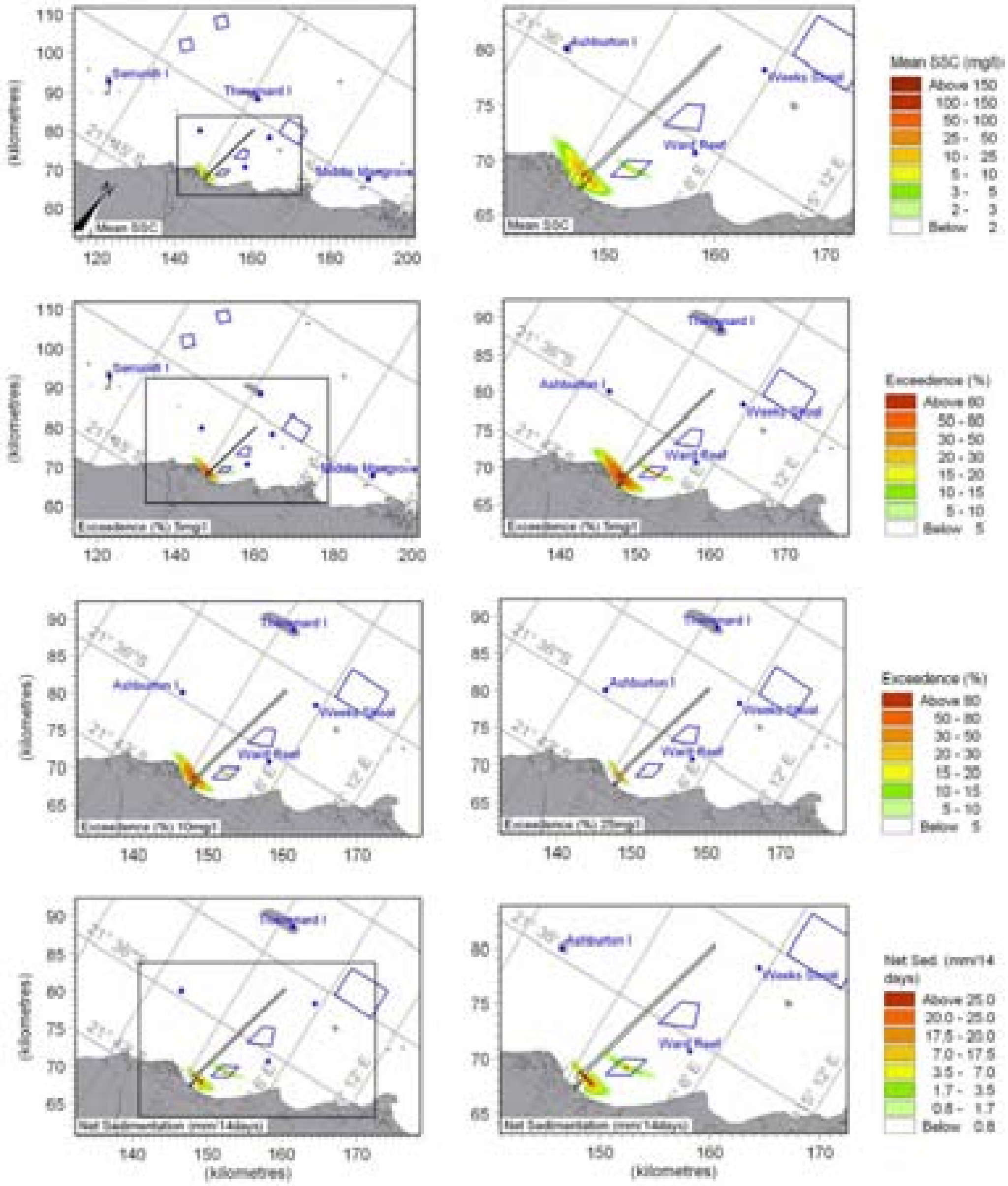

Figure W.4 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 1*

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W-7

Dredge Scenario: Scenario 1
Climatic Scenario: Transitional B
Spill Rate Estimate: Low ("Realistic") Case

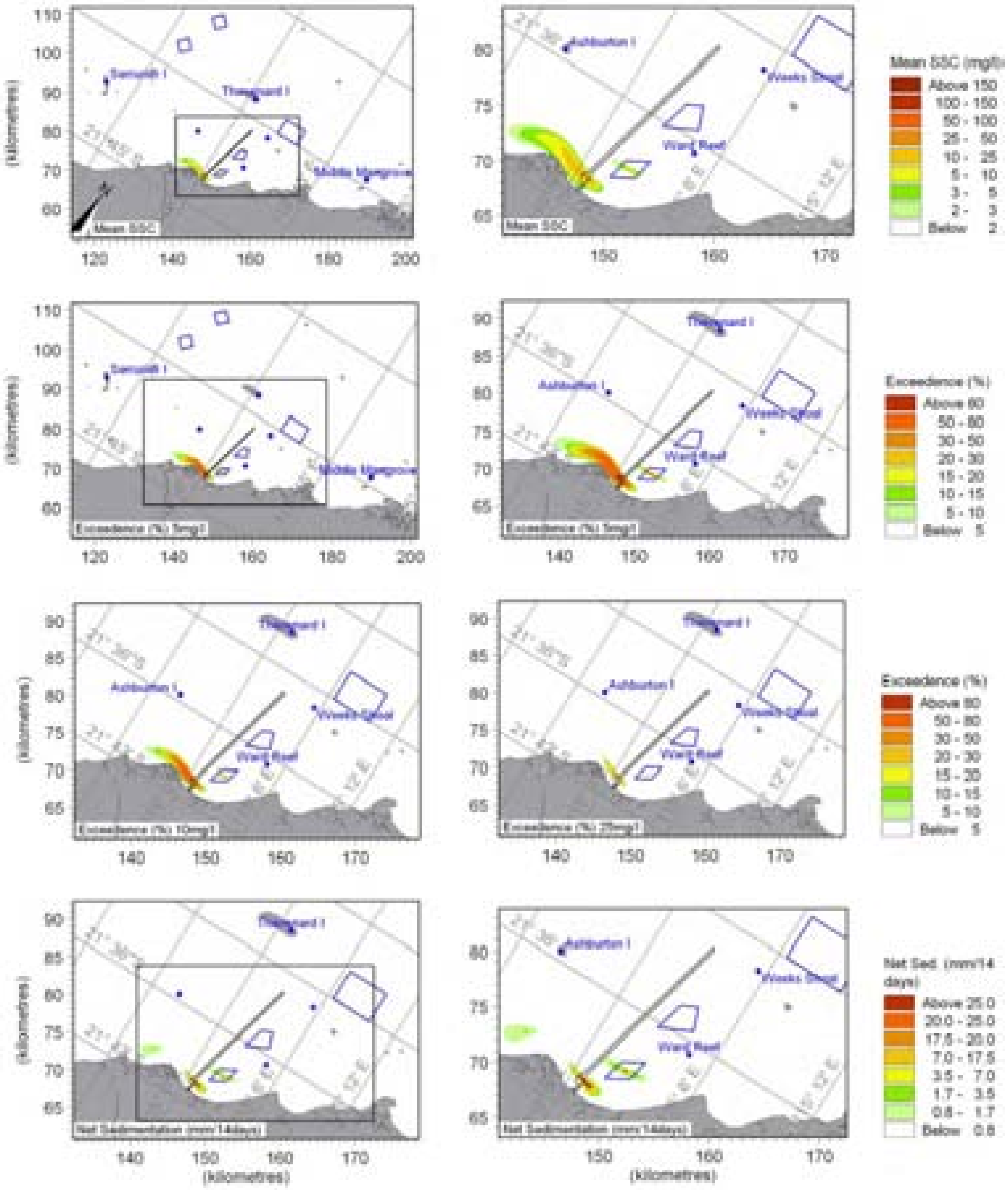

Figure W.5 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 1*

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W-8

Dredge Scenario:	Scenario 1
Climatic Scenario:	Winter A
Spill Rate Estimate:	Low ("Realistic") Case

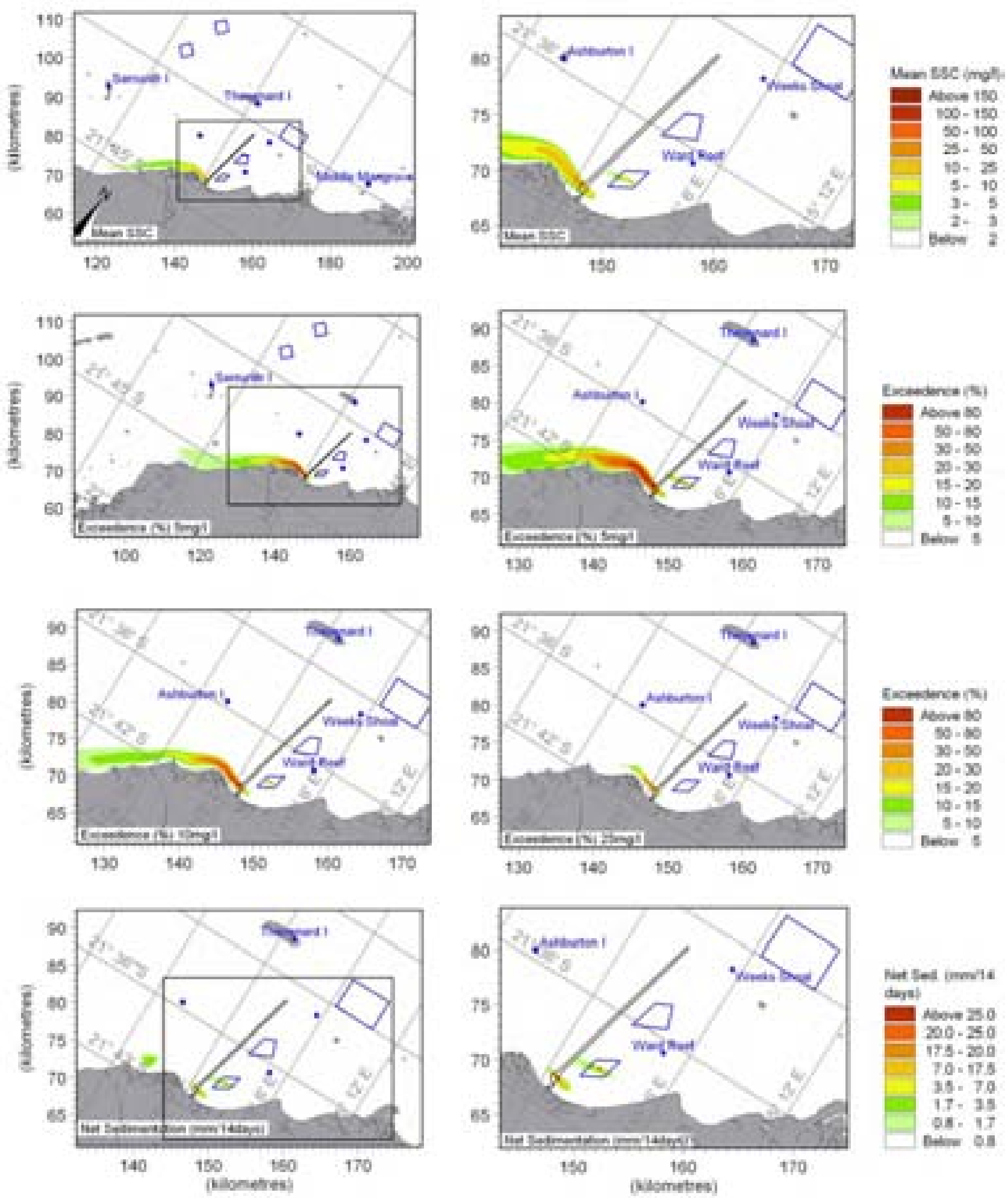

Figure W.6 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 1

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W-9

Dredge Scenario: Scenario 1
Climatic Scenario: Winter B
Spill Rate Estimate: Low ("Realistic") Case

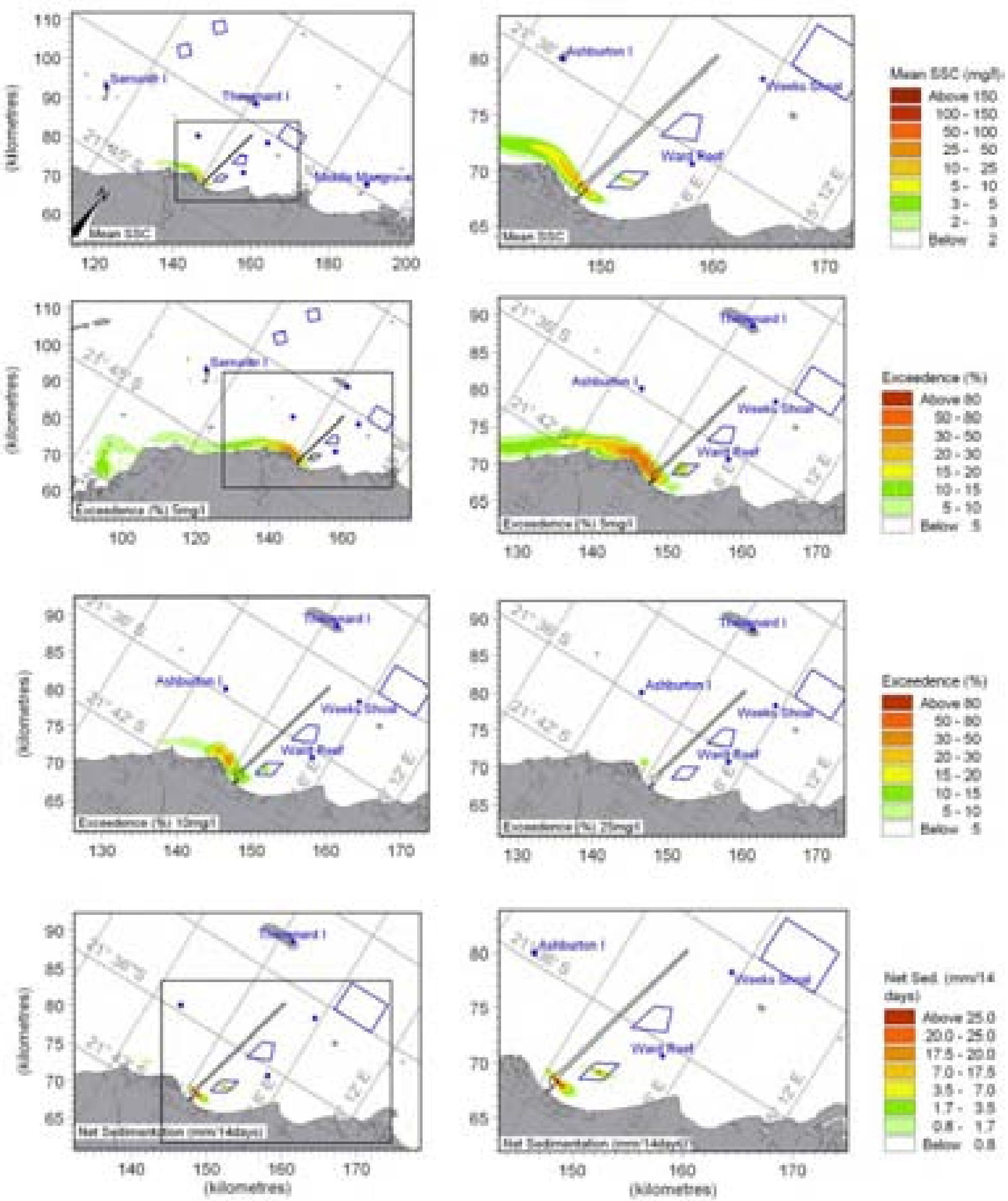

Figure W.7 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 1

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W.5 Results for High (Worst Case) Spill Rates

Dredge Scenario:	Scenario 1
Climatic Scenario:	Summer A
Spill Rate Estimate:	High ("Worst Case")

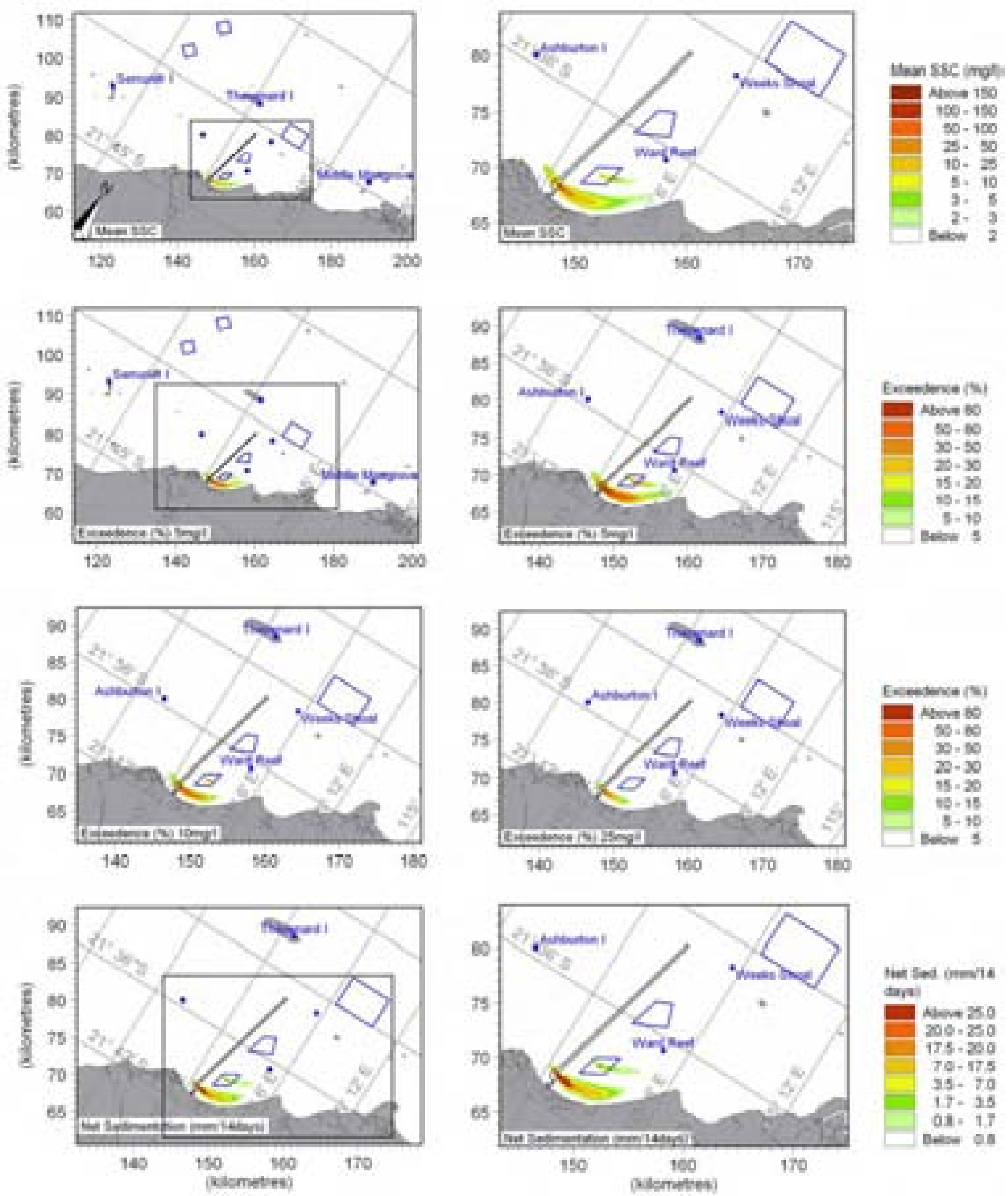

Figure W.8 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/ 14 days) of dredging and disposal works for Scenario 1

W-11

Dredge Scenario: Scenario 1
Climatic Scenario: Summer B
Spill Rate Estimate: High ("Worst Case")

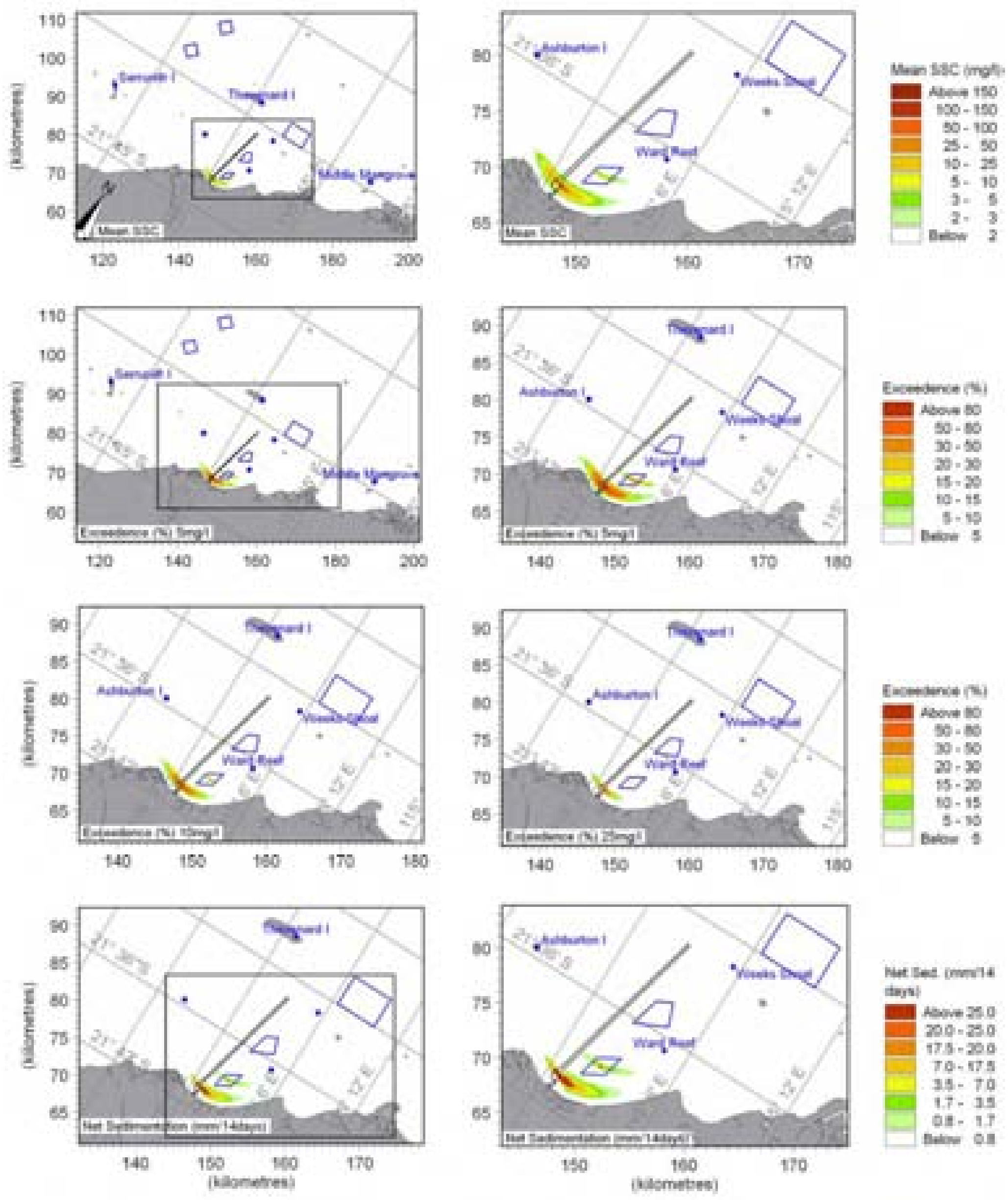

Figure W.9 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/ 14 days) of dredging and disposal works for Scenario 1*

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W-12

Dredge Scenario: Scenario 1
Climatic Scenario: Transitional A
Spill Rate Estimate: High ("Worst Case")

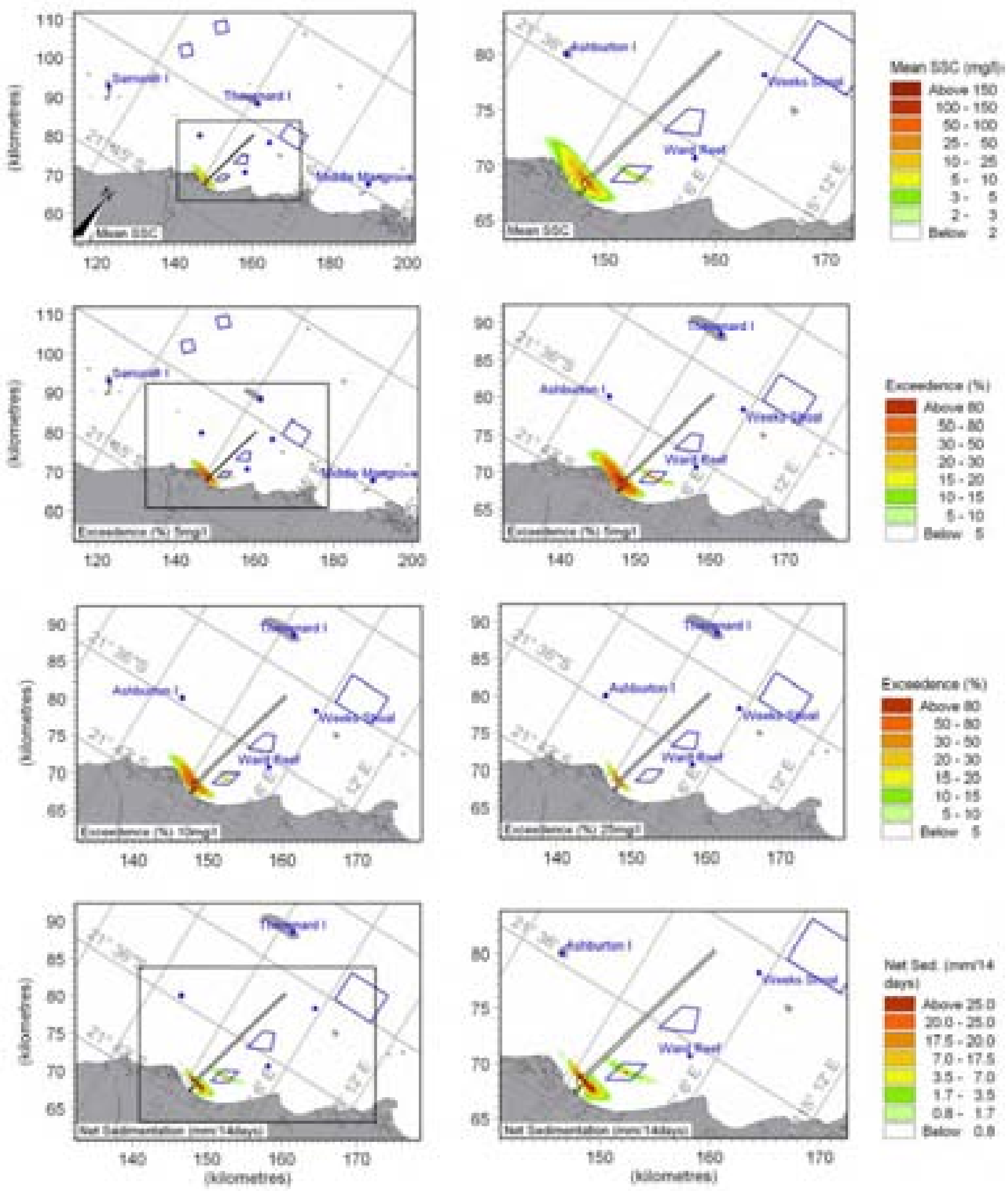

Figure W.10 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/ 14 days) of dredging and disposal works for Scenario 1

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W-13

Dredge Scenario: Scenario 1
Climatic Scenario: Transitional B
Spill Rate Estimate: High ("Worst Case")

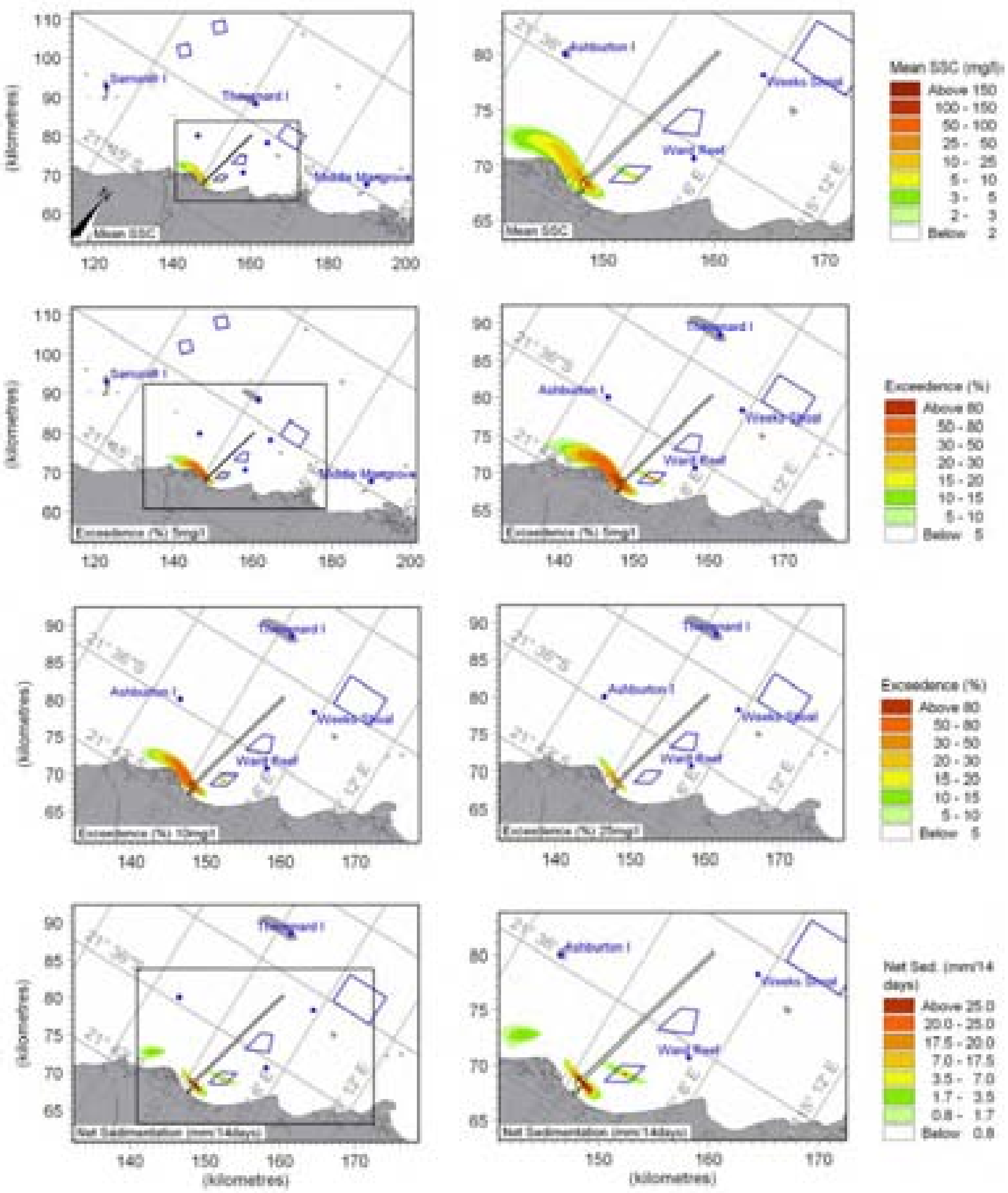

Figure W.11 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/ 14 days) of dredging and disposal works for Scenario 1

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W-14

Dredge Scenario: Scenario 1
Climatic Scenario: Winter A
Spill Rate Estimate: High ("Worst Case")

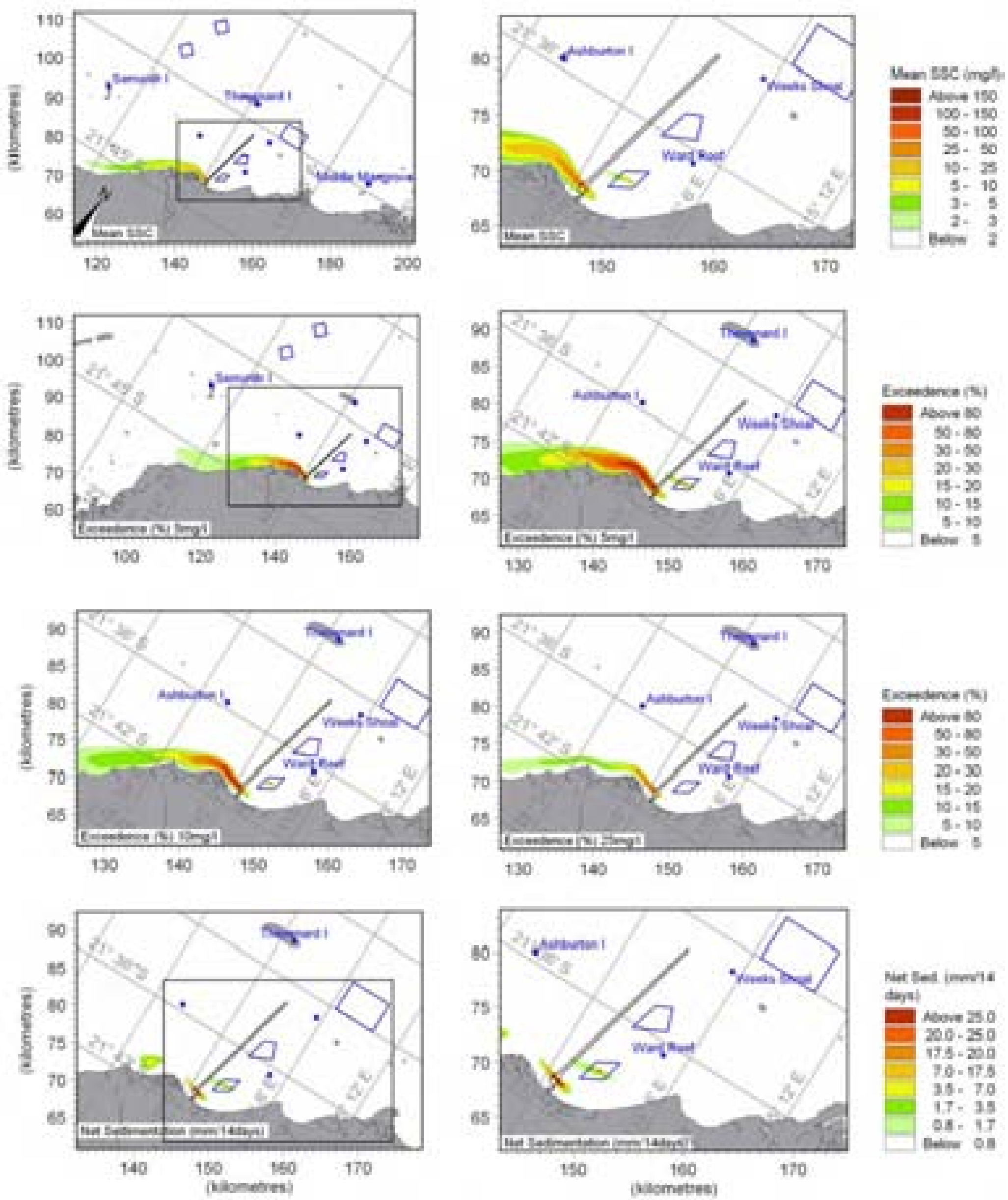

Figure W.12 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/ 14 days) of dredging and disposal works for Scenario 1

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Dredge Scenario: Scenario 1
Climatic Scenario: Winter B
Spill Rate Estimate: High ("Worst Case")

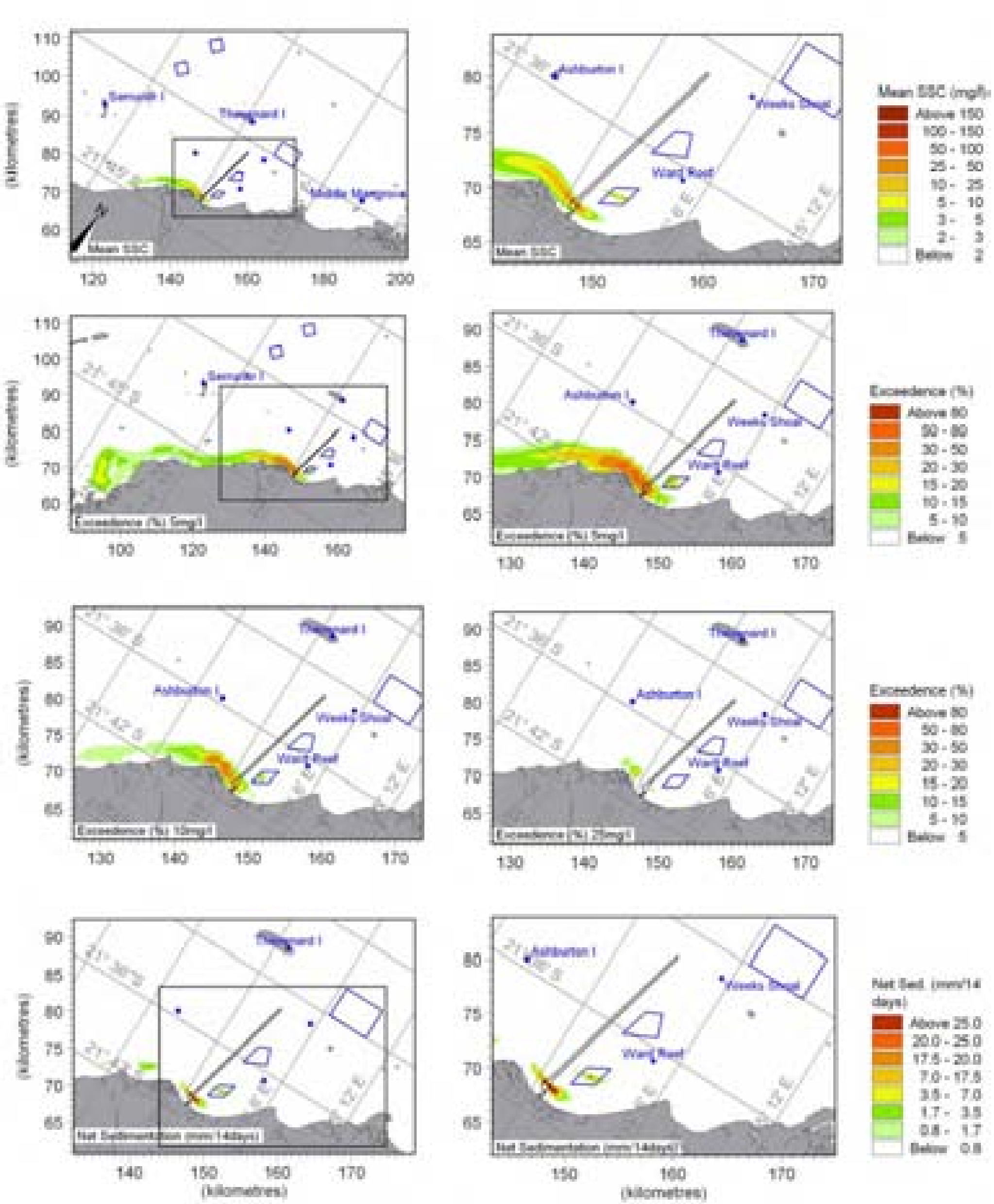

Figure W.13 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 1

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A P P E N D I X X :

Results for Dredge Scenario 2 Based on MesoLAPS Winds

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X RESULTS FOR DREDGE SCENARIO 2 BASED ON MESOLAPS WINDS

This appendix presents results from the sediment transport model based on hydrodynamics driven by the MesoLAPS wind fields. The reader is referred to the following sections of the main report and additional appendices for further information;

- Section 4.1.3.2 *Wind Fields*
- Section 6.2 *Results for the Dredging of the Shipping Channel*
- Appendix D *Hydrodynamic Model Validation and Calibration*

X.1 Statistical Plots

The established impact criteria (DHI (2010) *Dredge Plume Impact Assessment Report)* are based on sediment loads, both in terms of excess suspended concentrations and sedimentation rates, over 14 day periods. In terms of exposure and impacts, both the concentrations and the duration of the event is important, which is expressed through the exceedence probability of given limits.

For each simulated case, a set of plots showing the statistical output used in the impact assessment have been produced. All plots are for excess concentrations, i.e. sediments originating from the dredging operations and exclusive of ambient concentrations.

Each mosaic plot comprises:

- Mean excess concentration at two scales
- Exceedence of 5mg/l excess concentration at two scales
- Exceedence of 10mg/l excess concentration
- Exceedence of 25mg/l excess concentration
- Net sedimentation rates at two zoomed levels at the site

Note that all concentrations are presented as depth-averaged values. All values are derived over the assessment period (2nd neap/spring tidal cycle of the month for each climatic scenario), i.e. after at least 14 days warm-up period. Exceedences are expressed in percentage time over the assessment period that the exceedence limit is exceeded.

X.2 Description of Dredge Scenario 2

Nearshore Dredging: CSD in PLF basin

- CSD with pumping to barges at -3m LAT for transport to Site C
- Bathymetry with fully dredged access channel to -3m LAT, partly dredged 150m wide channel to -8.3m LAT
- Material available for re-suspension in dredged channel, Site A and Site C
- Includes MOF breakwaters

The locations for the various dredge and placement activities are outlined in Figure X.1, while defined low (realistic) and high (worst-case) spill rates applied in Dredging Scenario 2 are listed in Table 3.2 of the main report.

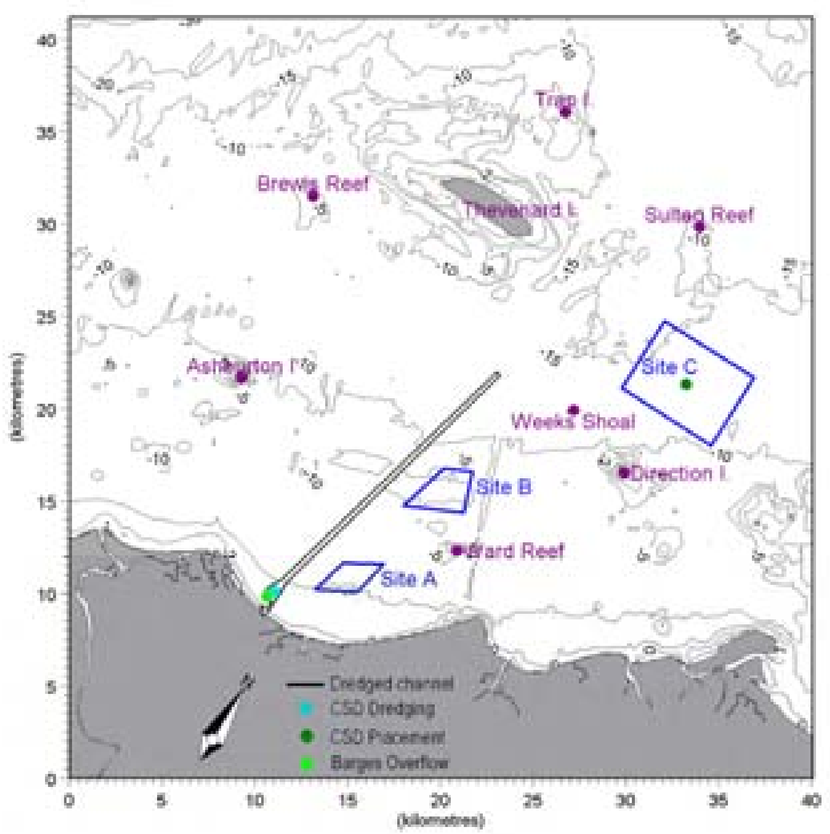

Figure X.1 Sketch of locations for Dredging Scenario 2.

X.3 Summary of Results

Specific observations for Dredge Scenario 2 include:

- The plumes from the CSD dredging of the PLF combined with the overflow of barges at the -3m LAT contour within the PLF leads to a continuous plume running along the coastline – predominantly eastward during summer and westward during winter.
- The plume extends to Beadon Point and MESOLaps with a mean concentration in the order of 10mg/l during strong summer conditions and to Entrance Point at about 25-50mg/l during winter for “worst case” spill conditions. These values are reduced to 5-10mg/l at MESOLaps during summer and 10-25mg/l at Entrance Point during winter for the “realistic” spill rates.
- Excess concentrations of 5 mg/l are exceeded more than 80% of the time at Entrance Point during strong winter conditions, and about 50% of the time at MESOLaps during strong summer conditions.
- The barge filling and overflowing at the -3m LAT contour maintains the plume well landward of Ward Reef.

X.4 Results for Low (Realistic) Spill Rates

Dredge Scenario:	Scenario 2
Climatic Scenario:	Summer A
Spill Rate Estimate:	Low ("Realistic") Case

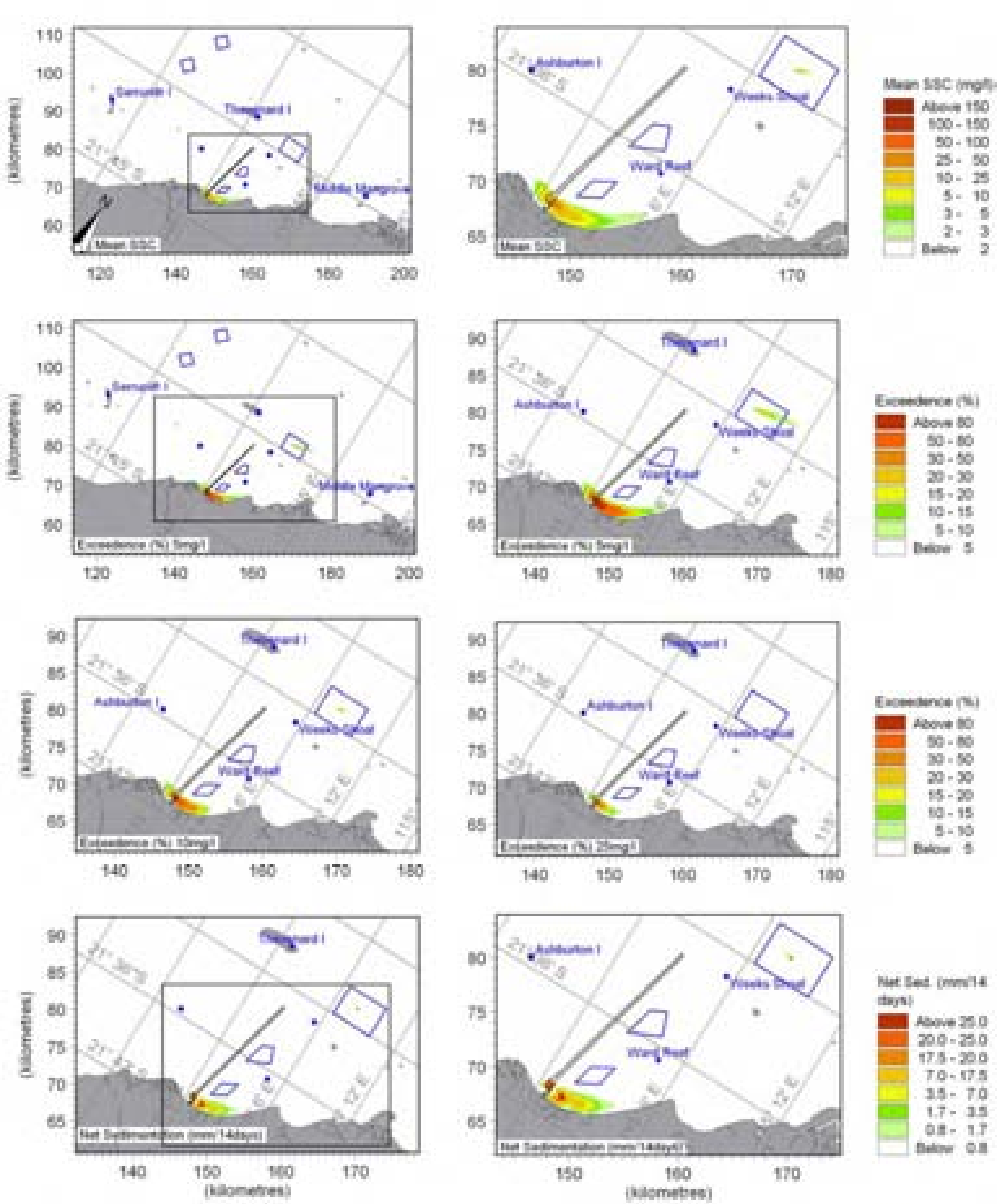

Figure X.2 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 2*

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X-4

Dredge Scenario: Scenario 2
Climatic Scenario: Summer B
Spill Rate Estimate: Low ("Realistic") Case

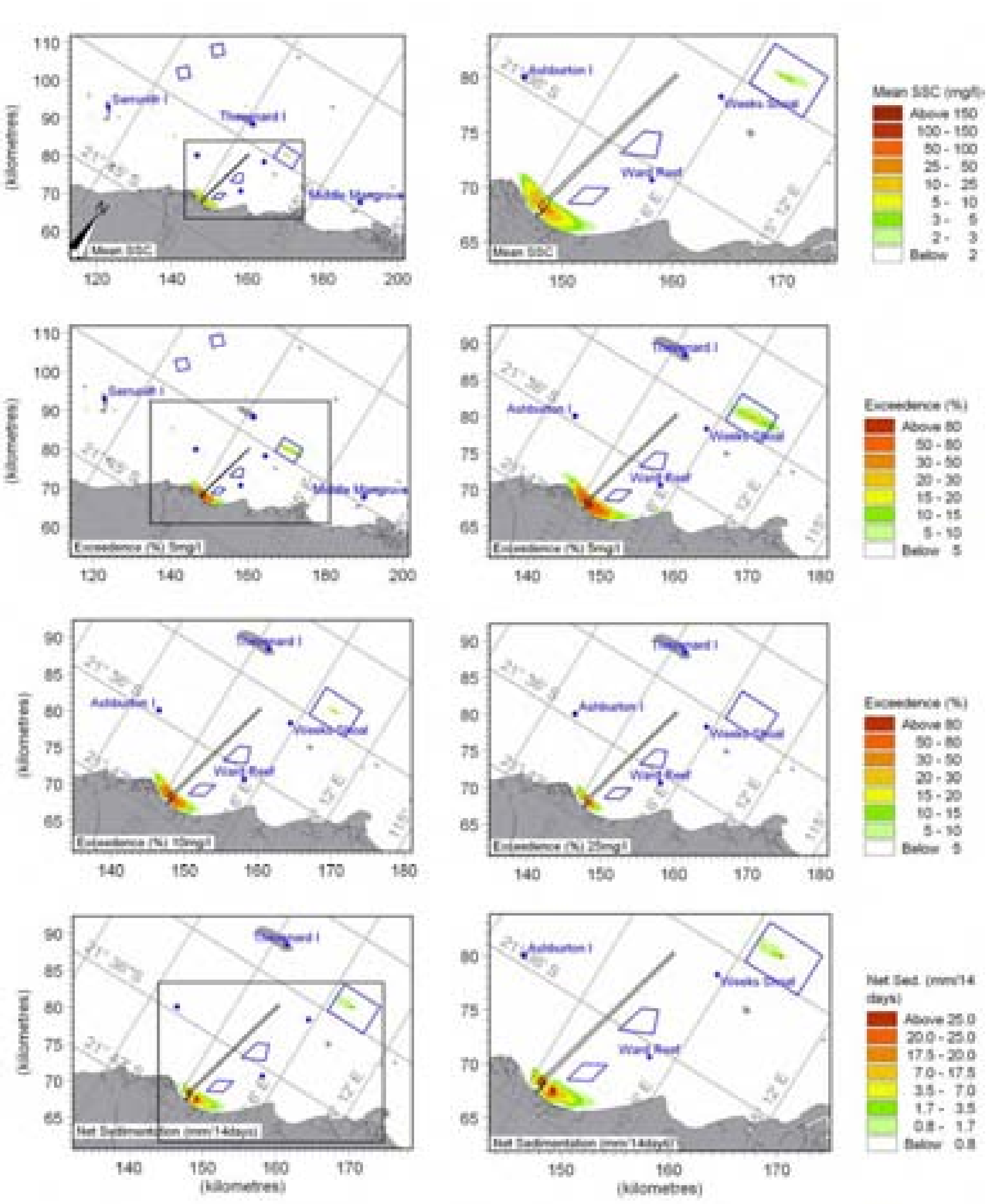

Figure X.3 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 2

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X-5

Dredge Scenario: Scenario 2
Climatic Scenario: Transitional A
Spill Rate Estimate: Low ("Realistic") Case

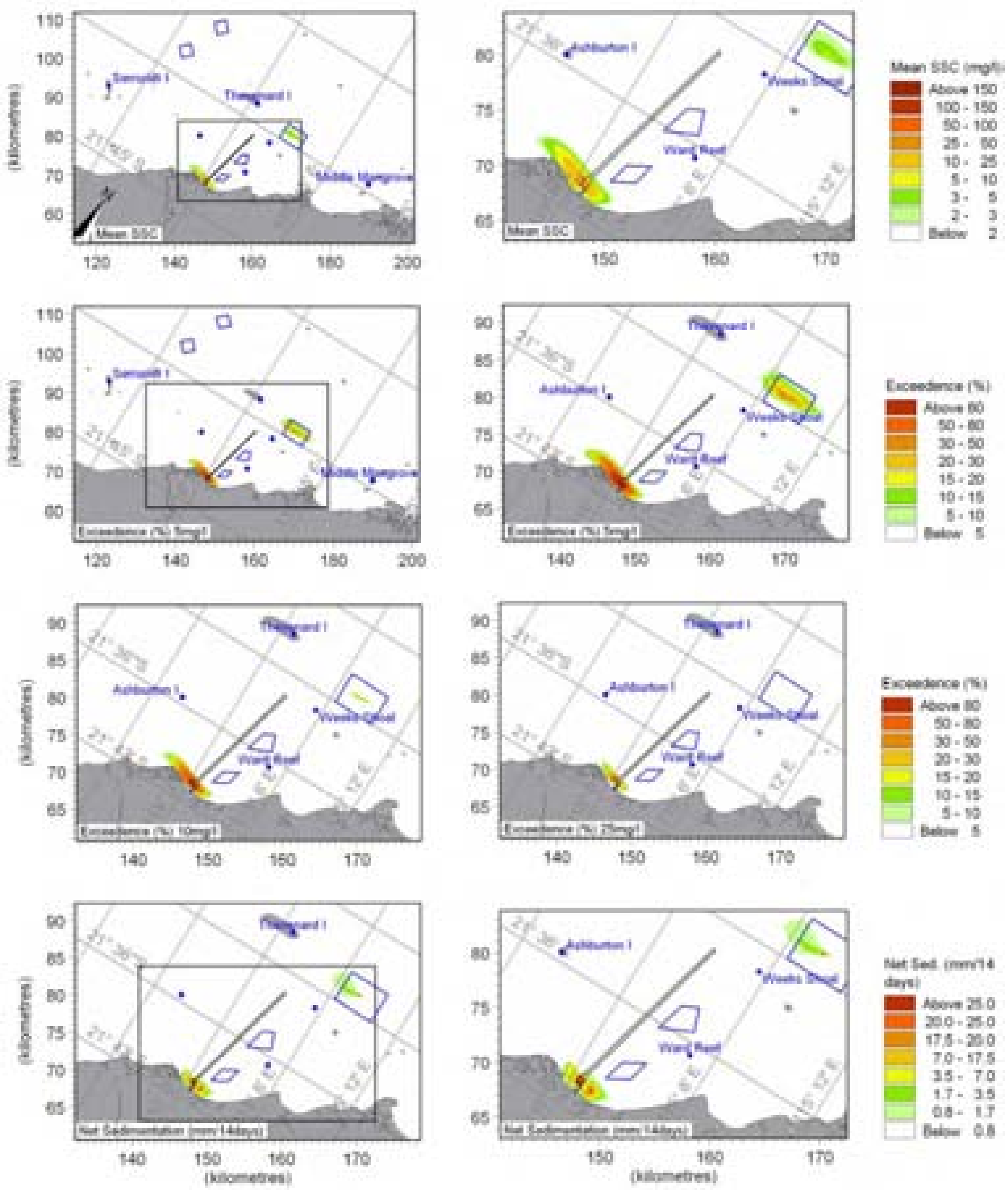

Figure X.4 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 2*

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Dredge Scenario: Scenario 2
Climatic Scenario: Transitional B
Spill Rate Estimate: Low ("Realistic") Case

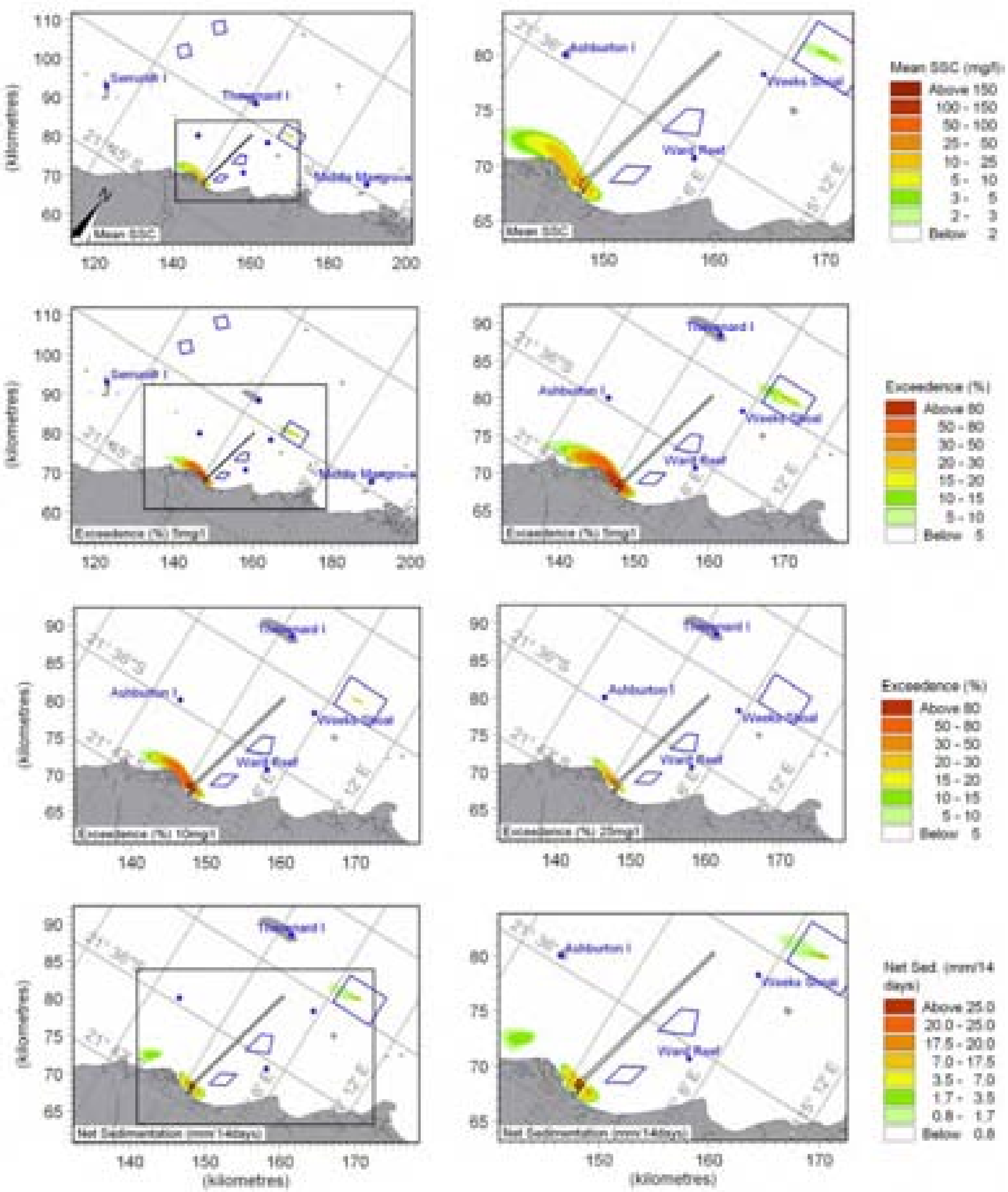

Figure X.5 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 2*

X-7

Dredge Scenario: Scenario 2
Climatic Scenario: Winter A
Spill Rate Estimate: Low ("Realistic") Case

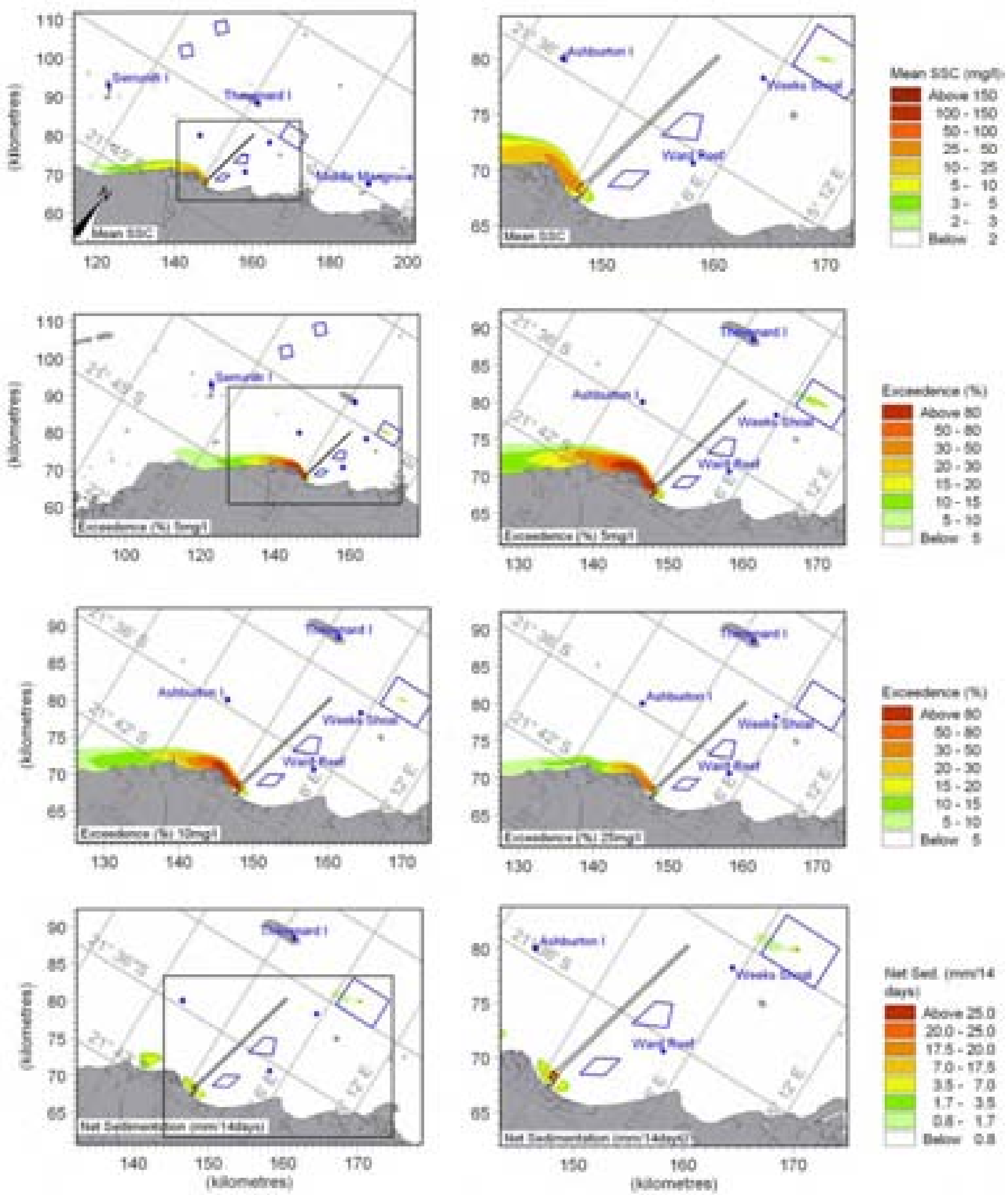

Figure X.6 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 2

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X-8

Dredge Scenario:	Scenario 2
Climatic Scenario:	Winter B
Spill Rate Estimate:	Low ("Realistic") Case

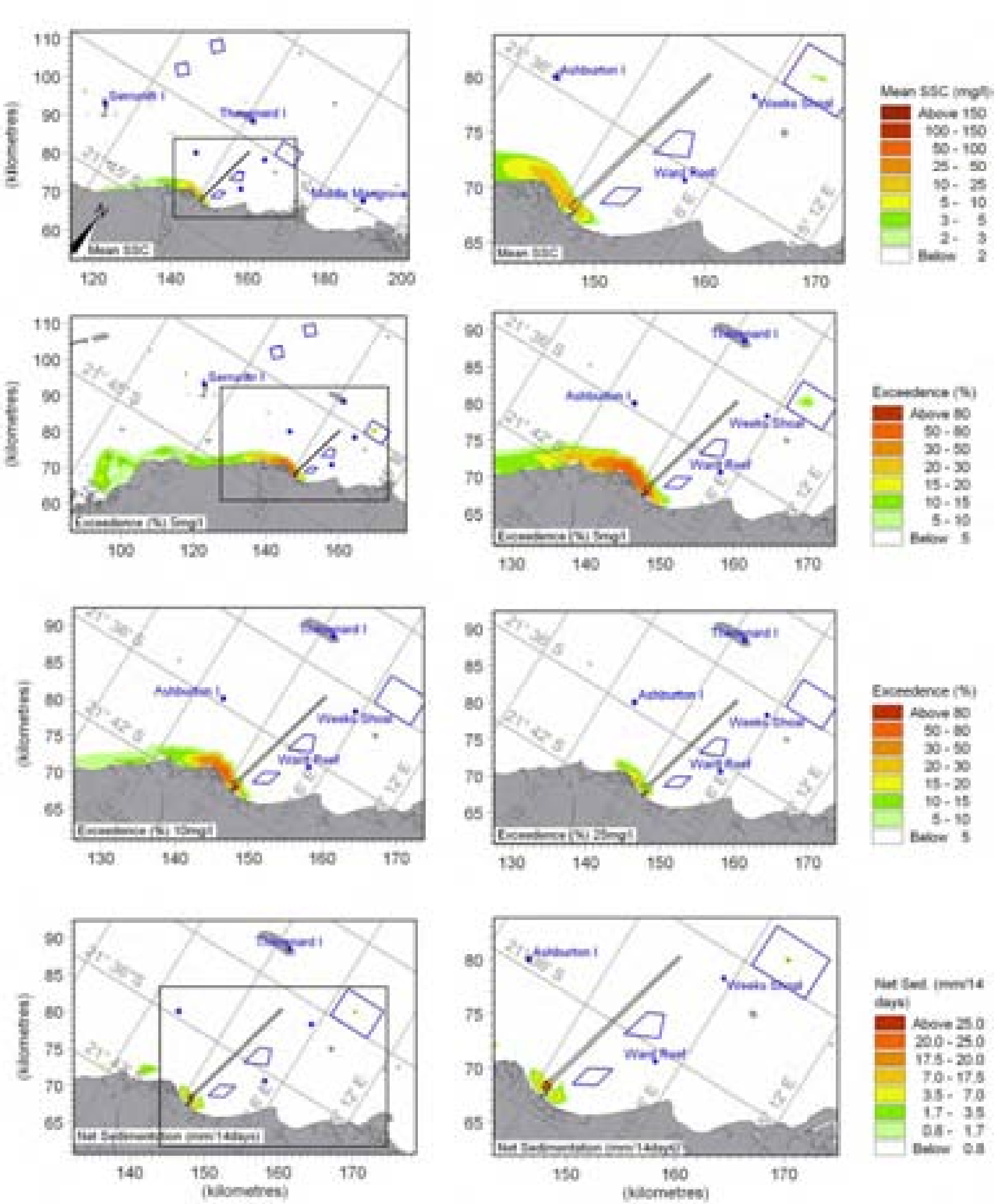

Figure X.7 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 2

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X.5 Results for High (Worst Case) Spill Rates

Dredge Scenario: Scenario 2
Climatic Scenario: Summer A
Spill Rate Estimate: High ("Worst Case")

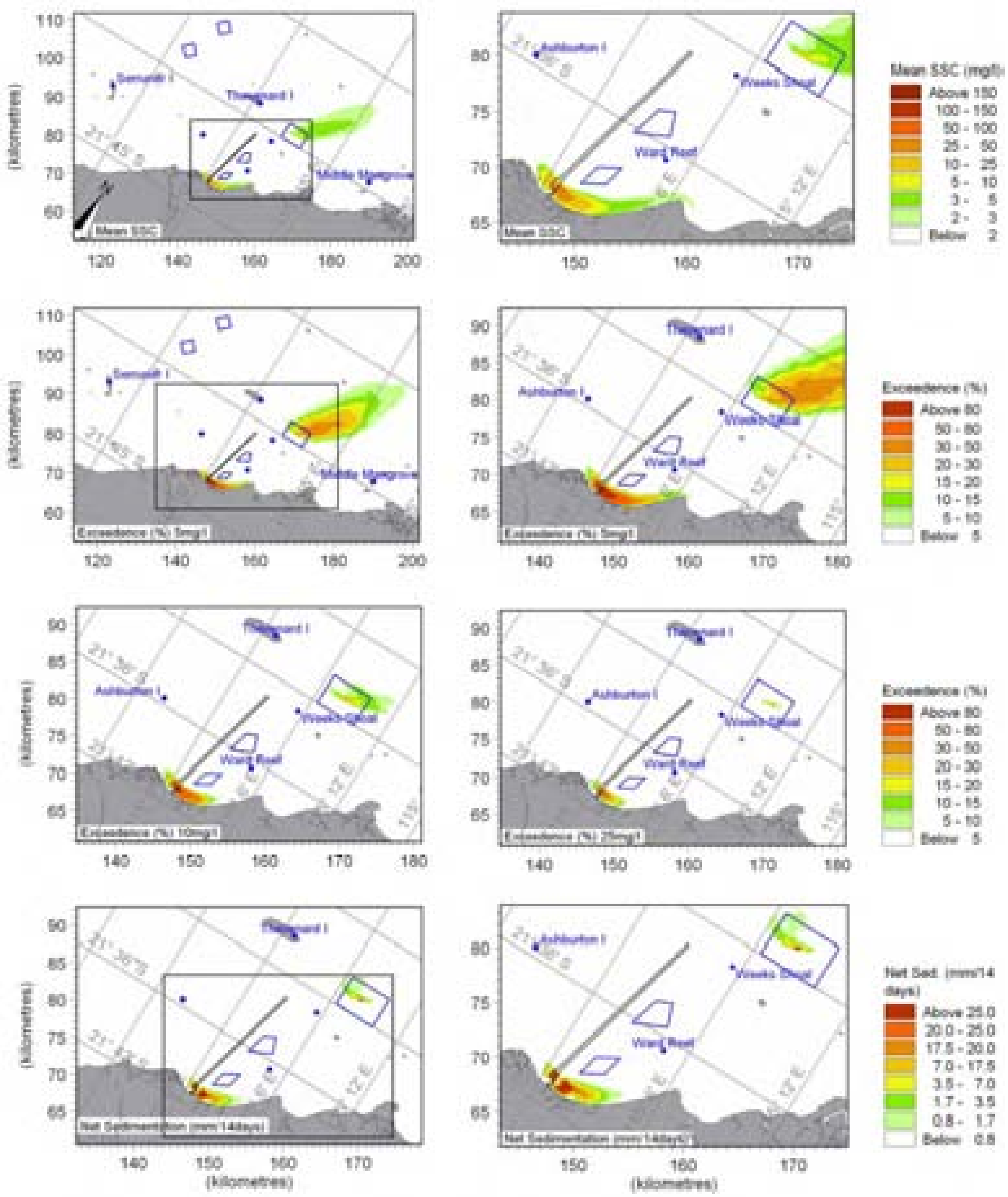

Figure X.8 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 2

X-10

Dredge Scenario: Scenario 2
Climatic Scenario: Summer B
Spill Rate Estimate: High ("Worst Case")

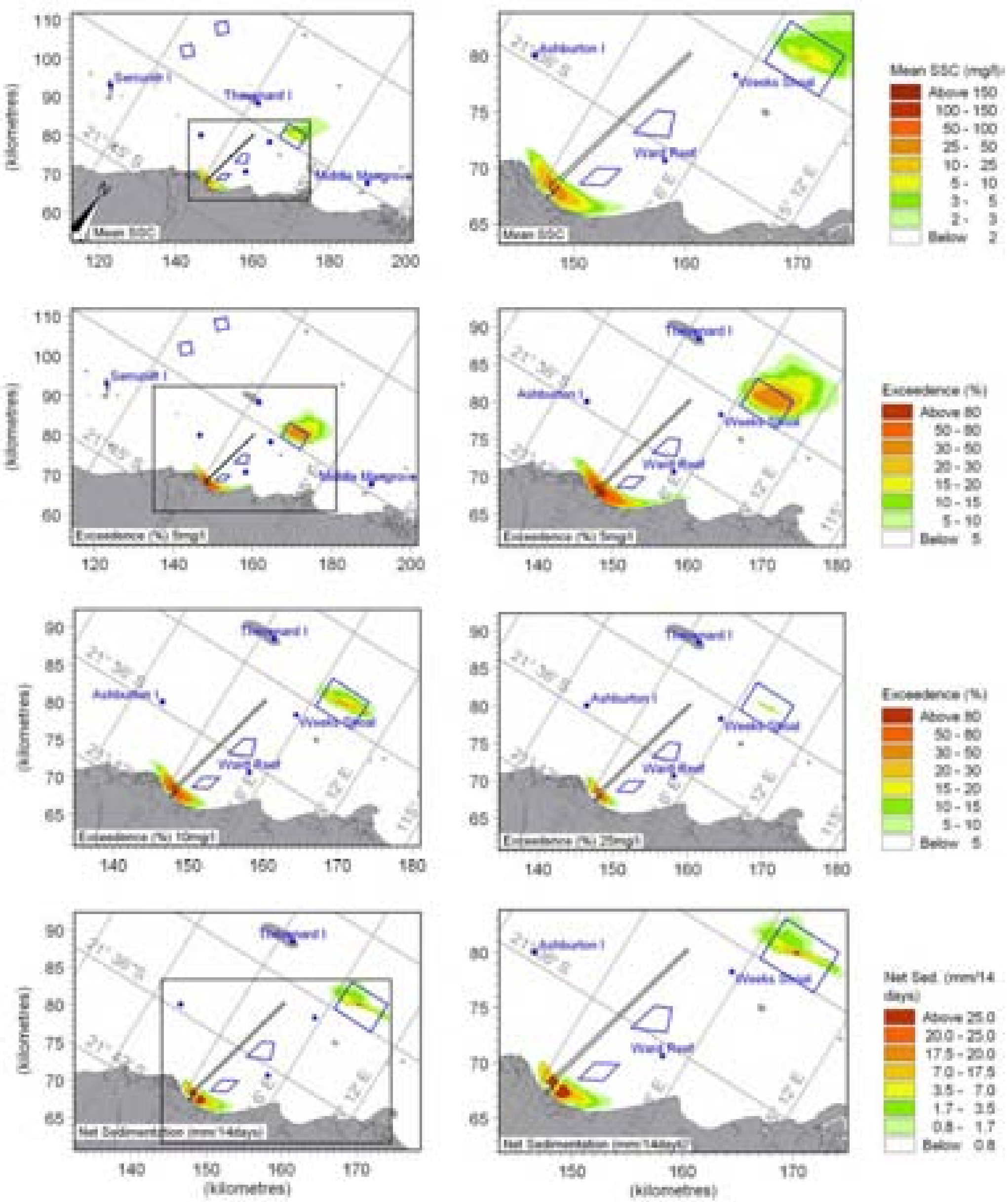

Figure X.9 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 2*

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X-11

Dredge Scenario: Scenario 2
Climatic Scenario: Transitional A
Spill Rate Estimate: High ("Worst Case")

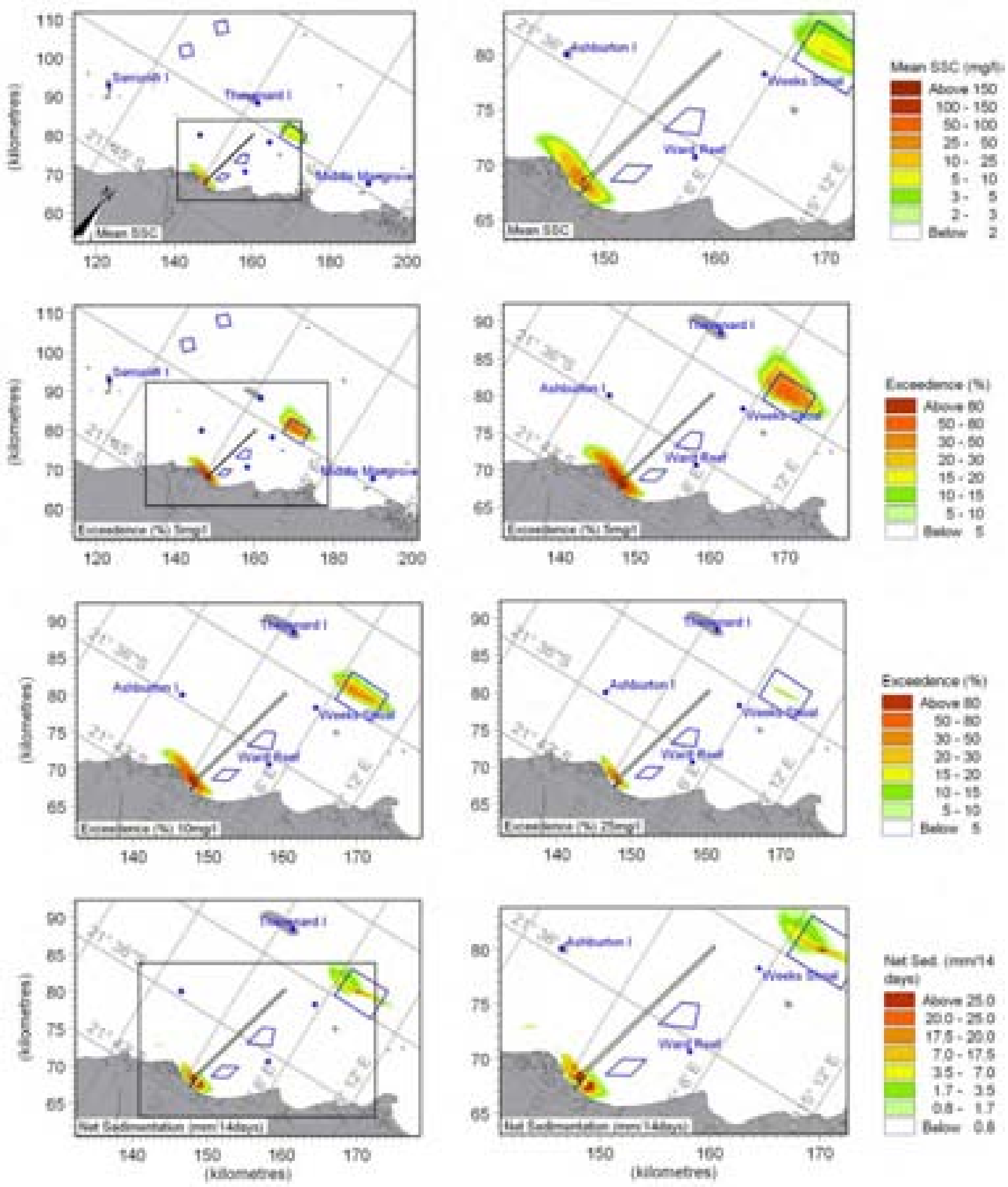

Figure X.10 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 2)

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Dredge Scenario: Scenario 2
Climatic Scenario: Transitional B
Spill Rate Estimate: High ("Worst Case")

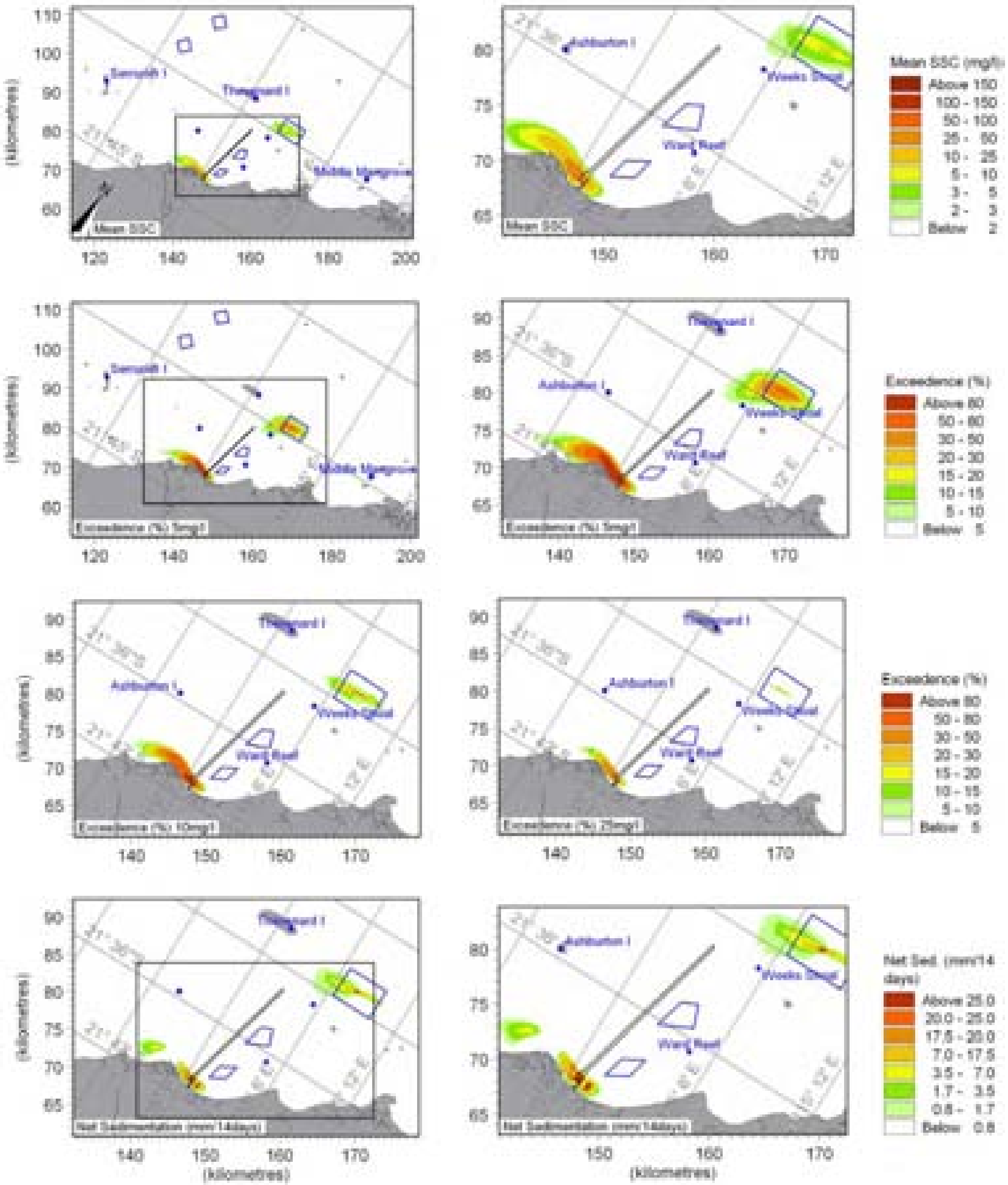

Figure X.11 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 2

X-13

Dredge Scenario: Scenario 2
Climatic Scenario: Winter A
Spill Rate Estimate: High ("Worst Case")

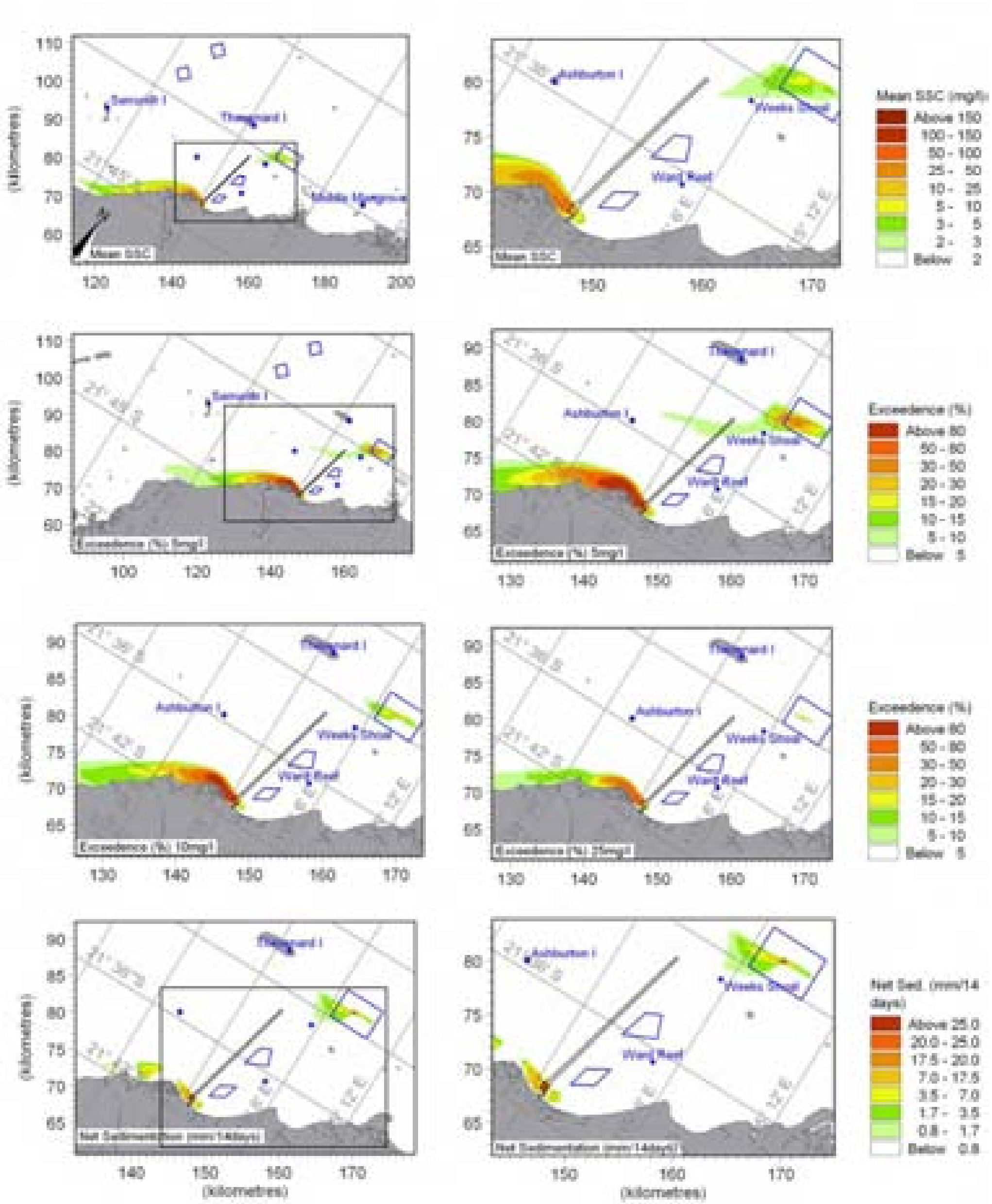

Figure X.12 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 2

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X-14

Dredge Scenario: Scenario 2
Climatic Scenario: Winter B
Spill Rate Estimate: High ("Worst Case")

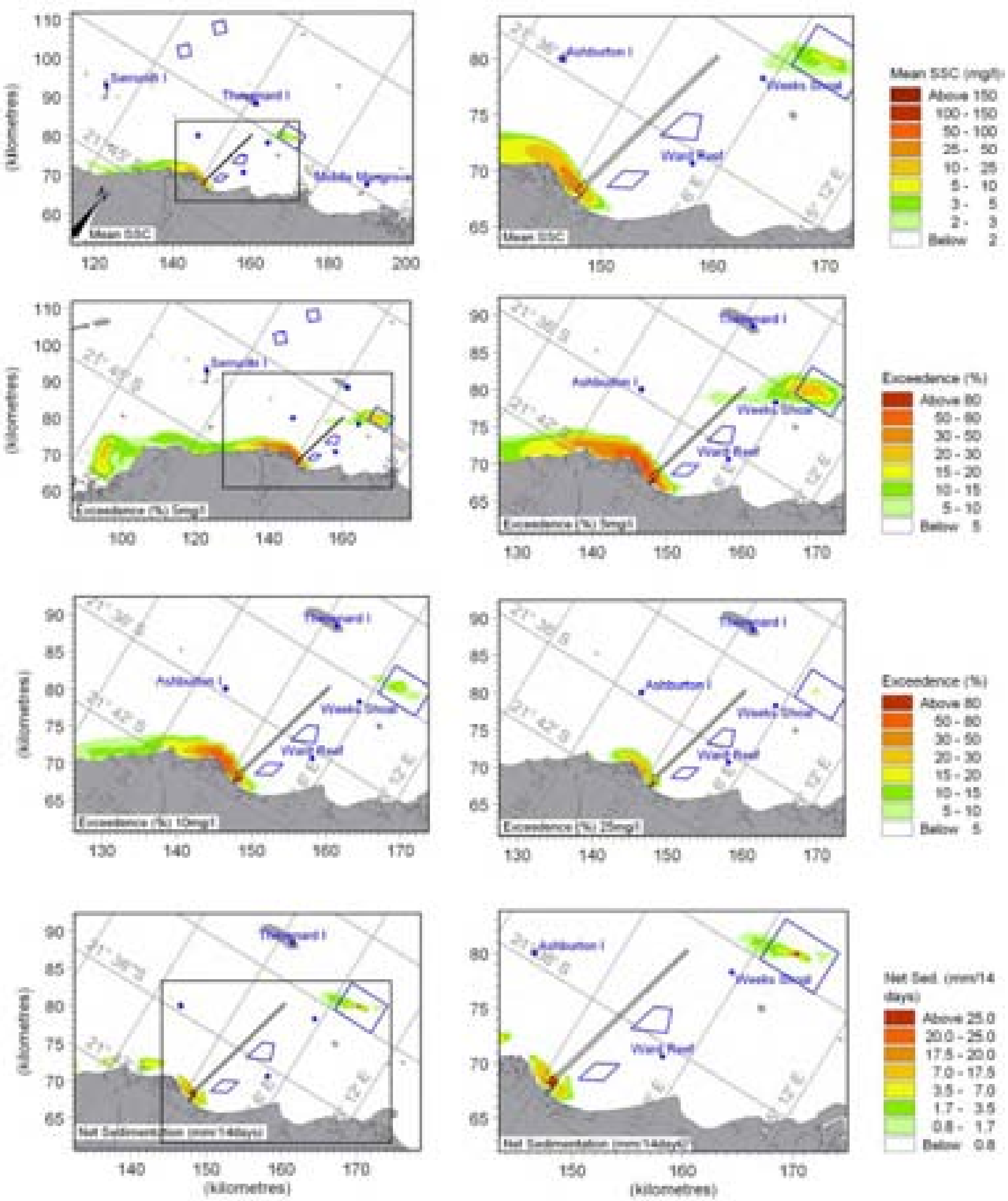

Figure X.13 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 2

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APPENDIX Y:

Results for Dredge Scenario 3 Based on MesoLAPS Winds

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FIGURES AND TABLES

Y RESULTS FOR DREDGE SCENARIO 3 BASED ON MESOLAPS WINDS

This appendix presents results from the sediment transport model based on hydrodynamics driven by the MesoLAPS wind fields. The reader is referred to the following sections of the main report and additional appendices for further information;

- Section 4.1.3.2 *Wind Fields*
- Section 6.2 *Results for the Dredging of the Shipping Channel*
- Appendix D *Hydrodynamic Model Validation and Calibration*

Y.1 Statistical Plots

The established impact criteria (DHI (2010) *Dredge Plume Impact Assessment Report)* are based on sediment loads, both in terms of excess suspended concentrations and sedimentation rates, over 14 day periods. In terms of exposure and impacts, both the concentrations and the duration of the event is important, which is expressed through the exceedence probability of given limits.

For each simulated case, a set of plots showing the statistical output used in the impact assessment have been produced. All plots are for excess concentrations, i.e. sediments originating from the dredging operations and exclusive of ambient concentrations.

Each mosaic plot comprises:

- Mean excess concentration at two scales
- Exceedence of 5mg/l excess concentration at two scales
- Exceedence of 10mg/l excess concentration
- Exceedence of 25mg/l excess concentration
- Net sedimentation rates at two zoomed levels at the site

Note that all concentrations are presented as depth-averaged values. All values are derived over the assessment period (2^{nd} neap/spring tidal cycle of the month for each climatic scenario), i.e. after at least 14 days warm-up period. Exceedences are expressed in percentage time over the assessment period that the exceedence limit is exceeded.

Y.2 Description of Dredge Scenario 3

Nearshore Dredging: CSD in MOF

- CSD with pumping to barges and transport and disposal at Site C
- Bathymetry with fully dredged, 75m wide channel to -6m LAT and barge access channel.
- Material available for re-suspension in dredged channel, Sites A & C.
- Includes MOF breakwaters

Offshore Dredging: Approach Channel – Section 4 sand

- 5,000m^3 TSHD with disposal at placement Site C
- Dredging along Sections 4 to bring PLF approach channel down to -8m LAT

The locations for the various dredge and placement activities are outlined in Figure Y.1, while defined low (realistic) and high (worst-case) spill rates applied in Dredging Scenario 3 are listed in Table 3.2 of the man report.

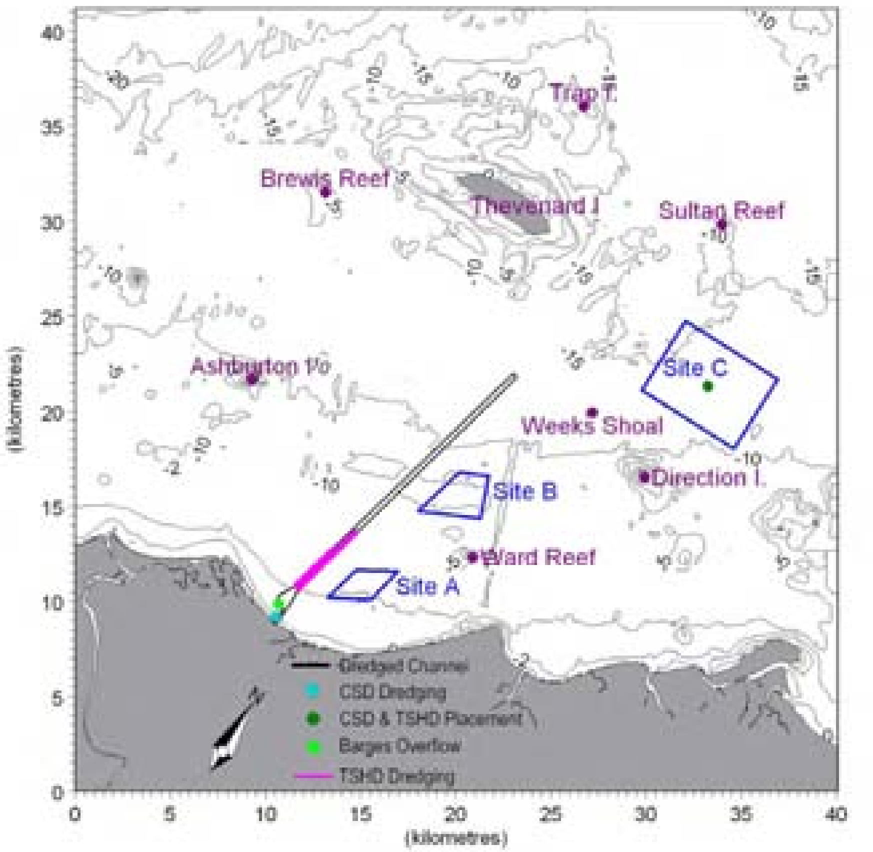

Figure Y.1 Sketch of locations for Dredging Scenario 3.

Y.3 Summary of Results

Specific observations for Dredge Scenario 3 include:

- The plumes from the nearshore CSD dredging of the PLF with pumping ashore leads to an elongated plume “hugging” the coastline in a predominantly easterly direction during summer and westerly direction during winter.
- The 5,000m^3 TSHD operation leads to a lower concentration plume along Section 4 of the channel.
- The combined CSD and TSHD plume creates a wide band along the coastline, just missing Ward Reef.

Y.4 Results for Low (Realistic) Spill Rates

Dredge Scenario: Scenario 3
Climatic Scenario: Summer A
Spill Rate Estimate: Low ("Realistic") Case

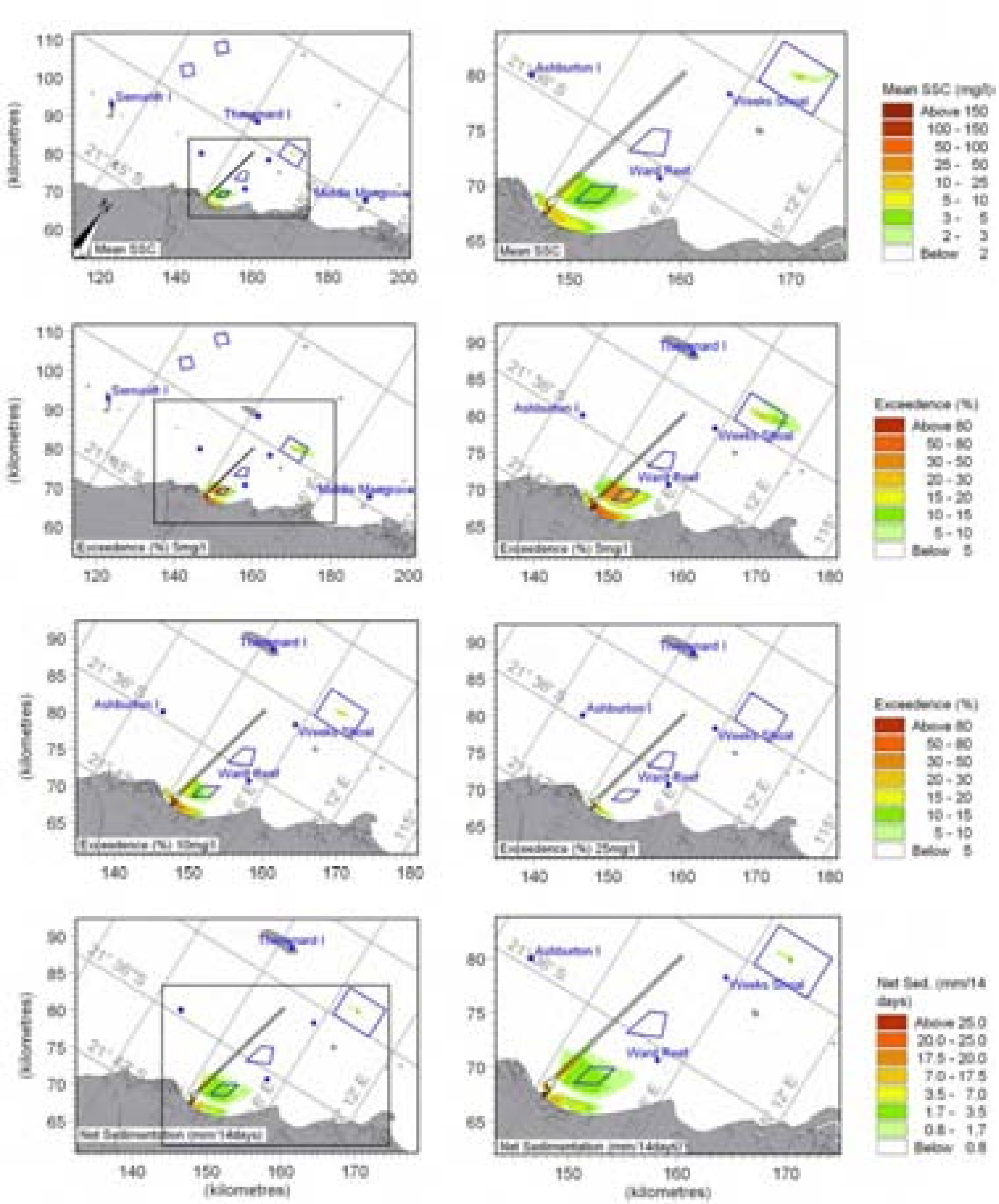

Figure Y.2 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 3

Y-4

Dredge Scenario: Scenario 3
Climatic Scenario: Summer B
Spill Rate Estimate: Low ("Realistic") Case

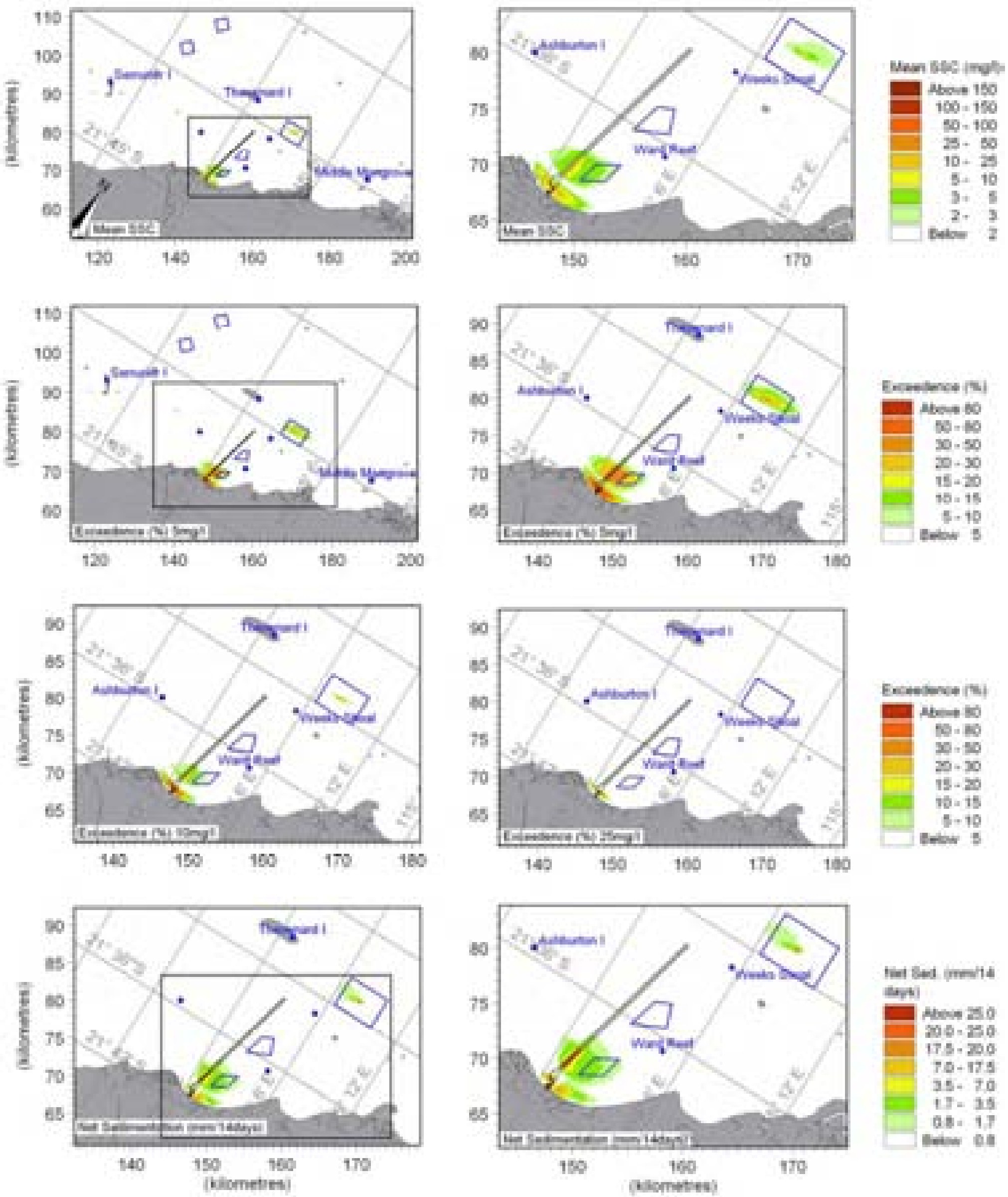

Figure Y.3 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 3*

DHI Water & Environment

Y-5

Dredge Scenario:	Scenario 3
Climatic Scenario:	Transitional A
Spill Rate Estimate:	Low ("Realistic") Case

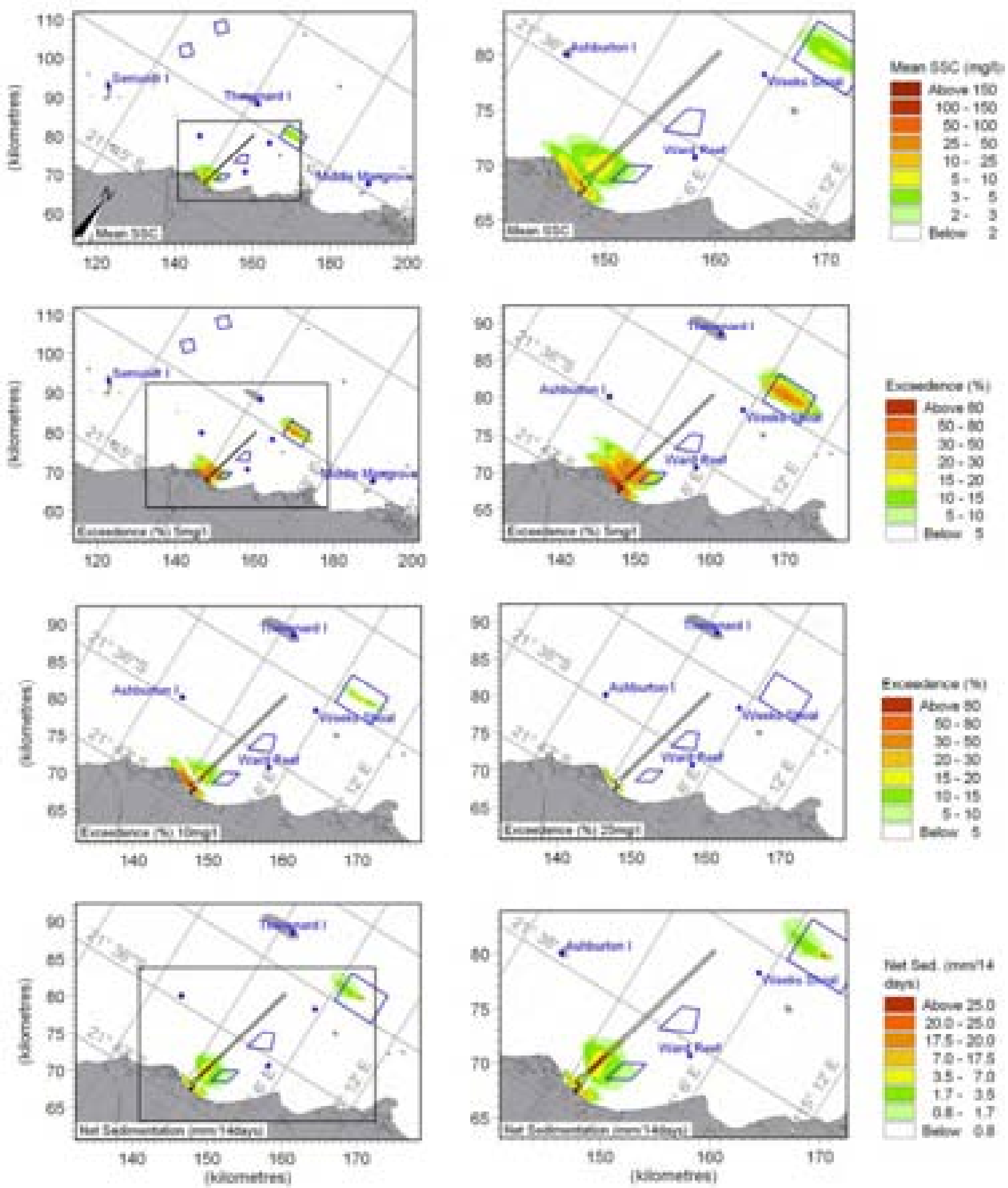

Figure Y.4 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 3)*

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Y-6

Dredge Scenario: Scenario 3
Climatic Scenario: Transitional B
Spill Rate Estimate: Low ("Realistic") Case

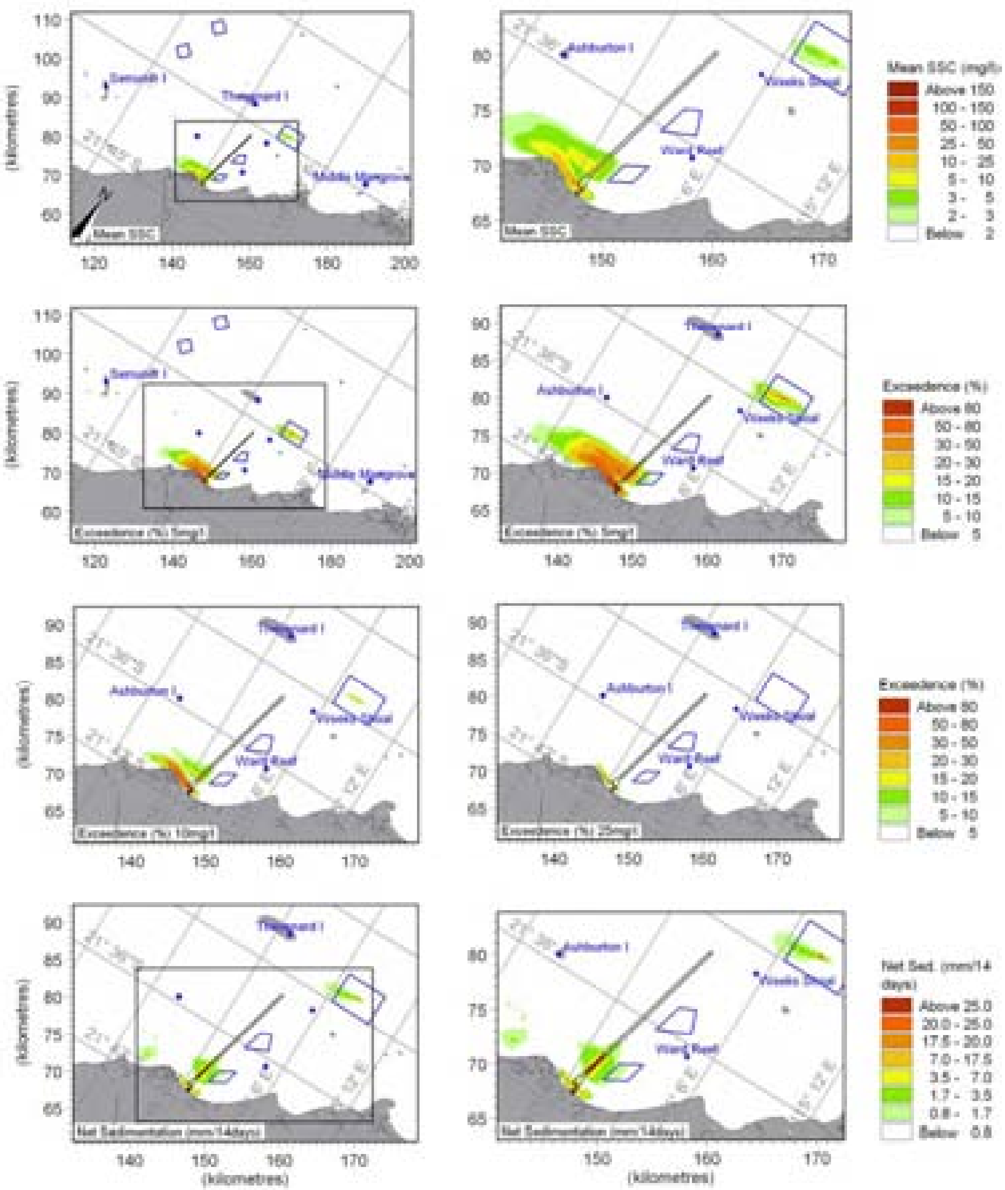

Figure Y.5 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 3*

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Y-7

Dredge Scenario: Scenario 3
Climatic Scenario: Winter A
Spill Rate Estimate: Low ("Realistic") Case

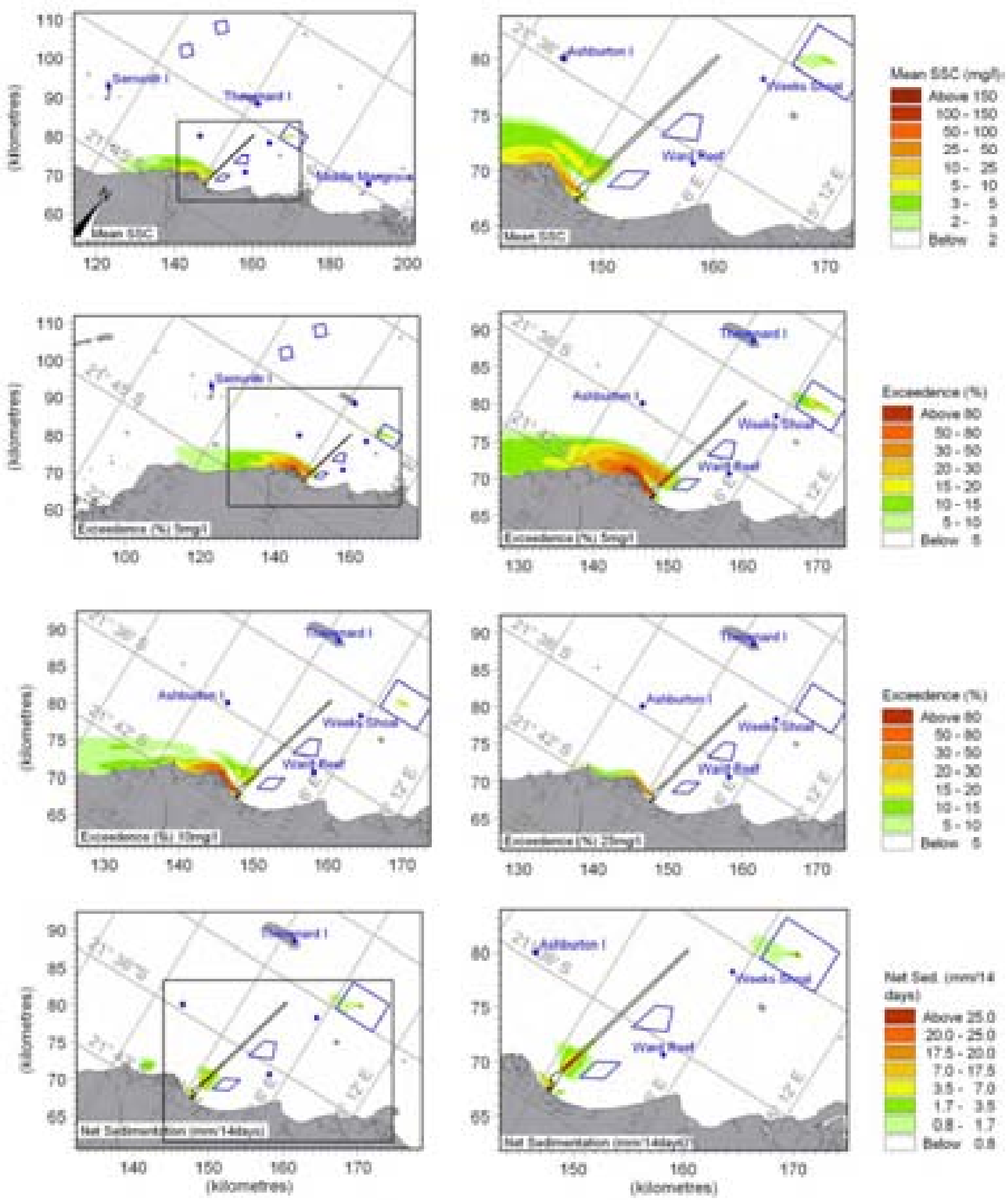

Figure Y.6 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 3

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Dredge Scenario: Scenario 3
Climatic Scenario: Winter B
Spill Rate Estimate: Low ("Realistic") Case

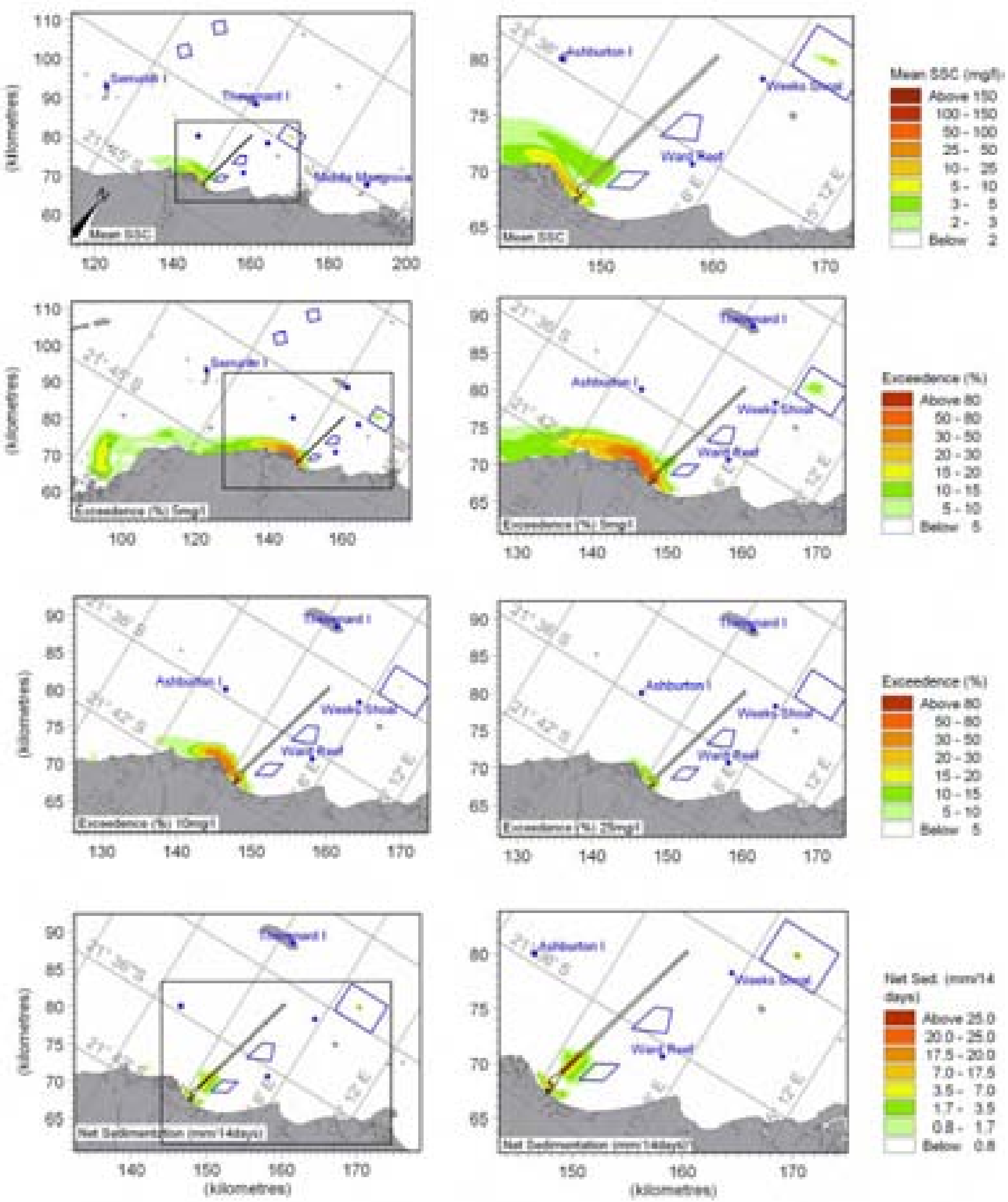

Figure Y.7 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 3

Y.5 Results for High (Worst Case) Spill Rates

Dredge Scenario:	Scenario 3
Climatic Scenario:	Summer A
Spill Rate Estimate:	High (“Worst Case”)

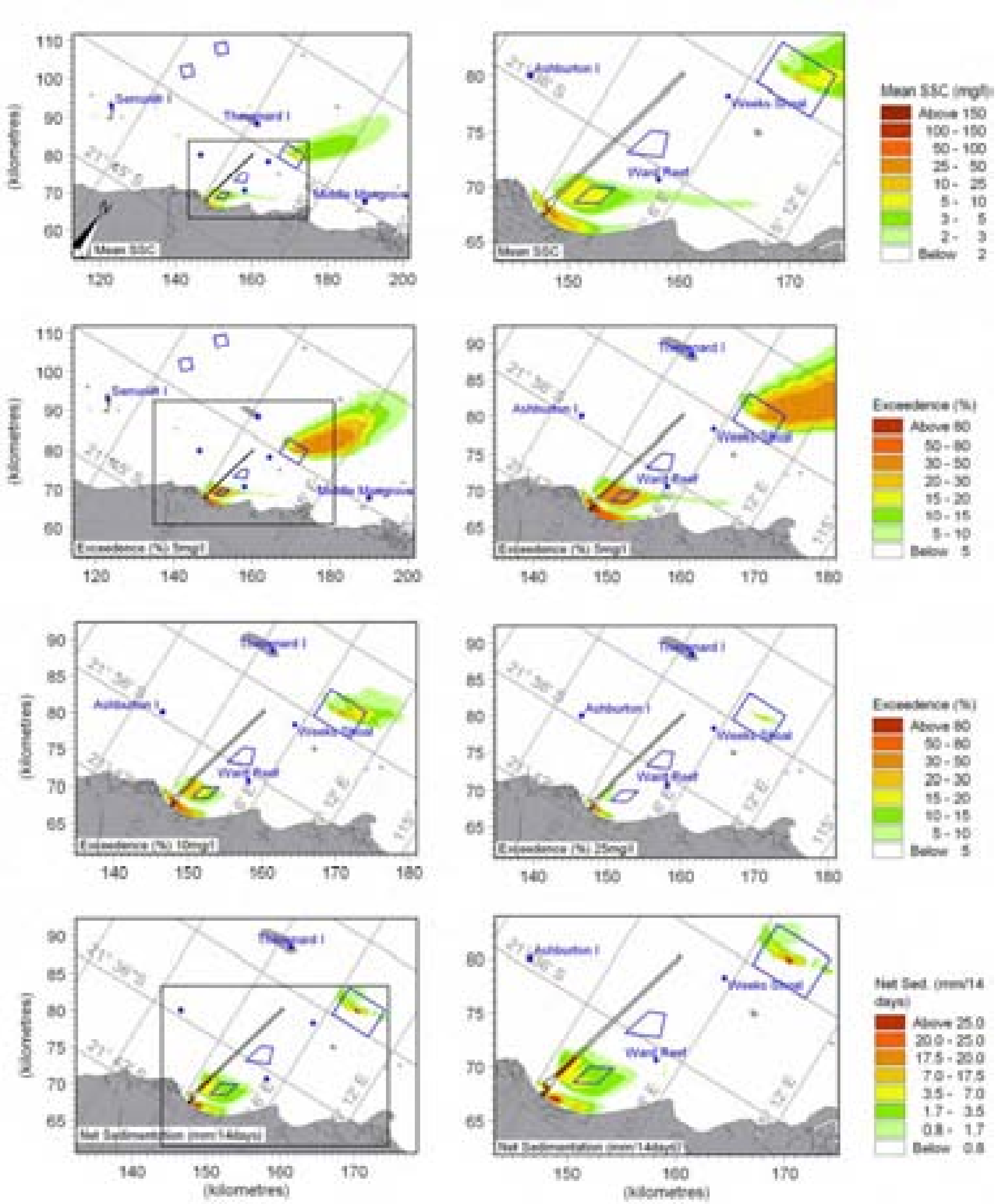

Figure Y.8 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 3

Y-10

Dredge Scenario: Scenario 3
Climatic Scenario: Summer B
Spill Rate Estimate: High ("Worst Case")

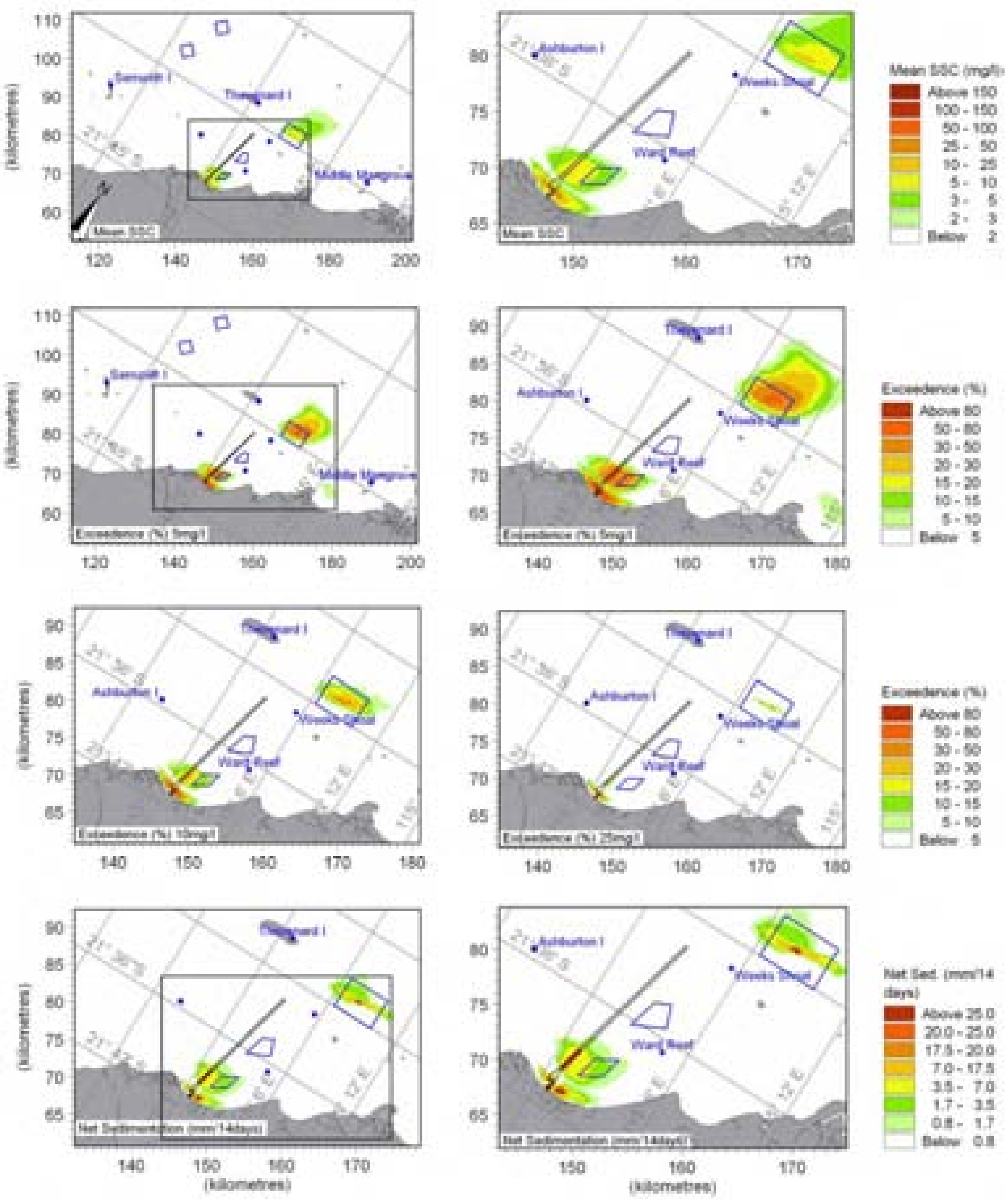

Figure Y.9 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 3*

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Y-11

Dredge Scenario: Scenario 3
Climatic Scenario: Transitional A
Spill Rate Estimate: High ("Worst Case")

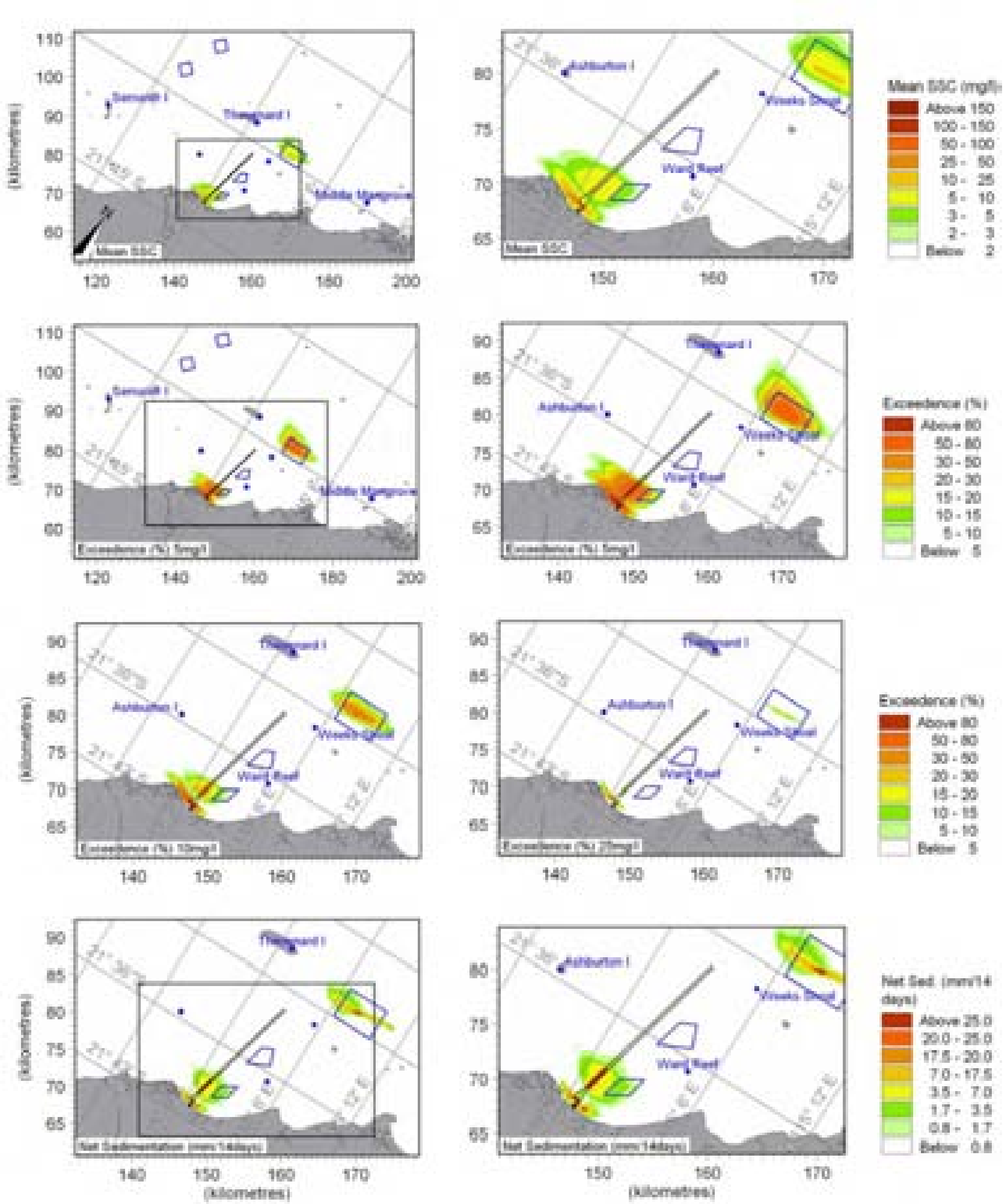

Figure Y.10 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 3*

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Y-12

Dredge Scenario: Scenario 3
Climatic Scenario: Transitional B
Spill Rate Estimate: High ("Worst Case")

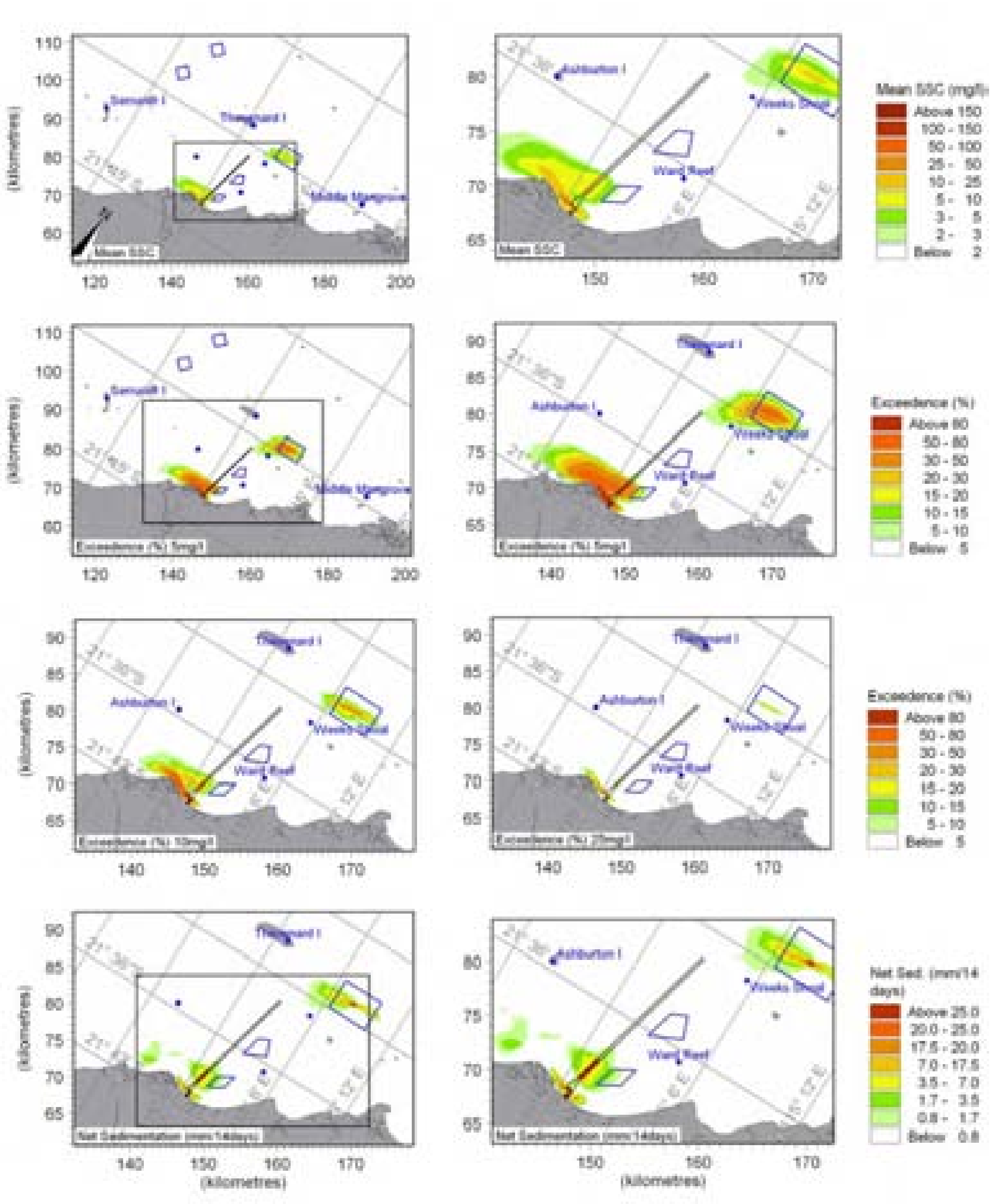

Figure Y.11 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 3*

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Y-13

Dredge Scenario: Scenario 3
Climatic Scenario: Winter A
Spill Rate Estimate: High ("Worst Case")

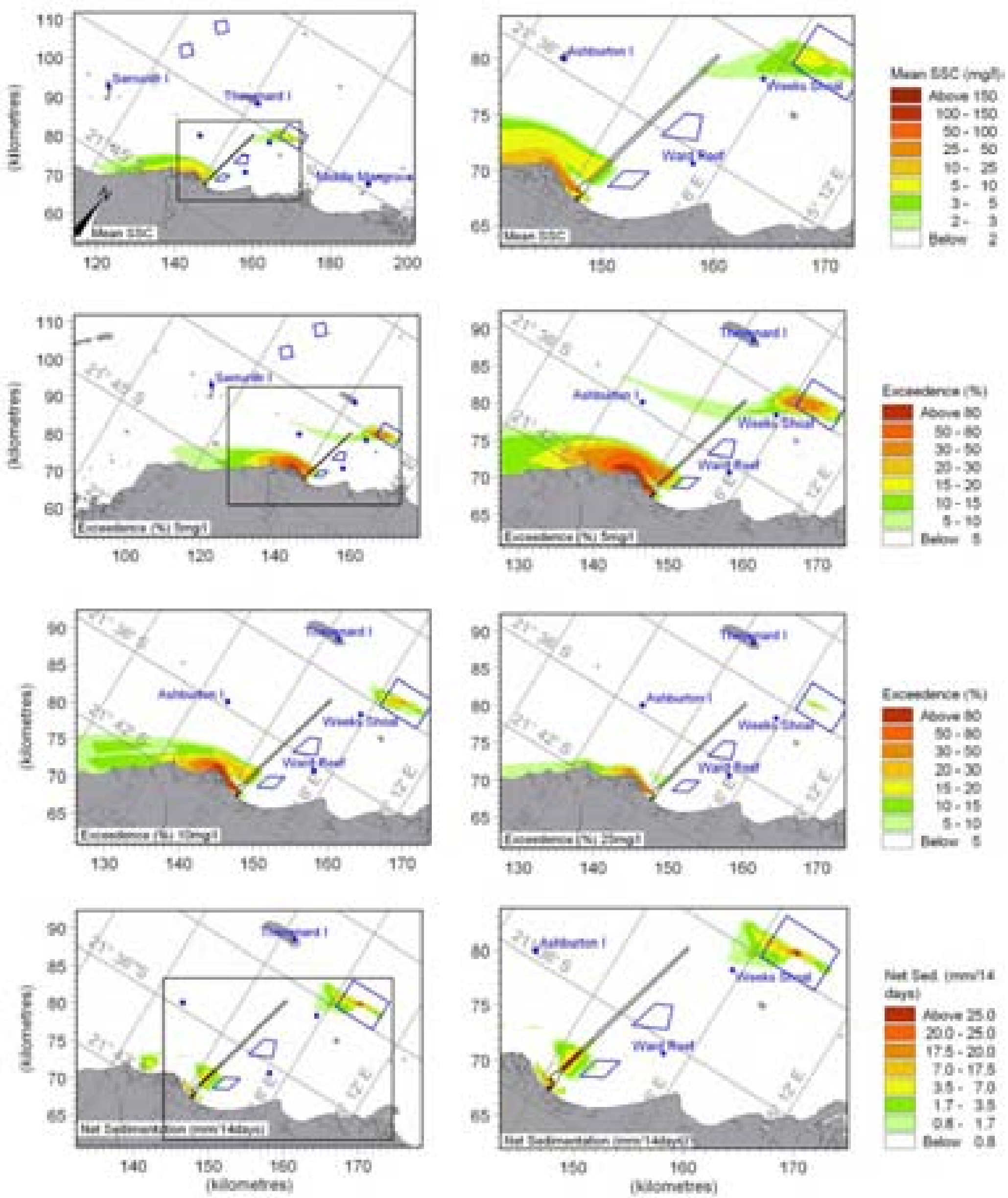

Figure Y.12 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 3*

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Y-14

Dredge Scenario: Scenario 3
Climatic Scenario: Winter B
Spill Rate Estimate: High ("Worst Case")

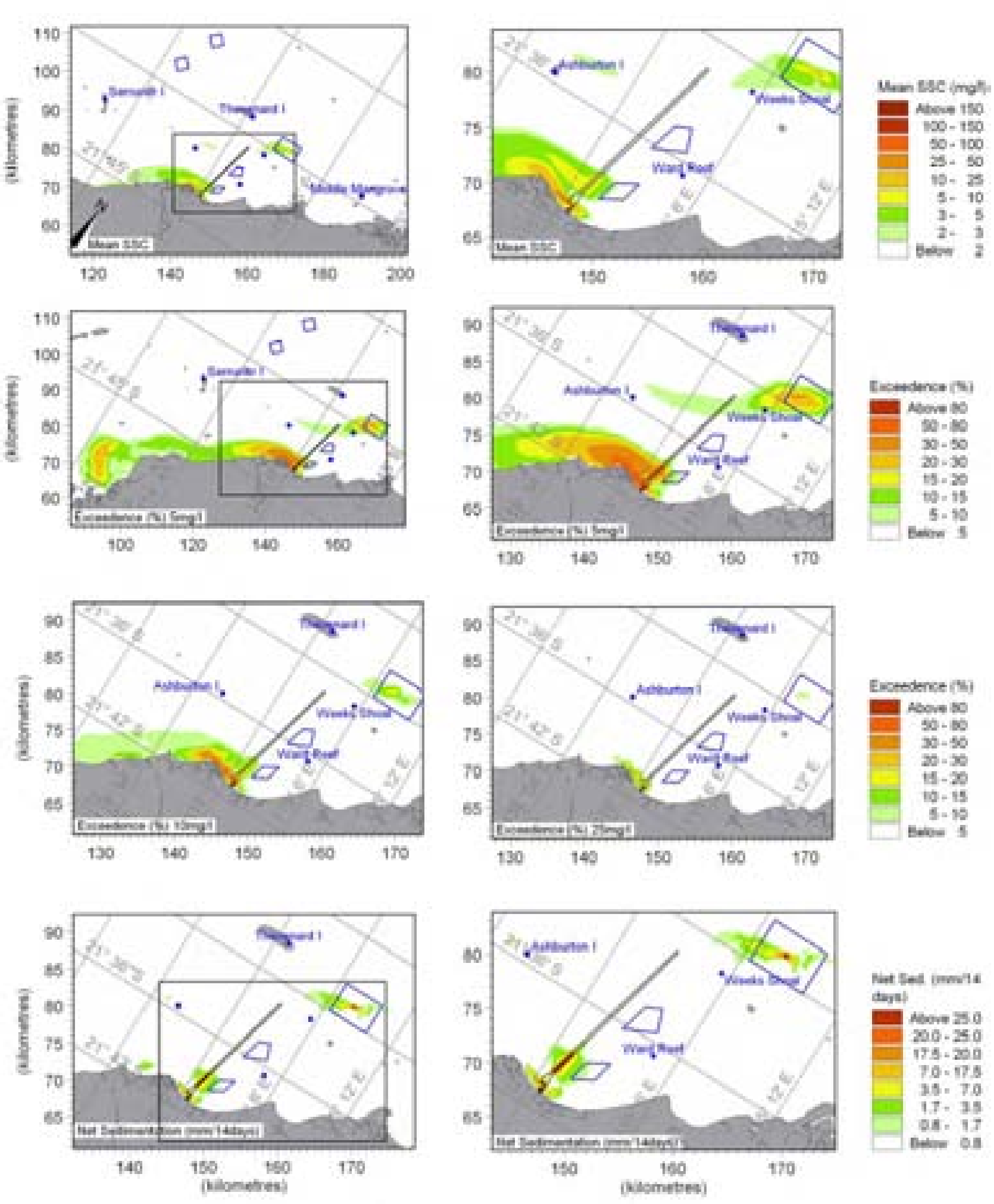

Figure Y.13 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario*

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Results for Dredge Scenario 4 Based on MesoLAPS Winds

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FIGURES AND TABLES

Z RESULTS FOR DREDGE SCENARIO 4 BASED ON MESOLAPS WINDS

This appendix presents results from the sediment transport model based on hydrodynamics driven by the MesoLAPS wind fields. The reader is referred to the following sections of the main report and additional appendices for further information;

- Section 4.1.3.2 *Wind Fields*
- Section 6.2 *Results for the Dredging of the Shipping Channel*
- Appendix D *Hydrodynamic Model Validation and Calibration*

Z.1 Statistical Plots

The established impact criteria (DHI (2010) *Dredge Plume Impact Assessment Report)* are based on sediment loads, both in terms of excess suspended concentrations and sedimentation rates, over 14 day periods. In terms of exposure and impacts, both the concentrations and the duration of the event is important, which is expressed through the exceedence probability of given limits.

For each simulated case, a set of plots showing the statistical output used in the impact assessment have been produced. All plots are for excess concentrations, i.e. sediments originating from the dredging operations and exclusive of ambient concentrations.

Each mosaic plot comprises:

- Mean excess concentration at two scales
- Exceedence of 5mg/l excess concentration at two scales
- Exceedence of 10mg/l excess concentration
- Exceedence of 25mg/l excess concentration
- Net sedimentation rates at two zoomed levels at the site

Note that all concentrations are presented as depth-averaged values. All values are derived over the assessment period (2^{nd} neap/spring tidal cycle of the month for each climatic scenario), i.e. after at least 14 days warm-up period. Exceedences are expressed in percentage time over the assessment period that the exceedence limit is exceeded.

Z.2 Description of Dredge Scenario 4

Nearshore Dredging: PLF Basin – weak rock

- 10,000m^3 TSHD in PLF
- Disposal at Site C
- Bathymetry with fully dredged MOF and MOF channel, partly dredged PLF basin to -12m LAT
- Material available for suspension in dredged channel
- Include MOF dredged basin and MOF breakwaters.

Offshore Dredging: Approach Channel – Section 1 sand

- 10,000m^3 TSHD with disposal at placement Site C
- Dredging along Section 1

- Partly dredged approach channel along entire length
- Material available for re-suspension along channel and in placement Sites A and C

The locations for the various dredge and placement activities are outlined in Figure Z.1, while defined low (realistic) and high (worst-case) spill rates applied in Dredging Scenario 3 are listed in Table 3.2 of the man report.

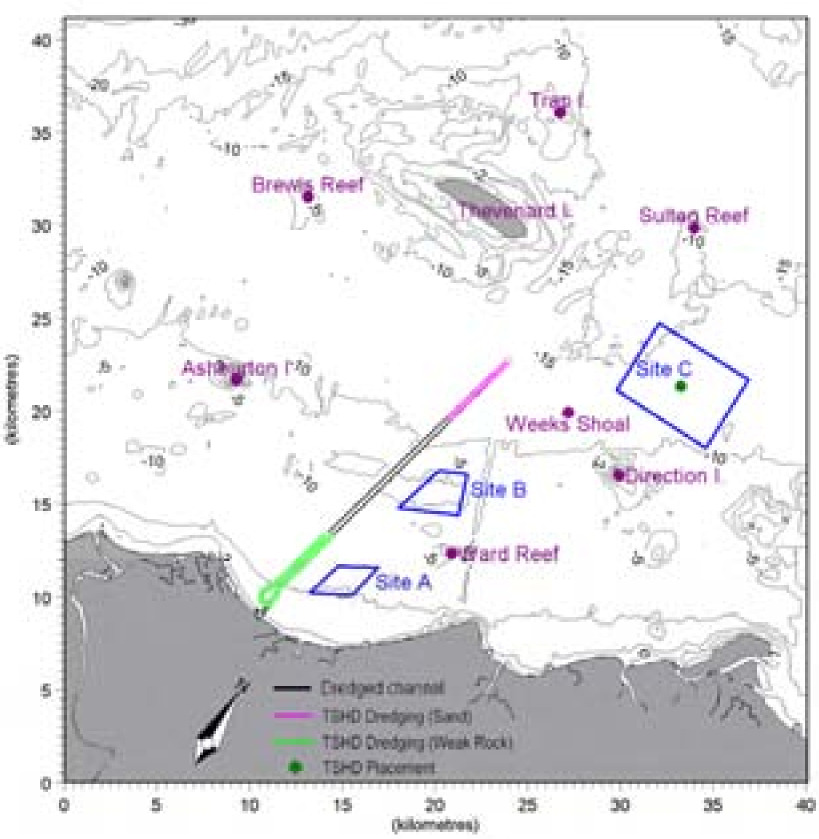

Figure Z.1 Sketch of locations for Dredging Scenario 4.

Z.3 Summary of Results

Specific observations for Dredge Scenario 4 include:

- The plumes from the 10,000m^3 TSHD dredging weak rock in the PLF are much lower in concentration than the corresponding plume dredging in sand at Section 1.
- The plumes from the TSHD dredging at Section 1 combines with the plumes generated from the placement at Site C.
- The plumes from Placement Site C are much less intense than for Scenario 4 due to the lower total production (and dumping) rates.
- The PLF dredging generates a plume that runs along the coastline in a predominantly easterly direction during summer and westerly direction during winter.

- As the weak rock dredging stretches out into Section 4, the nearshore plume tends to split into a component running along the coastline and a component separating from the coastline.
- The plume generated from Section 5 of the PLF / PLF Approach channel skirts Ward Reef to the south.

Z.4 Results for Low (Realistic) Spill Rates

Dredge Scenario: Scenario 4
Climatic Scenario: Summer A
Spill Rate Estimate: Low ("Realistic") Case

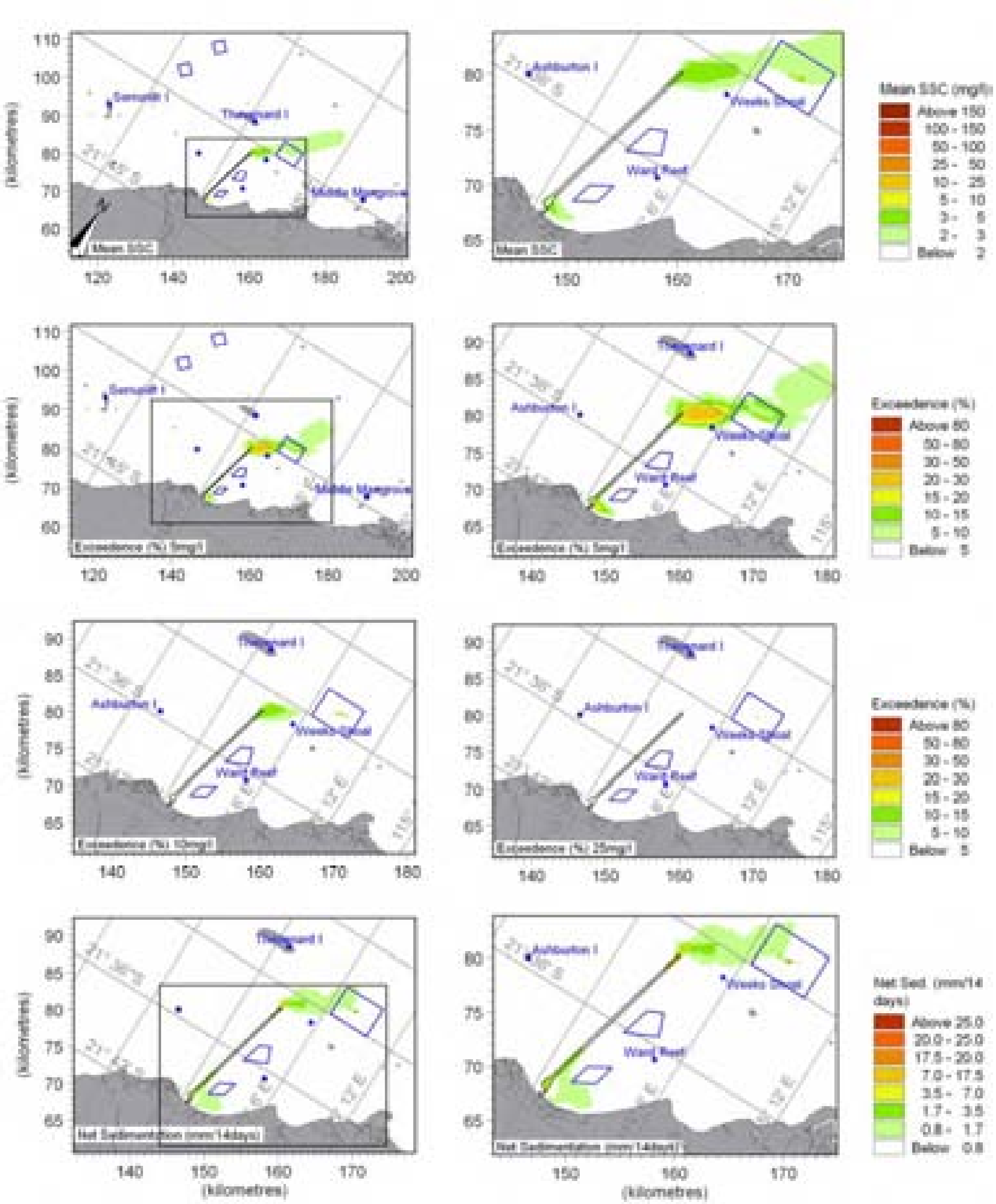

Figure Z.2 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 4*

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Z-5

Dredge Scenario:	Scenario 4
Climatic Scenario:	Summer B
Spill Rate Estimate:	Low ("Realistic") Case

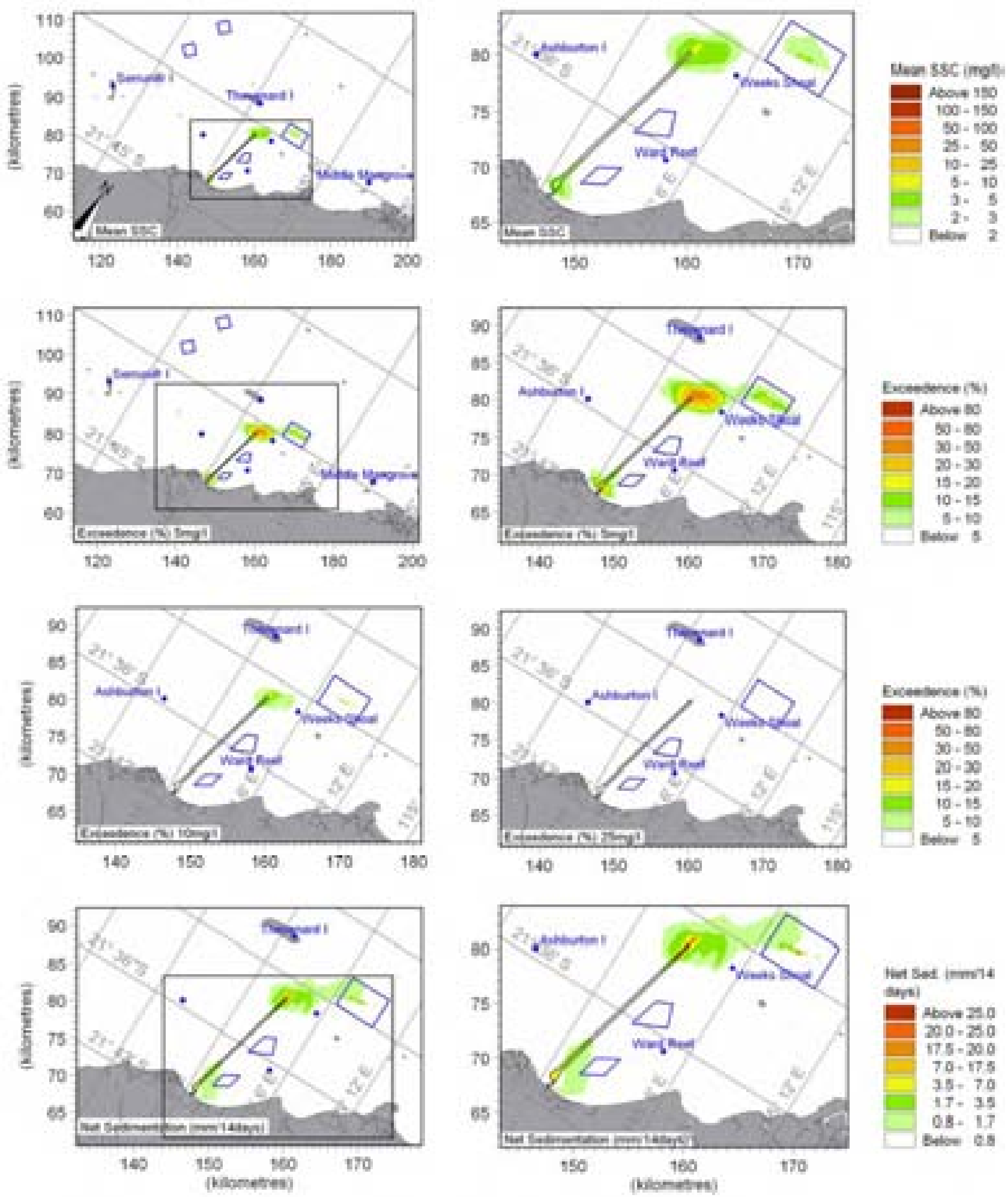

Figure Z.3 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 4

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Z-6

Dredge Scenario: Scenario 4
Climatic Scenario: Transitional A
Spill Rate Estimate: Low ("Realistic") Case

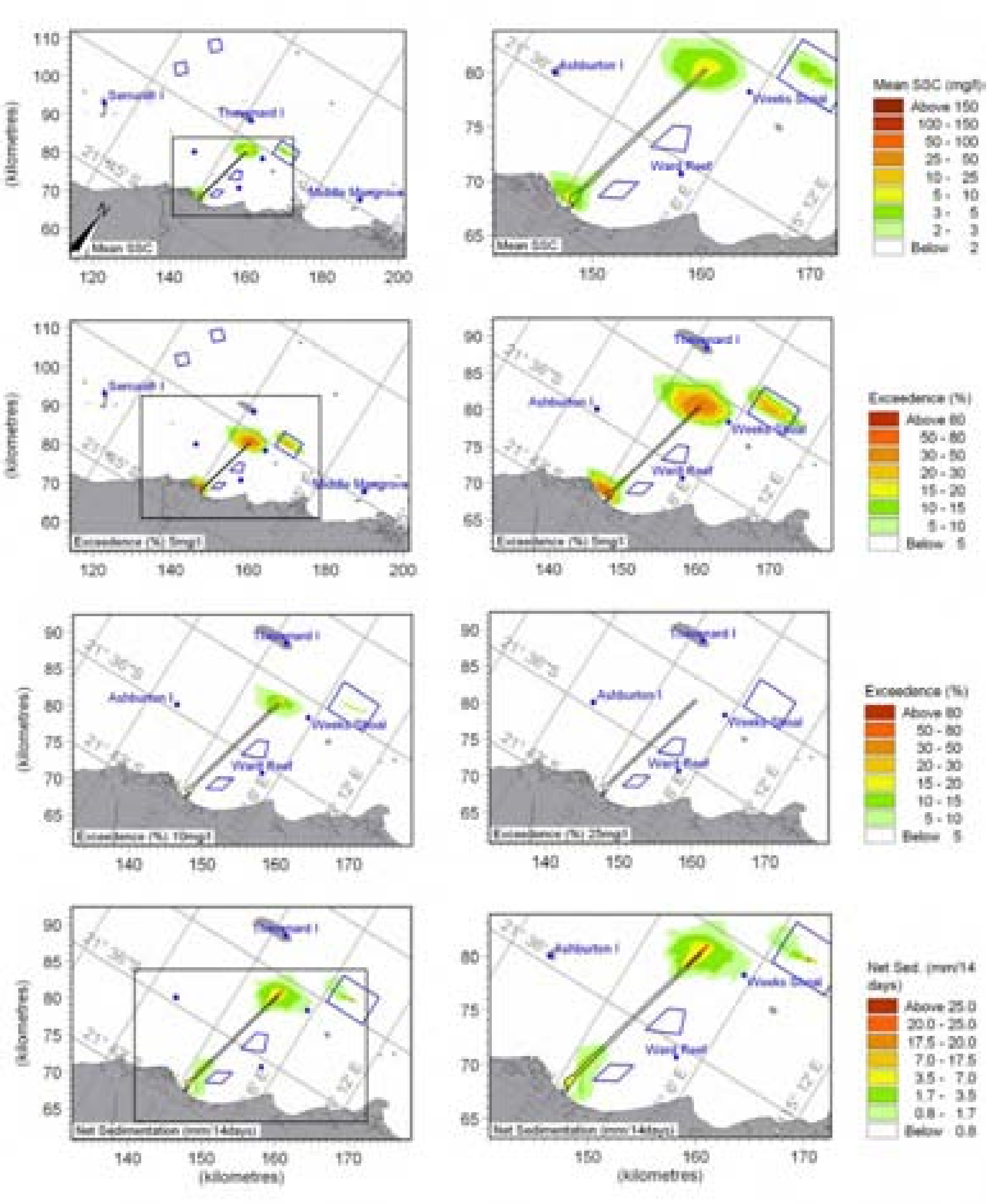

Figure Z.4 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 4*

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Z-7

Dredge Scenario: Scenario 4
Climatic Scenario: Transitional B
Spill Rate Estimate: Low ("Realistic") Case

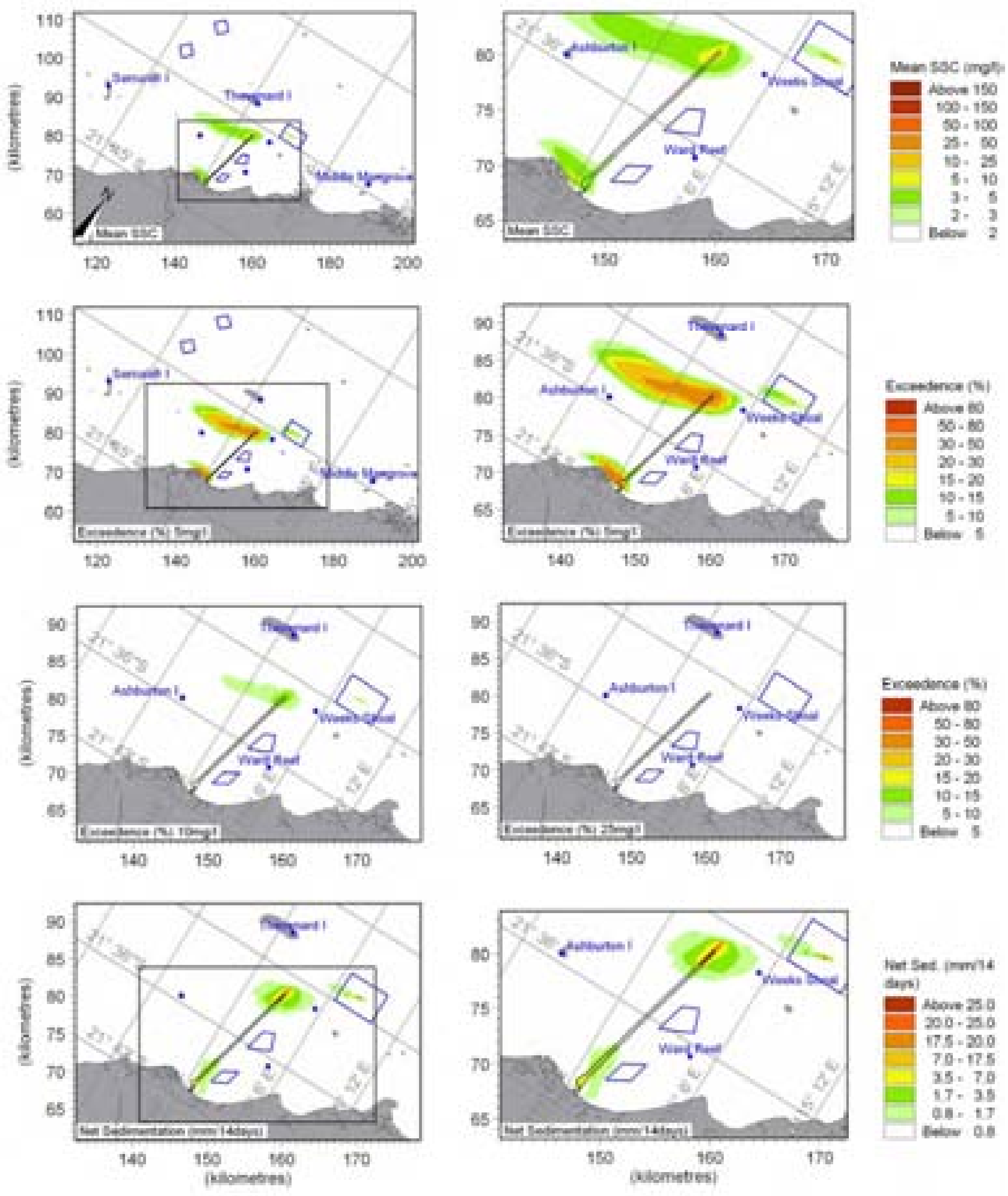

Figure Z.5 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 4

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Dredge Scenario: Scenario 4
Climatic Scenario: Winter A
Spill Rate Estimate: Low ("Realistic") Case

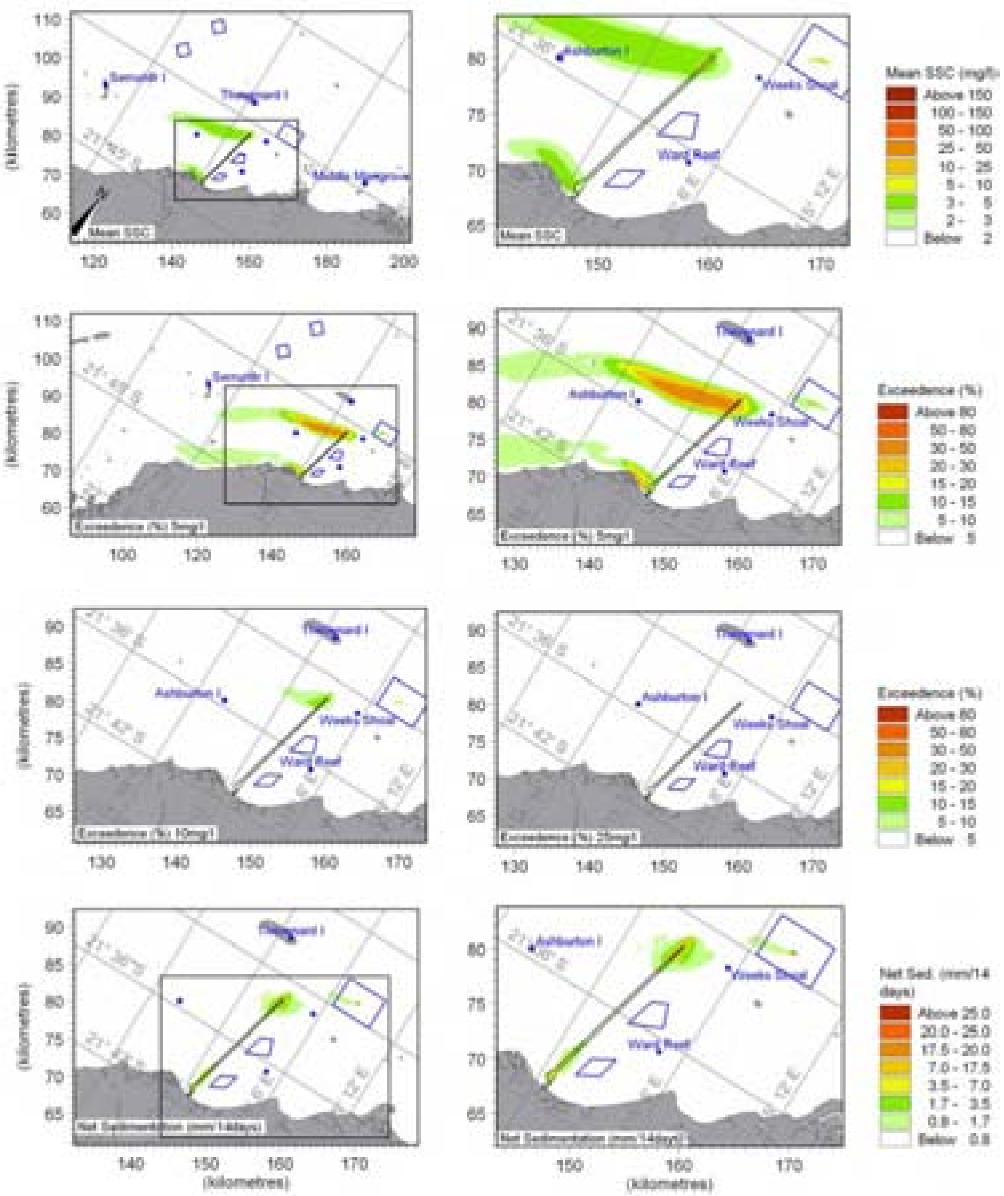

Figure Z.6 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 4*

Dredge Scenario: Scenario 4
Climatic Scenario: Winter B
Spill Rate Estimate: Low ("Realistic") Case

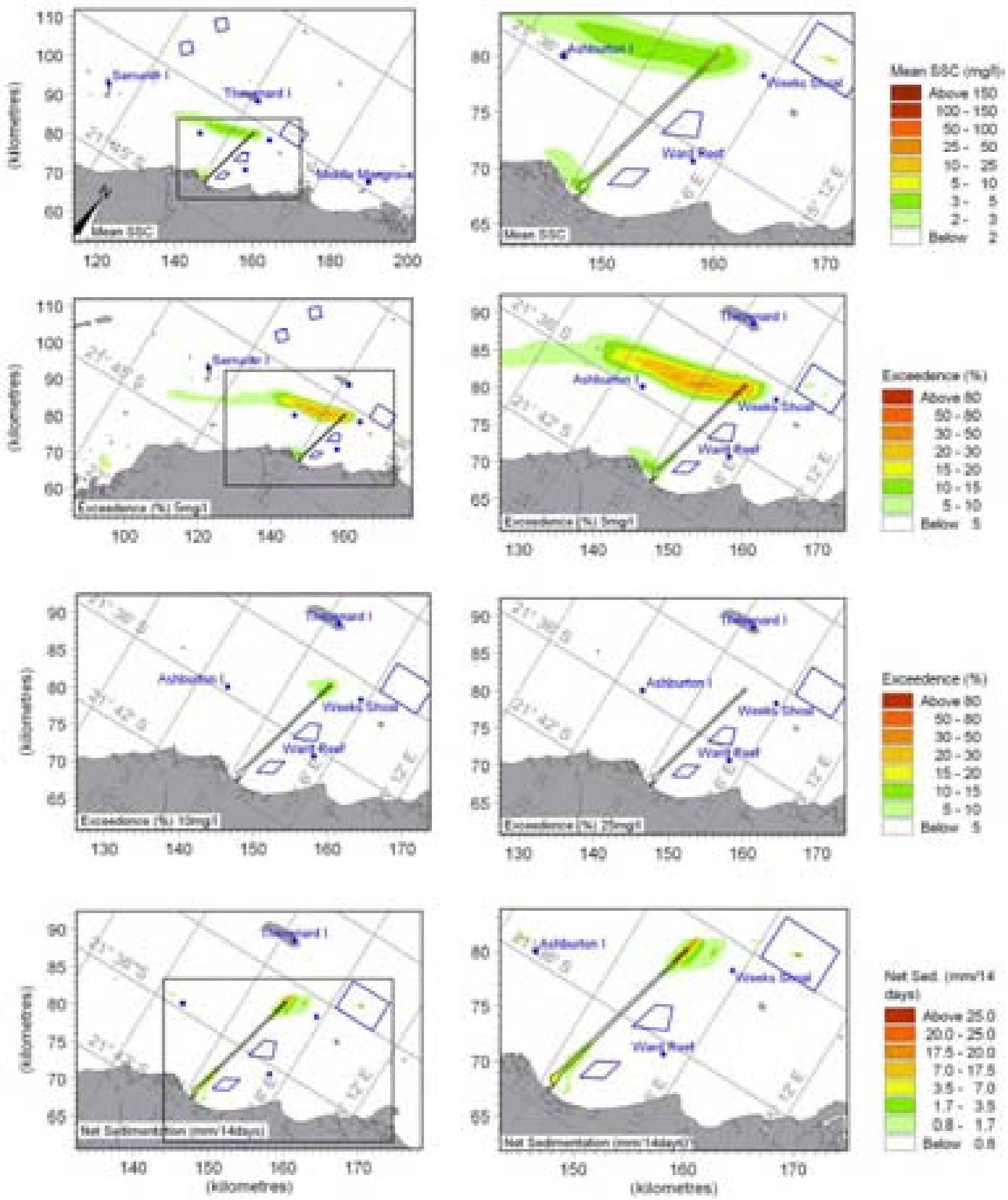

Figure Z.7 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 4*

Z.5 Results for High (Worst-Case) Spill Rates

Dredge Scenario: Scenario 4
Climatic Scenario: Summer A
Spill Rate Estimate: High ("Worst Case")

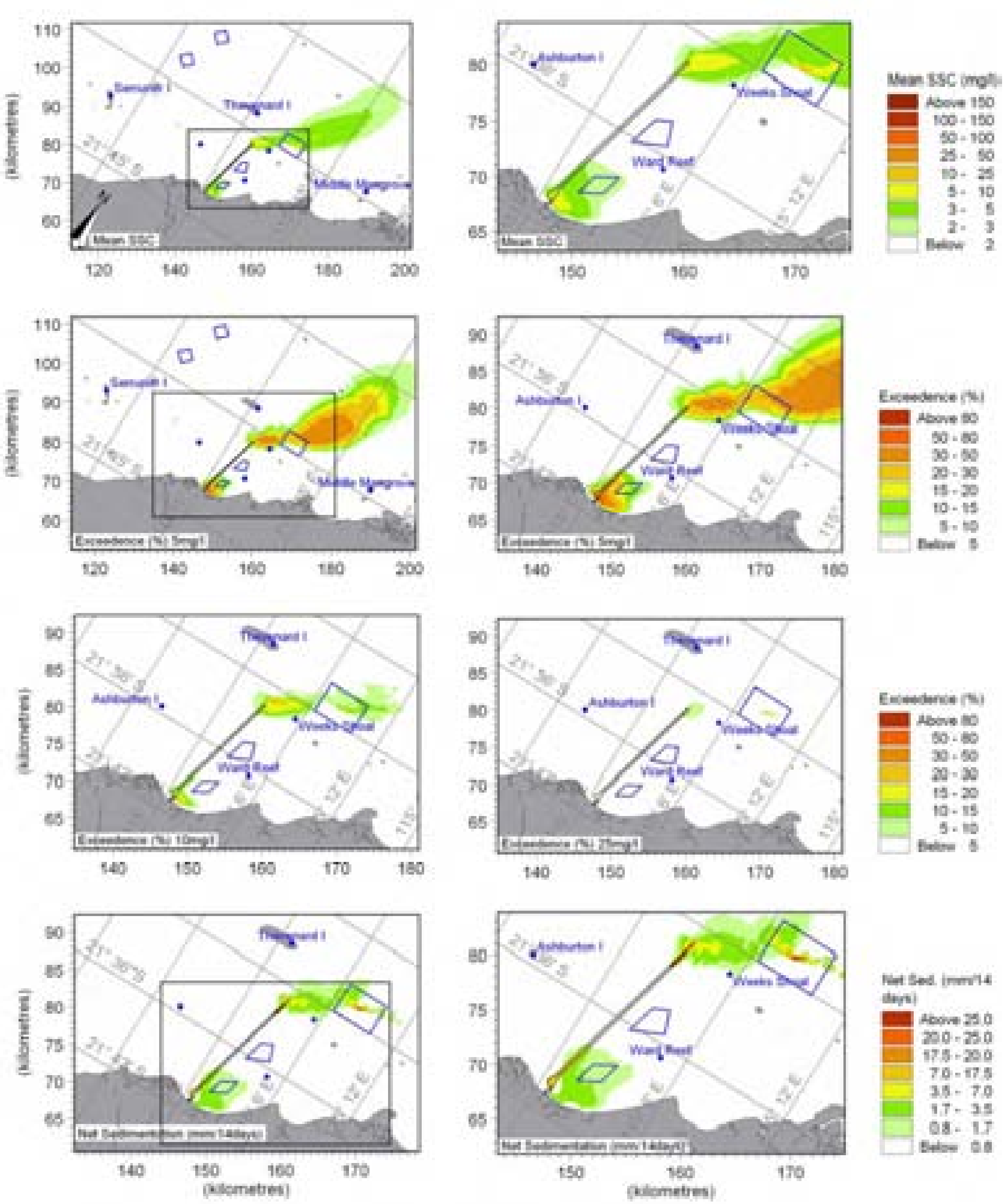

Figure Z.8 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 4

Z-11

Dredge Scenario: Scenario 4
Climatic Scenario: Summer B
Spill Rate Estimate: High ("Worst Case")

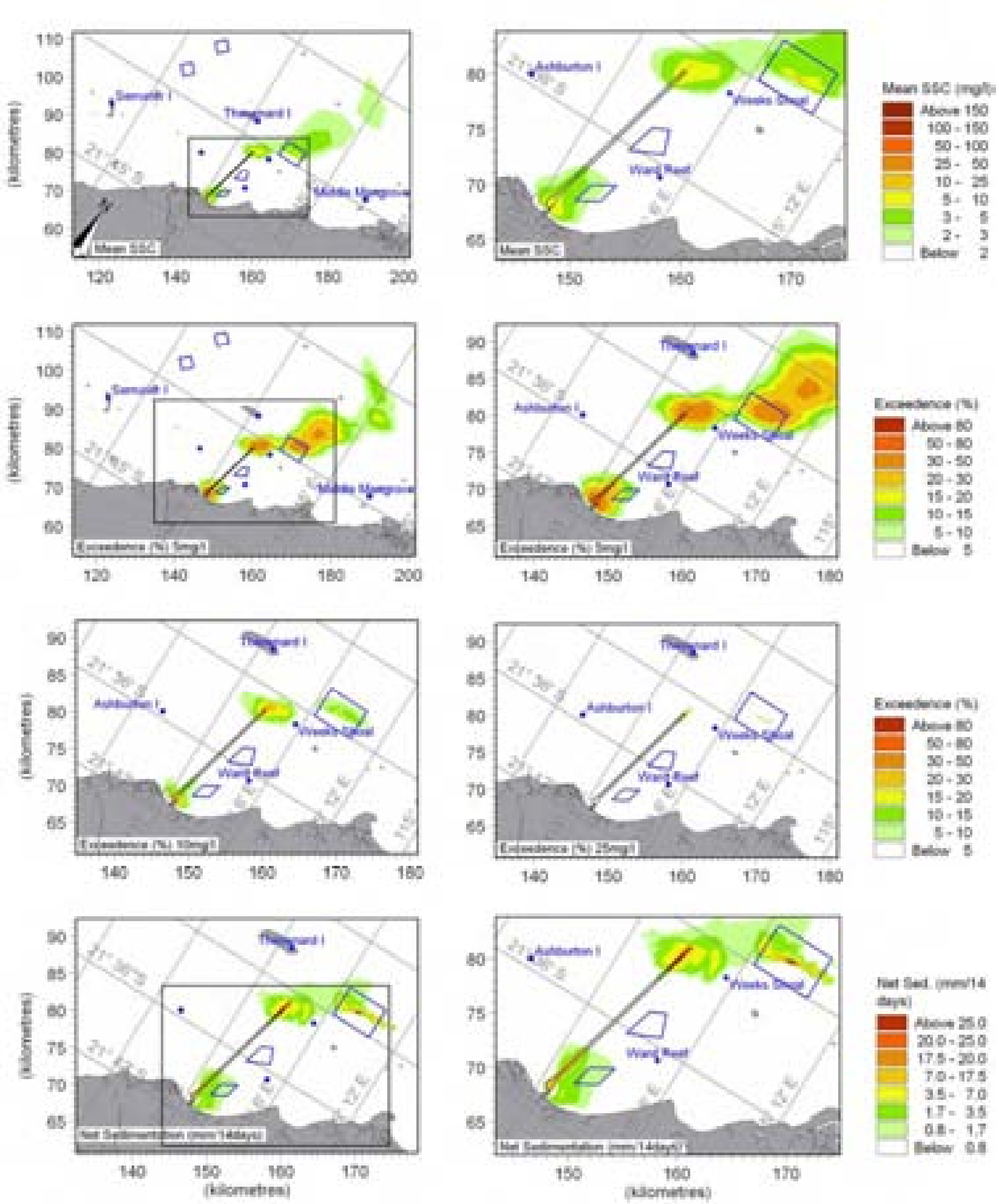

Figure Z.9 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 4*

DHI Water & Environment

Dredge Scenario: Scenario 4
Climatic Scenario: Transitional A
Spill Rate Estimate: High ("Worst Case")

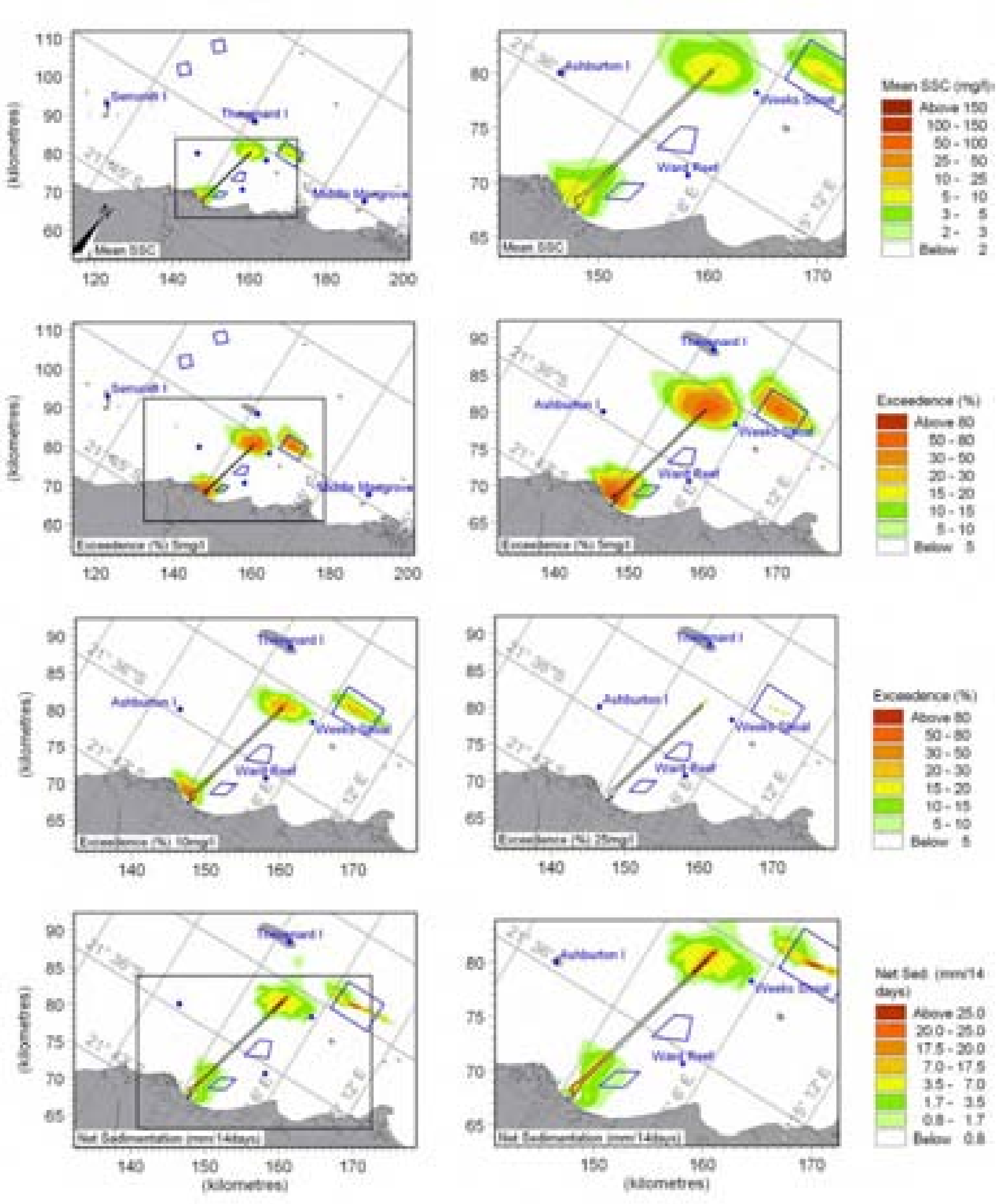

Figure Z.10 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 4

Z-13

Dredge Scenario: Scenario 4
Climatic Scenario: Transitional B
Spill Rate Estimate: High ("Worst Case")

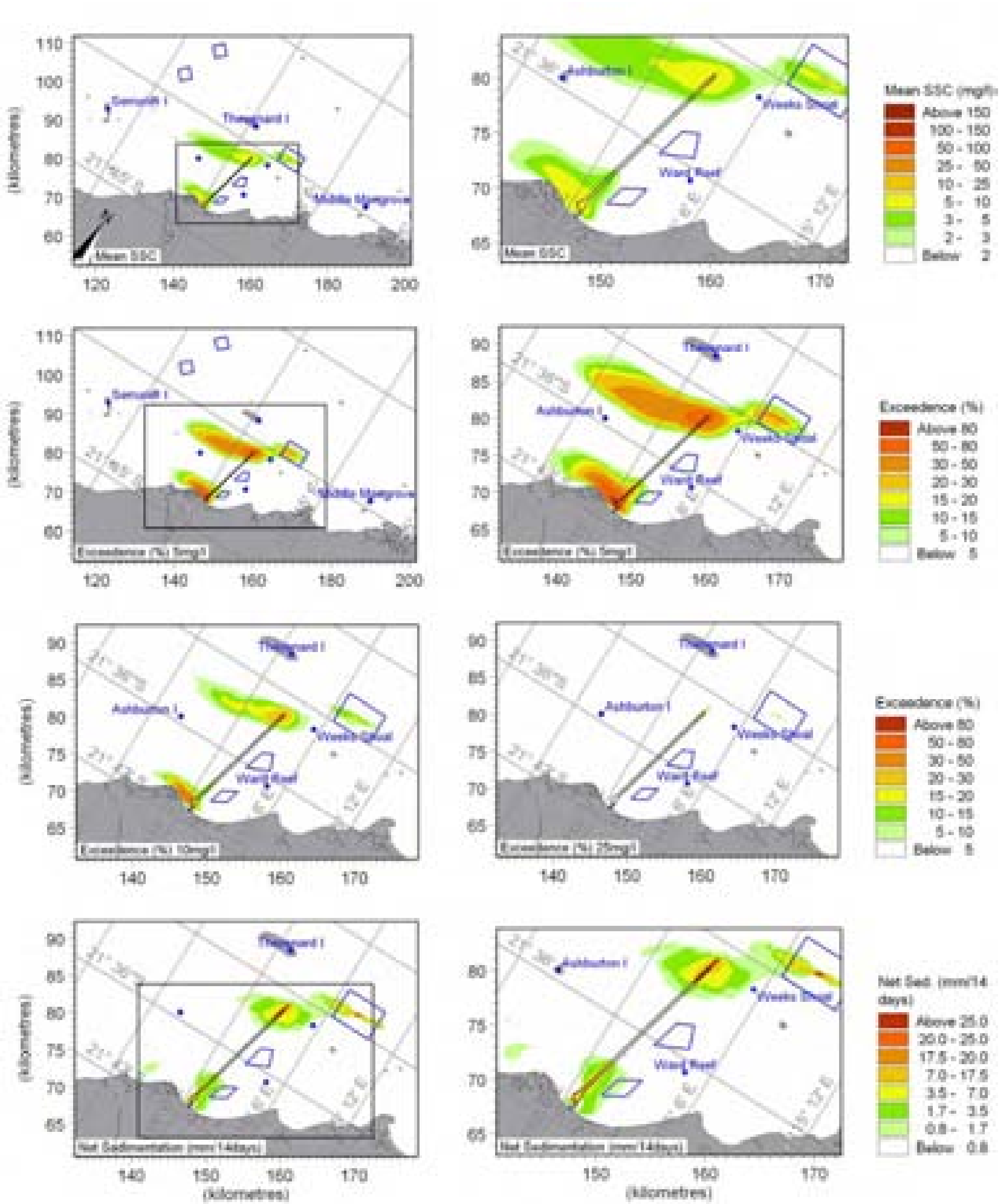

Figure Z.11 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 4

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Z-14

Dredge Scenario: Scenario 4
Climatic Scenario: Winter A
Spill Rate Estimate: High ("Worst Case")

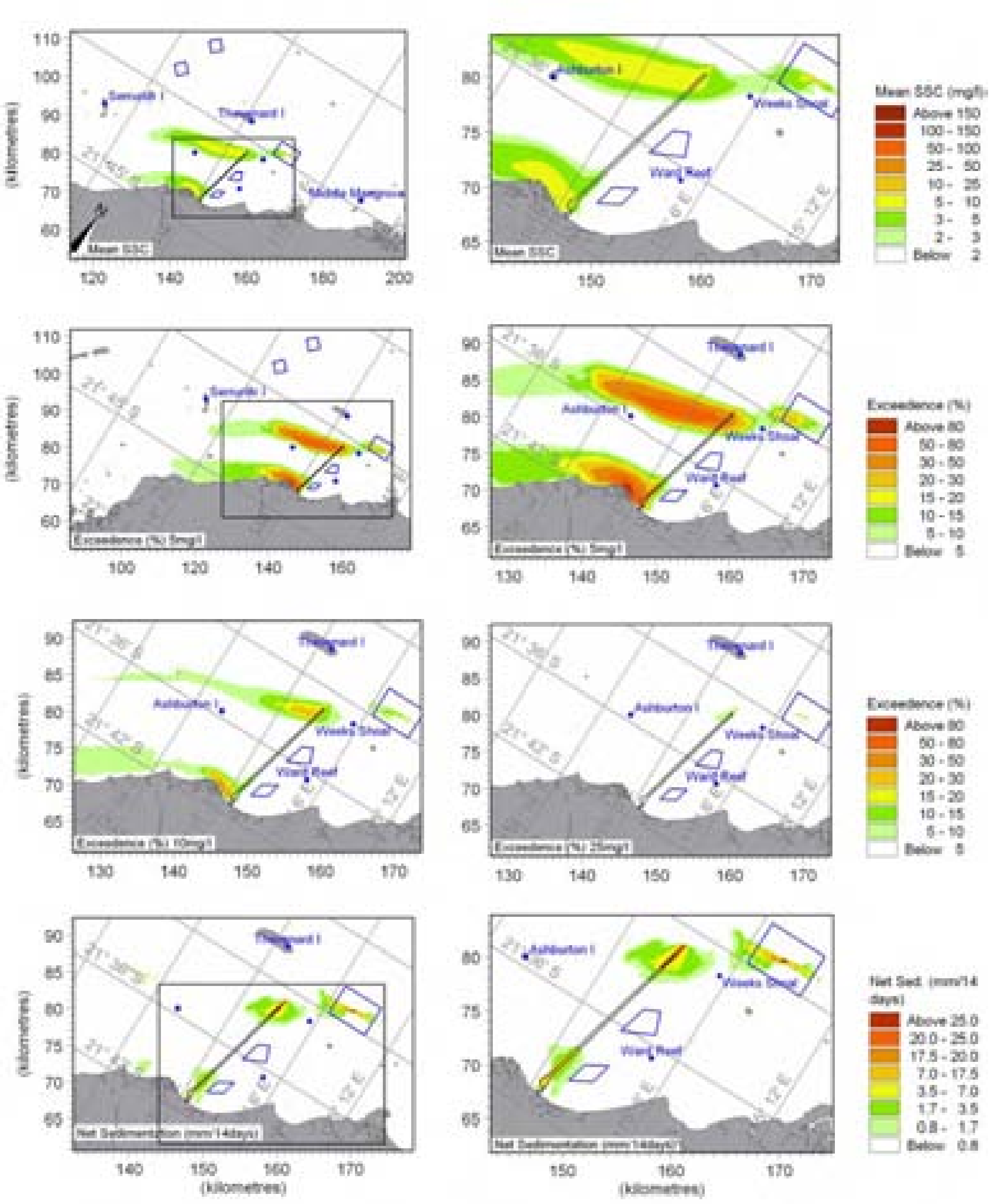

Figure Z.12 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 4

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Z-15

Dredge Scenario: Scenario 4
Climatic Scenario: Winter B
Spill Rate Estimate: High ("Worst Case")

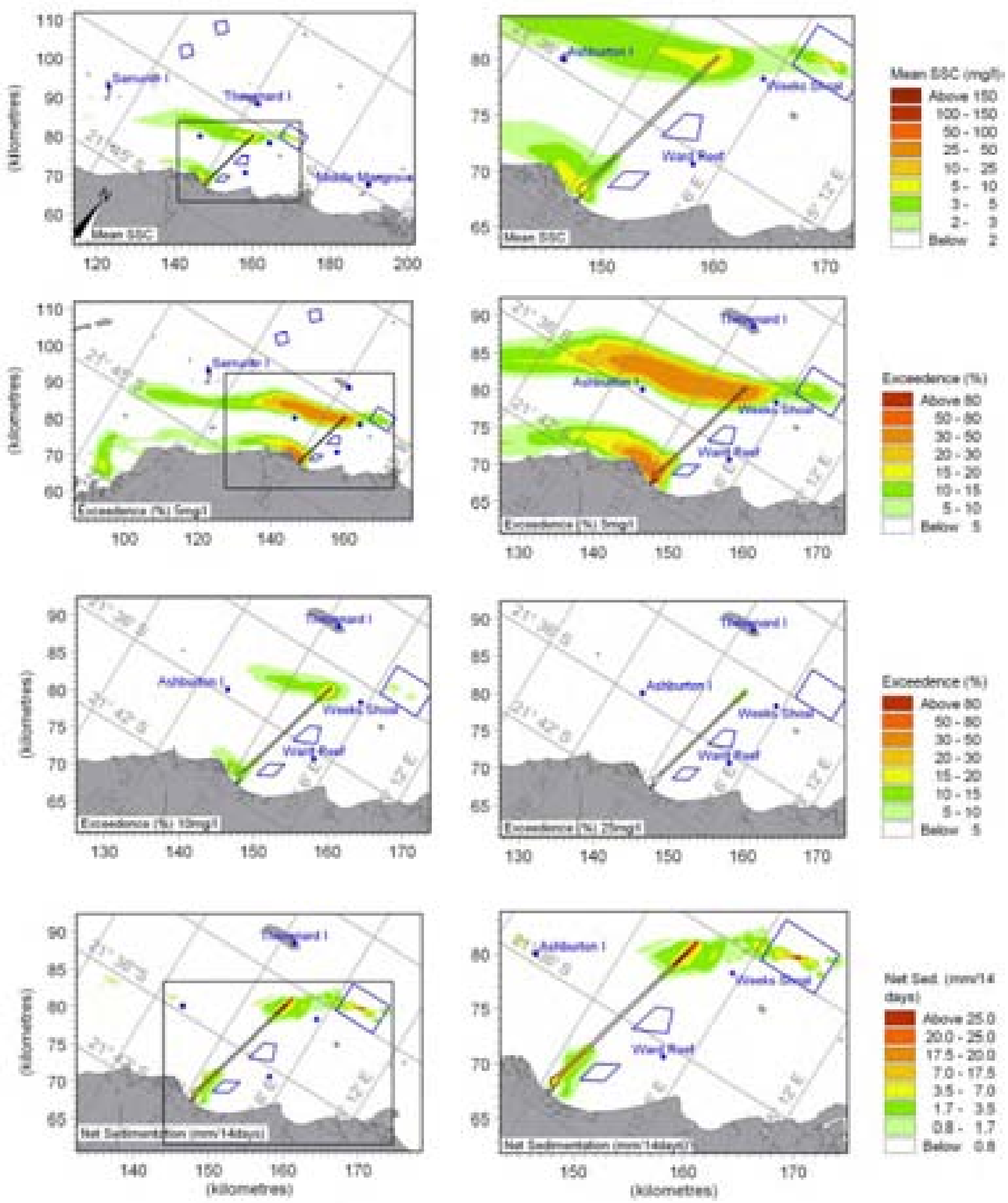

Figure Z.13 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 4*

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Wheatstone Project
Dredge Spoil Modelling

A P P E N D I X   A A :

Results for Dredge Scenario 5 Based on MesoLAPS Winds

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FIGURES AND TABLES

AA RESULTS FOR DREDGE SCENARIO 5 BASED ON MESOLAPS WINDS

This appendix presents results from the sediment transport model based on hydrodynamics driven by the MesoLAPS wind fields. The reader is referred to the following sections of the main report and additional appendices for further information;

- Section 4.1.3.2 *Wind Fields*
- Section 6.2 *Results for the Dredging of the Shipping Channel*
- Appendix D *Hydrodynamic Model Validation and Calibration*

AA.1 Statistical Plots

The established impact criteria (DHI (2010) *Dredge Plume Impact Assessment Report)* are based on sediment loads, both in terms of excess suspended concentrations and sedimentation rates, over 14 day periods. In terms of exposure and impacts, both the concentrations and the duration of the event is important, which is expressed through the exceedence probability of given limits.

For each simulated case, a set of plots showing the statistical output used in the impact assessment have been produced. All plots are for excess concentrations, i.e. sediments originating from the dredging operations and exclusive of ambient concentrations.

Each mosaic plot comprises:

- Mean excess concentration at two scales
- Exceedence of 5mg/l excess concentration at two scales
- Exceedence of 10mg/l excess concentration
- Exceedence of 25mg/l excess concentration
- Net sedimentation rates at two zoomed levels at the site

Note that all concentrations are presented as depth-averaged values. All values are derived over the assessment period (2^{nd} neap/spring tidal cycle of the month for each climatic scenario), i.e. after at least 14 days warm-up period. Exceedences are expressed in percentage time over the assessment period that the exceedence limit is exceeded.

AA.2 Description of Dredge Scenario 5

General

- Bathymetry with fully dredged MOF, MOF channel and PLF basin. Partly dredged approach channel along entire length
- Material available for resuspension along all dredged areas and in placement Sites A and C
- Include MOF dredged basin and MOF breakwaters.

Offshore Dredging 1: Approach Channel – Section 3 sand

- 10,000 m^3 TSHD with disposal at placement Site C
- Dredging along Section 3

Offshore Dredging 2: Approach Channel – weak rock

- 10,000 m^3 TSHD with disposal at placement Site C
- Dredging along Sections 1 & 2

The locations for the various dredge and placement activities are outlined in Figure AA.1, while defined low (realistic) and high (worst-case) spill rates applied in Dredging Scenario 3 are listed in Table 3.2 of the man report.

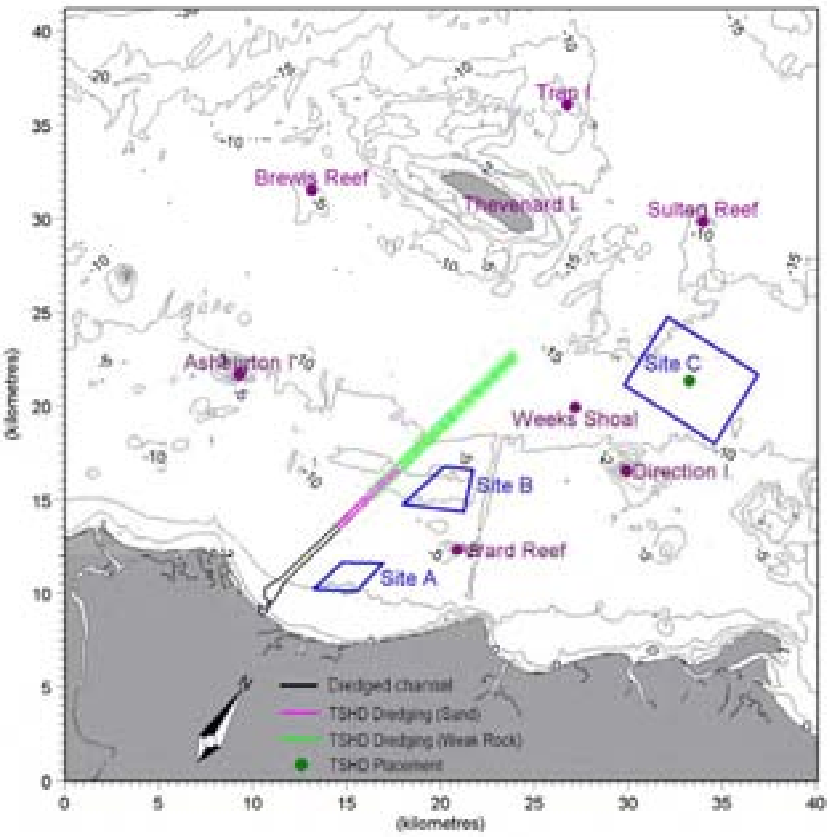

Figure AA.1 Sketch of locations for Dredging Scenario 5.

AA.3 Summary of Results

Specific observations for Dredge Scenario 5 include:

- The plumes from the 10,000m^3 TSHD dredging weak rock in the PLF channel are much lower in concentration than the corresponding plume dredging in sand at Section 3.
- The (lower concentration) plumes from the TSHD dredging at Sections 1 and 2 combine with the plumes generated from the sand dredging at Section 3 as well as the plumes from placement at Site C.
- The plume generated from Section 3 of the PLF Approach channel skirts Ward Reef on the northern side.
- The plume generated from Section 3 of the PLF Approach channel runs across Placement Site B.
- Ashburton Island is exposed to low concentration plumes during winter and some transitional conditions.

AA.4 Results for Low (Realistic) Spill Rates

Dredge Scenario:	Scenario 5
Climatic Scenario:	Summer A
Spill Rate Estimate:	Low ("Realistic") Case

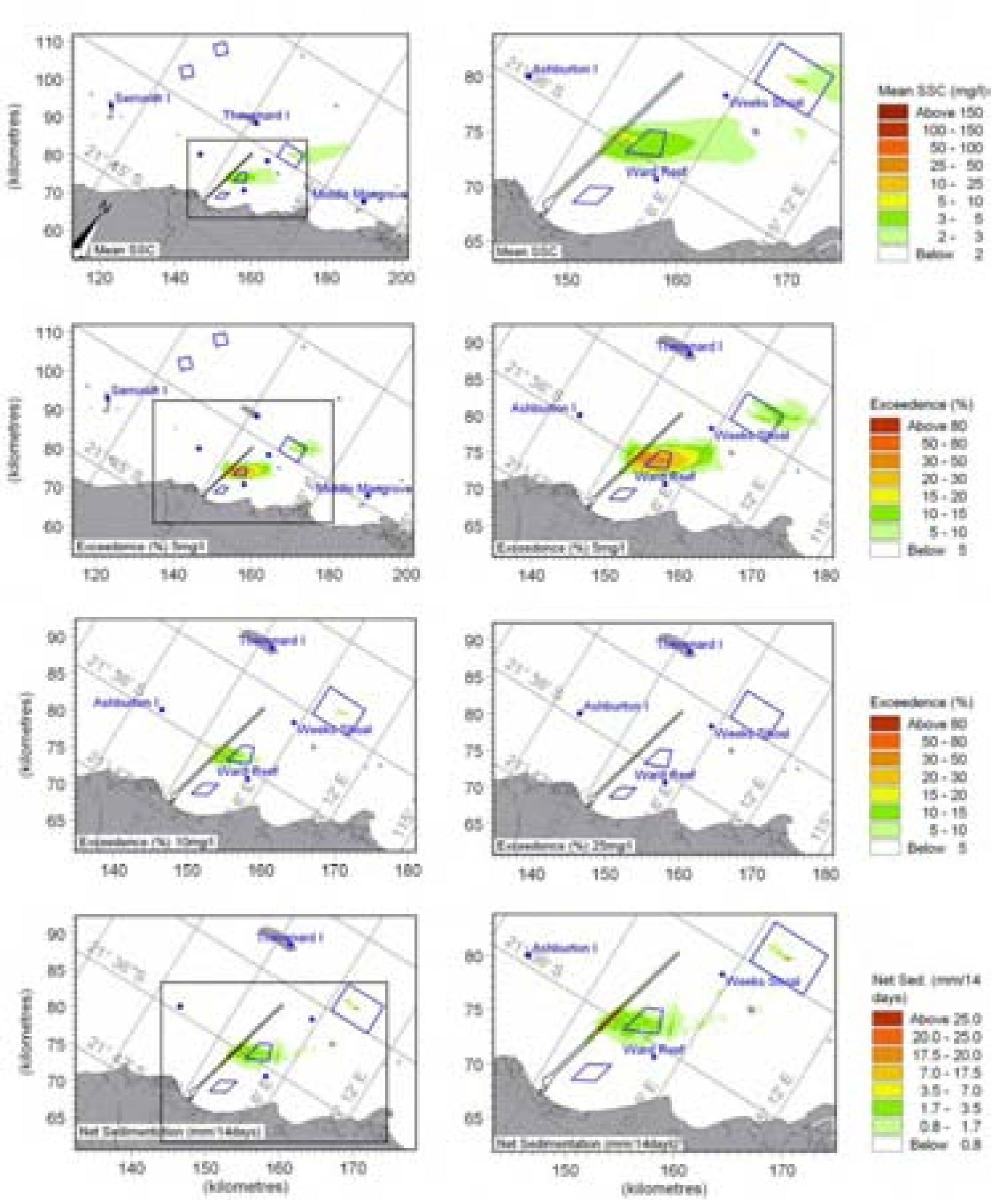

Figure AA.2 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 5

AA-4

Dredge Scenario: Scenario 5
Climatic Scenario: Summer B
Spill Rate Estimate: Low ("Realistic") Case

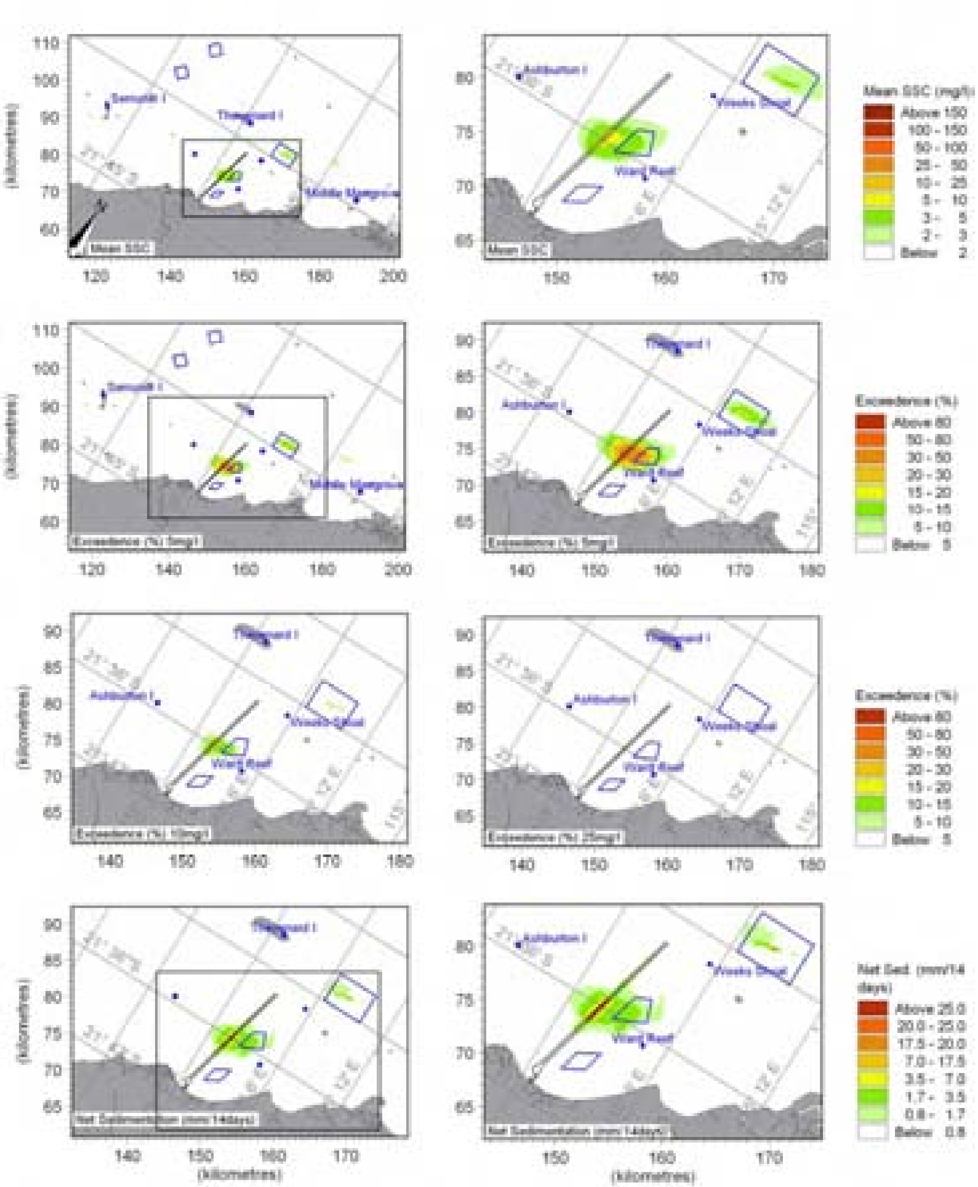

Figure AA.3 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 5

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AA-5

Dredge Scenario:	Scenario 5
Climatic Scenario:	Transitional A
Spill Rate Estimate:	Low ("Realistic") Case

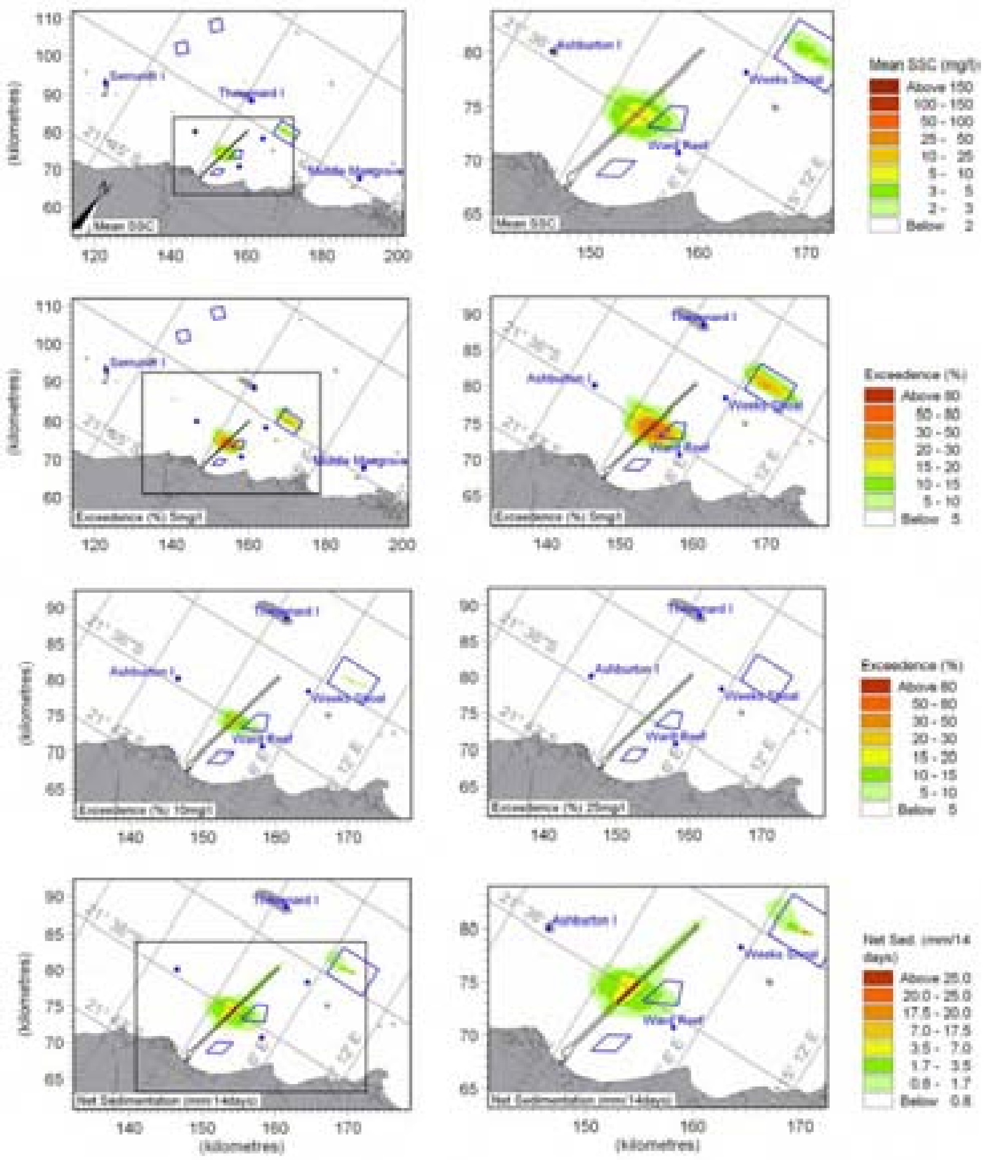

Figure AA.4 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 5

AA-6

Dredge Scenario: Scenario 5
Climatic Scenario: Transitional B
Spill Rate Estimate: Low ("Realistic") Case

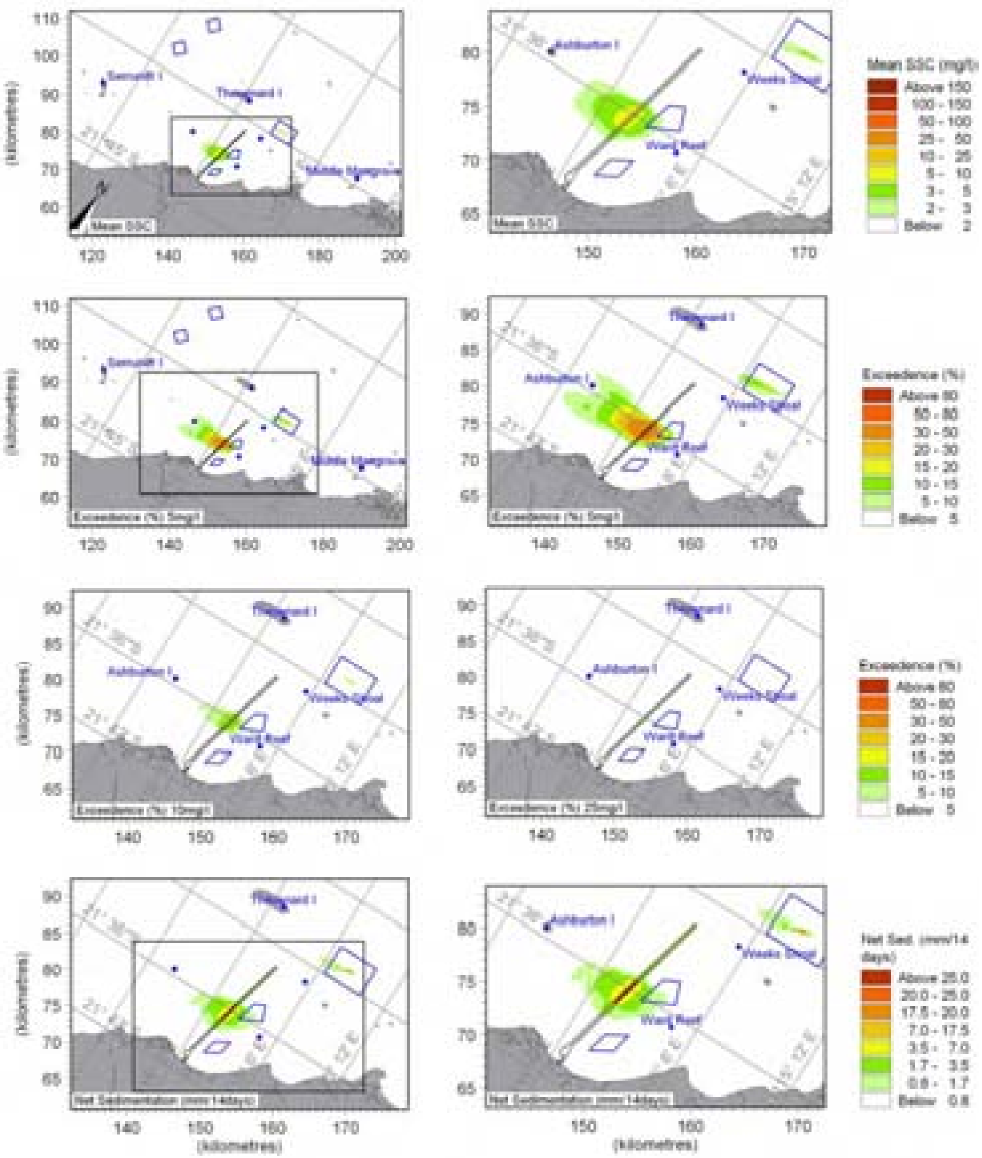

Figure AA.5 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 5

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AA-7

Dredge Scenario: Scenario 5
Climatic Scenario: Winter A
Spill Rate Estimate: Low ("Realistic") Case

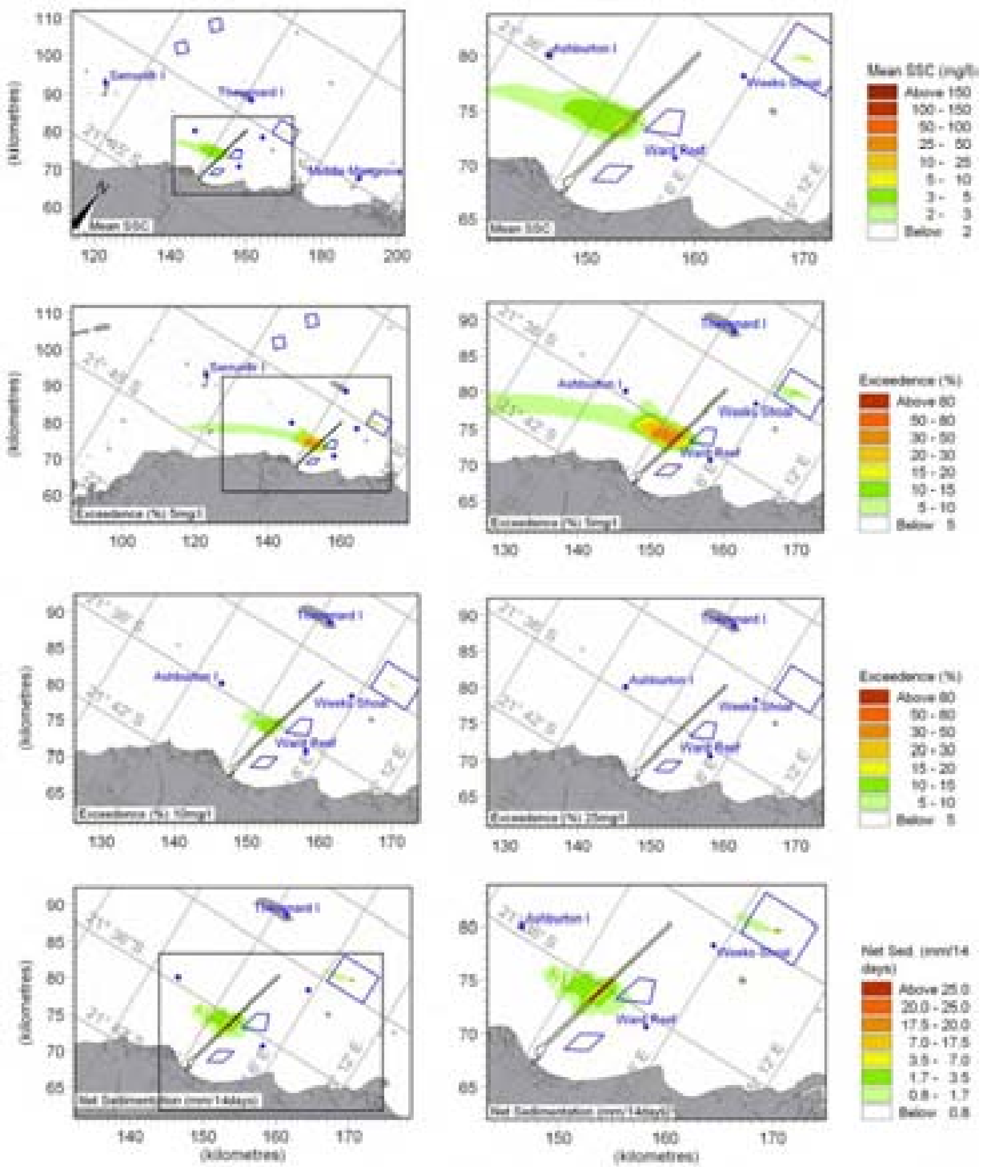

Figure AA.6 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 5

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AA-8

Dredge Scenario: Scenario 5
Climatic Scenario: Winter B
Spill Rate Estimate: Low ("Realistic") Case

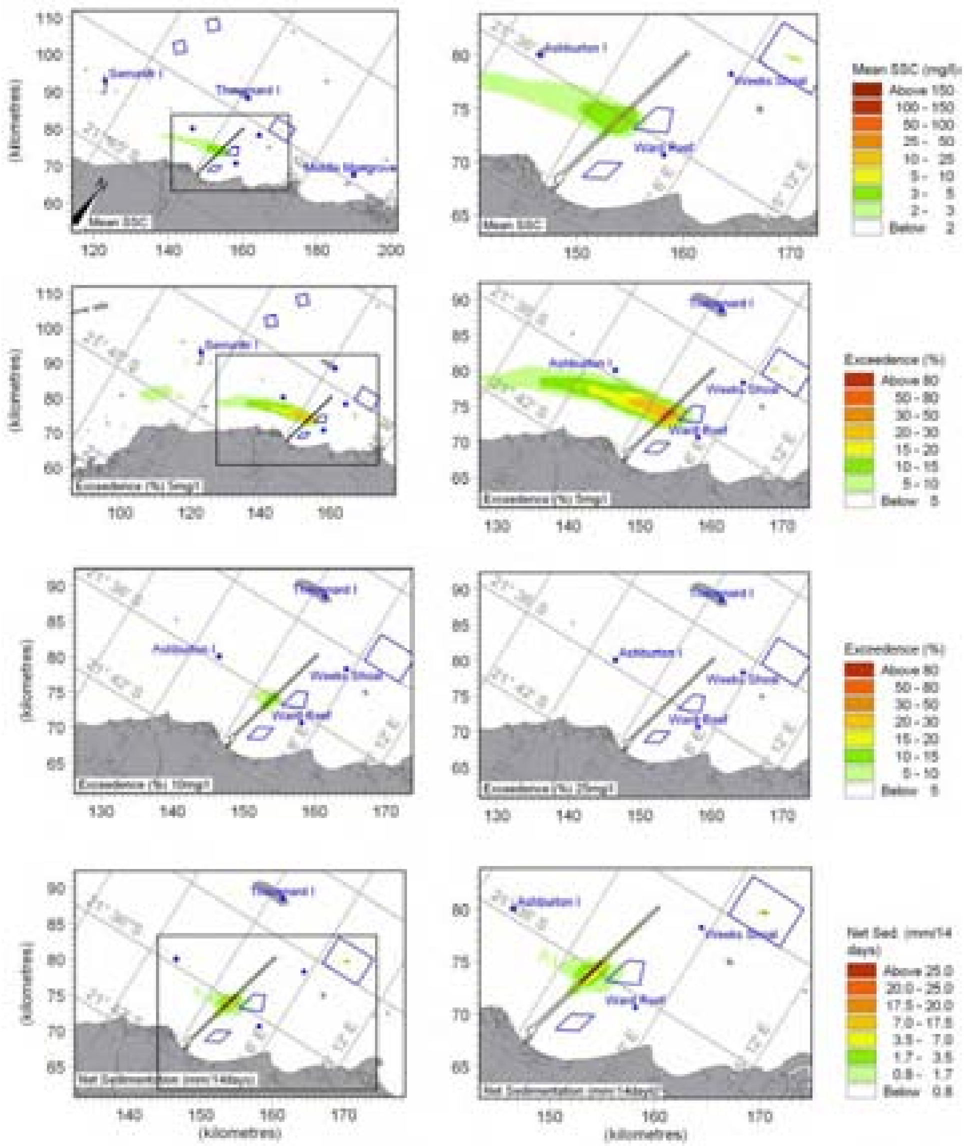

Figure AA.7 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 5

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AA.5 Results for High (Worst-Case) Spill Rates

Dredge Scenario: Scenario 5
Climatic Scenario: Summer A
Spill Rate Estimate: High ("Worst Case")

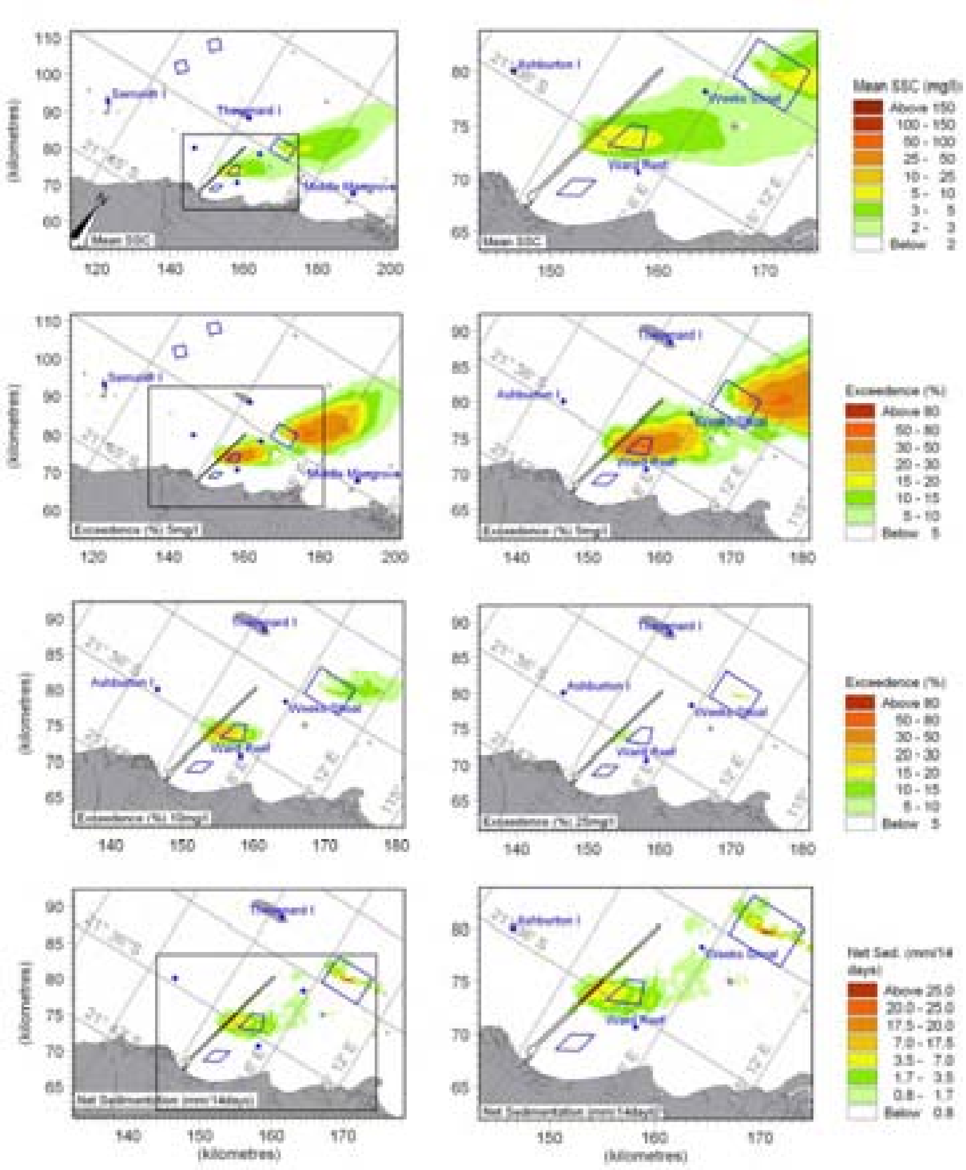

Figure AA.8 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 5

AA-10

Dredge Scenario: Scenario 5
Climatic Scenario: Summer B
Spill Rate Estimate: High ("Worst Case")

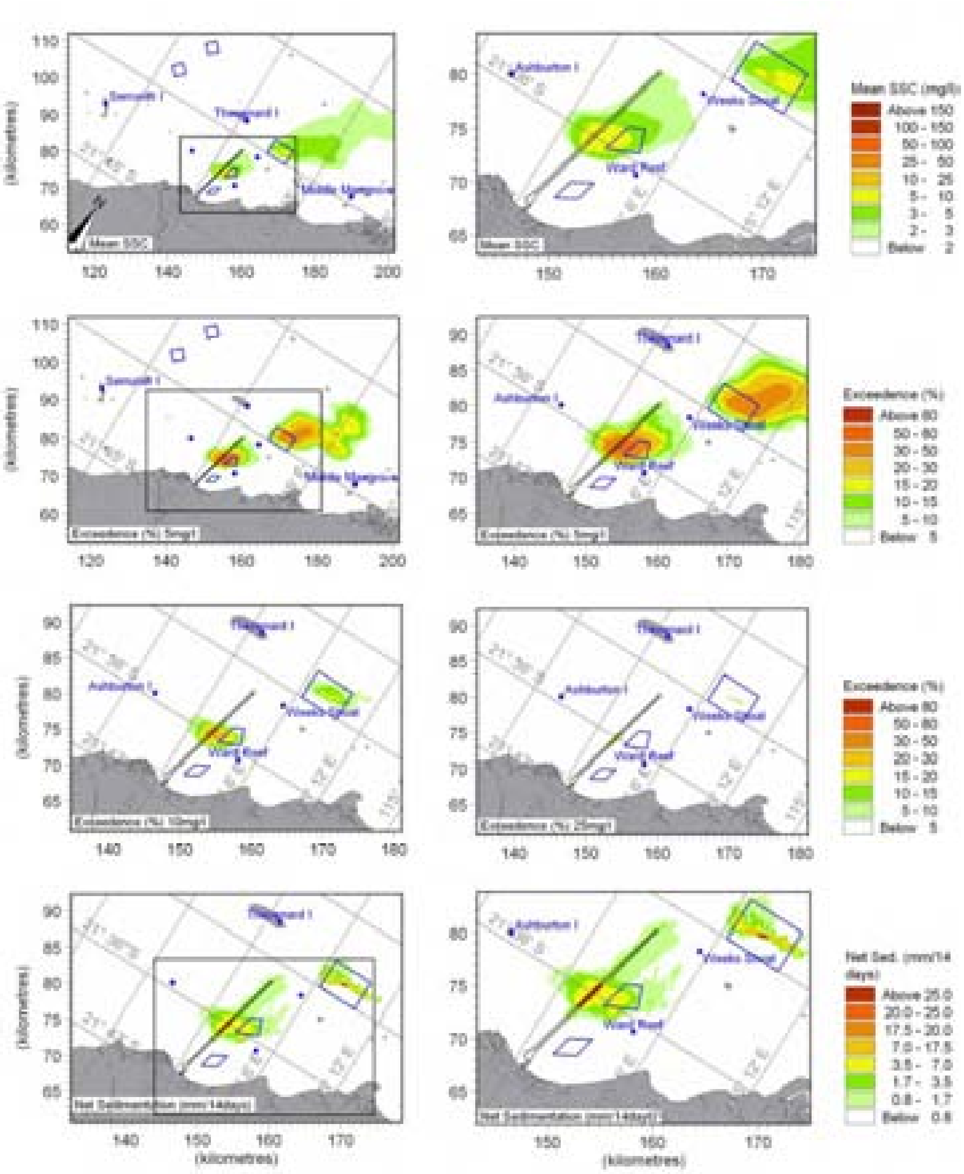

Figure AA.9 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 5

DHI Water & Environment

AA-11

Dredge Scenario: Scenario 5
Climatic Scenario: Transitional A
Spill Rate Estimate: High ("Worst Case")

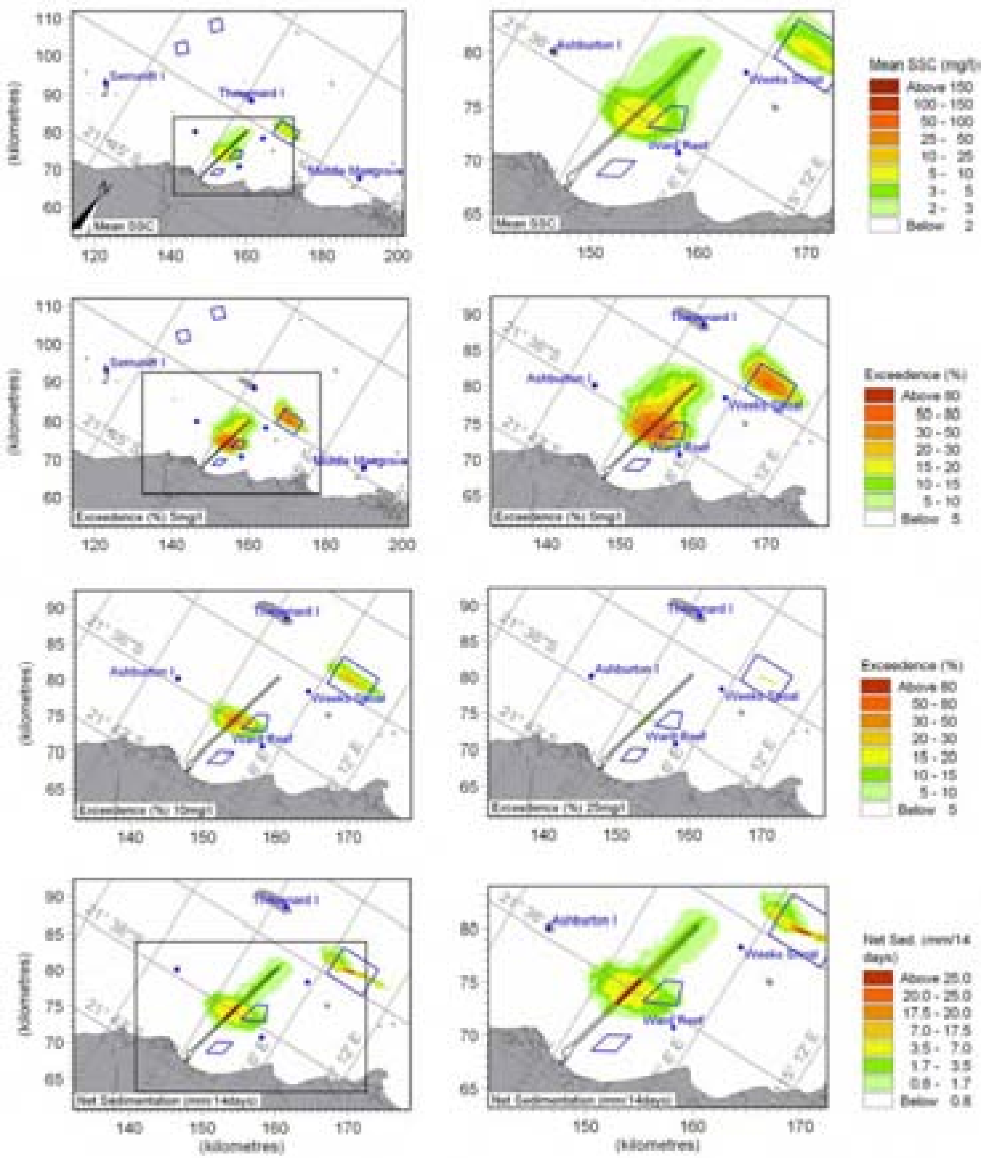

Figure AA.10 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 5

DHI Water & Environment

Dredge Scenario: Scenario 5
Climatic Scenario: Transitional B
Spill Rate Estimate: High ("Worst Case")

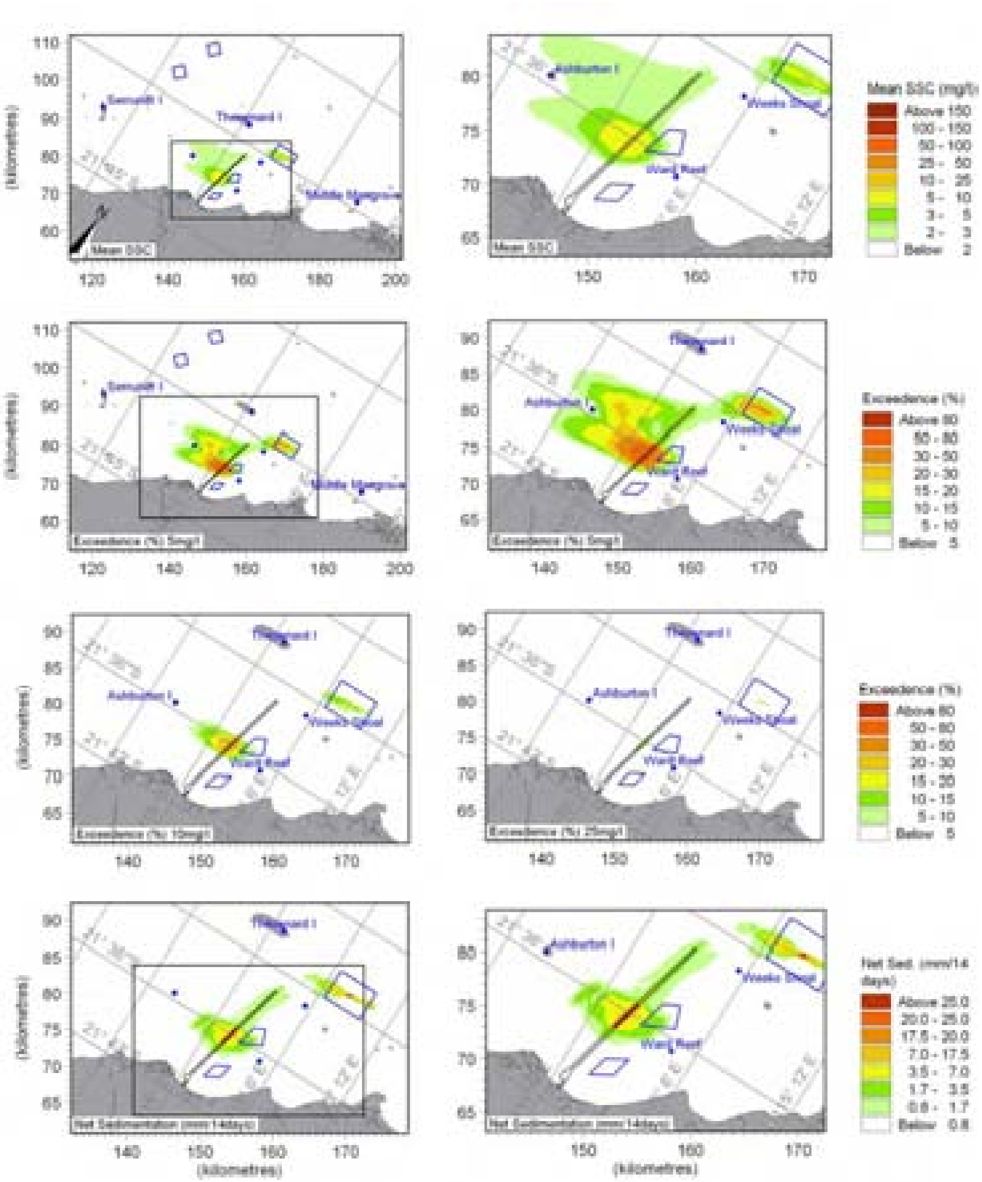

Figure AA.11 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 5

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AA-13

Dredge Scenario:	Scenario 5
Climatic Scenario:	Winter A
Spill Rate Estimate:	High ("Worst Case")

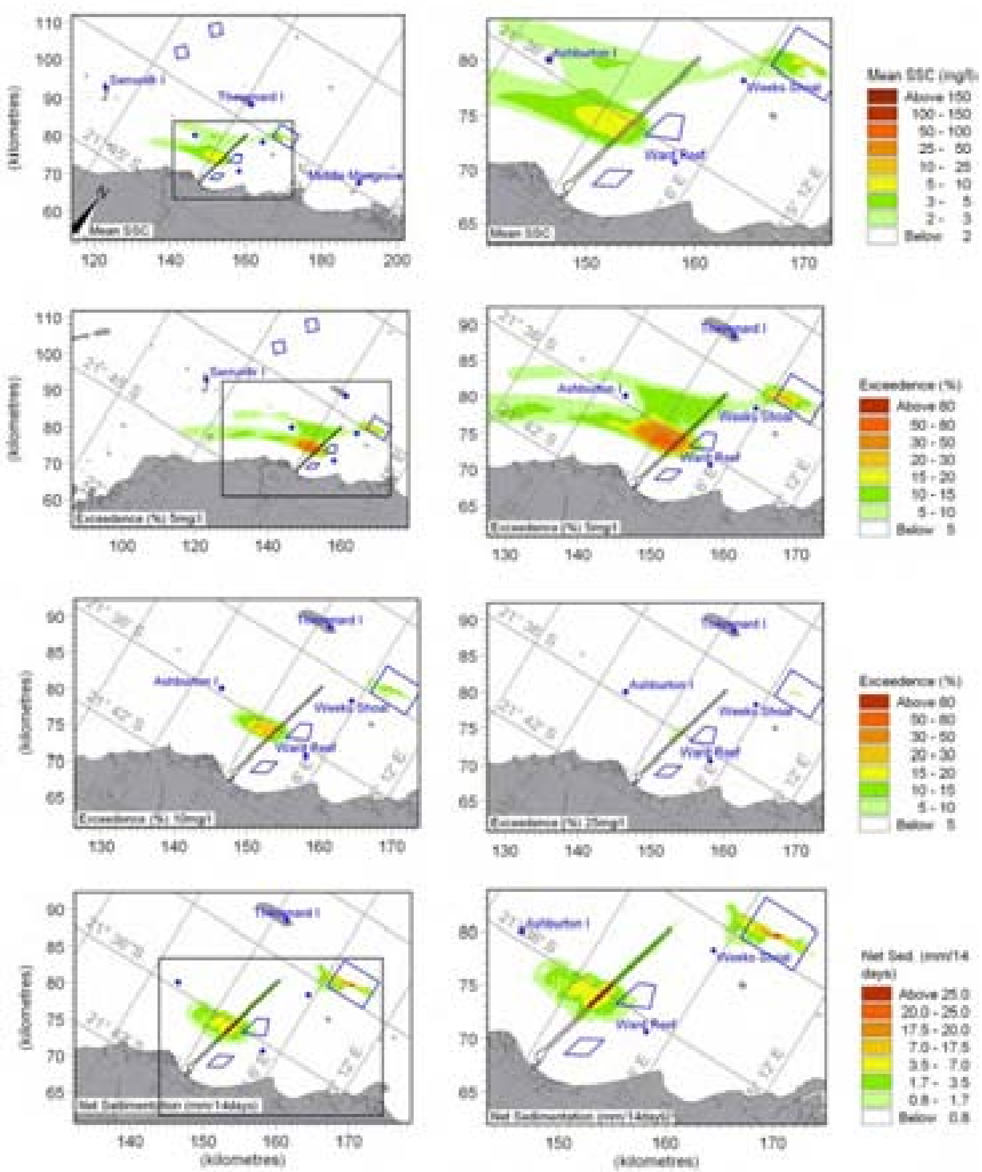

Figure AA.12 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 5

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Dredge Scenario:	Scenario 5
Climatic Scenario:	Winter B
Spill Rate Estimate:	High ("Worst Case")

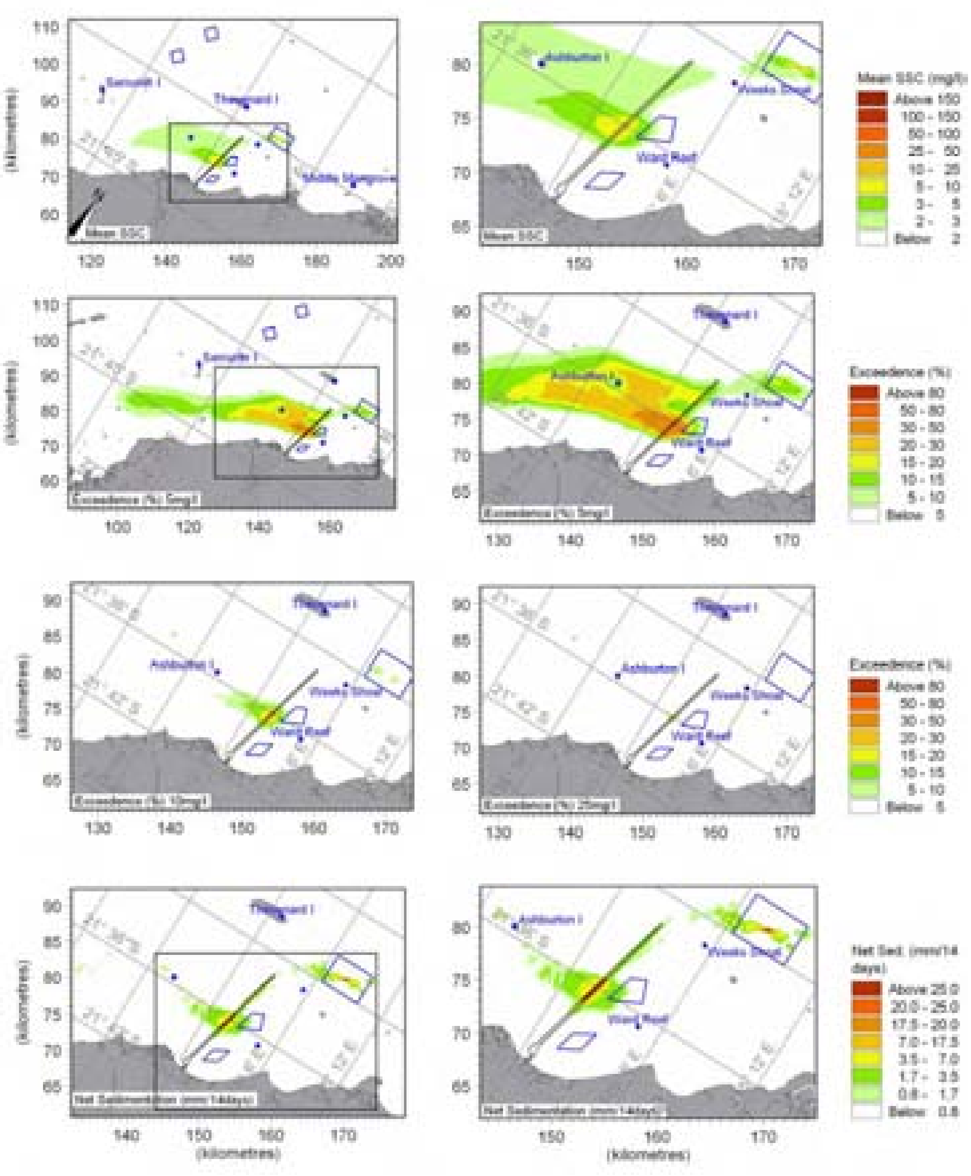

Figure AA.13 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 5

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Dredge Spoil Modelling

A P P E N D I X B B :

Results for Dredge Scenario 6 Based on MesoLAPS Winds

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BB RESULTS FOR DREDGE SCENARIO 6 BASED ON MESOLAPS WINDS

This appendix presents results from the sediment transport model based on hydrodynamics driven by the MesoLAPS wind fields. The reader is referred to the following sections of the main report and additional appendices for further information;

- Section 4.1.3.2 *Wind Fields*
- Section 6.2 *Results for the Dredging of the Shipping Channel*
- Appendix D *Hydrodynamic Model Validation and Calibration*

BB.1 Statistical Plots

The established impact criteria (DHI (2010) *Dredge Plume Impact Assessment Report)* are based on sediment loads, both in terms of excess suspended concentrations and sedimentation rates, over 14 day periods. In terms of exposure and impacts, both the concentrations and the duration of the event is important, which is expressed through the exceedence probability of given limits.

For each simulated case, a set of plots showing the statistical output used in the impact assessment have been produced. All plots are for excess concentrations, i.e. sediments originating from the dredging operations and exclusive of ambient concentrations.

Each mosaic plot comprises:

- Mean excess concentration at two scales
- Exceedence of 5mg/l excess concentration at two scales
- Exceedence of 10mg/l excess concentration
- Exceedence of 25mg/l excess concentration
- Net sedimentation rates at two zoomed levels at the site

Note that all concentrations are presented as depth-averaged values. All values are derived over the assessment period (2nd neap/spring tidal cycle of the month for each climatic scenario), i.e. after at least 14 days warm-up period. Exceedences are expressed in percentage time over the assessment period that the exceedence limit is exceeded.

BB.2 Description of Dredge scenario 6

General

- Bathymetry with fully dredged MOF, MOF channel and PLF basin. Partly dredged approach channel along entire length
- Material available for re-suspension along all dredged areas and in placement Sites A and C
- Include MOF dredged basin and MOF breakwaters.

Offshore Dredging 1: Approach Channel – Section 4 sand

- 10,000m^3 TSHD with disposal at placement Site C
- Dredging along Section 4

Offshore Dredging 2: Approach Channel – weak rock

- 10,000m^3 TSHD with disposal at placement Site C
- Dredging along Sections 3 & 4

The locations for the various dredge and placement activities are outlined in Figure BB.1, while defined "realistic" and "worst case" spill rates for Dredging Scenario 6 are listed in Table 3.2 of the main report.

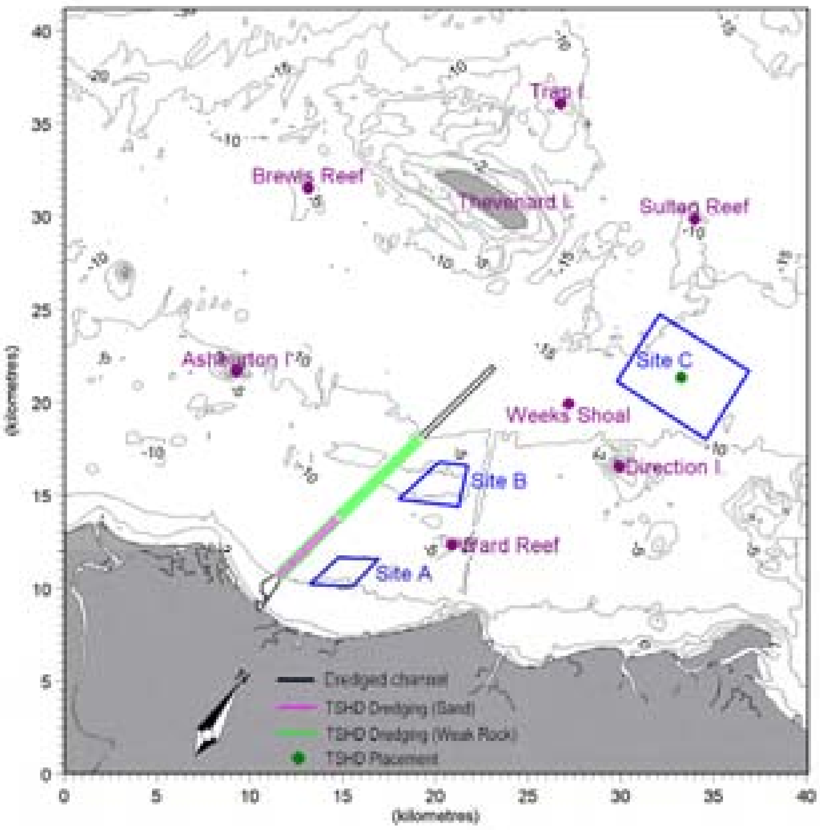

Figure BB.1 Sketch of locations for Dredging Scenario 6.

BB.3 Summary of Results

Specific observations for Dredge Scenario 6 include:

- The (lower concentration) plumes from the TSHD dredging at Sections 3 and 4 combine with the plumes generated from the sand dredging at Section 4 to generate a higher concentration plume.
- Mean excess concentrations of 10mg/l extends up to 25km to the east during strong summer conditions and up to 10km to the west during strong winter conditions for worst case spill rates.
- The plume generated from Section 4 of the PLF Approach channel overlaps Ward Reef during summer conditions

BB.4 Results for Low (Realistic) Spill Rates

Dredge Scenario: Scenario 6
Climatic Scenario: Summer A
Spill Rate Estimate: Low ("Realistic") Case

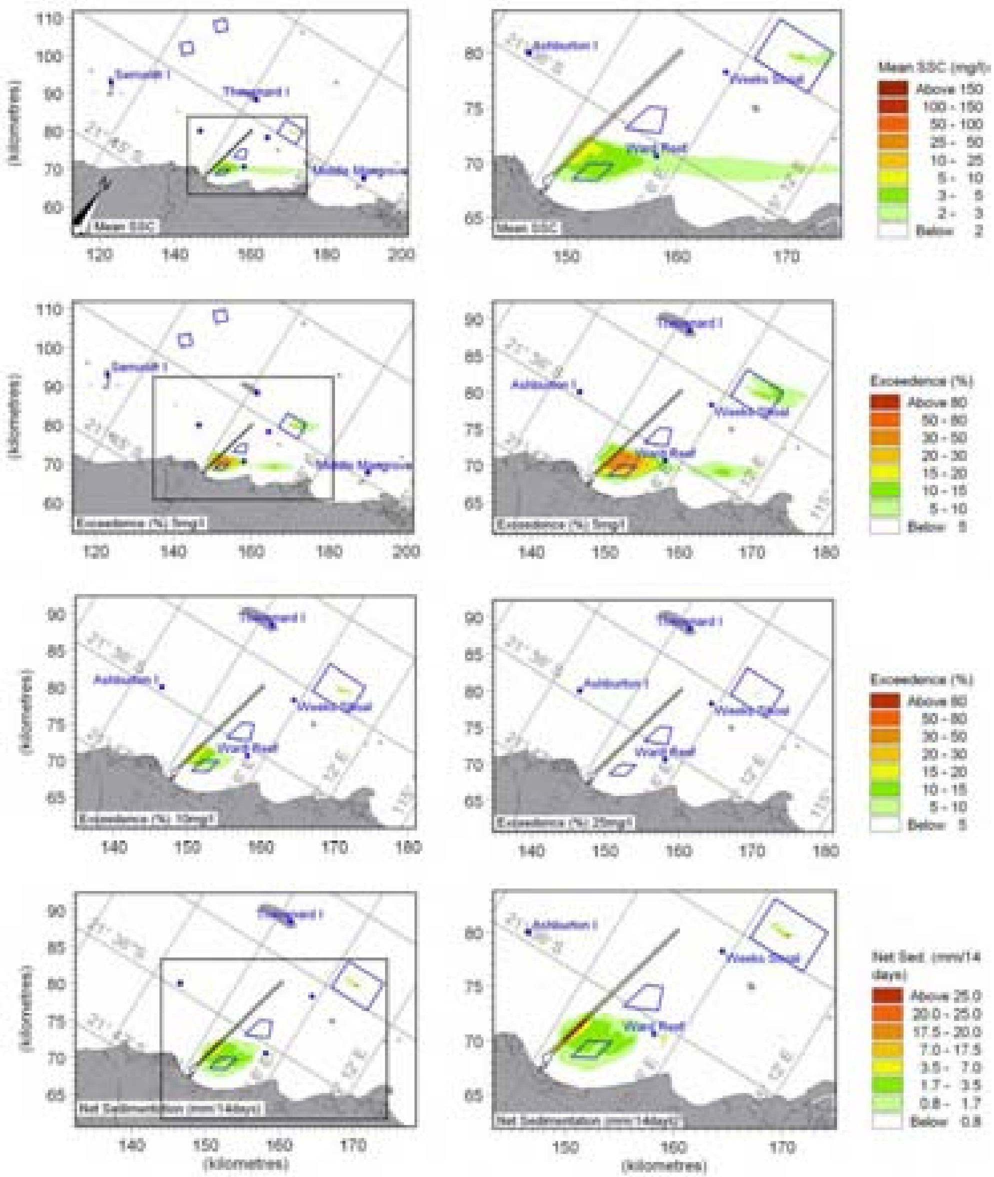

Figure BB.2 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 6

DHI Water & Environment

BB-4

Dredge Scenario: Scenario 6
Climatic Scenario: Summer B
Spill Rate Estimate: Low ("Realistic") Case

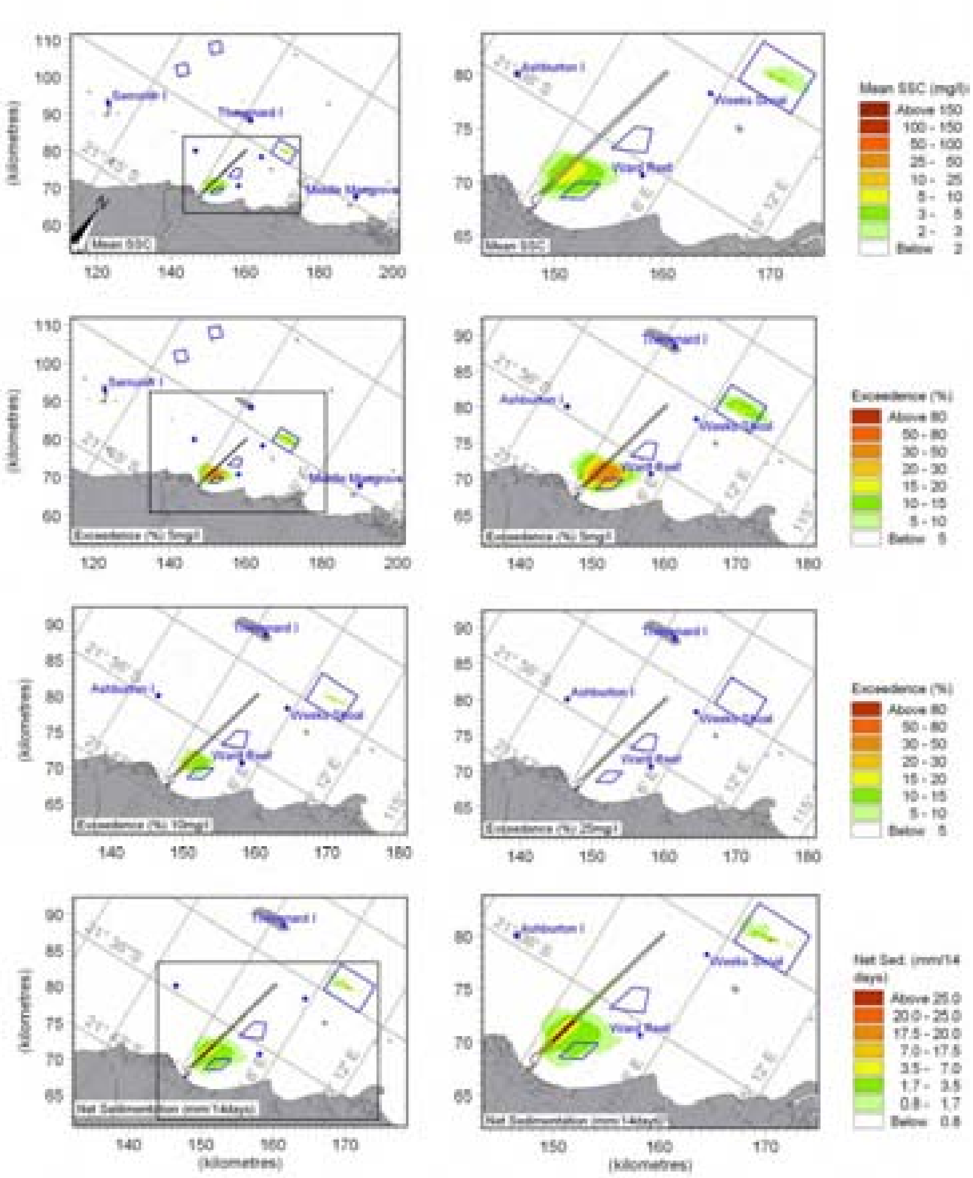

Figure BB.3 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 6

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BB-5

Dredge Scenario: Scenario 6
Climatic Scenario: Transitional A
Spill Rate Estimate: Low ("Realistic") Case

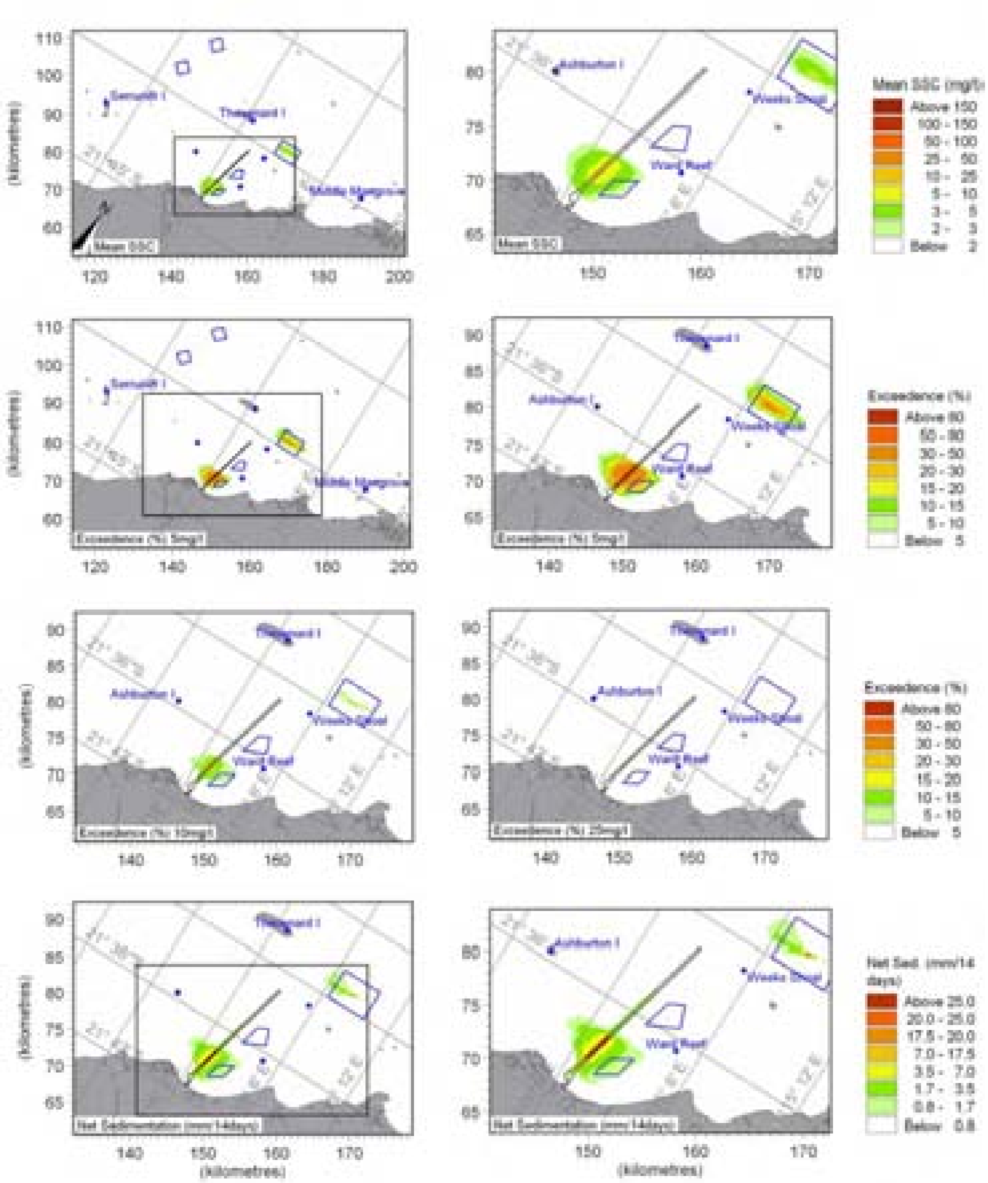

Figure BB.4 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 6

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BB-6

Dredge Scenario:	Scenario 6
Climatic Scenario:	Transitional B
Spill Rate Estimate:	Low ("Realistic") Case

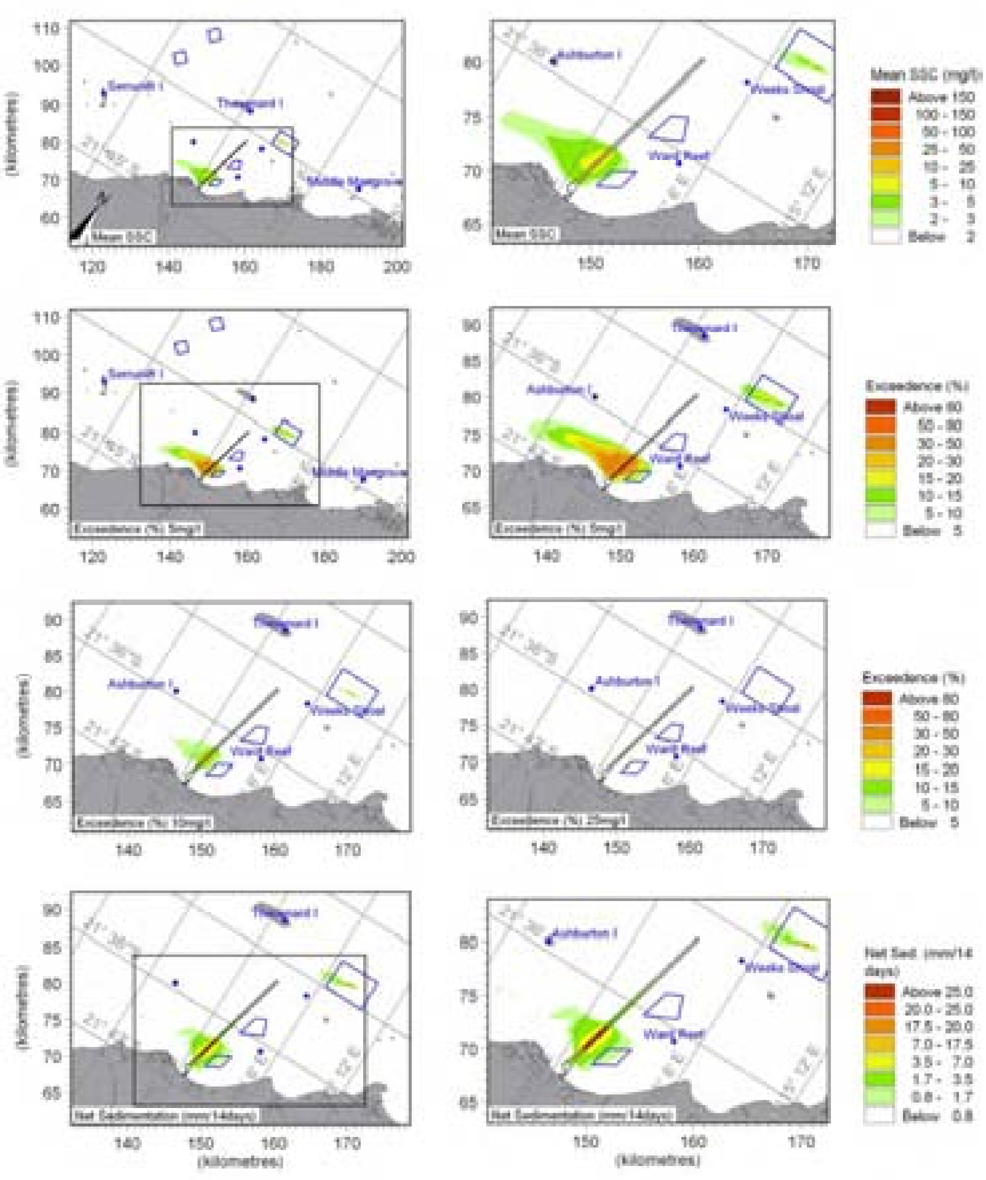

Figure BB.5 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 6

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BB-7

Dredge Scenario: Scenario 6
Climatic Scenario: Winter A
Spill Rate Estimate: Low ("Realistic") Case

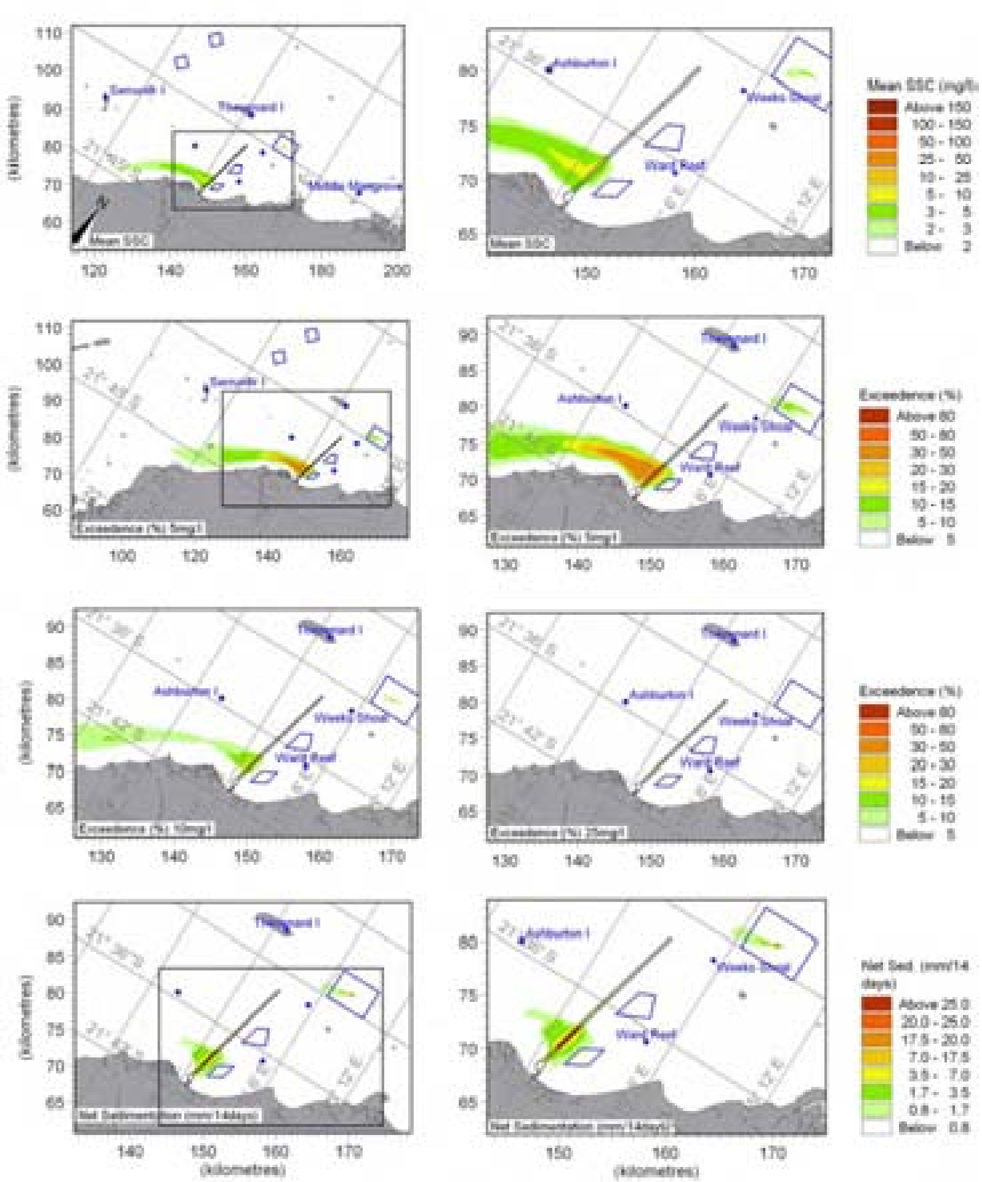

Figure BB.6 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 6

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BB-8

Dredge Scenario: Scenario 6
Climatic Scenario: Winter B
Spill Rate Estimate: Low ("Realistic") Case

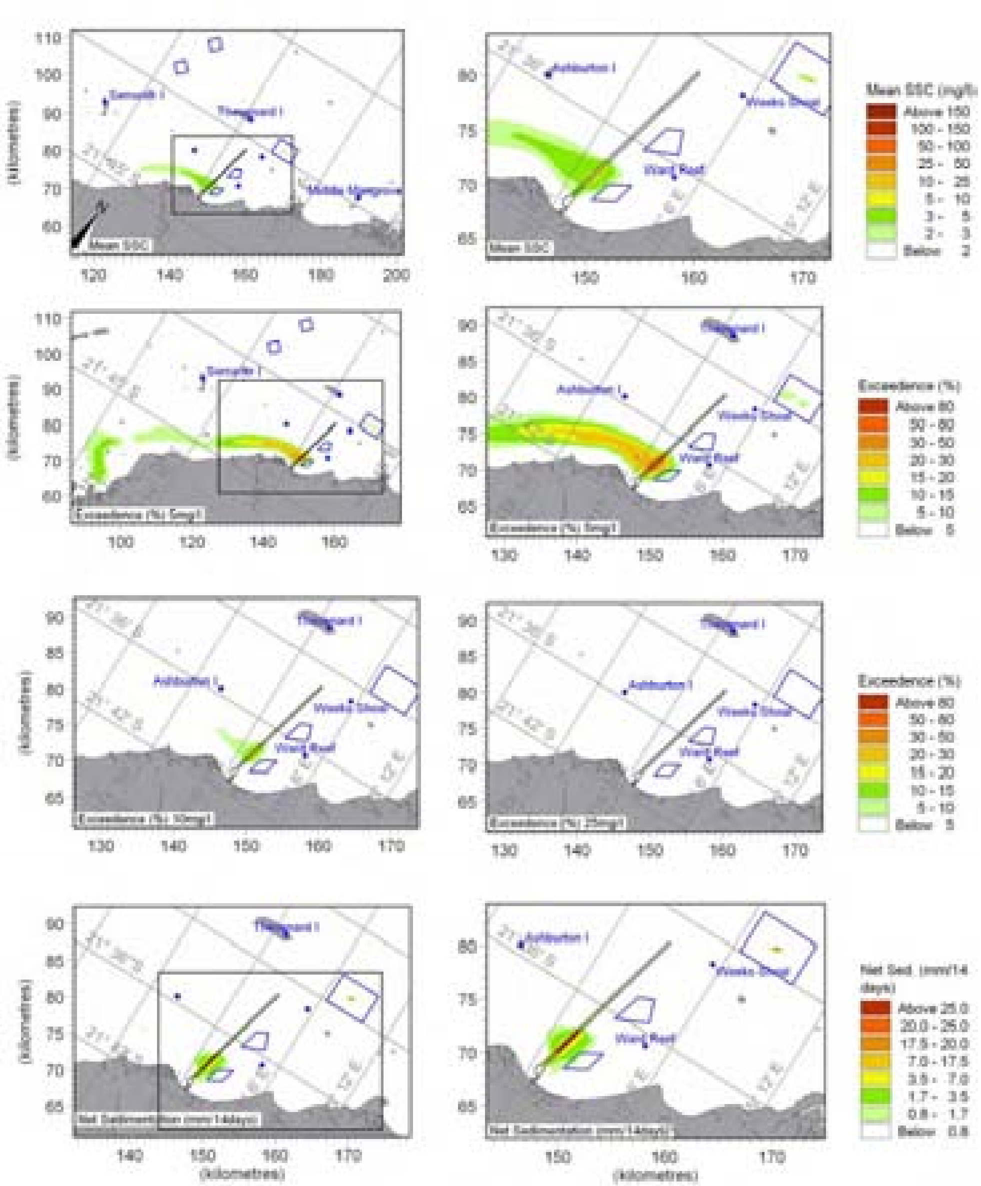

Figure BB.7 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 6

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BB.5 Results for High (Worst-Case) Spill Rates

Dredge Scenario: Scenario 6
Climatic Scenario: Summer A
Spill Rate Estimate: High ("Worst Case")

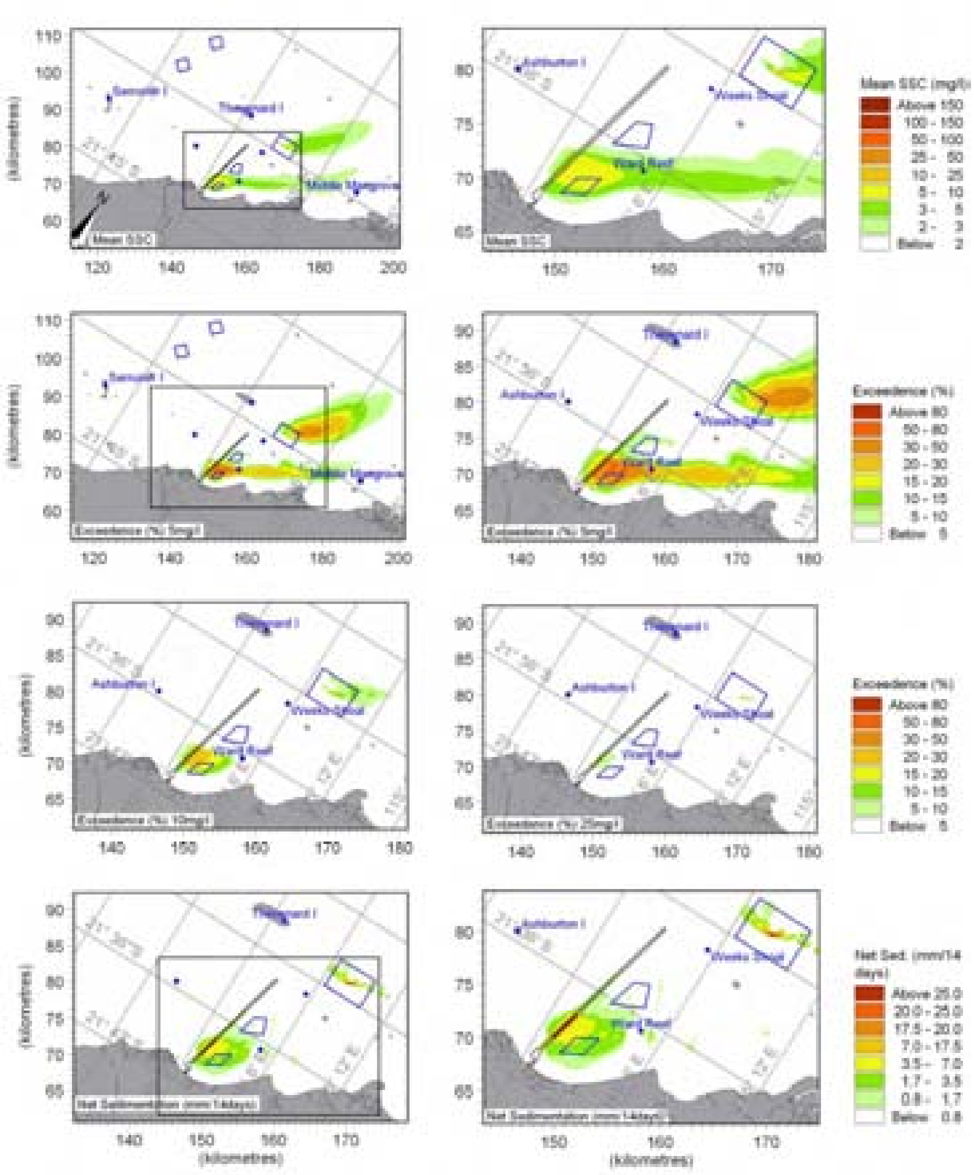

Figure BB.8 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 6

BB-10

Dredge Scenario: Scenario 6
Climatic Scenario: Summer B
Spill Rate Estimate: High ("Worst Case")

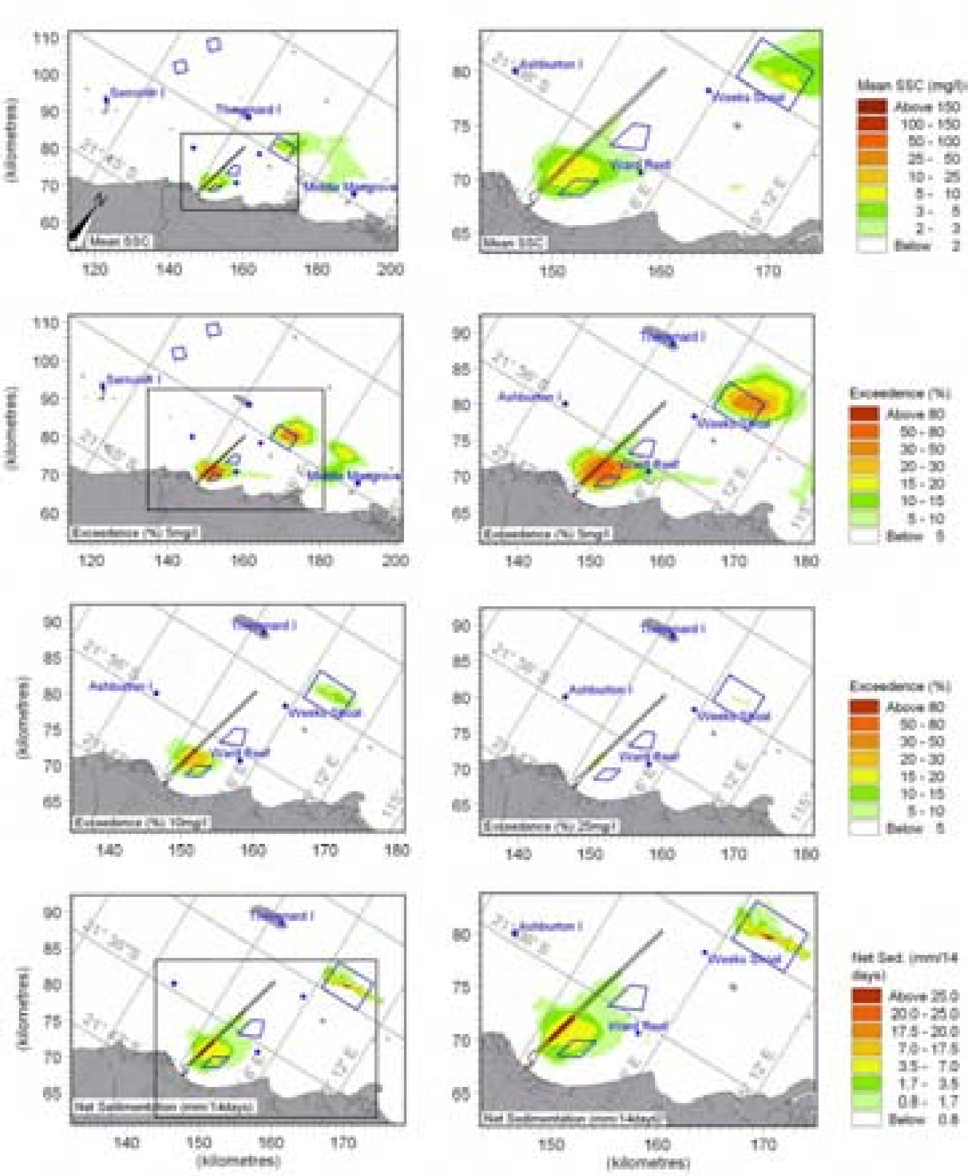

Figure BB.9 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 6

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BB-11

Dredge Scenario: Scenario 6
Climatic Scenario: Transitional A
Spill Rate Estimate: High ("Worst Case")

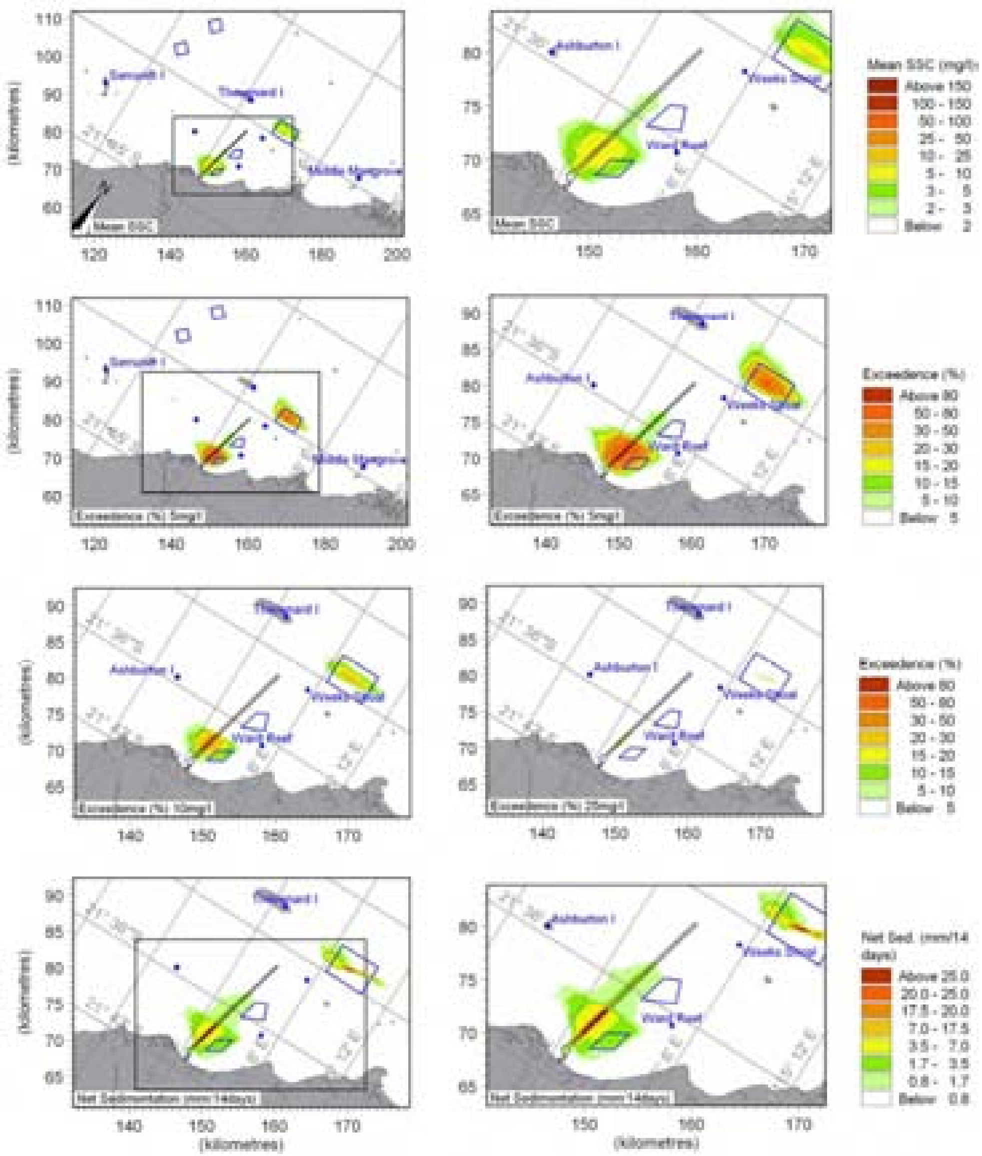

Figure BB.10 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 6

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BB-12

Dredge Scenario: Scenario 6
Climatic Scenario: Transitional B
Spill Rate Estimate: High ("Worst Case")

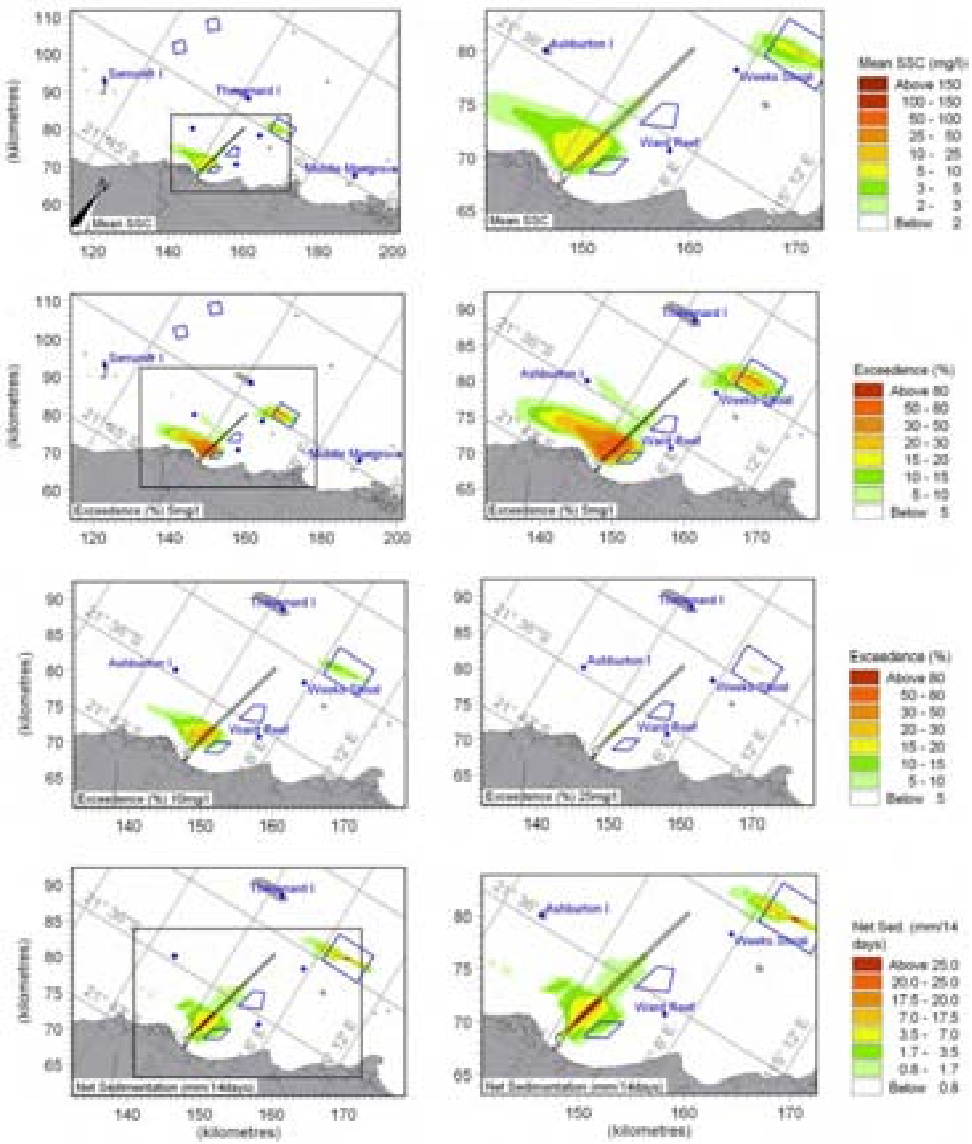

Figure BB.11 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 6

DHI Water & Environment

BB-13

Dredge Scenario: Scenario 6
Climatic Scenario: Winter A
Spill Rate Estimate: High ("Worst Case")

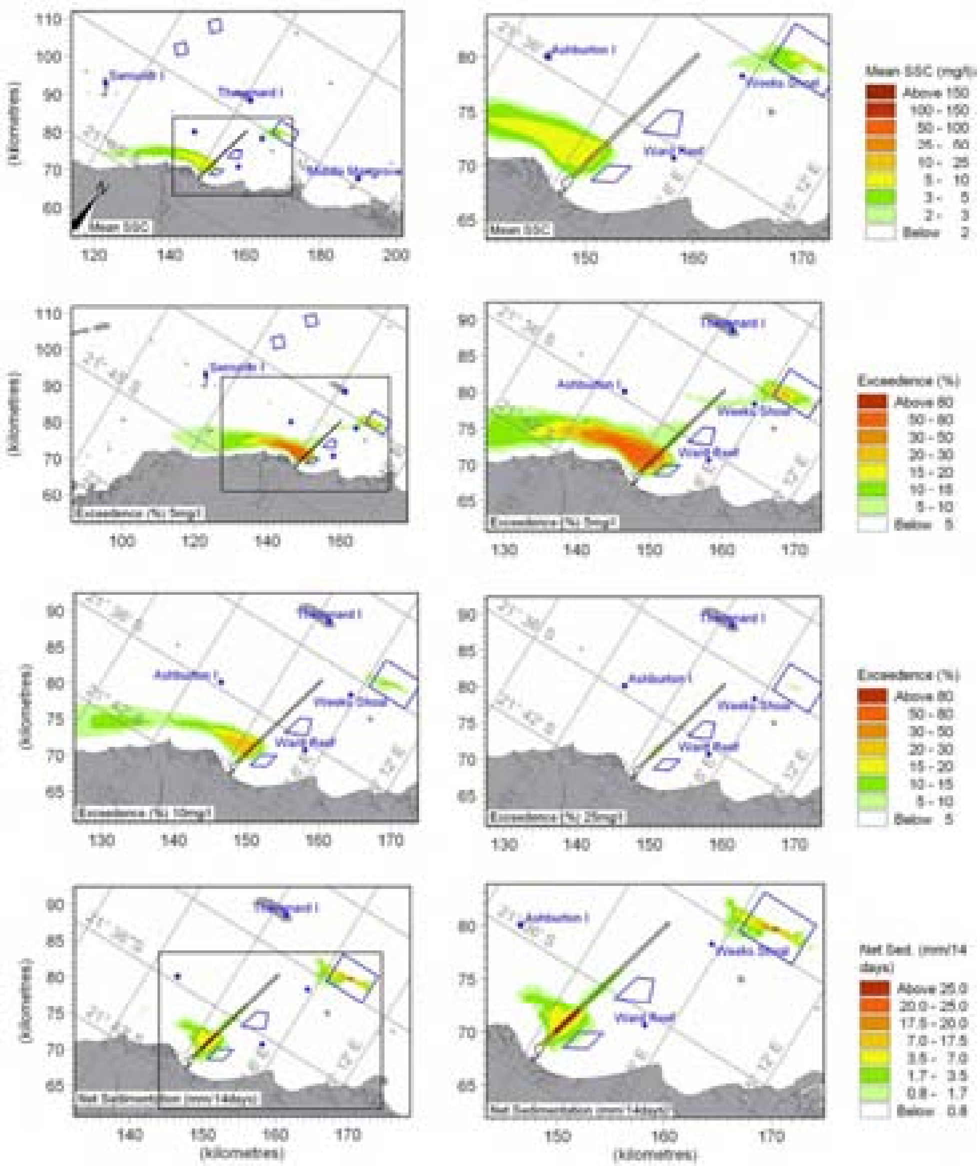

Figure BB.12 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 6

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BB-14

Dredge Scenario:	Scenario 6
Climatic Scenario:	Winter B
Spill Rate Estimate:	High ("Worst Case")

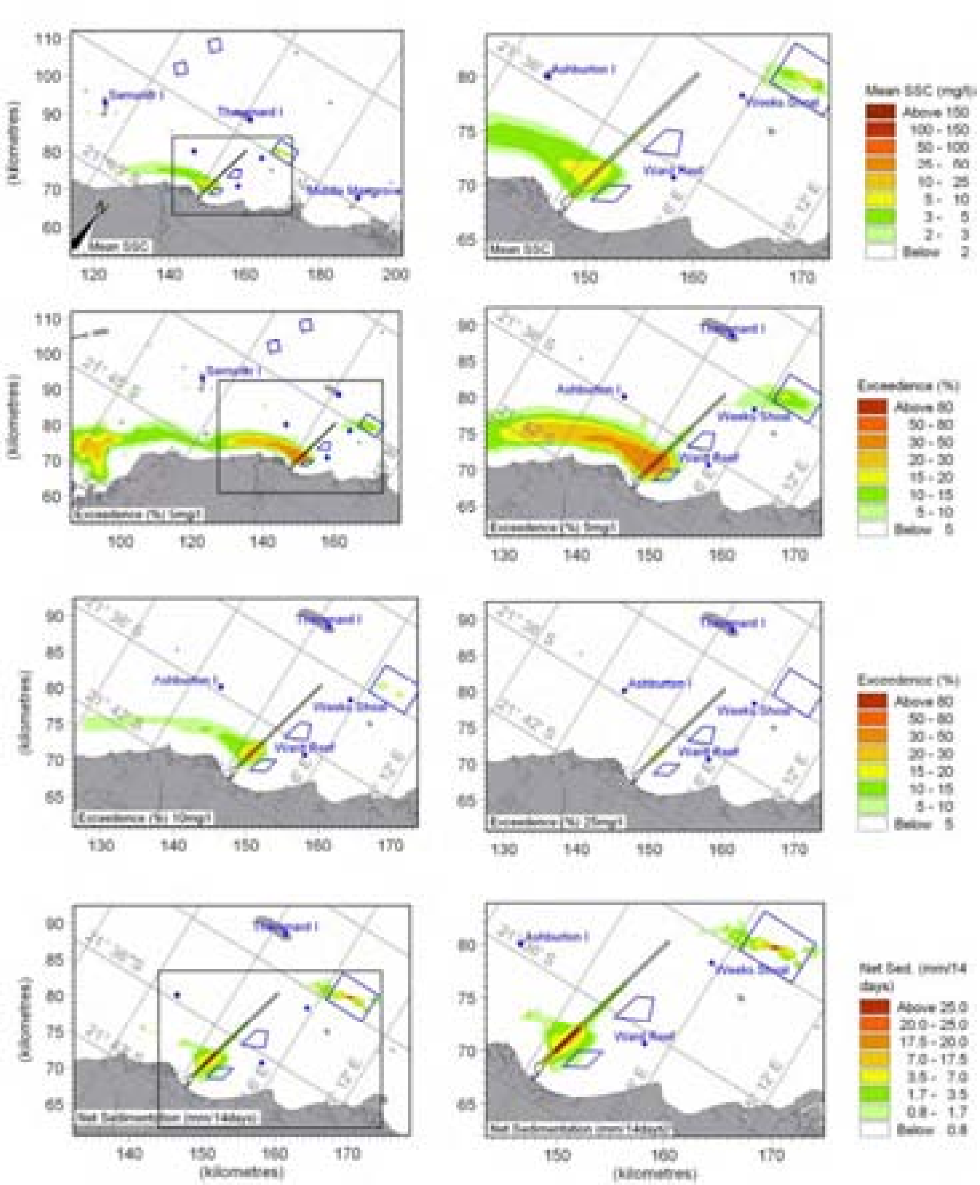

Figure BB.13 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 6

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A P P E N D I X   C C :

Results for Dredge Scenario 7 Based on MesoLAPS Winds

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CC RESULTS FOR DREDGE SCENARIO 7 BASED ON MESOLAPS WINDS

This appendix presents results from the sediment transport model based on hydrodynamics driven by the MesoLAPS wind fields. The reader is referred to the following sections of the main report and additional appendices for further information;

- Section 4.1.3.2 *Wind Fields*
- Section 6.2 *Results for the Dredging of the Shipping Channel*
- Appendix D *Hydrodynamic Model Validation and Calibration*

CC.1 Statistical Plots

The established impact criteria (DHI (2010) *Dredge Plume Impact Assessment Report)* are based on sediment loads, both in terms of excess suspended concentrations and sedimentation rates, over 14 day periods. In terms of exposure and impacts, both the concentrations and the duration of the event is important, which is expressed through the exceedence probability of given limits.

For each simulated case, a set of plots showing the statistical output used in the impact assessment have been produced. All plots are for excess concentrations, i.e. sediments originating from the dredging operations and exclusive of ambient concentrations.

Each mosaic plot comprises:

- Mean excess concentration at two scales
- Exceedence of 5mg/l excess concentration at two scales
- Exceedence of 10mg/l excess concentration
- Exceedence of 25mg/l excess concentration
- Net sedimentation rates at two zoomed levels at the site

Note that all concentrations are presented as depth-averaged values. All values are derived over the assessment period (2nd neap/spring tidal cycle of the month for each climatic scenario), i.e. after at least 14 days warm-up period. Exceedences are expressed in percentage time over the assessment period that the exceedence limit is exceeded.

CC.2 Description of Dredge scenario 7A

General

- Bathymetry with fully dredged MOF, MOF channel and PLF basin. Partly dredged approach channel along entire length
- Material available for re-suspension along all dredged areas and in placement Sites A and C
- Include MOF dredged basin and MOF breakwaters.

Offshore Dredging: Approach Channel – Section 2 sand

- 10,000m^3 TSHD with disposal at placement Site C
- Dredging along Section 2

The locations for the various dredge and placement activities are outlined in Figure CC.1, while defined "realistic" and "worst case" spill rates for Dredging Scenario 7 are listed in Table 3.2 of the main report.

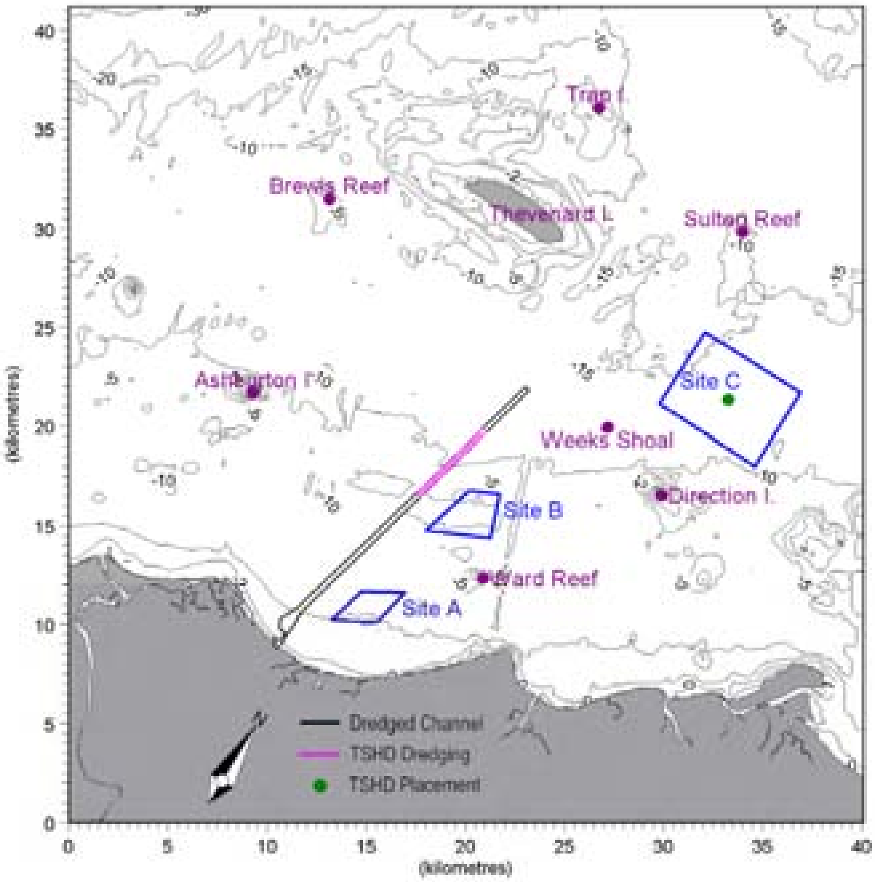

Figure CC.1 Sketch of locations for Dredging Scenario 7.

CC.3 Summary of Results

Specific observations for Dredge Scenario 7 include:

- During summer conditions, the plumes emitted from dredging in Section 2 combine with the plumes from Site C to form a larger plume.
- The plumes generated from Section 2 overlap several reefs found along the 10m contour area.

CC.4 Results for Low (Realistic) Spill Rates

Dredge Scenario: Scenario 7
Climatic Scenario: Summer A
Spill Rate Estimate: Low ("Realistic") Case

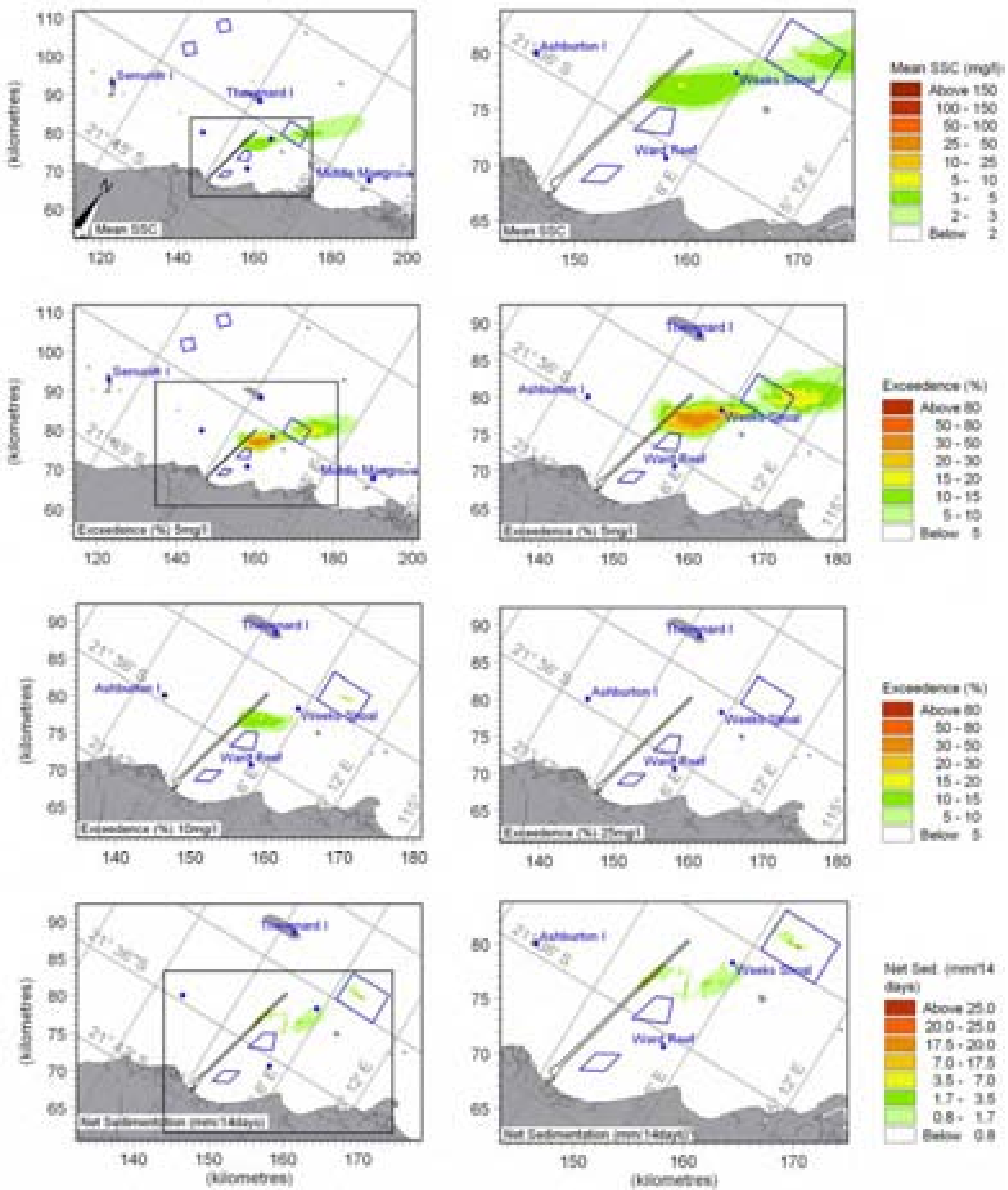

Figure CC.2 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7

CC-4

Dredge Scenario: Scenario 7
Climatic Scenario: Summer B
Spill Rate Estimate: Low ("Realistic") Case

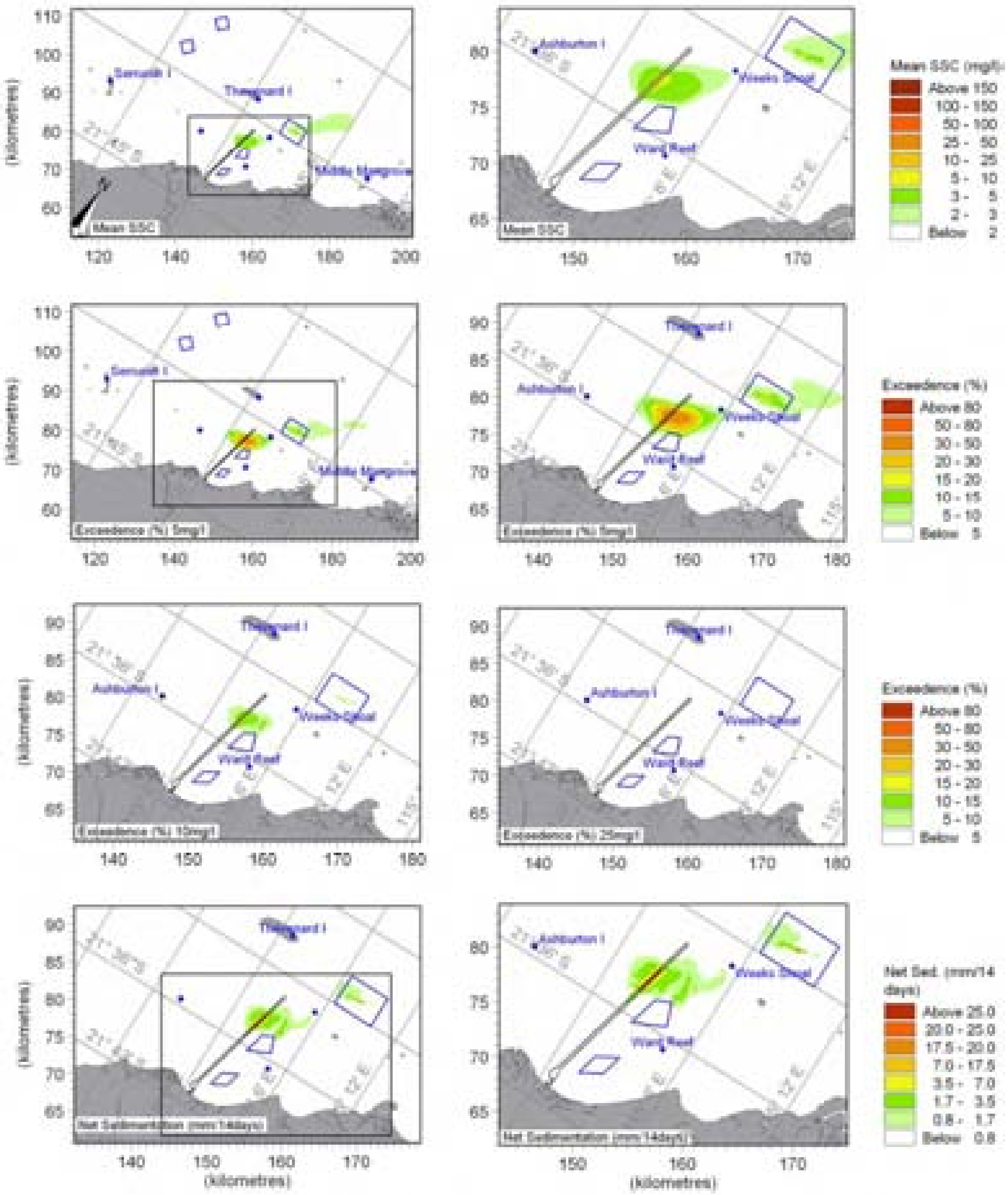

Figure CC.3 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7

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CC-5

Dredge Scenario:	Scenario 7
Climatic Scenario:	Transitional A
Spill Rate Estimate:	Low ("Realistic") Case

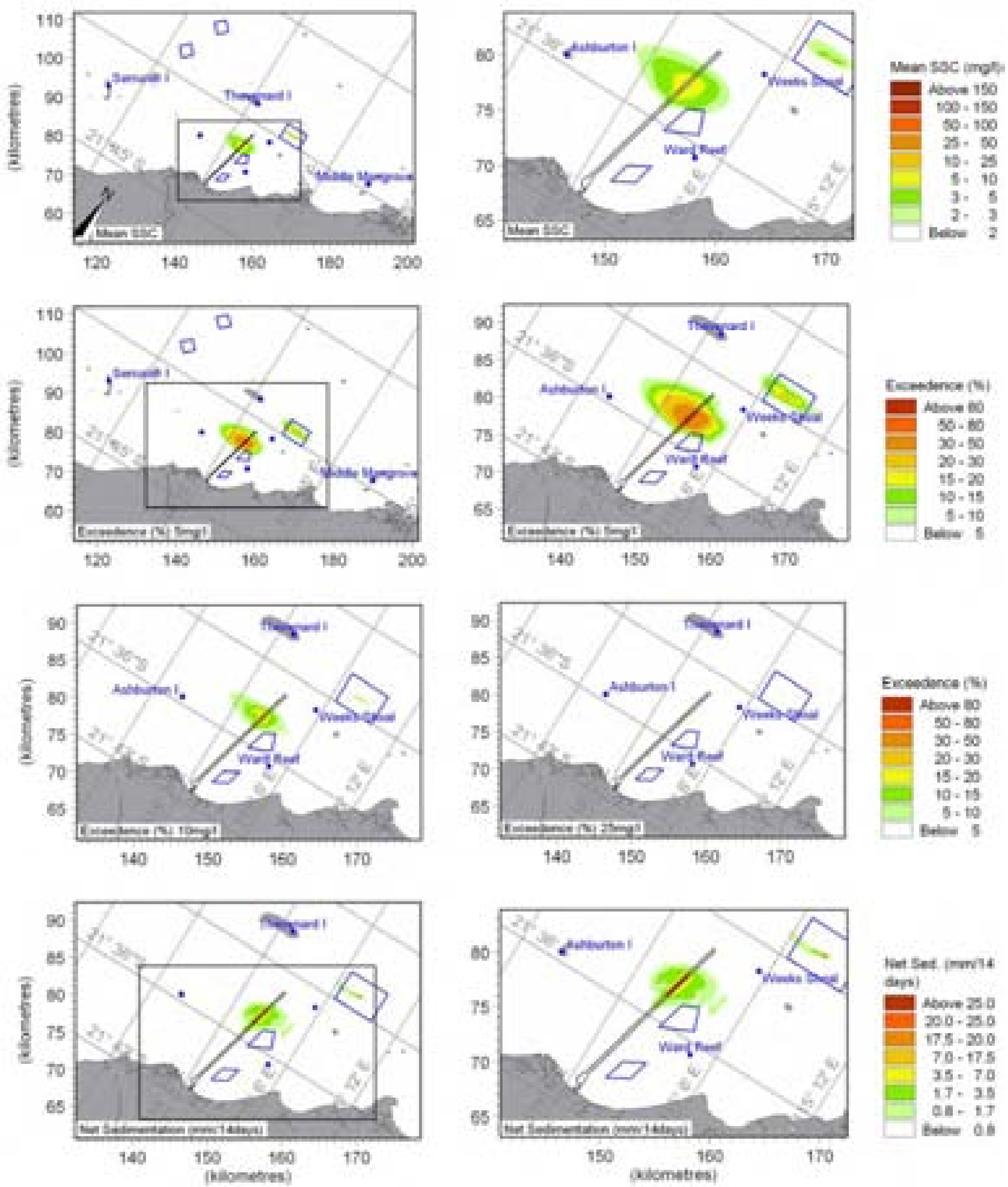

Figure CC.4 *Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7*

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CC-6

Dredge Scenario: Scenario 7
Climatic Scenario: Transitional B
Spill Rate Estimate: Low ("Realistic") Case

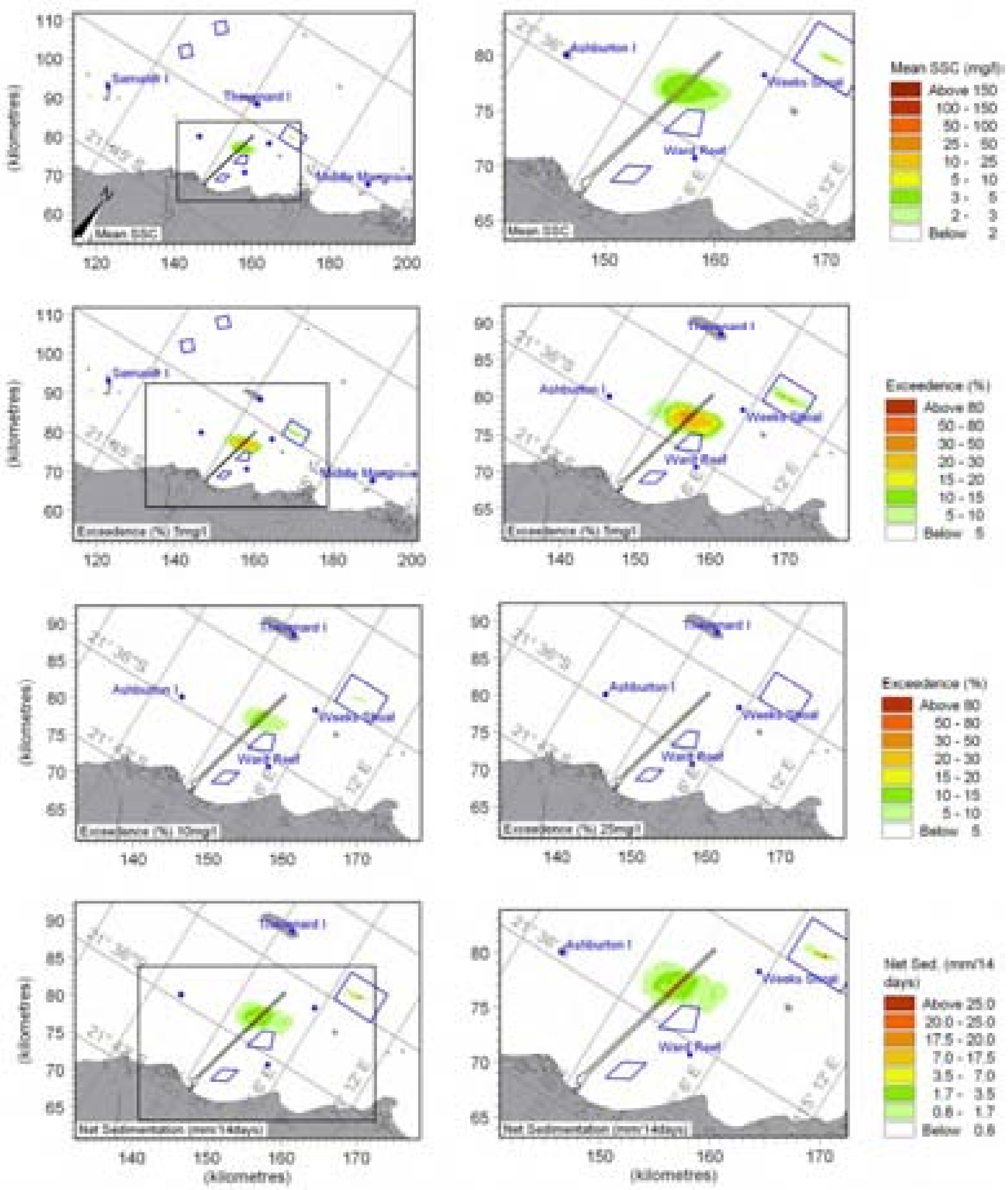

Figure CC.5 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7

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CC-7

Dredge Scenario: Scenario 7
Climatic Scenario: Winter A
Spill Rate Estimate: Low ("Realistic") Case

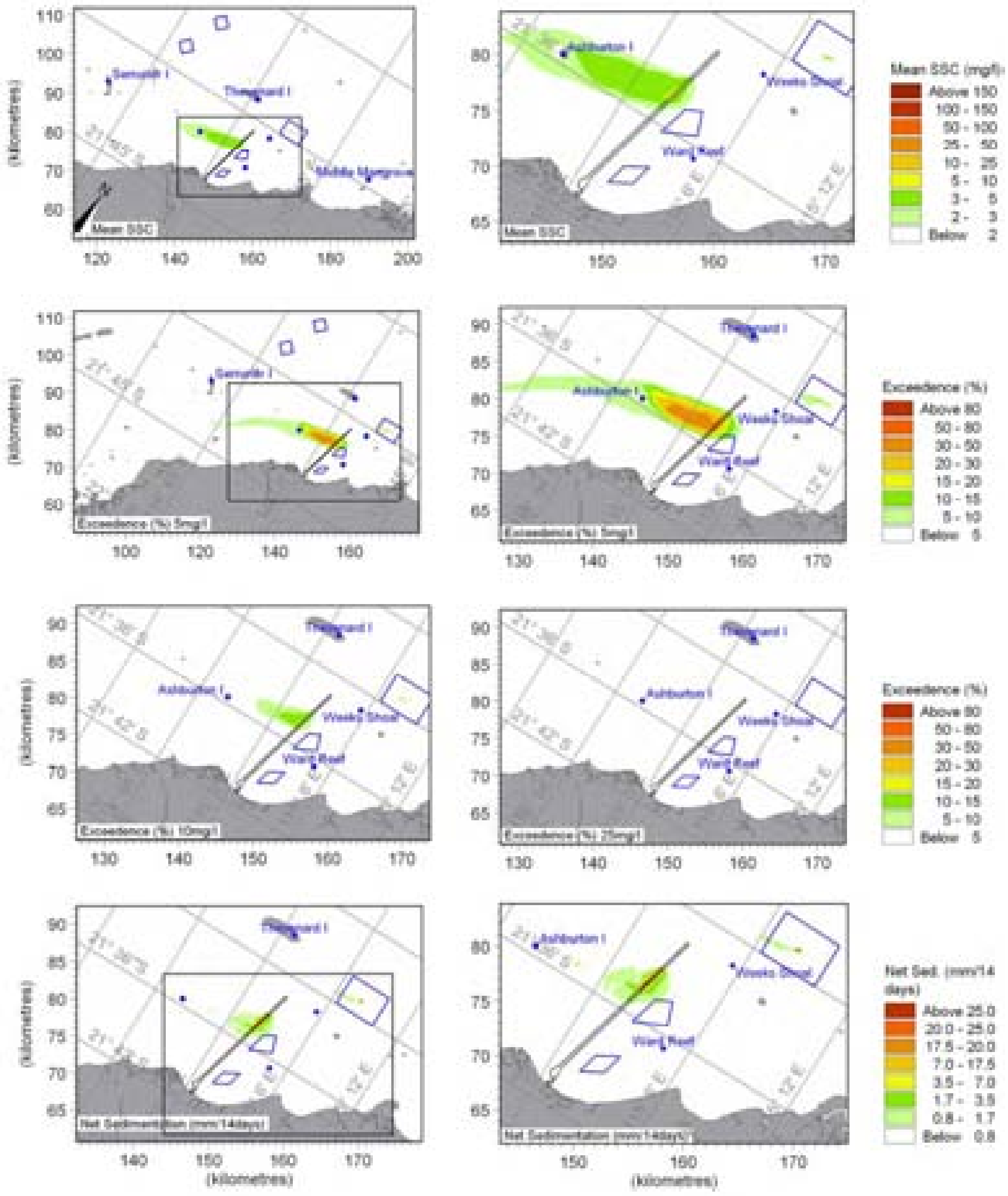

Figure CC.6 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7

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CC-8

Dredge Scenario: Scenario 7
Climatic Scenario: Winter B
Spill Rate Estimate: Low ("Realistic") Case

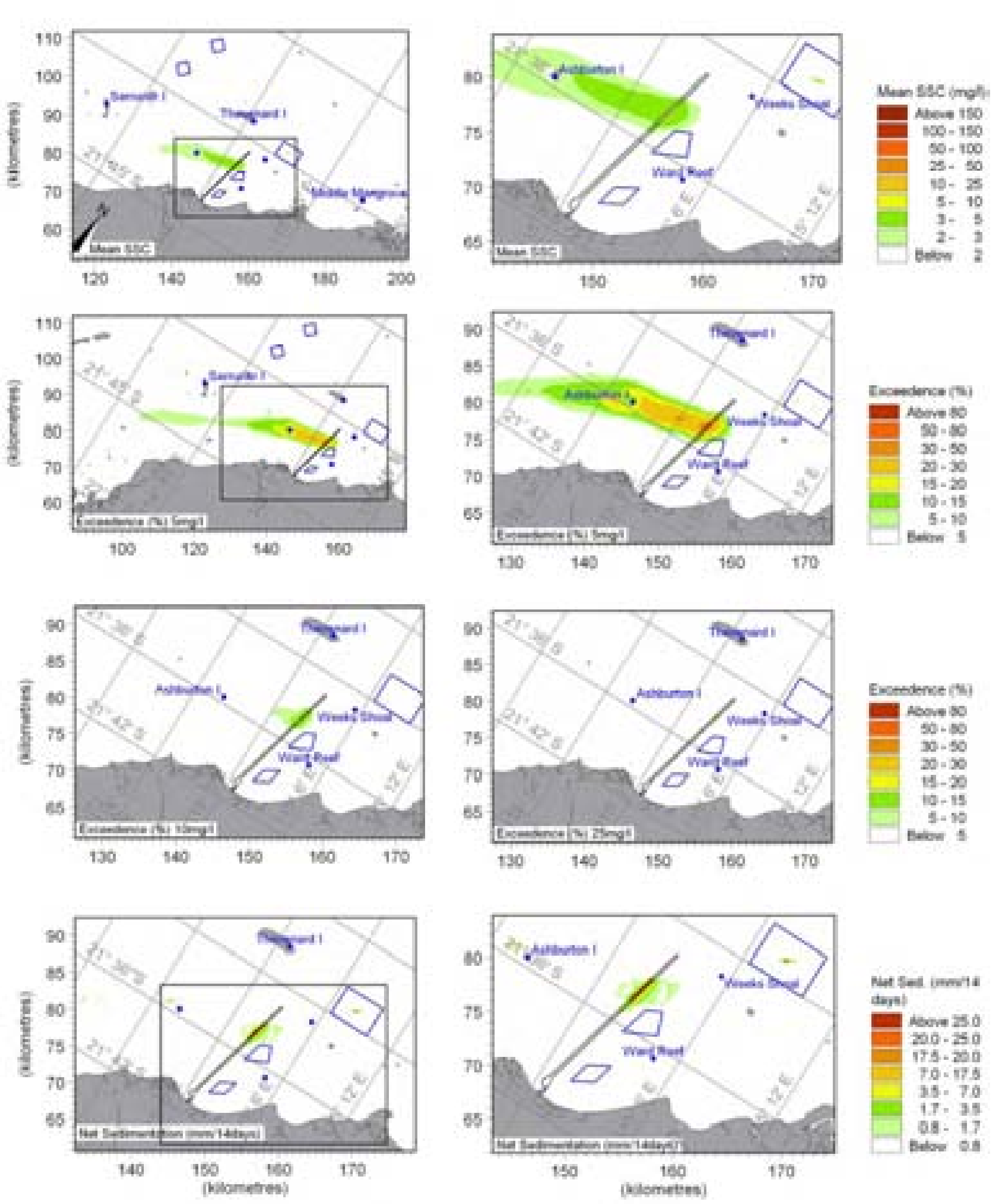

Figure CC.7 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7

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CC.5 Results for High (Worst-Case) Spill Rates

Dredge Scenario:	Scenario 7
Climatic Scenario:	Summer A
Spill Rate Estimate:	High ("Worst Case")

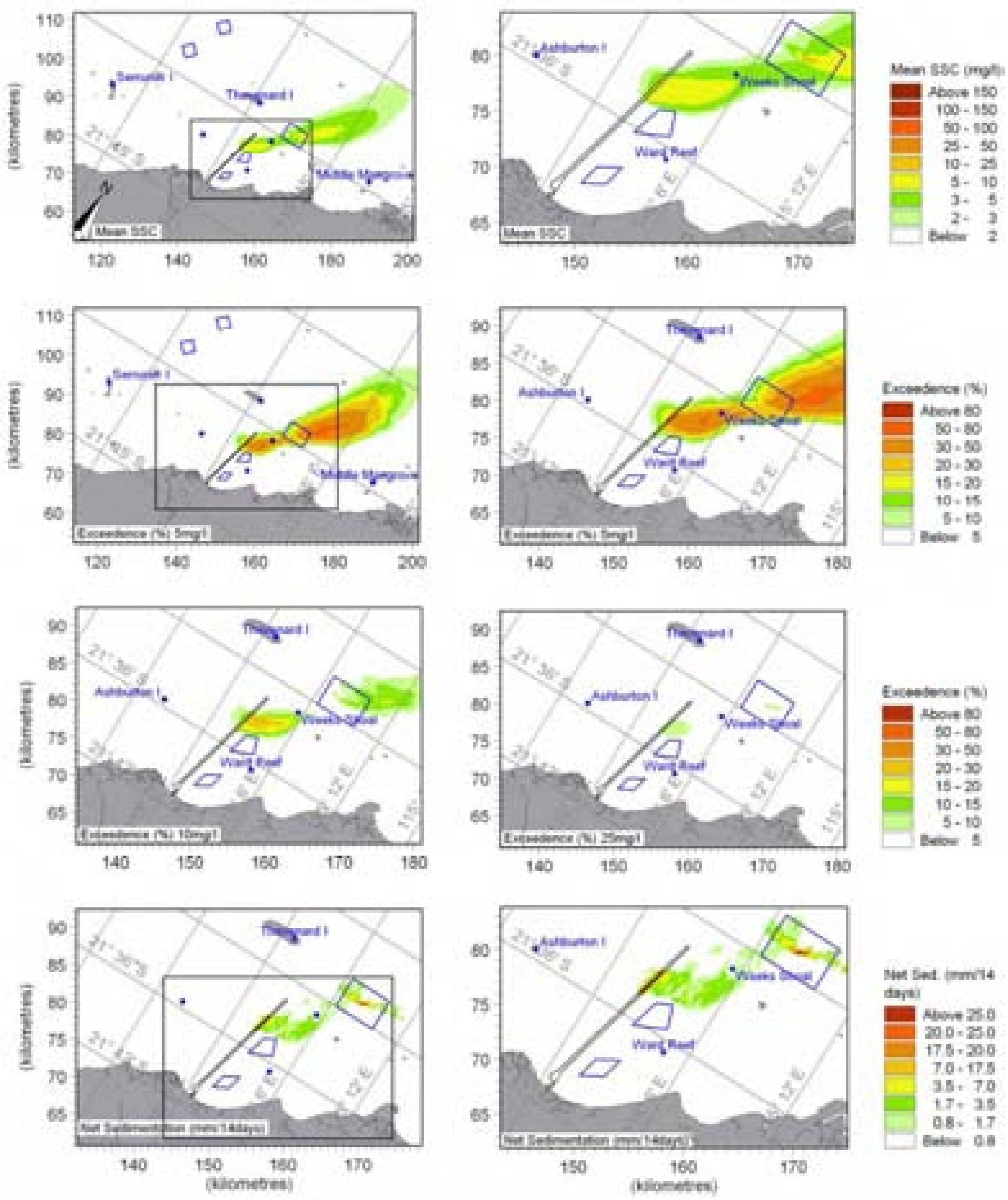

Figure CC.8 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7

CC-10

Dredge Scenario: Scenario 7
Climatic Scenario: Summer B
Spill Rate Estimate: High ("Worst Case")

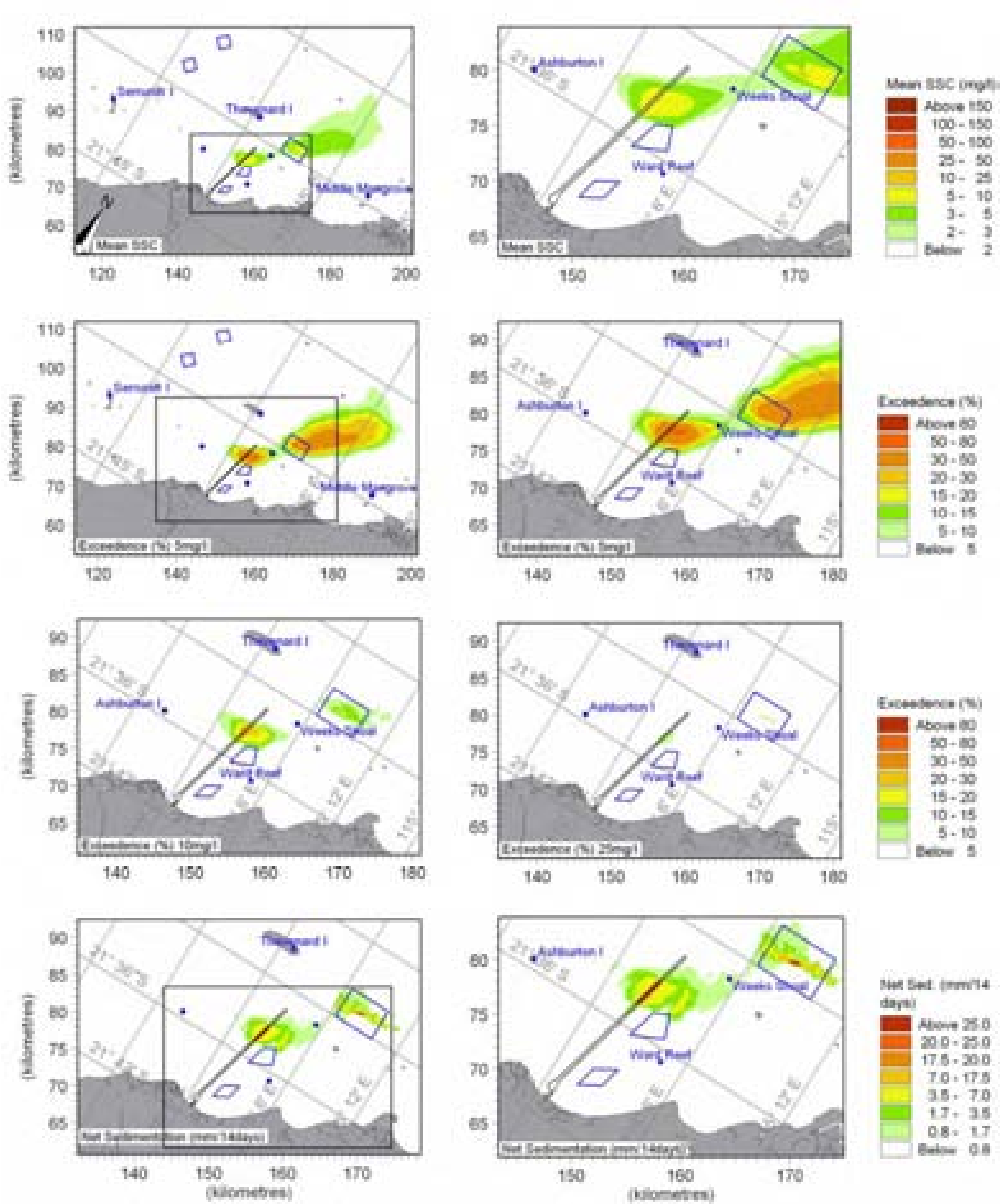

Figure CC.9 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7

DHI Water & Environment

CC-11

Dredge Scenario:	Scenario 7
Climatic Scenario:	Transitional A
Spill Rate Estimate:	High ("Worst Case")

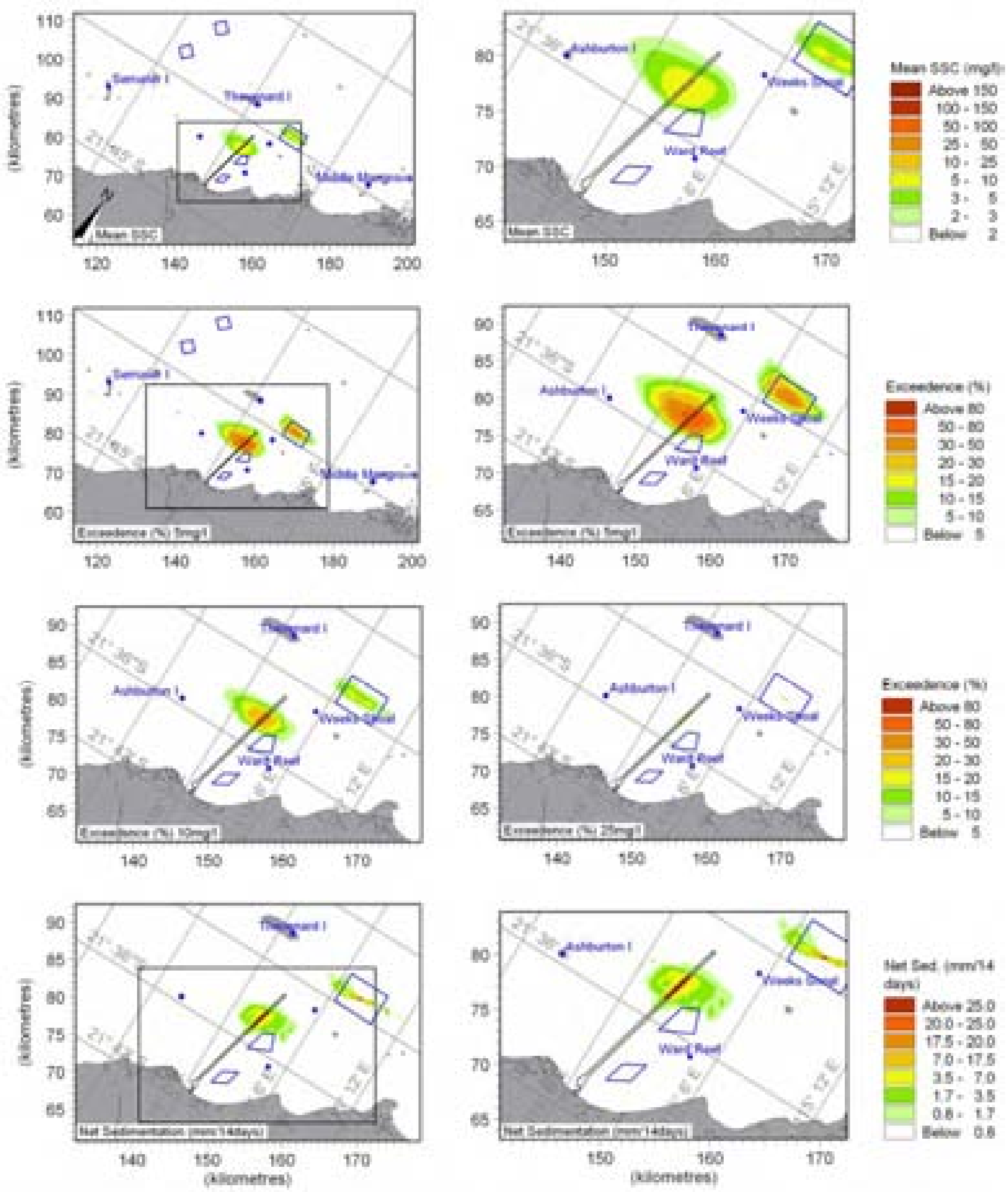

Figure CC.10 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7

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CC-12

Dredge Scenario:	Scenario 7
Climatic Scenario:	Transitional B
Spill Rate Estimate:	High ("Worst Case")

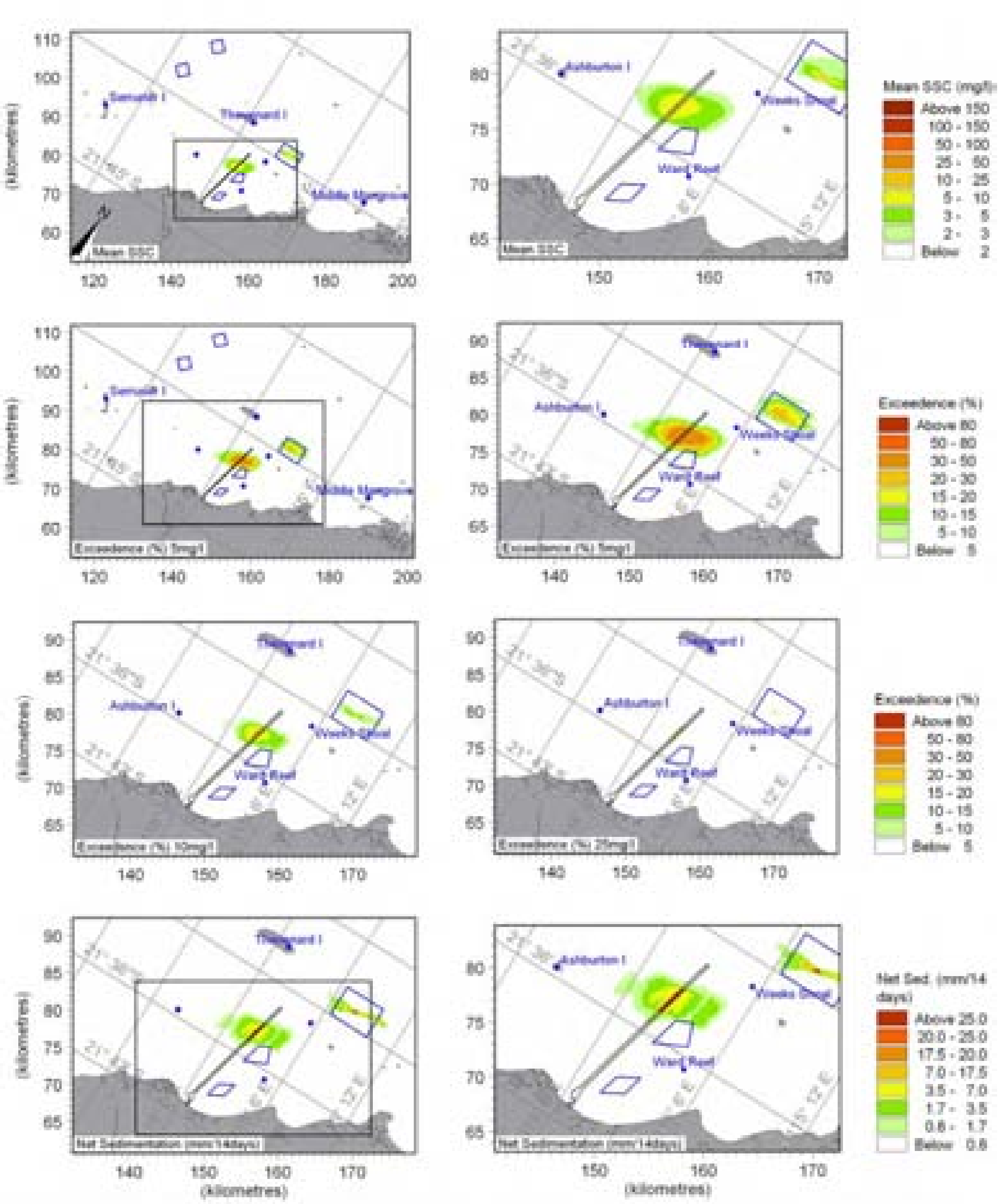

Figure CC.11 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7

DHI Water & Environment

CC-13

Dredge Scenario: Scenario 7
Climatic Scenario: Winter A
Spill Rate Estimate: High ("Worst Case")

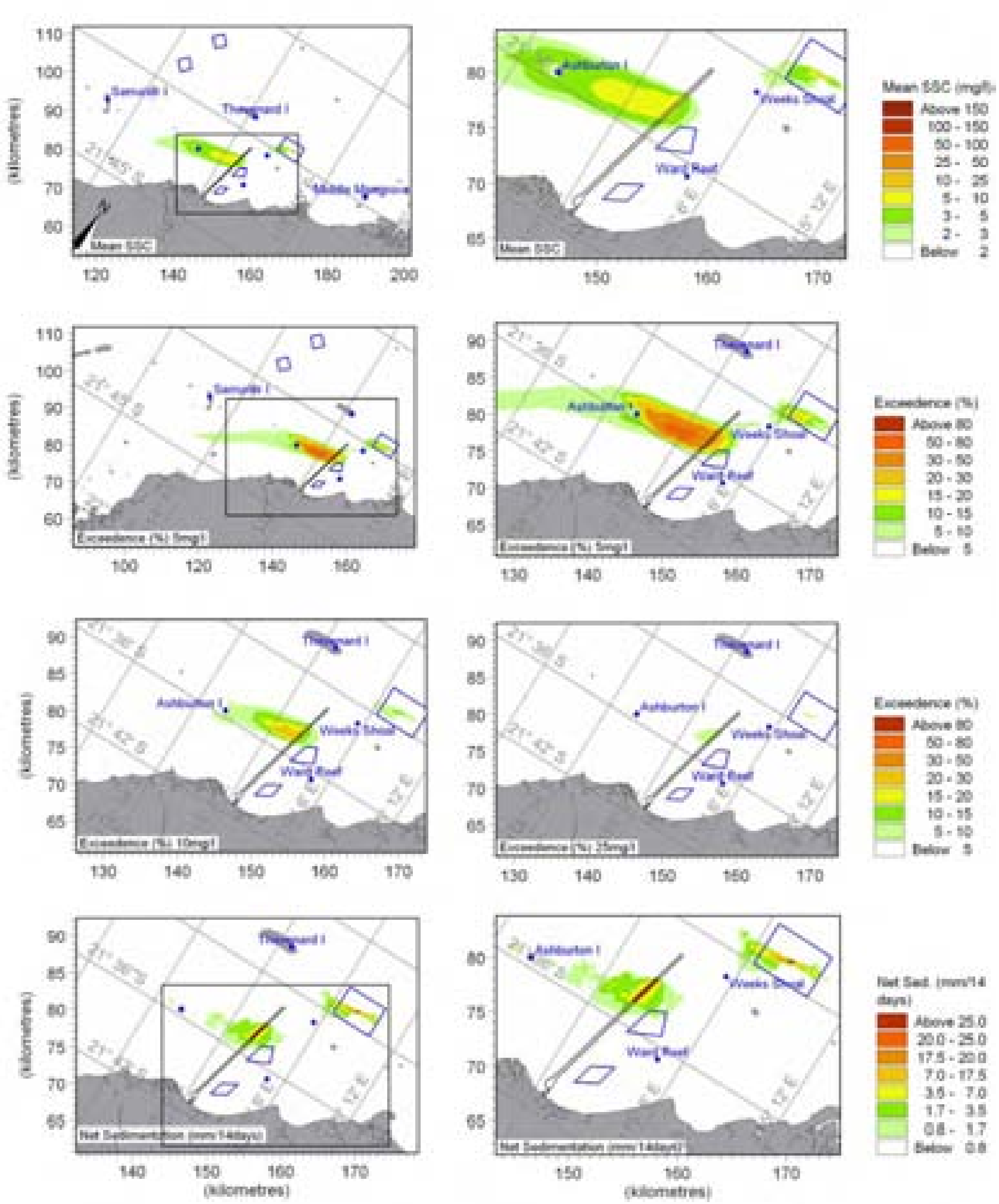

Figure CC.12 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7

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CC-14

Dredge Scenario:	Scenario 7
Climatic Scenario:	Winter B
Spill Rate Estimate:	High ("Worst Case")

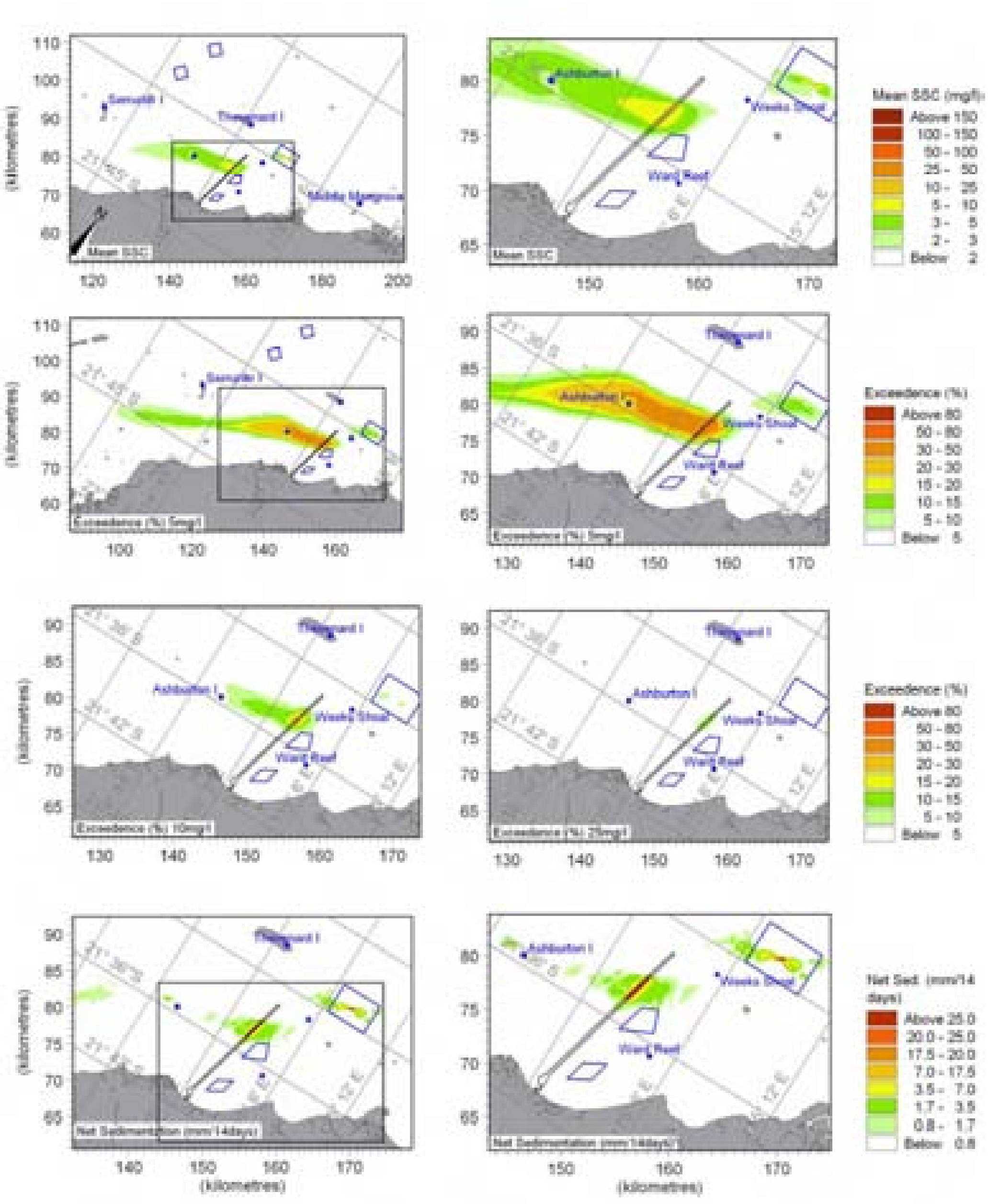

Figure CC.13 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7

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APPENDIX DD:

Results for Dredge Scenario 7A Based on MesoLAPS Winds

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DD RESULTS FOR DREDGE SCENARIO 7A BASED ON MESOLAPS WINDS

This appendix presents results from the sediment transport model based on hydrodynamics driven by the MesoLAPS wind fields. The reader is referred to the following sections of the main report and additional appendices for further information;

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- Section 6.2 *Results for the Dredging of the Shipping Channel*
- Appendix D *Hydrodynamic Model Validation and Calibration*

DD.1 Statistical Plots

The established impact criteria (DHI (2010) *Dredge Plume Impact Assessment Report)* are based on sediment loads, both in terms of excess suspended concentrations and sedimentation rates, over 14 day periods. In terms of exposure and impacts, both the concentrations and the duration of the event is important, which is expressed through the exceedence probability of given limits.

For each simulated case, a set of plots showing the statistical output used in the impact assessment have been produced. All plots are for excess concentrations, i.e. sediments originating from the dredging operations and exclusive of ambient concentrations.

Each mosaic plot comprises:

- Mean excess concentration at two scales
- Exceedence of 5mg/l excess concentration at two scales
- Exceedence of 10mg/l excess concentration
- Exceedence of 25mg/l excess concentration
- Net sedimentation rates at two zoomed levels at the site

Note that all concentrations are presented as depth-averaged values. All values are derived over the assessment period (2nd neap/spring tidal cycle of the month for each climatic scenario), i.e. after at least 14 days warm-up period. Exceedences are expressed in percentage time over the assessment period that the exceedence limit is exceeded.

DD.2 Description of Dredge scenario 7A

General

- Scenario 7A is a mitigated version of Scenario 7 to avoid overflow in critical zone.

Offshore Dredging: Approach Channel – Section 2 sand with operational mitigation

- 10,000m^3 TSHD with disposal at placement Site C
- Dredging along Section 2 and parts of Sections 1 and 3 with operational mitigation to avoid overflow in “no overflow” zone.

For each dredge cycle, the TSHD starts dredging at the centre of the “no overflow” zone within Section 2. It takes 25 minutes, corresponding to a sailing distance of 1.5km for a speed of 1m/s (app. 2knots) before overflow starts. The dredger keeps dredging for another 3km with overflow. The dredger dredges towards south and north, respectively, on alternate trips. This leads to a 3 km section with no overflow with 3km with overflow on each side, i.e. the total channel section being dredged is 9km.

The locations for the various dredge and placement activities are outlined in Figure DD.1, while defined low (realistic) and high (worst case) spill rates applied in Dredge Scenario 7A are listed in Table 3.2 of the main report.

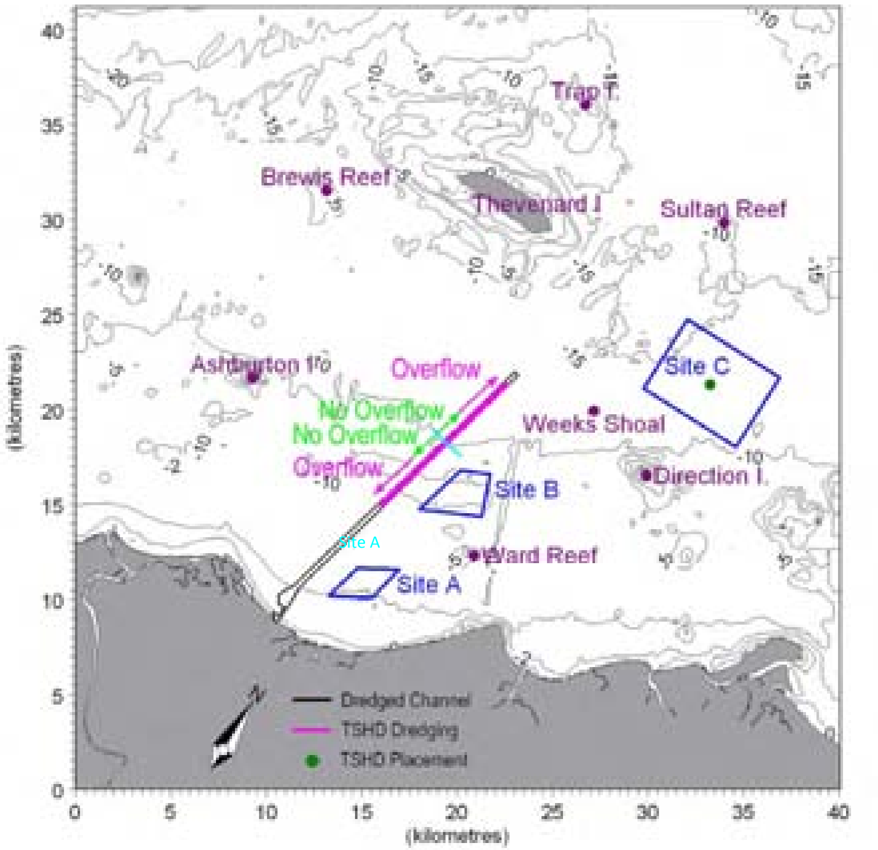

Figure DD.1 Sketch of locations for Dredge Scenario 7A.

DD.3 Summary of Results

Specific observations for Dredge Scenario 7A include:

- The no overflow zone is clearly distinguishable in the plots.
- The alternate dredging in two adjacent areas leads to much lower mean excess concentrations and exceedence values (the spill in tonnes/day along each section is only half compared to Section 2 in Scenario 7).
- Overall, the scenario leads to a larger area affected, but at much lower exceedences.
- The Mitigation is considered effective in reducing the impacts at the critical receptors adjacent to this sector of channel.

DD.4 Results for Low (Realistic) Spill Rates

Dredge Scenario:	Scenario 7A
Climatic Scenario:	Summer A
Spill Rate Estimate:	Low ("Realistic") Case

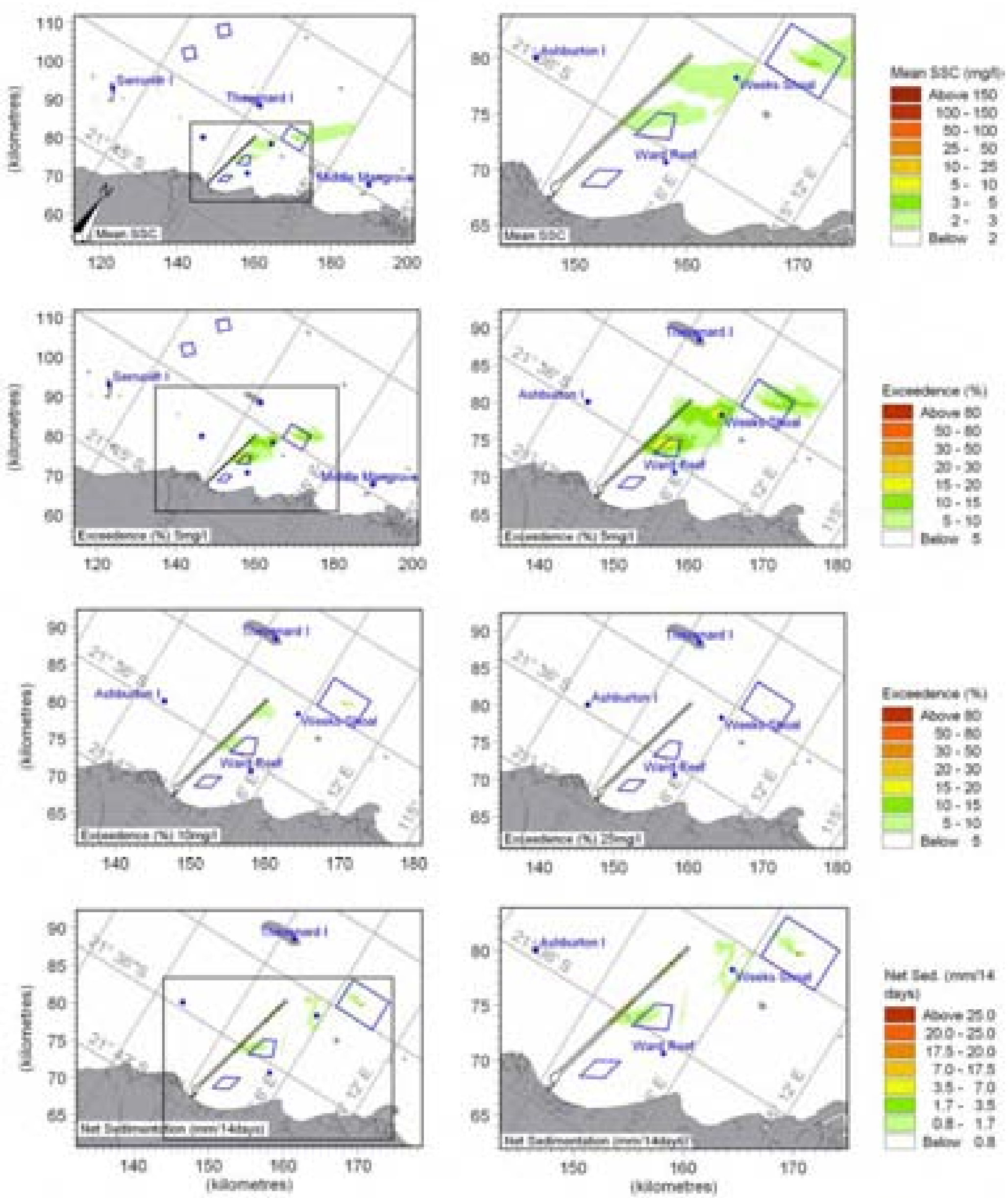

Figure DD.2 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7A

DD-4

Dredge Scenario: Scenario 7A
Climatic Scenario: Summer B
Spill Rate Estimate: Low ("Realistic") Case

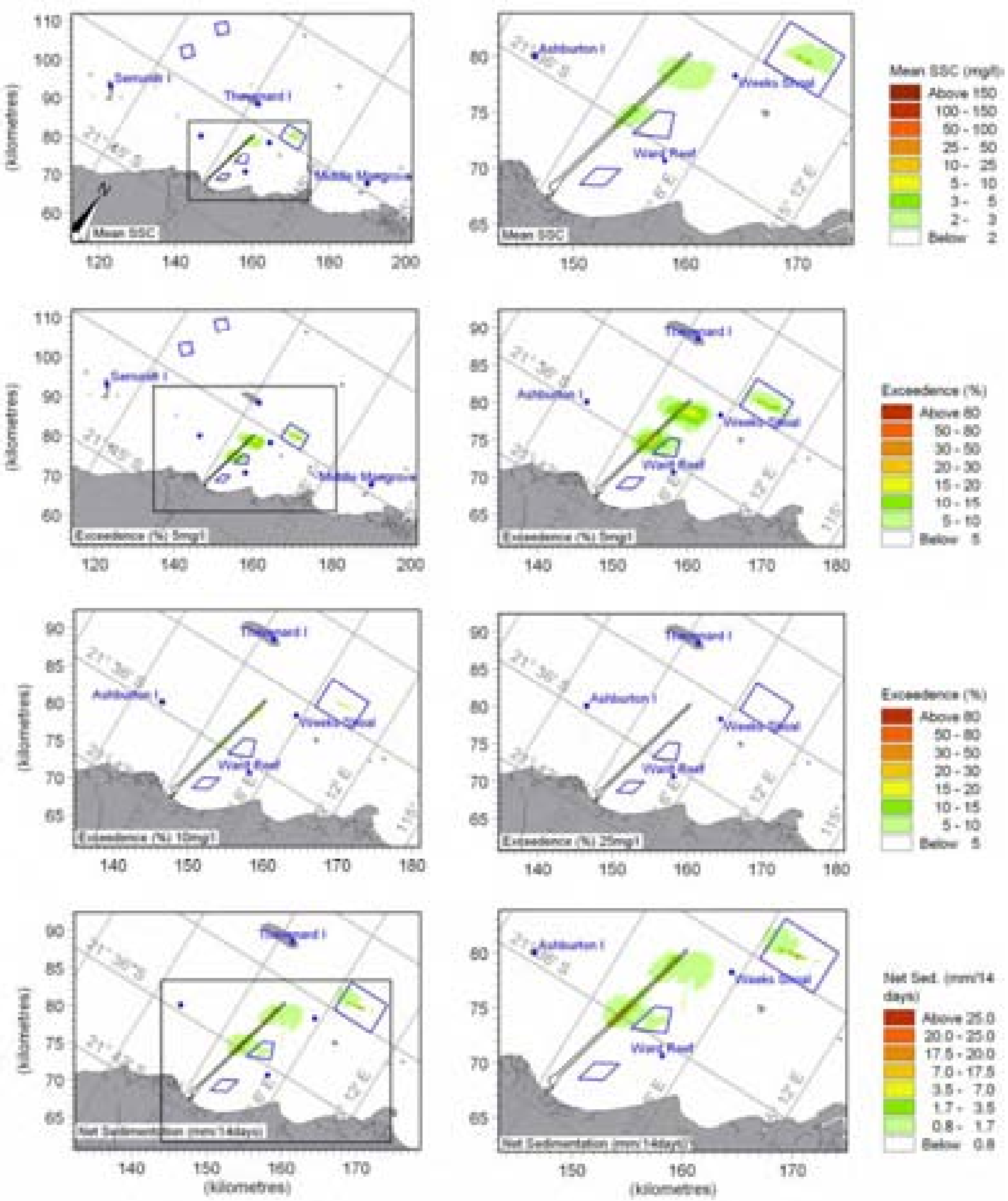

Figure DD.3 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7A

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DD-5

Dredge Scenario: Scenario 7A
Climatic Scenario: Transitional A
Spill Rate Estimate: Low ("Realistic") Case

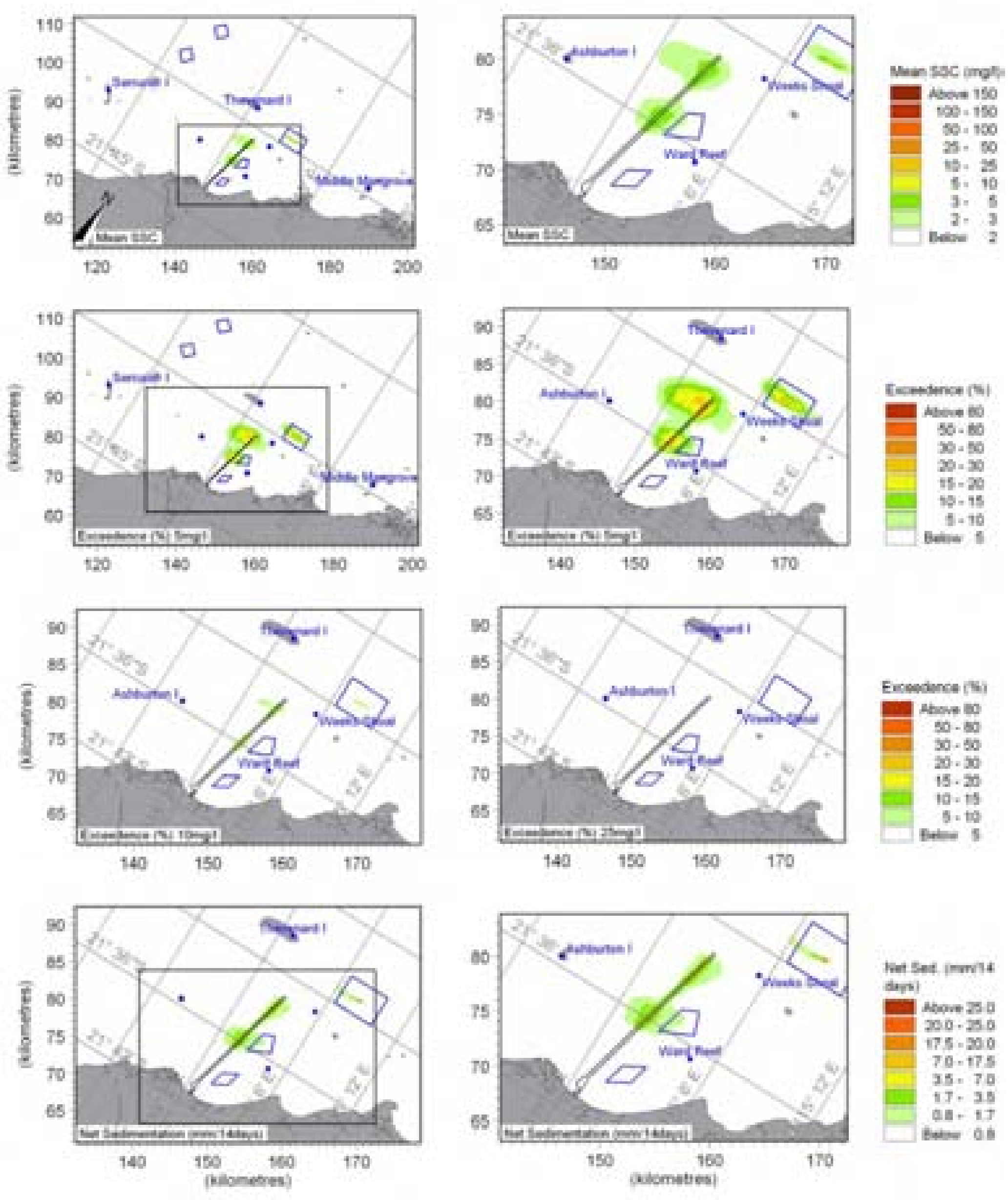

Figure DD.4 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7A

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DD-6

Dredge Scenario:	Scenario 7A
Climatic Scenario:	Transitional B
Spill Rate Estimate:	Low ("Realistic") Case

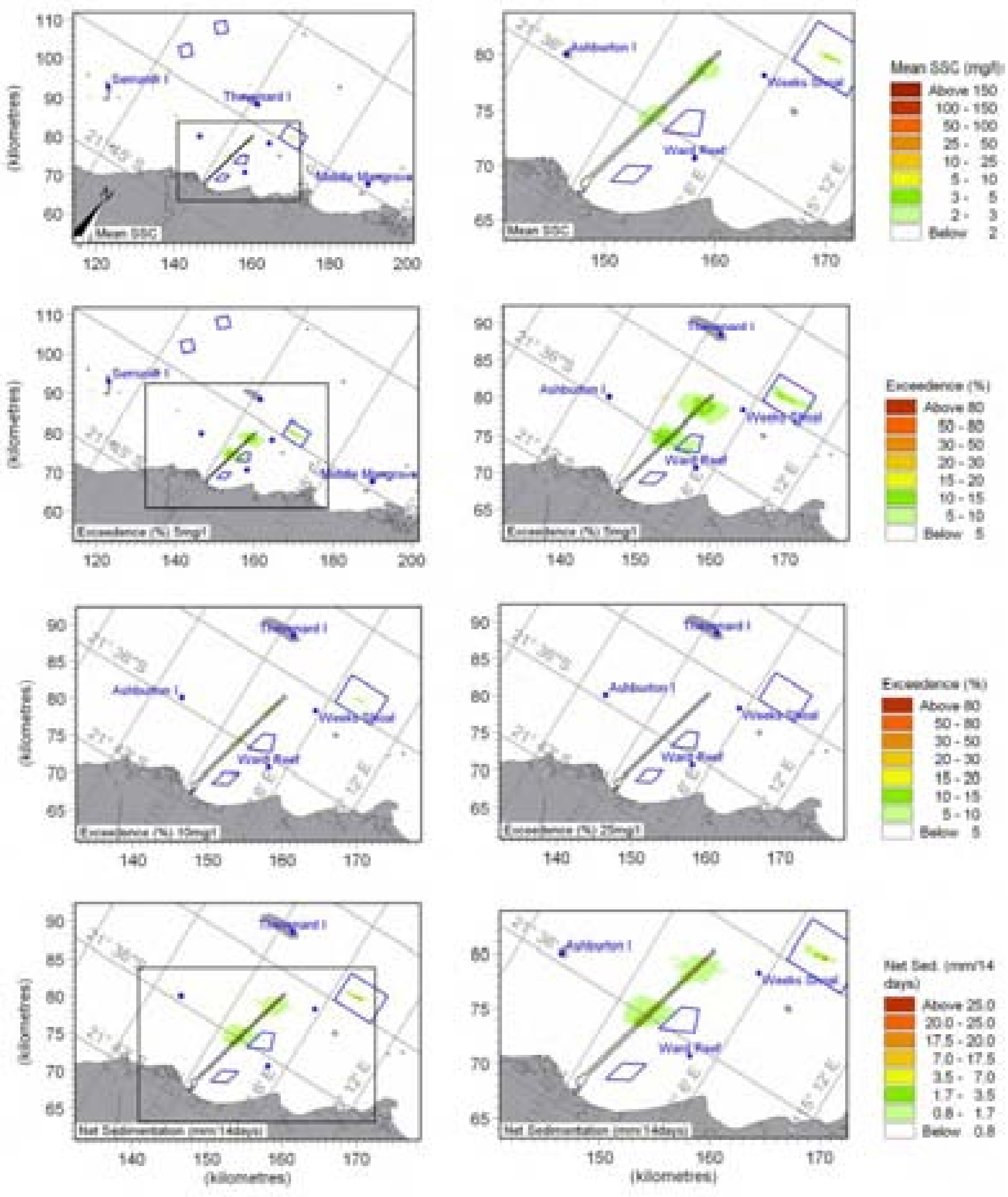

Figure DD.5 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7A

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DD-7

Dredge Scenario: Scenario 7A
Climatic Scenario: Winter A
Spill Rate Estimate: Low ("Realistic") Case

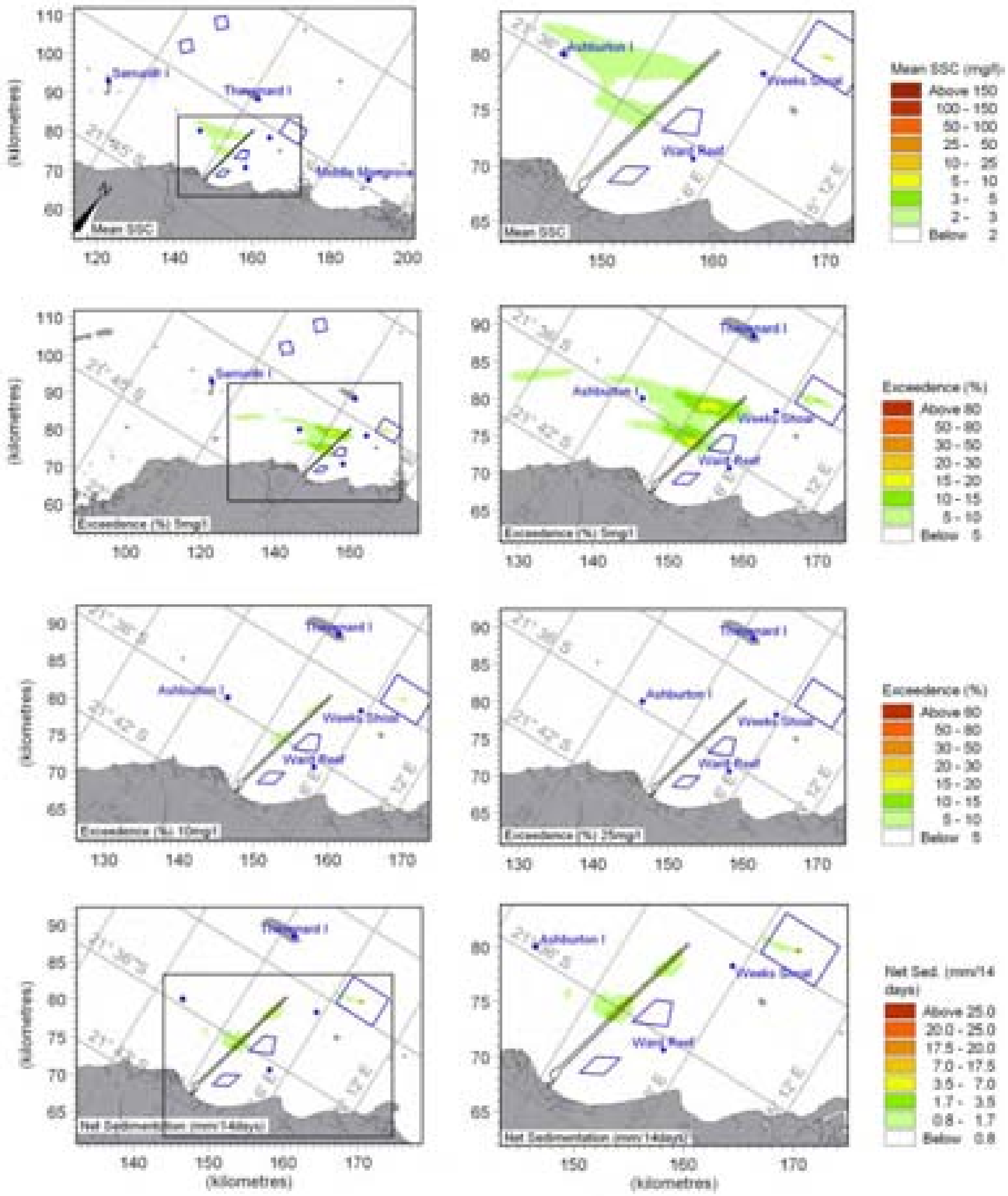

Figure DD.6 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7A

DD-8

Dredge Scenario: Scenario 7A
Climatic Scenario: Winter B
Spill Rate Estimate: Low ("Realistic") Case

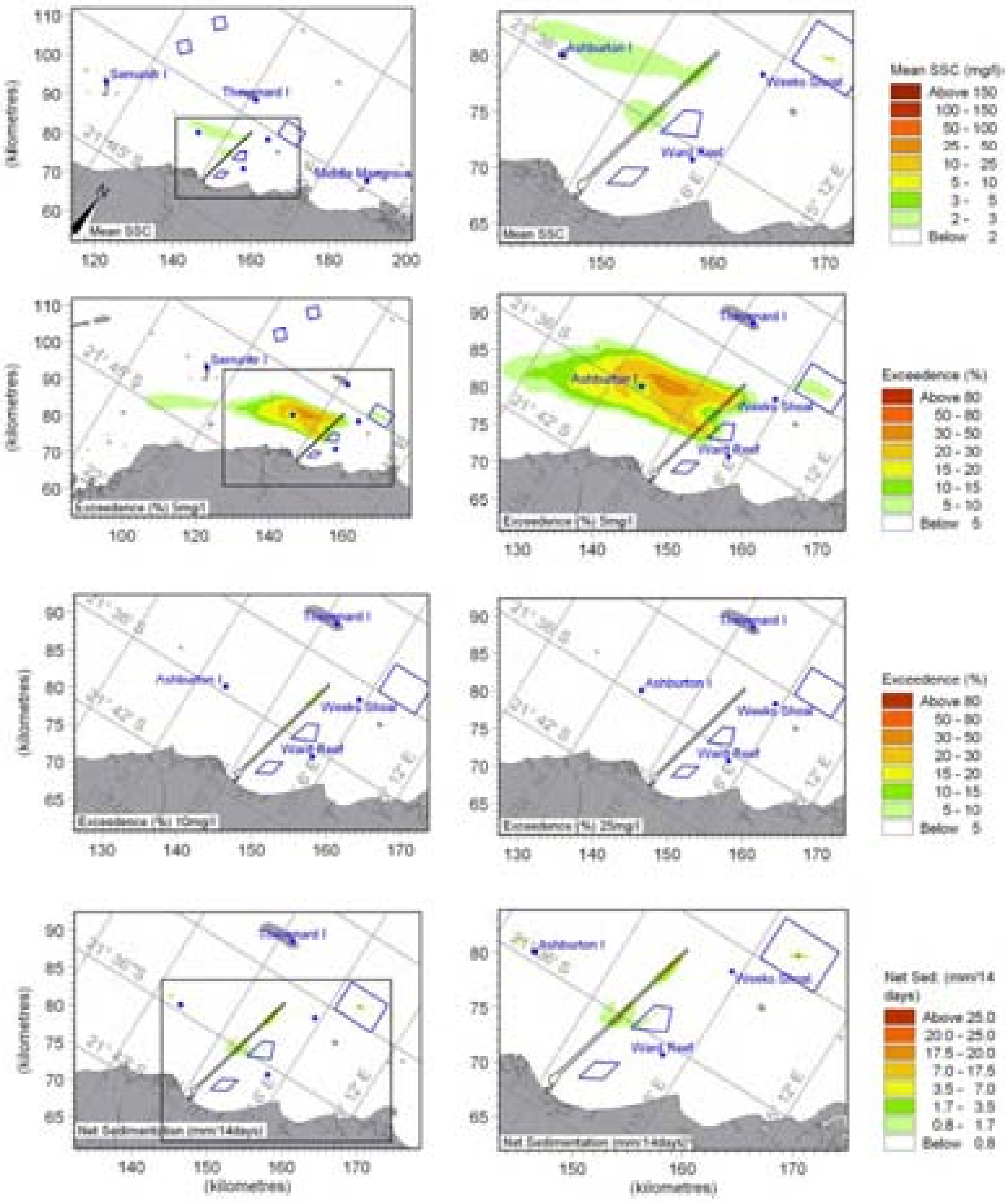

Figure DD.7 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7A

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DD.5 Results for High (Worst-Case) Spill Rates

Dredge Scenario:	Scenario 7A
Climatic Scenario:	Summer A
Spill Rate Estimate:	High ("Worst Case")

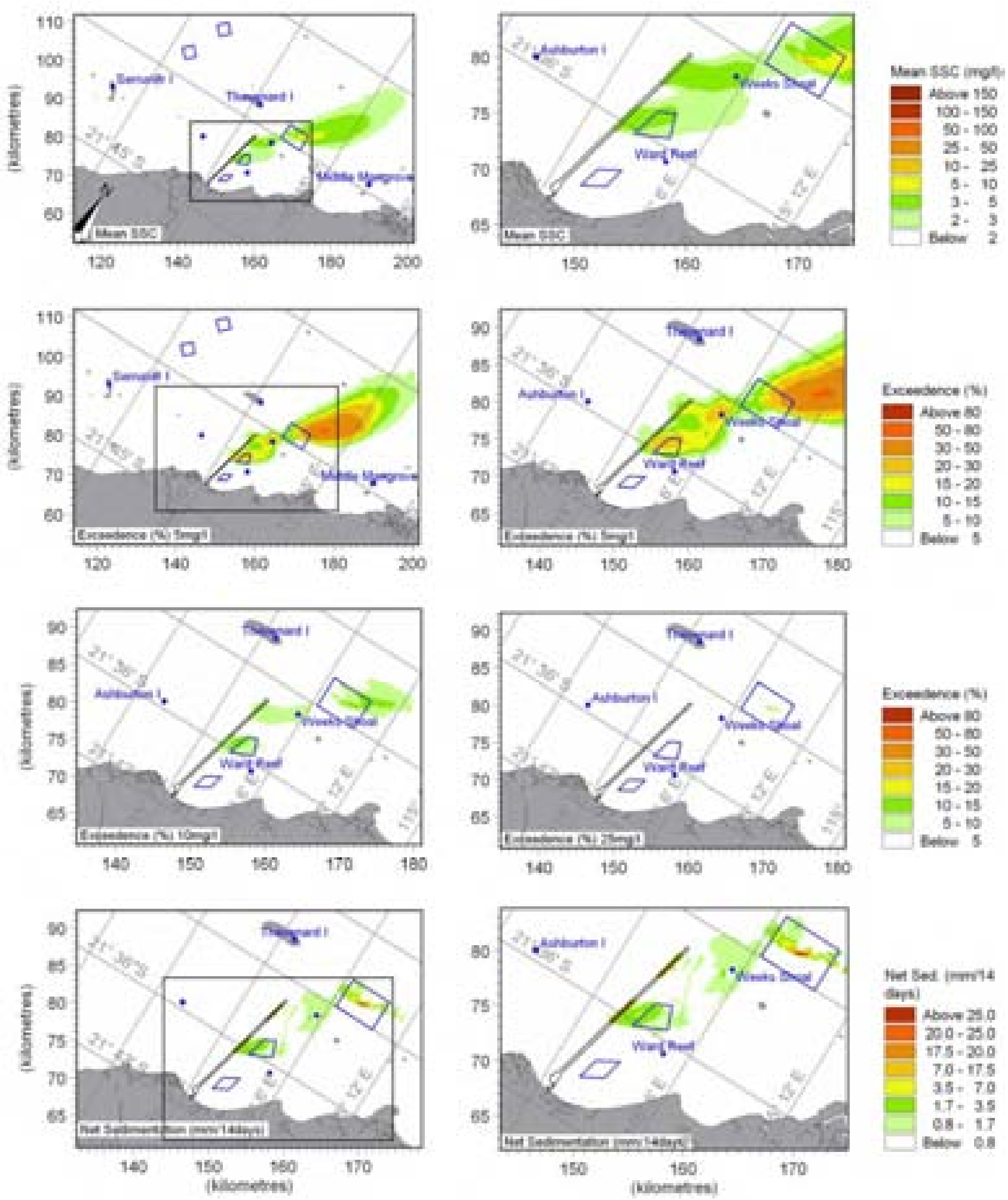

Figure DD.8 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7A.

DD-10

Dredge Scenario: Scenario 7A
Climatic Scenario: Summer B
Spill Rate Estimate: High ("Worst Case")

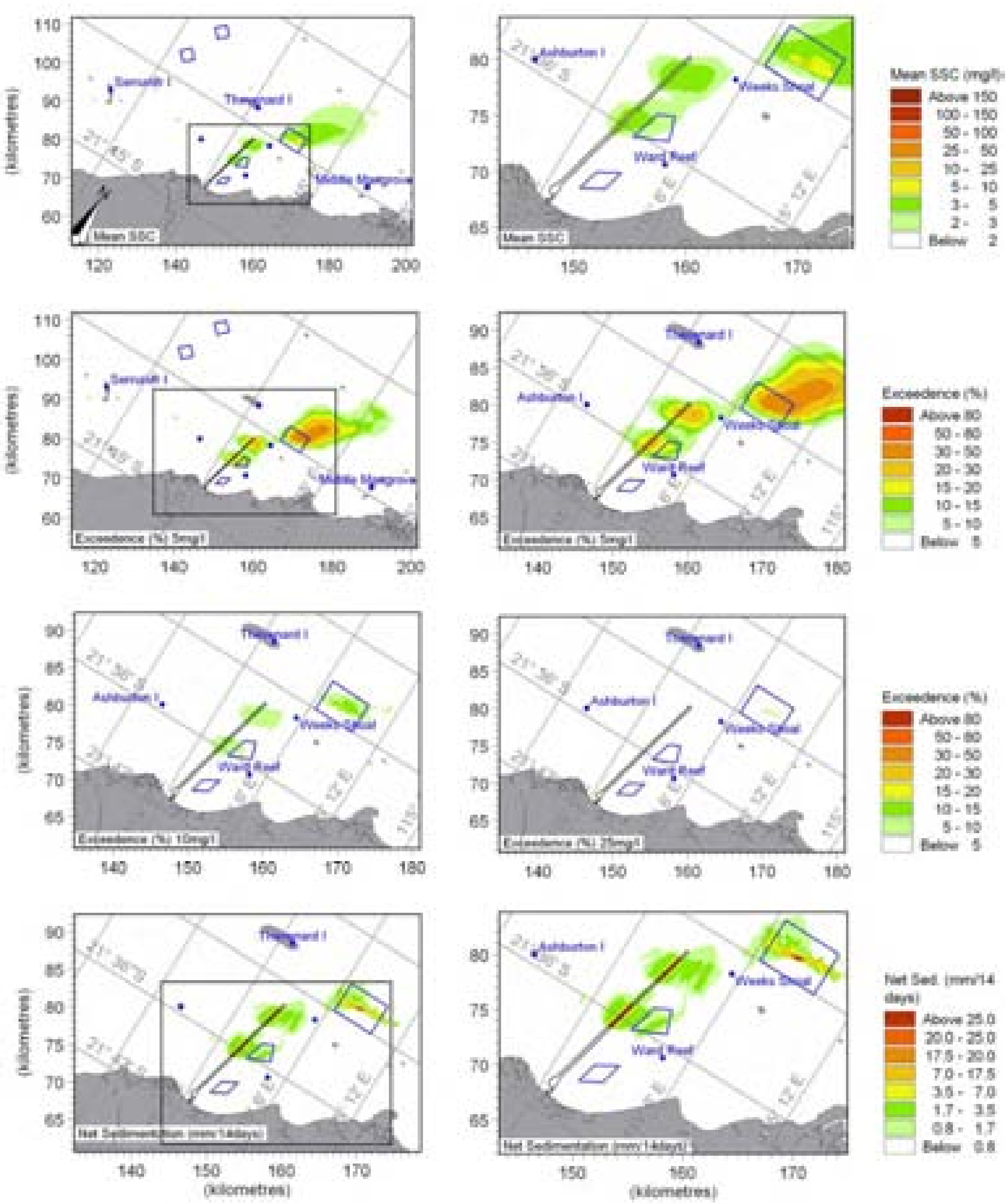

Figure DD.9 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7A.

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DD-11

Dredge Scenario:	Scenario 7A
Climatic Scenario:	Transitional A
Spill Rate Estimate:	High ("Worst Case")

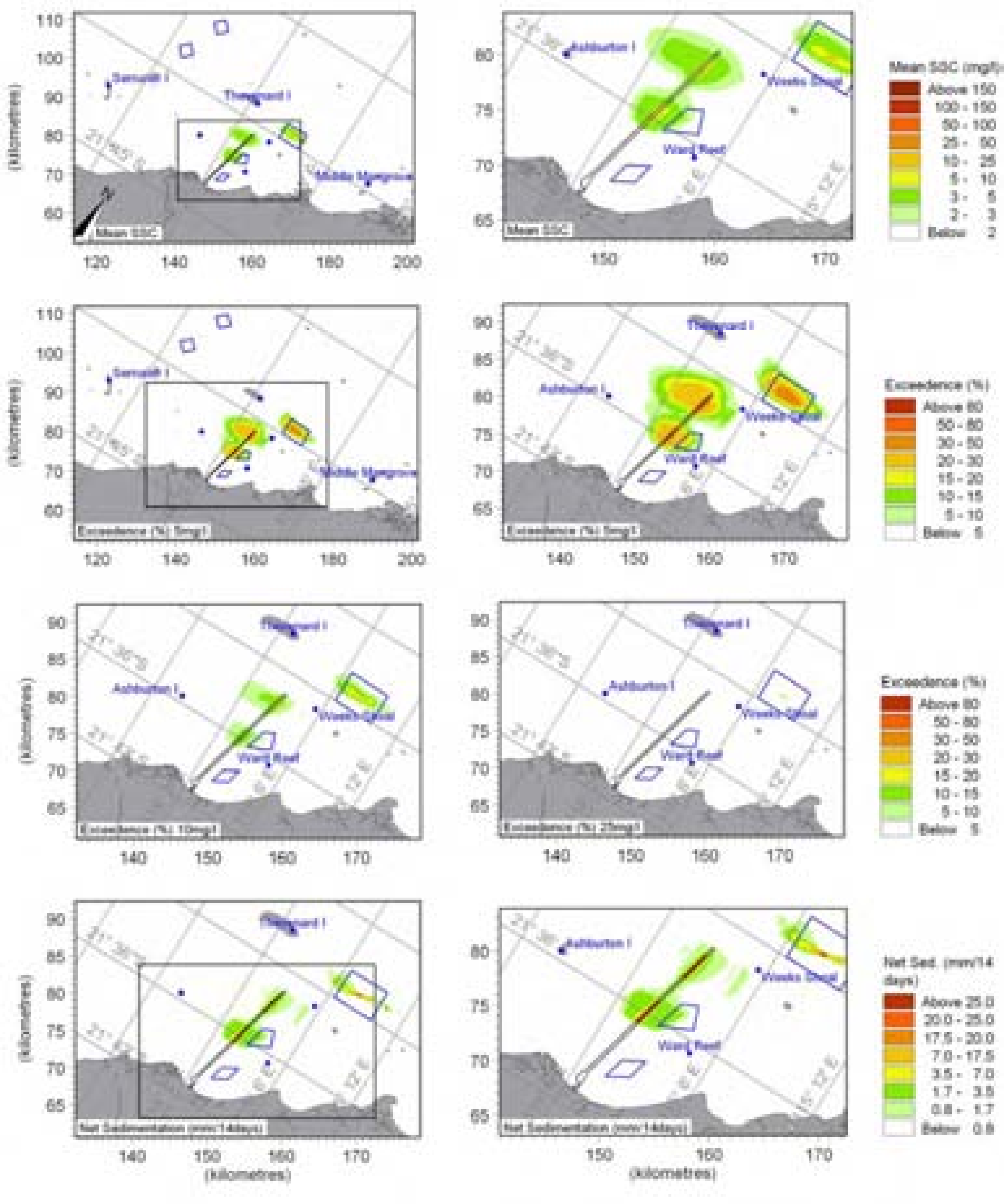

Figure DD.10 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7A

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DD-12

Dredge Scenario: Scenario 7A
Climatic Scenario: Transitional B
Spill Rate Estimate: High ("Worst Case")

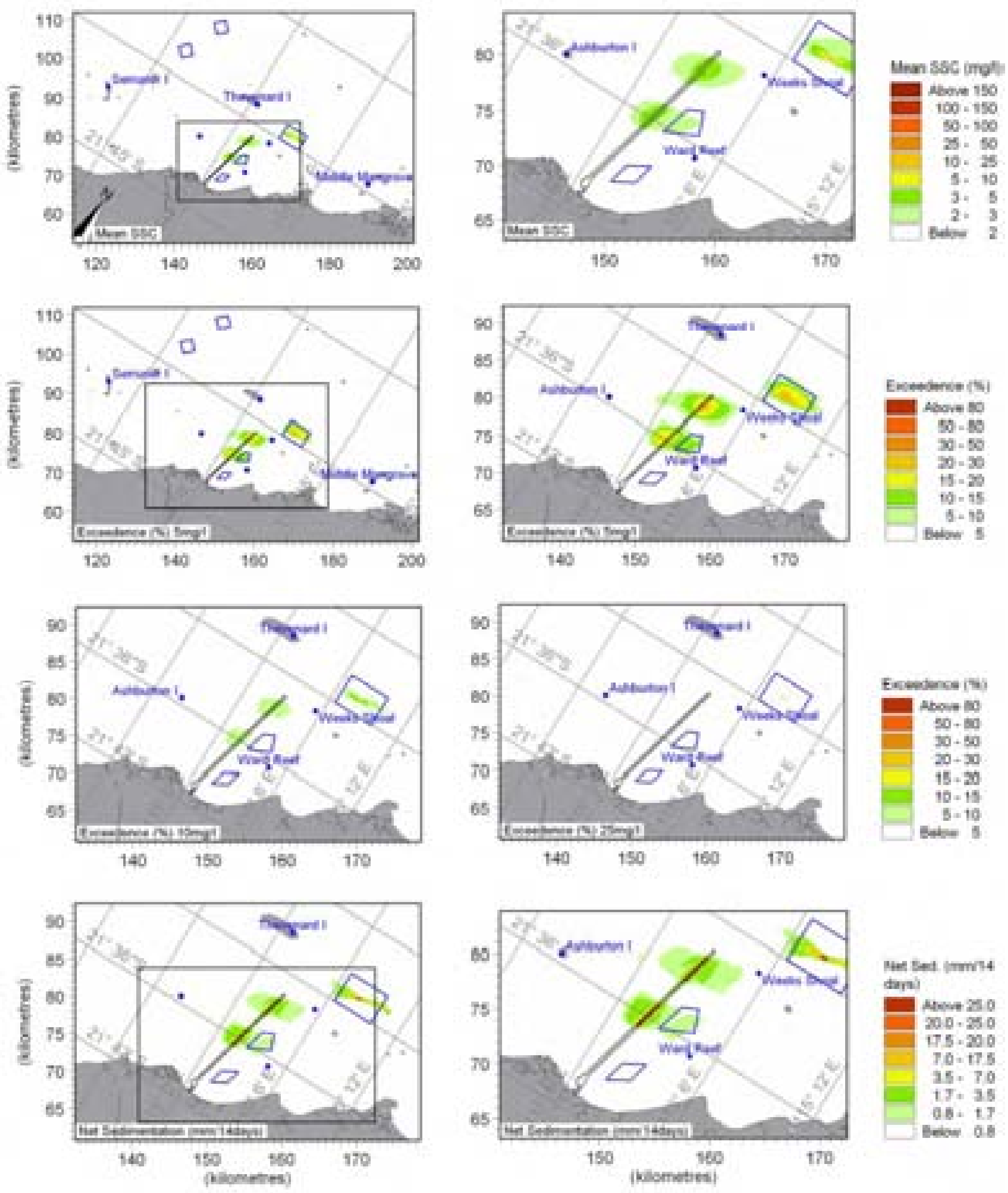

Figure DD.11 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7A

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DD-13

Dredge Scenario: Scenario 7A
Climatic Scenario: Winter A
Spill Rate Estimate: High ("Worst Case")

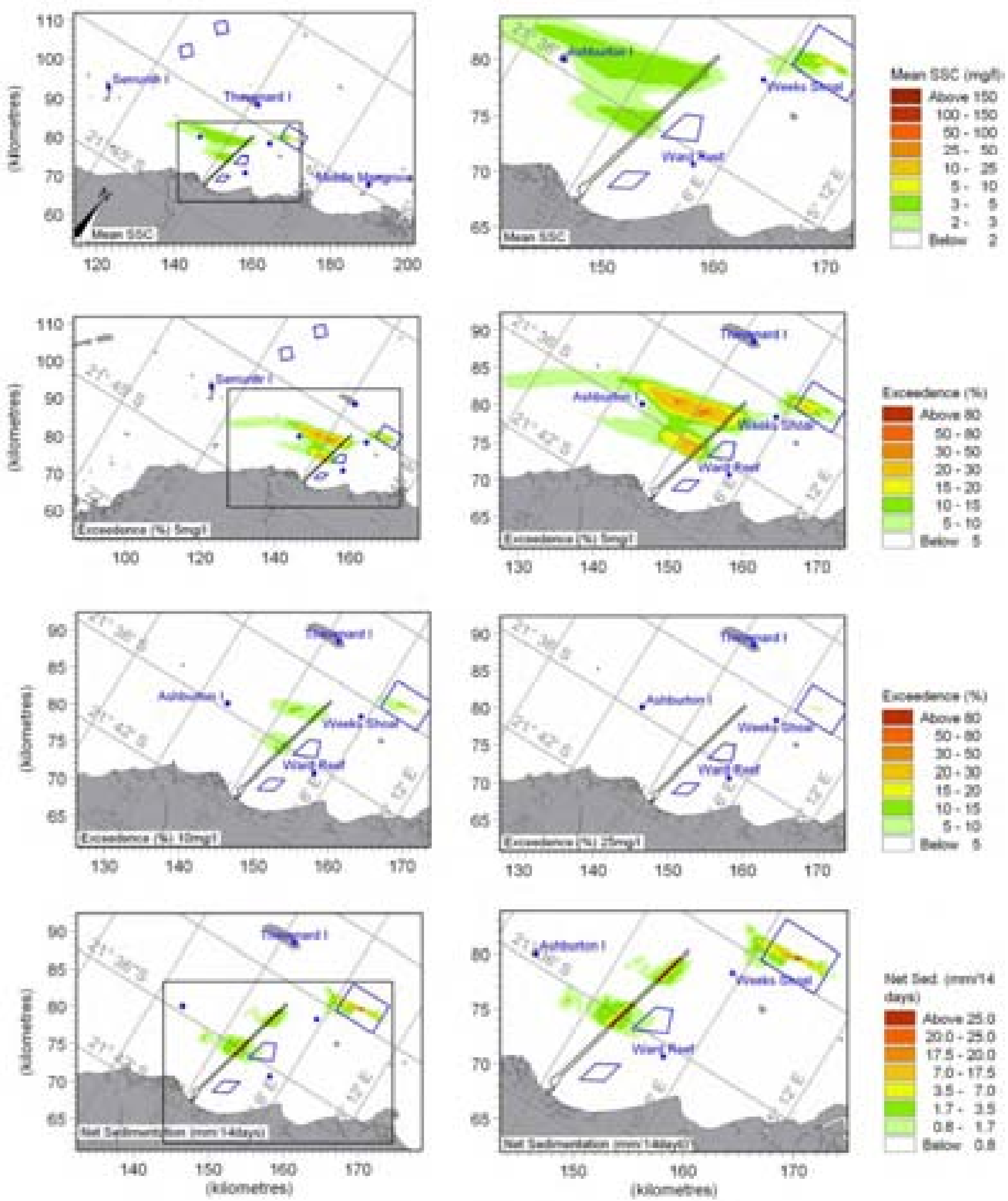

Figure DD.12 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7A

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DD-14

Dredge Scenario:	Scenario 7A
Climatic Scenario:	Winter - representative
Spill Rate Estimate:	High ("Worst Case")

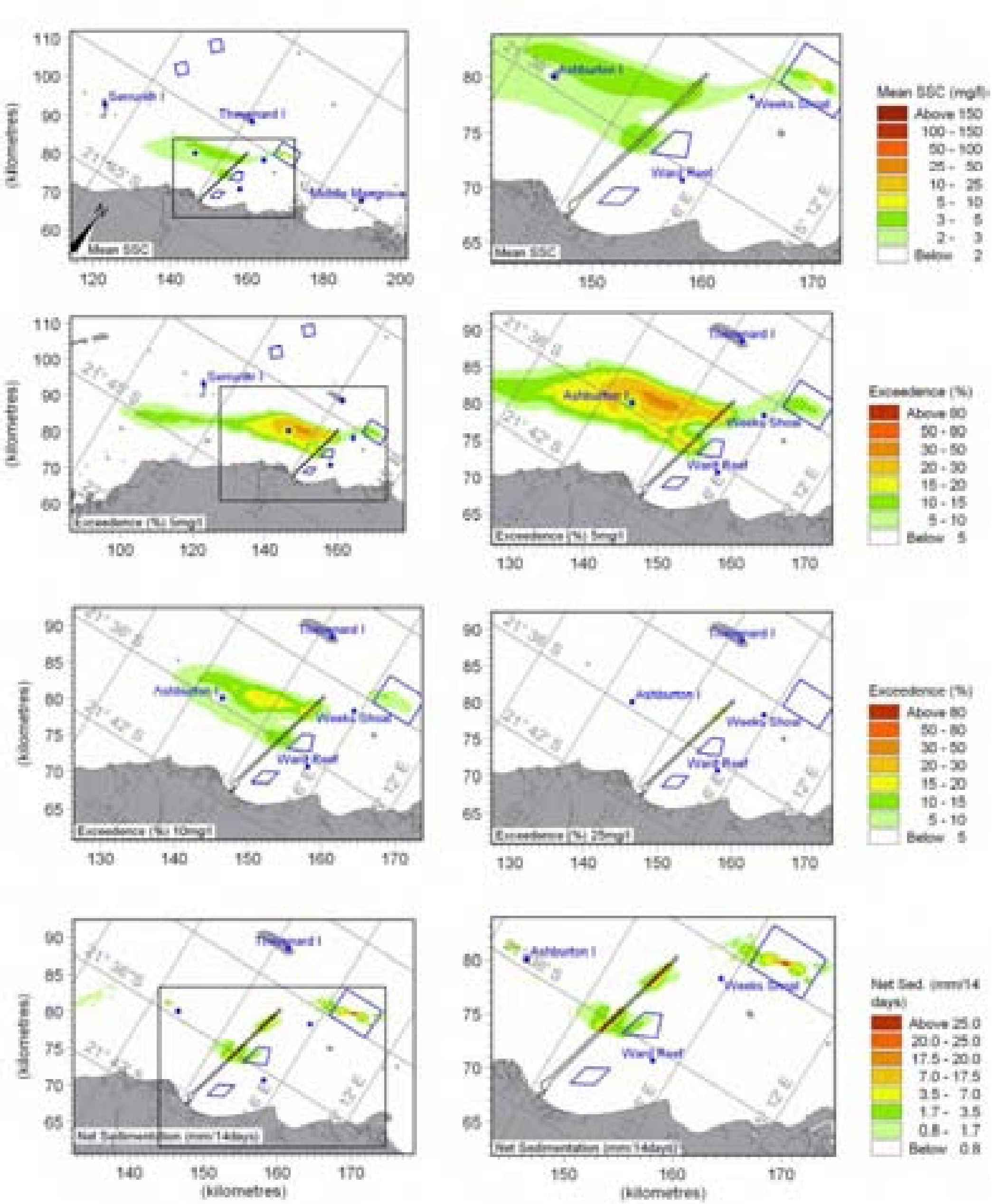

Figure DD.13 Map of mean excess concentration, exceedence (in percentage of time) of given threshold limits of excess suspended sediments and net sedimentation (in mm/14 days) for dredging and disposal works for Scenario 7A.

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1

Wheatstone Project
Dredge Spoil Modelling

A P P E N D I X   E E :

Spoil Ground Stability Assessment

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CONTENTS

FIGURES AND TABLES

EE SPOIL GROUND STABILITY

Five different spoil grounds – three in "nearshore", relatively shallow water in the vicinity of the dredged channel (Sites A, B and C) and two in deeper "offshore" waters (Sites D and E), see Figure EE.1 and Figure EE.2, are considered for the project. Site C is the main spoil ground with Site A scheduled to be used in the initial dredging of a temporary access channel to the MOF, Site B is a contingency for dredging in the vicinity of Ward Reef, and Sites D and E are intended for the fines from clean-up dredging only.

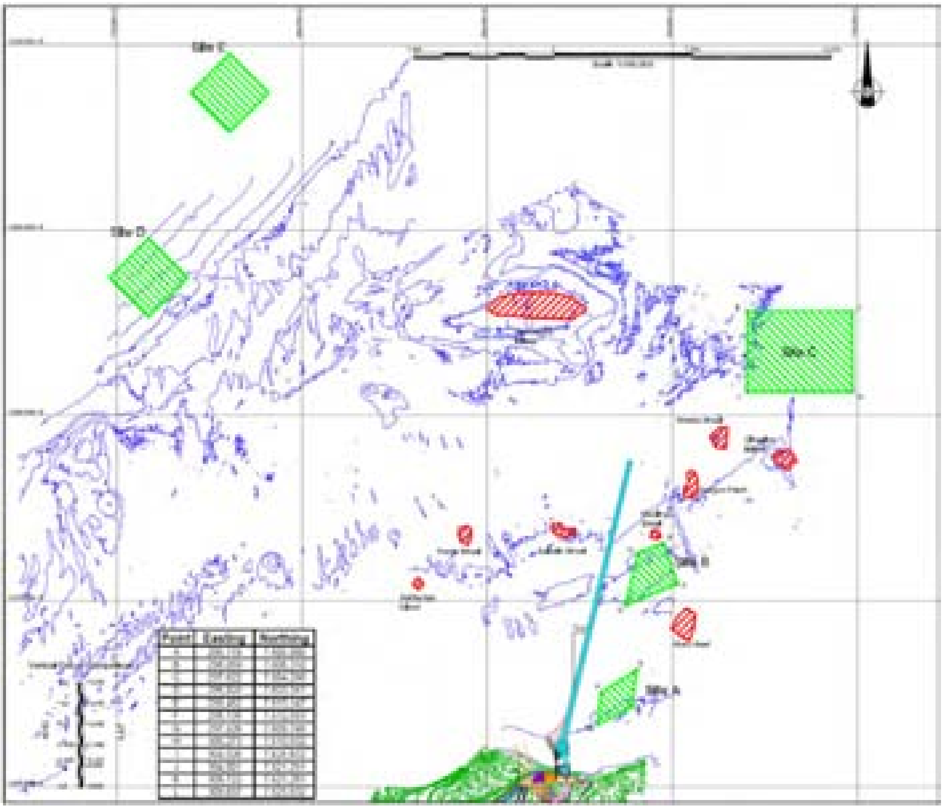

Figure EE.1 Location of dredge Placement Sites A, B, C, D and E (indicated with green polygons).

To address the environmental impacts of the spoil grounds, three components need to be considered:

1. The direct loss of habitats at the spoil grounds due to the operations – this may be of temporary or more permanent character depending on changes in the soil conditions and the potential for re-colonization.
2. The impacts to the surrounding areas from sediments emitted from the spoil grounds during the operations.
3. The impacts to the surrounding areas by sediments from the spoil grounds after completion of the project and placement activities.

Point 1 was addressed through the habitat assessment, and point 2 through the sediment plume modelling and definition of impact zones. The present Section addresses point 3.

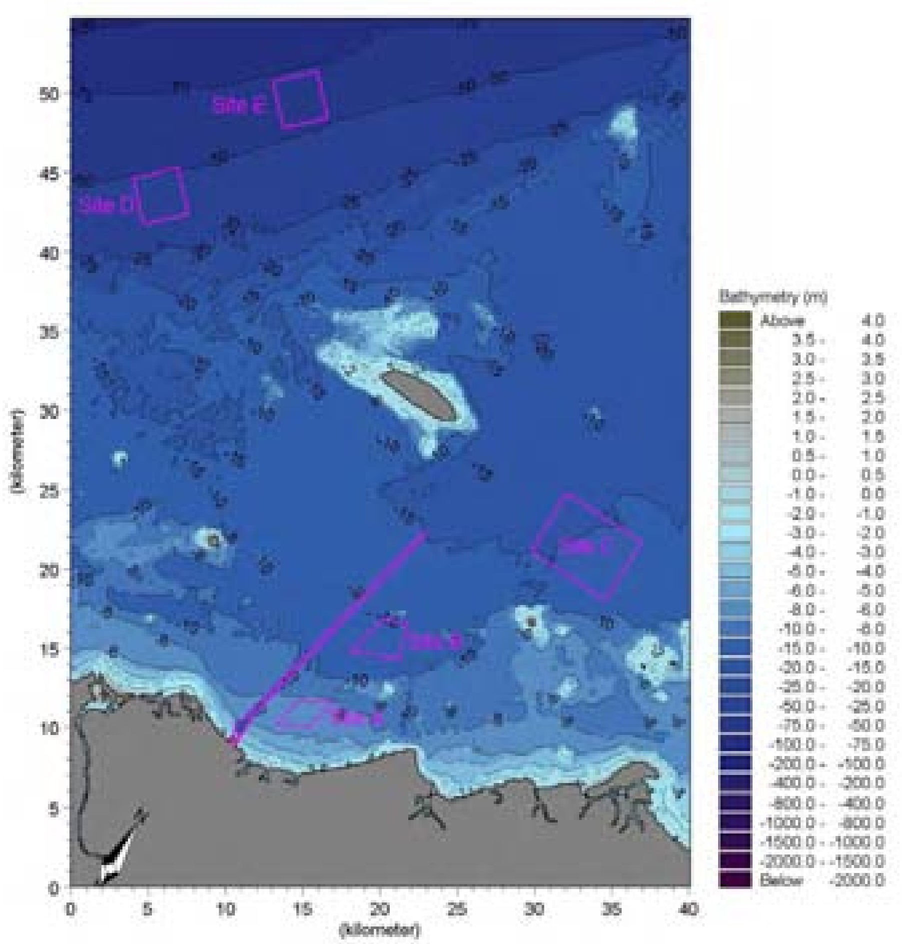

Figure EE.2 Model bathymetry (135m grid spacing) with locations of the spoil grounds.

Stability of the proposed spoil grounds is not simple to address. In addition to the combined forces from currents and waves acting on the bottom – expressed through the bottom shear stresses, the stability (or bottom mobility) is determined by the type of sediment and level of consolidation and cohesion.

The stability is assessed through 3 means:

1. An assessment of the bottom shear stresses and the corresponding "minimum stable" grain size, disregarding cohesion and consolidation.
2. An assessment of the changes in the bottom shear stresses due to the average change in bed level
3. An assessment of the existing surface sediment composition compared to the expected composition of the sediment to be placed at the spoil grounds.

EE.1 "Stable" Sediment Grain Size

A simple estimate of a stable sediment grain size can be derived from the critical shields parameter formulation for initiation of movement of sand particles:

$$\theta_c = \frac{\tau_b}{\rho g(s-1)d} = 0.05$$

where τ_b = bed-shear stress, g = acceleration of gravity, s = specific gravity (2.65), ρ = density of water and d = smallest grain size that is at rest. This can be rewritten:

$$d = \frac{\tau_b}{0.05\rho g(s-1)}$$

This formula only applies for sand as it is based on a force balance between gravity of the bed surface particles and the agitating force of the flow. It also assumes uniform sediment composition.

The cohesive forces are not included in the above and the formula is therefore not applicable to mud and clay fractions as well as certain sand/mud mixtures which have increased stability partly due to the cohesiveness and partly due to the reduced porosity in sand/mud mixtures. Using the above formula thus over-predicts mobility if mud is present and is therefore considered conservative. The assumptions tied to the formula are however not believed to be violated severely considering the grain size distribution documented in Ref. /9/ (see also Section EE.3) and should provide a reasonably first estimate of sediment mobility thresholds.

EE.1.1 Bottom Shear-Stress Maps

The bed shear stresses during summer, winter and transitional periods as well as during cyclonic events (not included in the other seasons) have been calculated using the MIKE 21 HD model complex set up for the dredge spoil modelling. The bed shear stresses are calculated using the parameterized model of Soulsby et. al. (Soulsby R.L., Hamm L., Klopman G., Myrhaug D., Simons R.R., and Thomas G.P., 1993. "Wave-current interaction within and outside the bottom boundary layer". Coastal Engineering, 21, 41-69), which provides the period-averaged bed shear stress in combined wave-current flow. Note that the results presented in the following are without the changes in bathymetry (reduced water depth) as a result of the disposal material. This is investigated separately in Section EE.2.

Maps of bed-shear stresses (N/m^2) exceeded 1%, 2% and 5% of time are presented in Figure EE.3 for simulated summer months, and in Figure EE.4 and Figure EE.5 for transitional and winter months. The proposed spoil ground locations as well as an outline of the dredged areas are outlined in pink. It is noted that the whereas the simulations include both waves and currents, they have not been set up to resolve the surf zone and the higher wave-induced currents and related shear stresses in the surf zone. The plots therefore do not represent the expected higher shear stresses in the surf zone. This has no bearing on the assessment of the shear stresses at the proposed spoil grounds or over the area in large.

Model results show that both the dredged channel and the proposed spoil grounds are located in areas of relatively low shear stresses, which points towards a relatively stable, potentially depositional environment. Summer shear stresses are slightly higher than during transitional and winter periods due to smaller waves during winter and slightly stronger wind driven currents during summer. Bottom shear stresses are significantly higher around headlands and over shallower and more exposed areas. However, there are peaks in the bottom shear stresses associated with higher currents (spring tide and strong wind driven flows) and/or wave events which have the capacity to re-suspend fine and coarser sediment, and although the project area is surrounded by areas of higher mobility, the area cannot be expected to be a deposition basin as such as there are large spatial variations in grain size distributions.

EE.1.2 Stable Grain Sizes

Based on the Shields formulation provided above, the shear stress maps can be converted to a corresponding map over the "minimum stable" grain size under the assumptions previously given. Figure EE.6 and Figure EE.7 shows maps of minimum stable grain sizes for the 2% and 5% exceeded bottom shear stresses, respectively.

Using this procedure the smallest grain size at rest for 95% of the time is estimated to 0.2 – 0.3 mm at spoil grounds A and B, and between 0.2 – 0.45 mm at Site C. This would imply that the area is composed by relatively coarse sand which is mobilized for a small percentage of time and perhaps during the very peak of the wave-induced oscillatory flow. The grab samples (see Section EE.3) support the conclusions above that the bed material is predominantly sandy and at certain locations relatively coarse. Based on the modelling results and the mean grain sizes from the grab samples it is concluded that the spoil ground C will be characterised by even coarser material as the wave-current induced bed-shear stresses are larger here. This is also confirmed in "Wheatstone Sediment Quality Assessment". Prepared for Chevron Australia Pty Ltd, 30 October 2009, which indicates that material is coarser within spoil ground C.

EE.1.3 Effects of Consolidation and Cohesive Forces

Consolidation and cohesive forces can increase the resistance to erosion. A criterion of $0.3 N/m^2$ is considered a typical critical value for initiation of erosion of mud beds which are subject to cohesive forces. This value is not exceeded under "normal" conditions for the offshore spoil ground locations D and E, whereas it is slightly exceeded at Sites A, B and C.

EE.1.4 Bed-shear Stresses during Cyclonic Events

The bed-shear stresses during Cyclone Vance (1999) have also been calculated using MIKE 21 with wind field information from:

- http://weather.unisys.com/hurricane/s_indian/index.html (JTWC Best Track)
- http://australiasevereweather.com/cyclones/1999/trak9903.htm (Monthly Global Tropical Cyclone Tracks March 1999)

Instantaneous maps of bed-shear stresses are shown in Figure EE.8 and Figure EE.9. These generally show very high bed-shear stresses. Although Vance was a very strong cyclone it is not necessarily the most critical cyclone for the area in terms of inducing seabed mobility, but it provides an example of the potential stresses induced during more extreme events. This illustrates that extreme conditions have the potential to mobilise the sea bottom throughout the shallow shelf area, and significant amounts of sediments are expected to be suspended during cyclones, which is in agreement with observations.

Whereas the sediment mobility is high and sediment transport rates can be high during cyclones, the events are normally relatively short lived, and the total transport in/out of the placement areas may therefore not be dominant. The overall patterns identified in previous bed-shear stress plots for summer, winter and transitional periods are also recognized during the cyclone event where in particular the eastern part of spoil ground C is subject to larger bottom stresses then at spoil ground A and B. During the height of the cyclone seabed mobility will be pronounced throughout the nearshore region and also offshore at spoil grounds D and E.

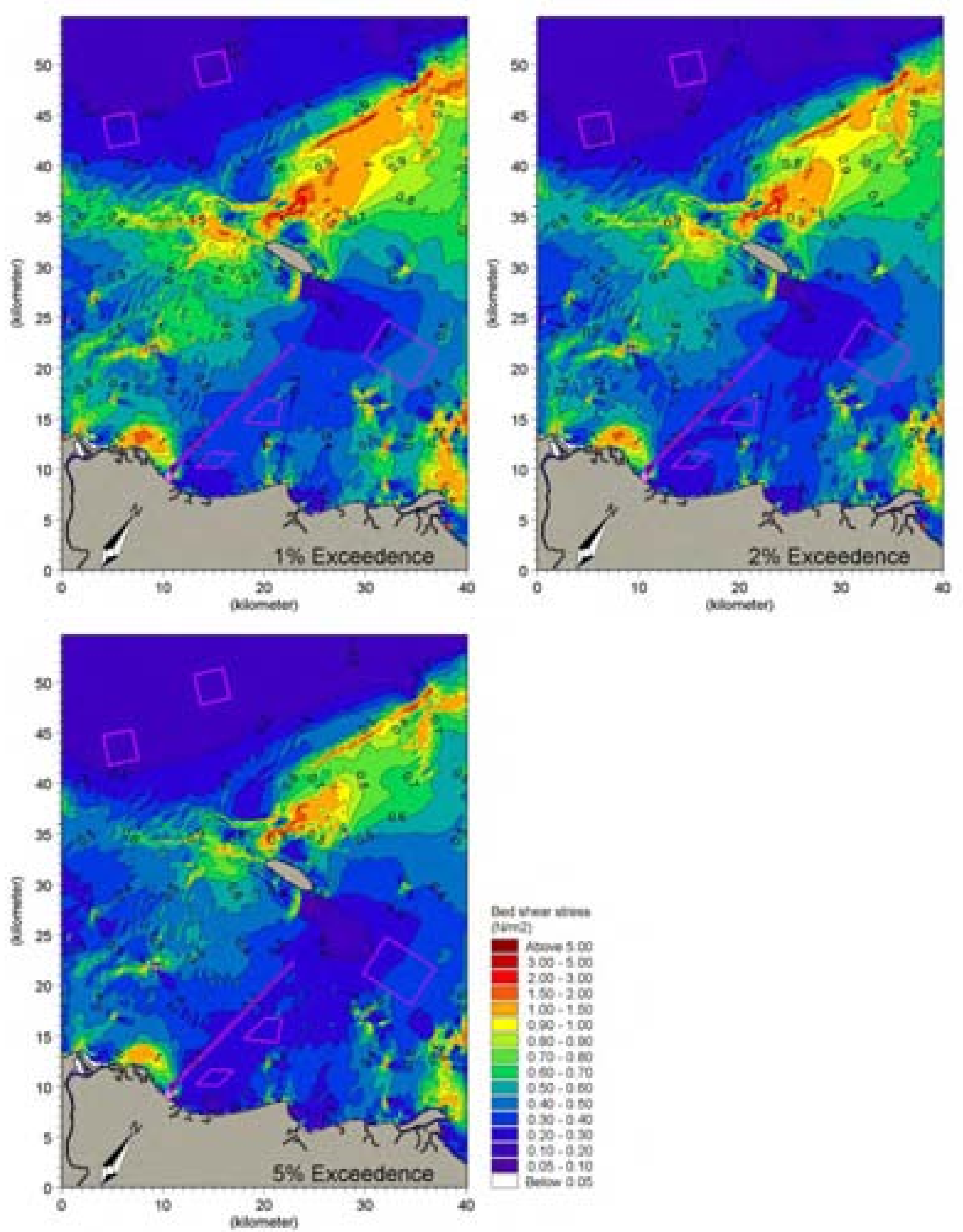

Figure EE.3 Maps of bed shear stresses exceeded 1%, 2% and 5% of the time during summer.

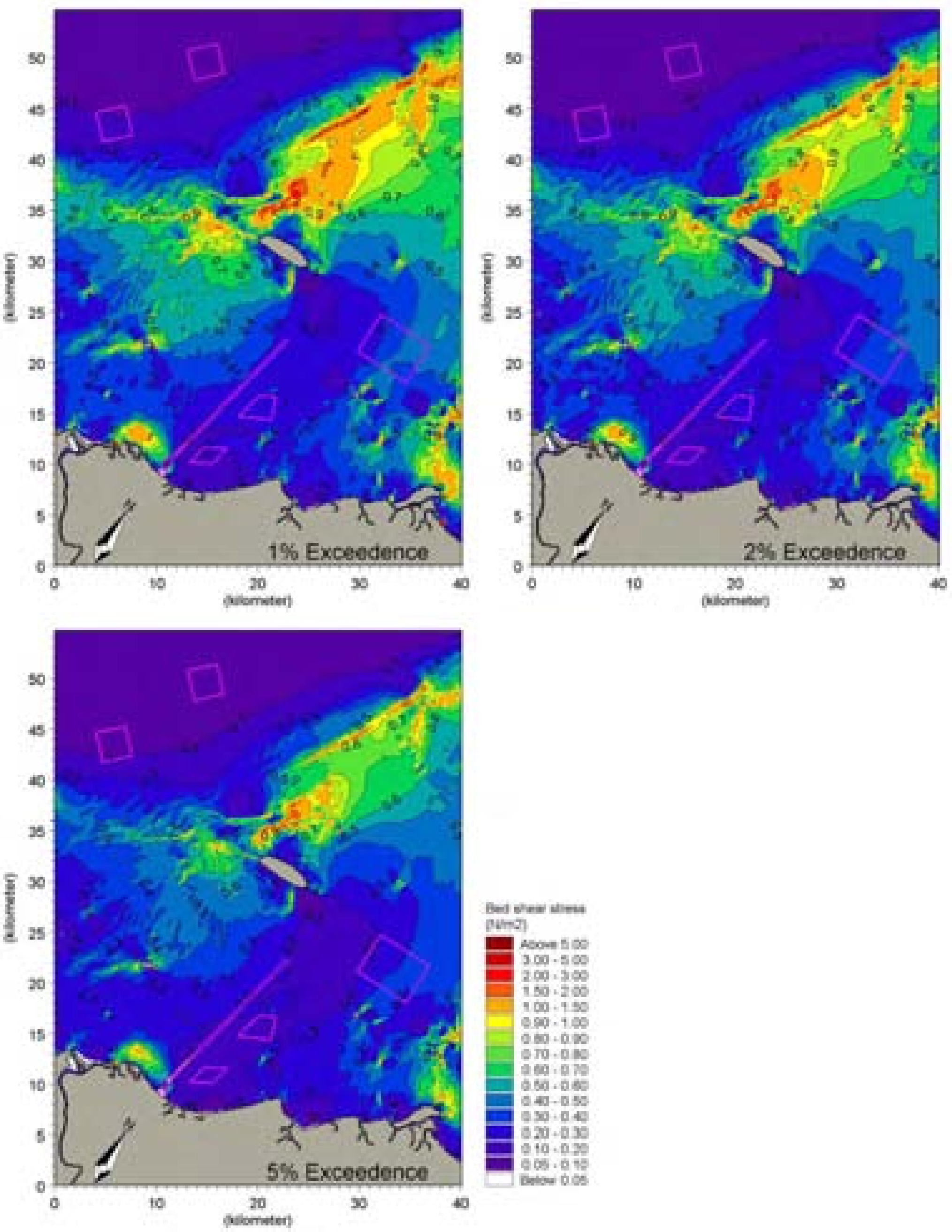

Figure EE.4 Maps of bed shear stresses exceeded 1%, 2% and 5% of the time during transitional months

EE-7

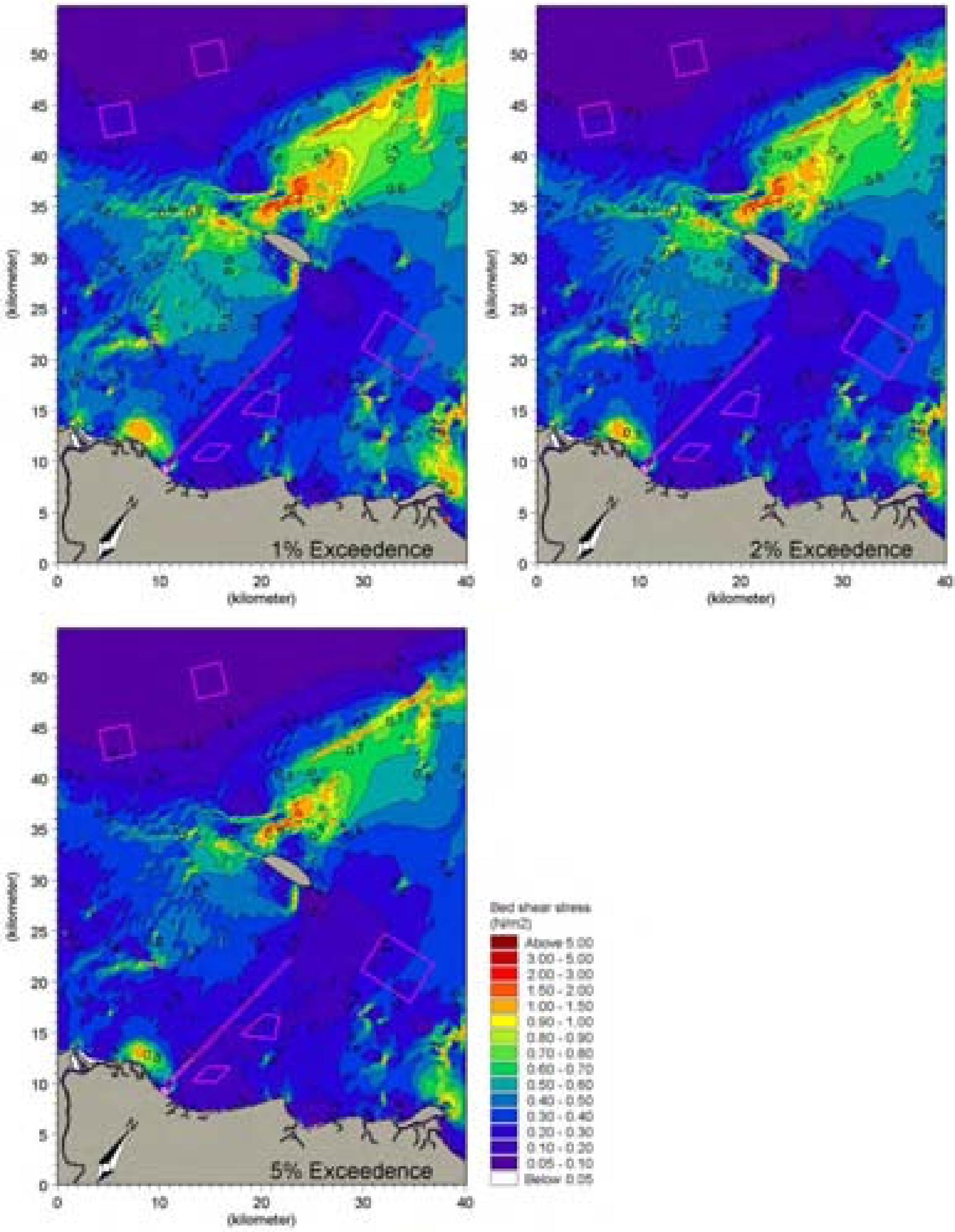

Figure EE.5 Maps of bed shear stresses exceeded 1%, 2% and 5% of the time during winter.

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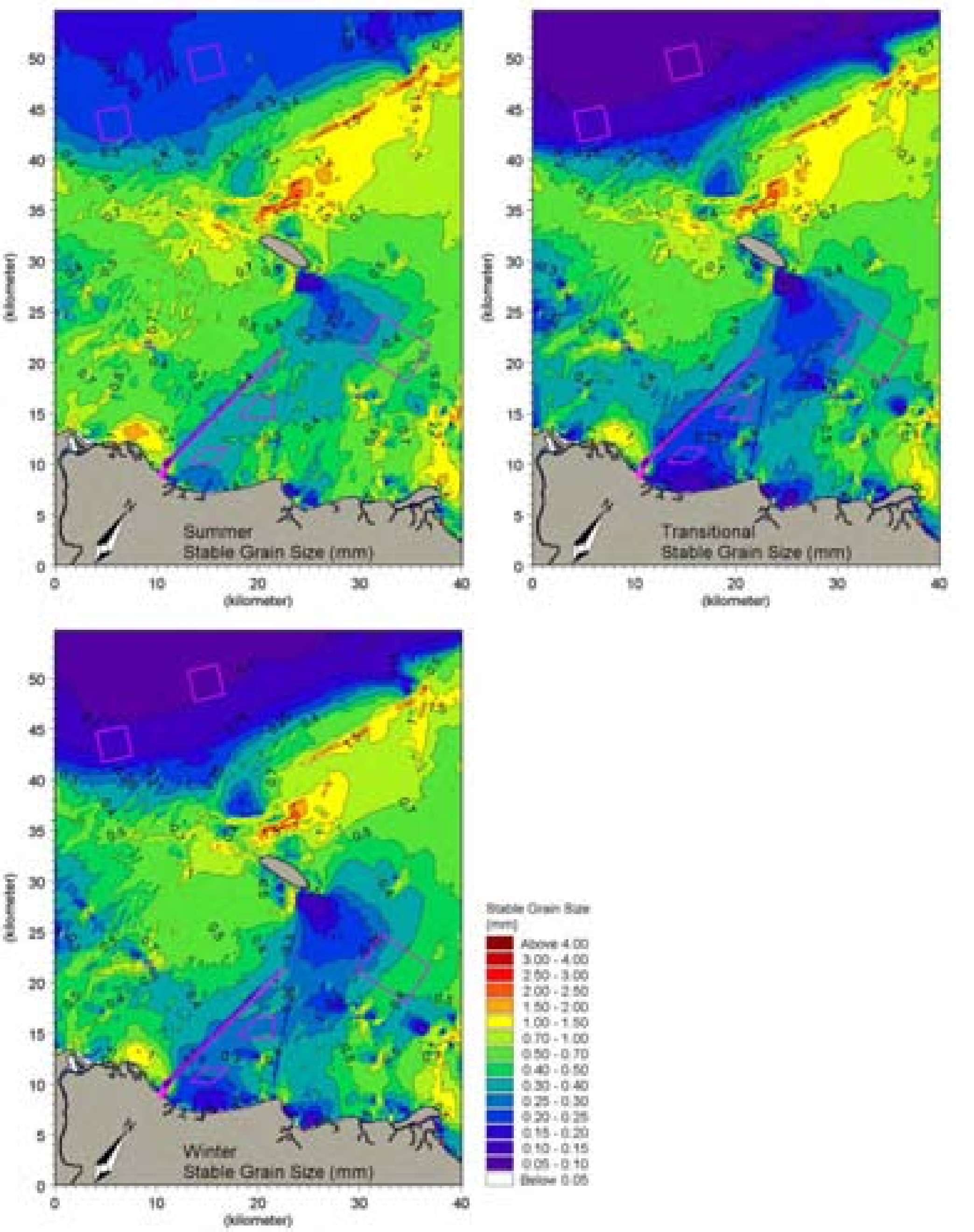

Figure EE.6 Maps of stable grain sizes for Summer, Transitional and Winter months for the 2% exceeded bottom shear stresses.

EE-9

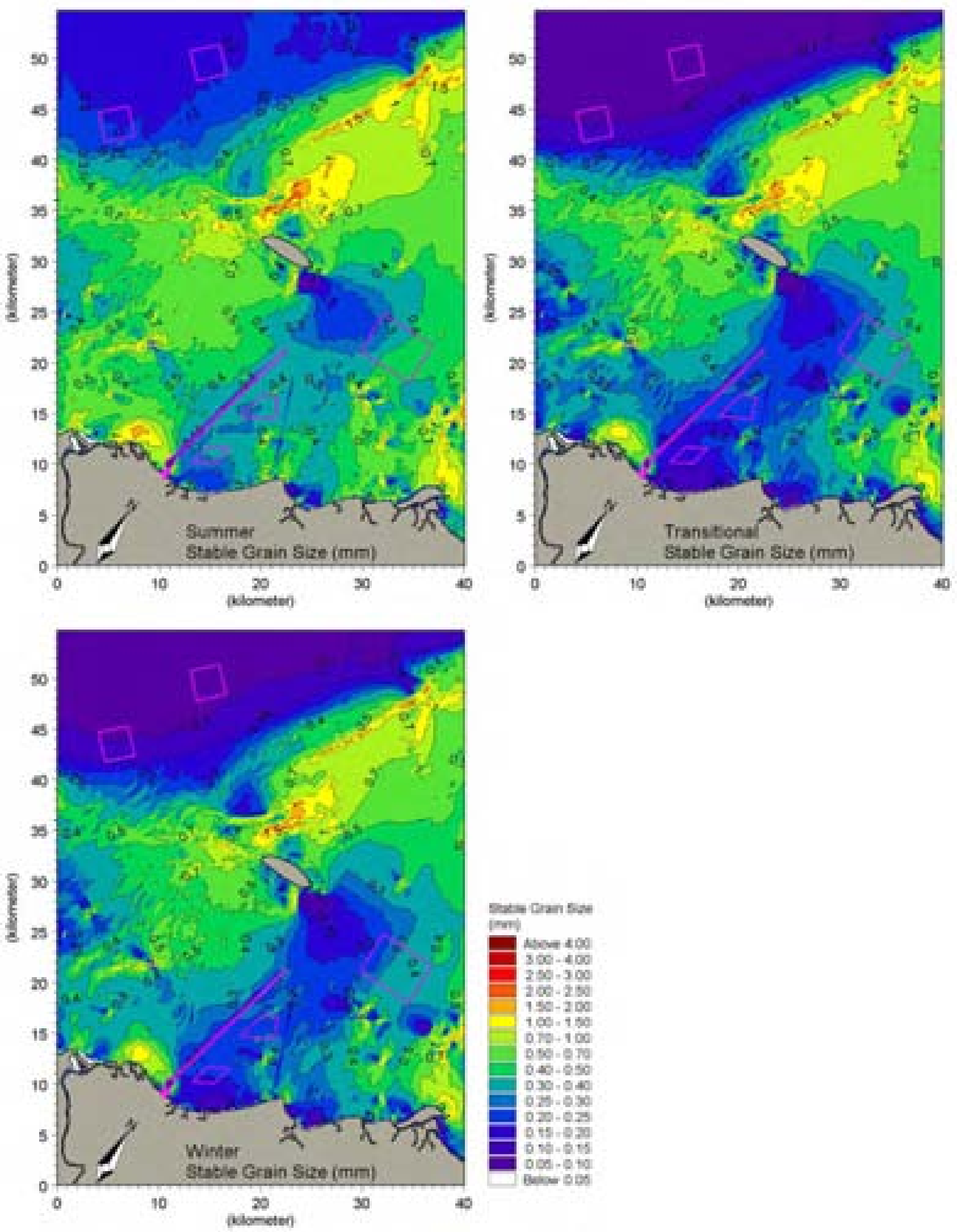

Figure EE.7 Maps of stable grain sizes for Summer, Transitional and Winter months for the 5% exceeded bottom shear stresses.

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EE-10

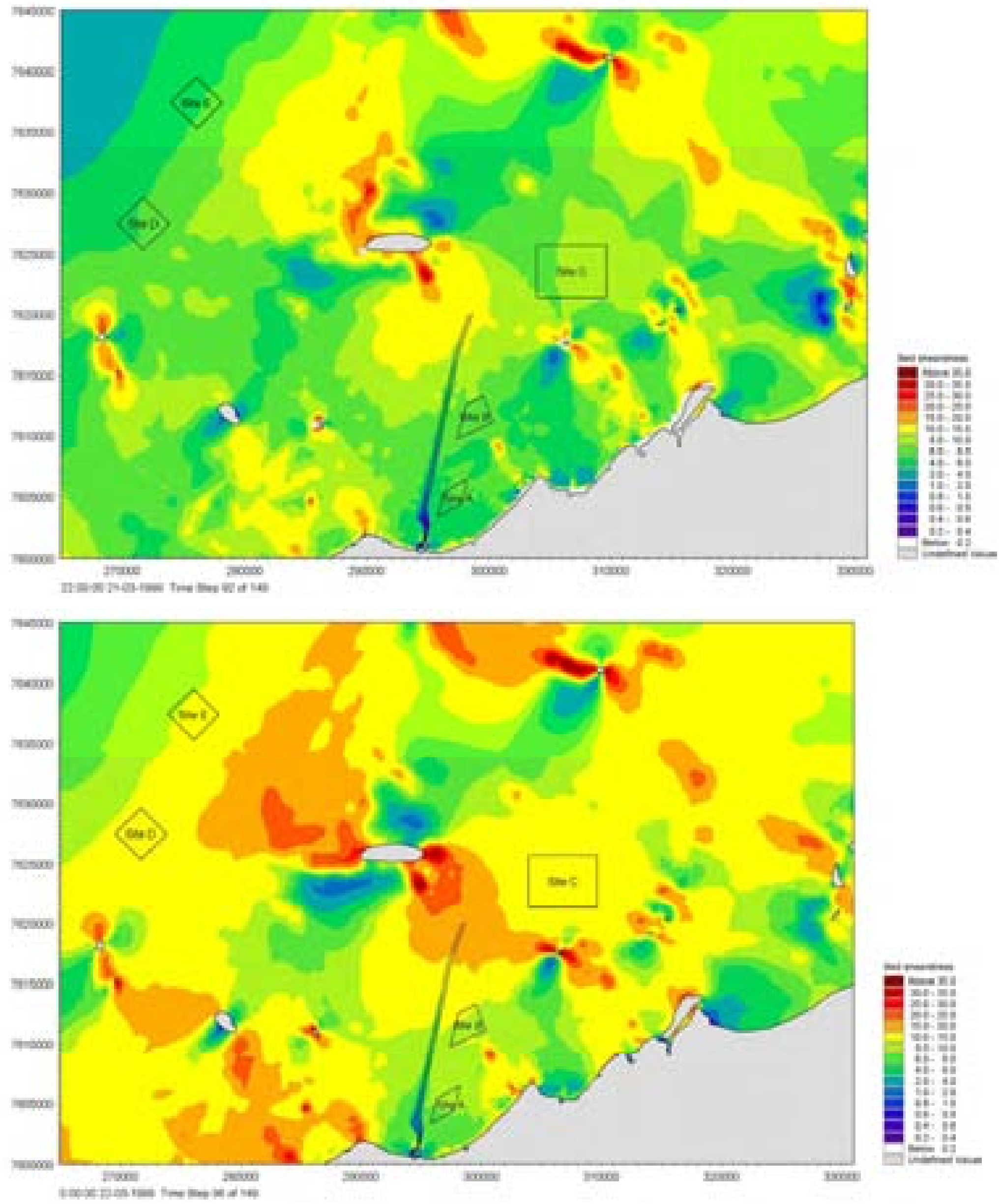

Figure EE.8 Sample maps of instantaneous bed-shear stresses during passage of cyclone Vance (1999)

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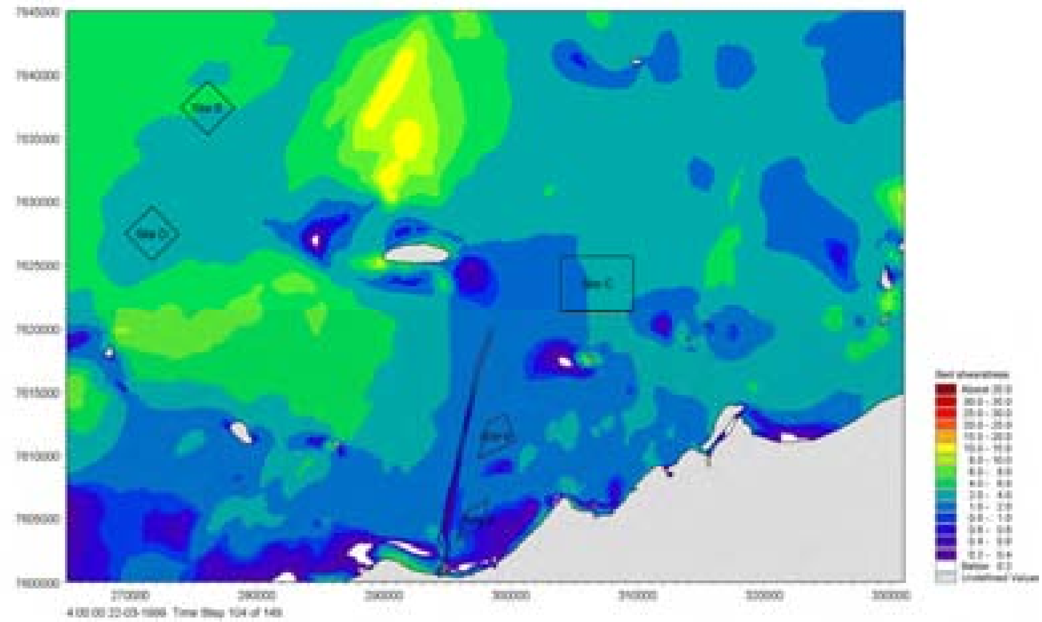

Figure EE.9 Sample maps of instantaneous bed-shear stresses during passage of cyclone Vance (1999)

EE.2 Bed-shear Stress Changes due to Bed Level Changes

The changes in bed-shear stresses as a result of changes in the bathymetry (reduced water depths) due to the disposal of material have been investigated. The volumes of material to be placed within disposal grounds A, B, C, D and E and the equivalent evenly distributed change in depth are taken from the dredge and disposal plan.

Simulated mean and maximum shear stresses during a 2 months summer period are shown for existing conditions and with the dredge channel and higher spoil grounds in place in Figure EE.10. The differences in mean and maximum bottom shear stresses for the three seasons are shown in Figure EE.11 and Figure EE.12, respectively.

The plots also demonstrate the differences due to the MOF and dredged areas. There is obviously a reduction within the dredged channel. Increases in mean bed shear stresses within the proposed spoil grounds only exceed 0.02 N/m^2 at the eastern half of Site C. Increases in maximum bed-shear stresses due to the reduced water depths over the spoil grounds are in the order of 0.02 N/m^2 except for the western portion of Site C which has significantly larger increases up to 0.1 N/m^2. This area is experiencing the highest shear stresses within the proposed spoil grounds under existing conditions.

Overall, the simulations illustrate that the changes in average bottom shear stresses due to the average changes in water depths are small and unlikely to lead to a significant change in the transport characteristics at the site. The placement of material at the spoil grounds will initially lead to irregular bottom topography, which locally will lead to more exposed areas and stronger currents. This will lead to local transport and an initial smoothing out of the bottom.

EE-12

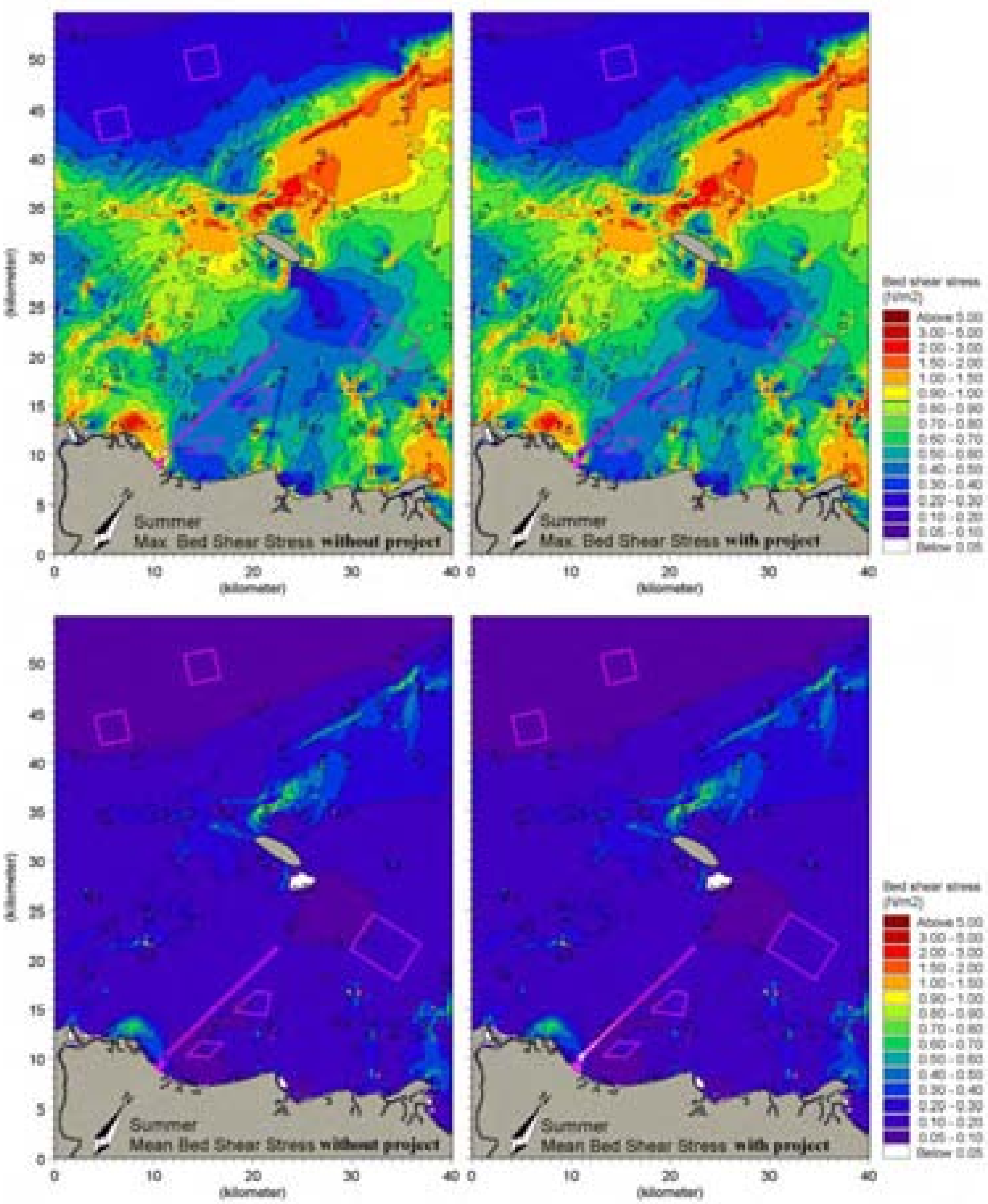

Figure EE.10 Simulated mean (bottom) and max (top) shear stresses without (left) and with (right) the changes in bathymetry due to dredging and disposal in place.

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EE-13

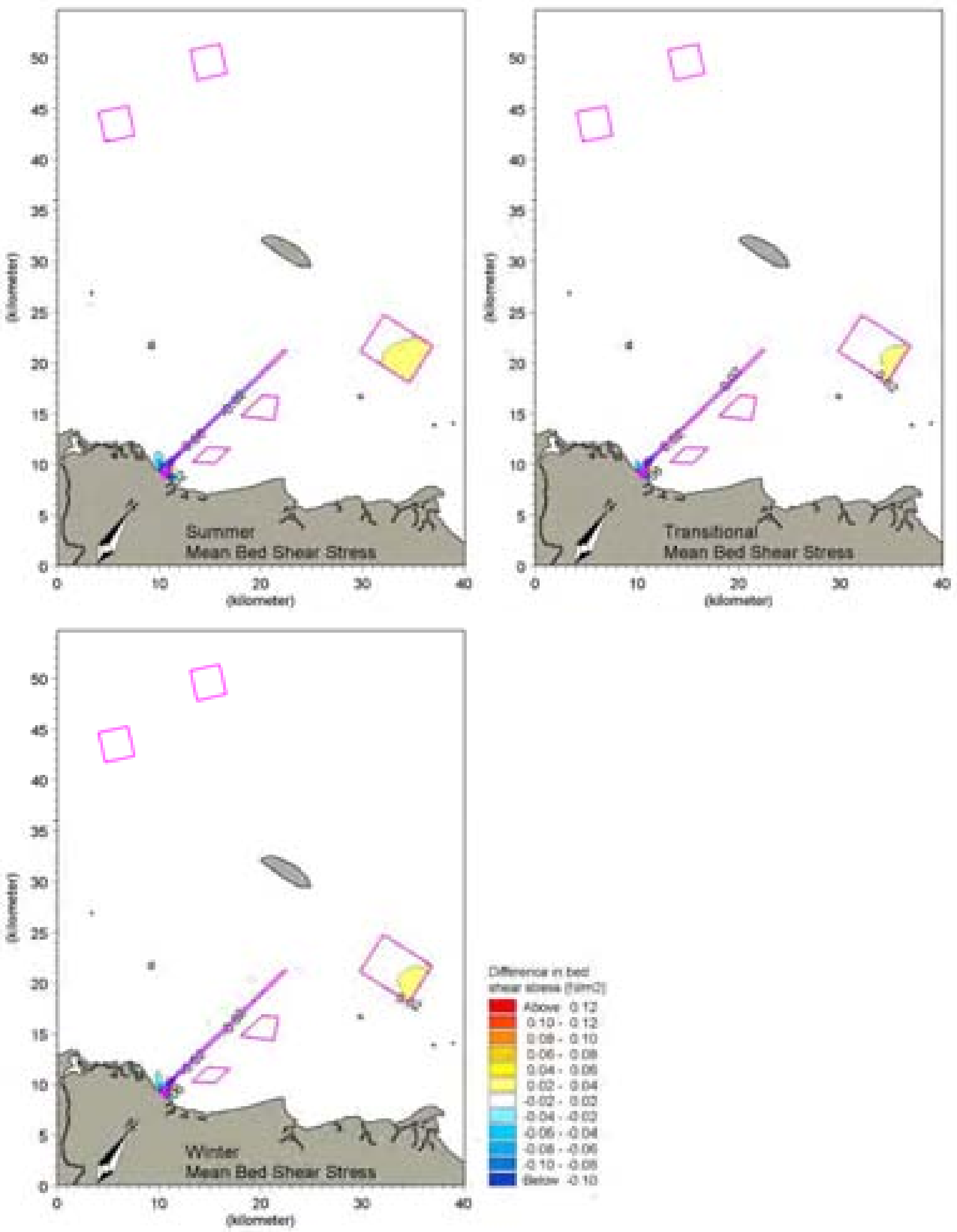

Figure EE.11 Differences in mean bed shear stresses due to the dredging and disposal

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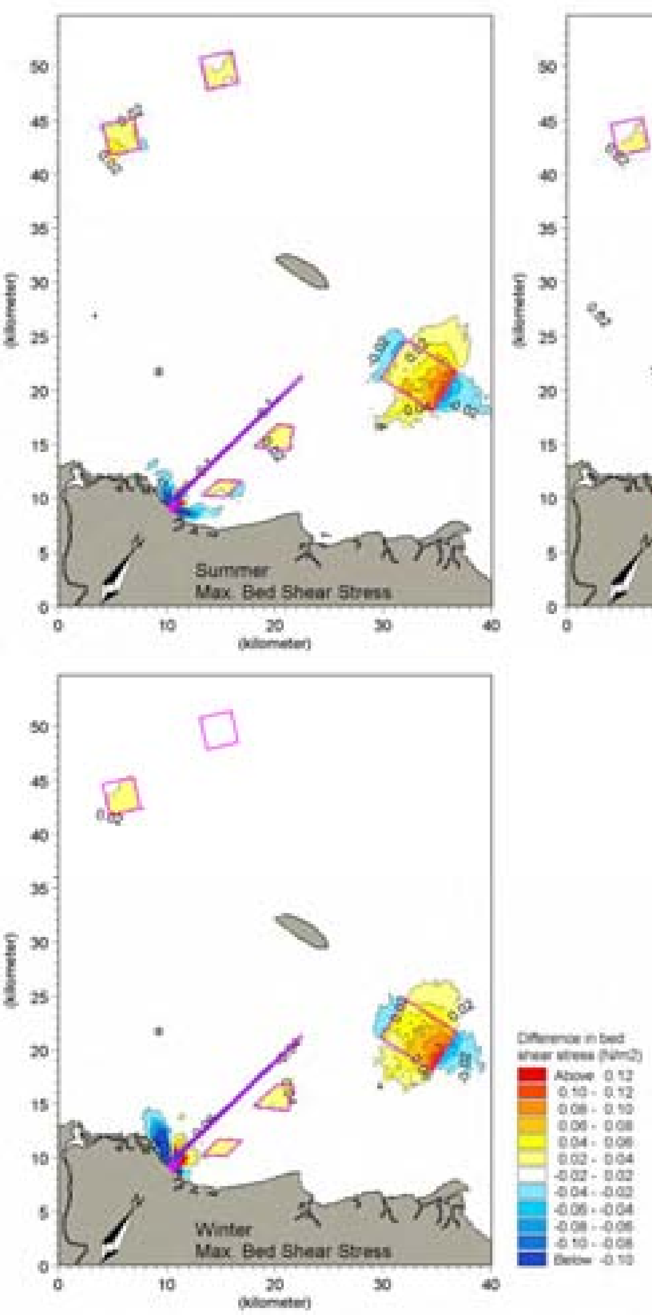

Figure EE.12 Differences in maximum bed shear stresses due to the dredging and disposal

EE.3 Sediment Characteristics and Spoil Ground Stability

The stability of the spoil grounds depend on the sediment composition. As outlined in previous sections, only relatively coarse sediment is stable under its own weight and related friction forces at the proposed spoil grounds, and for finer sediments, cohesive forces and consolidation is required to increase the stability both for the existing material and the expected composition of the material placed in the spoil grounds.

Normally, a criterion for stability at a placement site is that the new material should be similar or coarser than the parent (surface) material at the placement site.

Several grab sampling campaigns have been undertaken and mean grain sizes have been obtained within the Wheatstone area in general (see Figure EE.13 and Figure EE.14) and within the proposed spoil grounds in particular. Measured mean grain sizes throughout the region are indicated on Figure EE.13 and Figure EE.14 at the locations of grab samples. This shows variable mean grain sizes, but generally mean grain sizes in the sand fraction.

Grab samples within the proposed spoil grounds have been taken as well – see "Wheatstone Sediment Quality Assessment". Prepared for Chevron Australia Pty Ltd, 30 October 2009. The locations of the grab samples are presented in Figure EE.15 and the result of the sediment analysis of the samples are outlined in Table EE.1, which again shows predominantly sandy material.

The latest dredge and disposal plan (DDP) from LWI includes assumed particle size distributions for the material to be disposed. This is based on analysis carried out on samples taken within the dredge area (boreholes MD207 and MD210 to MD216) which show that the silt and clay fractions of the sandy material to be dredged are highly variable. Silt fractions may vary between 20% and 60% while the corresponding clay fractions in samples could range between 10% to over 30%. The assumed particle size distribution in the DDP indicates that only 16% of the material is coarser than 0.2mm, indicating that more than 80% of the material on average will be mobile based on Shields stability criterion as previously presented.

It is noted that some of the fines will be lost during the dredging and disposal operation, but there will still be a predominant fraction of fine sediments which is not statically stable at the spoil grounds.

According to "Wheatstone Sediment Quality Assessment". Prepared for Chevron Australia Pty Ltd, 30 October 2009the offshore spoil grounds are pre-dominantly composed of sand or coarser material. The percentage of sand/gravel here is close to 80% with only small amount of fines. Using the above formula and the simulated bed shear stresses (exceeded 5% of time) indicates that material with a grain size smaller than 0.1mm is mobile.

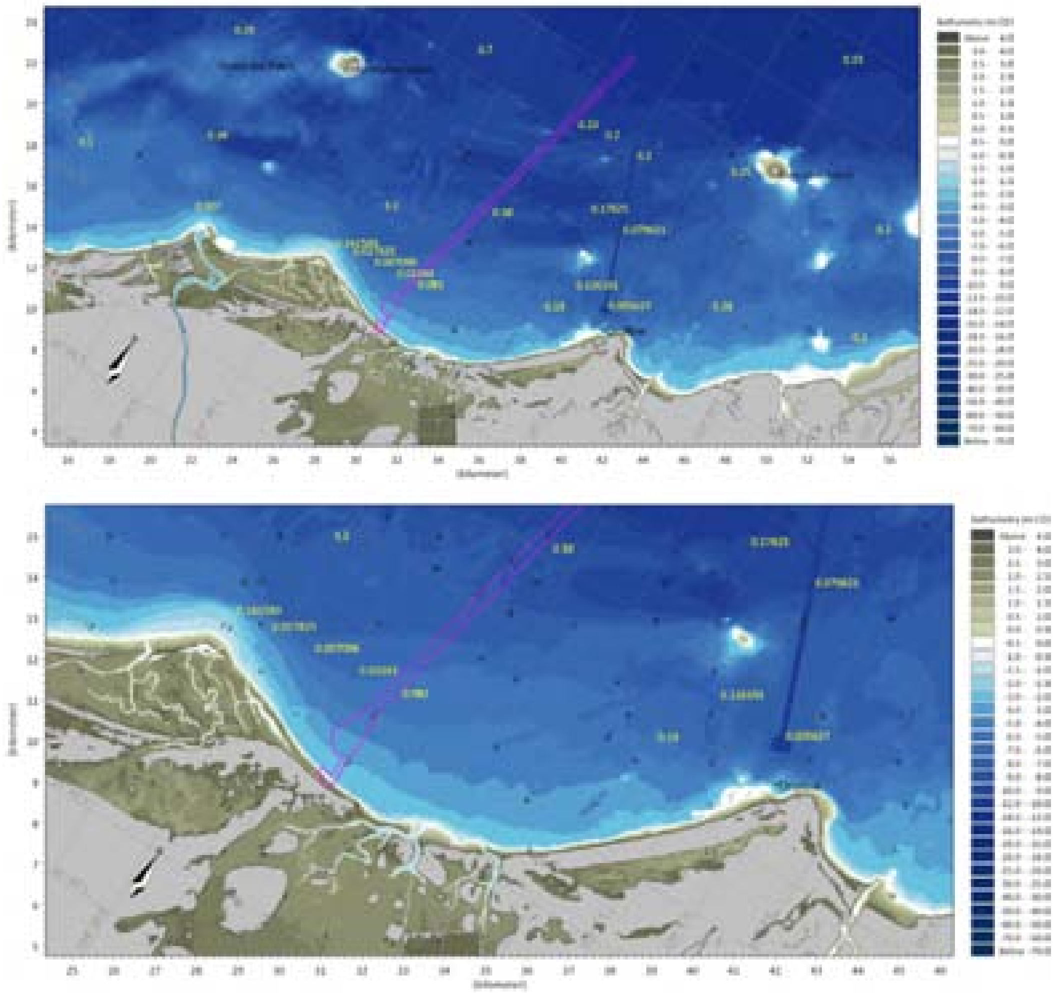

Figure EE.13 Mean grain sizes (mm) throughout the region.

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EE-17

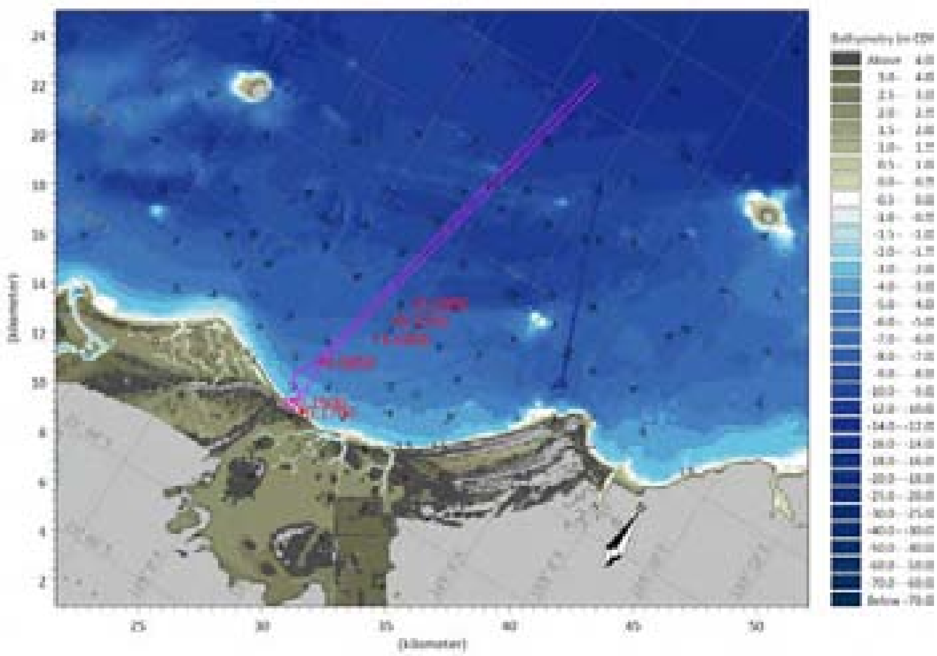

Figure EE.14 Mean grain sizes (mm) in the near-shore area at the site.

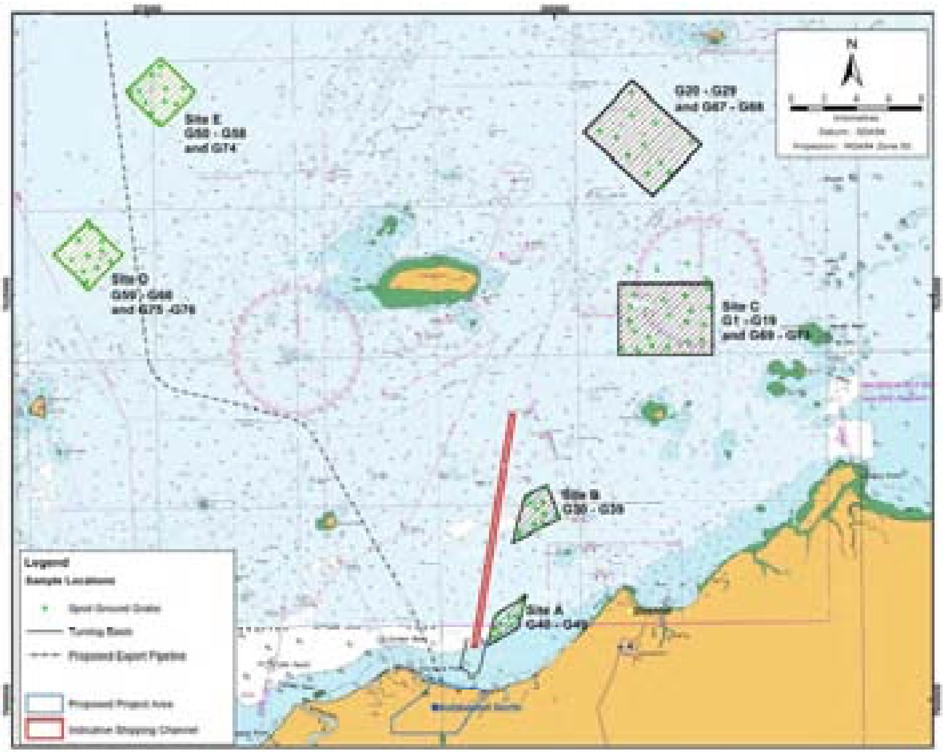

Figure EE.15 Locations of spoil ground grab samples

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Table EE.1 Percentages of sediments within proposed spoil grounds – from "Wheatstone Sediment Quality Assessment". Prepared for Chevron Australia Pty Ltd, 30 October 2009

Mean Sediment Grain Size in Wheatstone Dredge Area and Proposed Dredge Spoil Disposal Grounds					
Proposed Dredge Spoil Grounds	Cobbles (%) (>6cm)	Gravel (%) (>2mm)	Sand (%) (0.062-2 mm)	Silt (%) (2-60 µm)	Clay (%) (<2 µm)
Bechtel Spoil Ground Site A	0	15.8	58	9.6	16.6
Bechtel Spoil Ground Site B	0	12.6	60.6	10.2	16.6
Bechtel Spoil Ground Site C	0	9.2	70.8	6.7	13.3
Chevron Spoil Ground (E)	0	3	82	6.6	8.4
Chevron Alternative Spoil Ground (D)	0	4.6	69.8	12.2	13.4

EE.4 Overall Assessment

The assumed spoil material placed at spoil ground A, B and particularly C will not be stable as the material placed here does not initially resemble the parent material. Although part of the fines is lost during dredging and placement, the placed material is expected to be finer on average than the parent material at the spoil grounds.

The governing current and wave climate will change the composition of the dredged material towards the composition of the parent material. The rate of change is determined by the severity of the current and wave agitating forces as well as the consolidation and cohesive forces.

In the period after placement of material the following will take place:

- Emission of fines from the spoil ground. Exposed fines will be washed away during spring tide or during rough wave conditions. This will go on for a period of time after the dumping. It is noted, that the concentrations of fines related to the re-suspension are likely to be insignificant compared to the fines released during the dumping process.
- A smothering of the likely irregular bathymetry
- An armoring of the spoil ground by the coarser non-erodible fractions present in the spoil material. This process will tend to seal the seabed and fines in deeper layers of the spoil ground will not necessarily suspend.
- Consolidation process will start. This will slowly change the "erodibility" of the bottom. The consolidation process will depend on the material and perhaps on intermittent re-suspension processes for the upper layers.

The armoring and thus the sealing of the deposited material will be a slow process at spoil grounds D and E and the sealing of the deeper layers will be achieved with relatively finer fractions of the dumped material compared to the sealing material at spoil grounds A, B and particularly C. At spoil ground A, B and particularly C the emission will continue until the deeper layers are covered with coarser sediment which will obviously require more fines to be washed out. The total emission of fines (relative to the placed volumes) is therefore expected to be smaller at E and D and the emission process will take place over a longer period of time as the process of armoring will be slower here. The consolidation of the fine material will furthermore potentially lead to a stable bed where the cohesive forces increase the critical bed-shear stress for erosion to values of typically $0.3 N/m^2$ which is not exceeded during normal conditions.

During cyclonic conditions (Vance 1999), simulations show very high bottom shear stresses that indicate that the entire bottom becomes mobile, both at the spoil grounds and at the surrounding areas. This will likely lead to further smothering of the spoil grounds, i.e. the irregularities from the dumping will be leveled out, and some of the finer sediments previously sealed and buried will be exposed and re-suspend. Also, the consolidated material at E and D will re-suspend during cyclonic events. It is difficult to predict whether a cyclone would lead to a total loss or gain of material from the spoil grounds. This is determined by the balance between material transported into the spoil grounds compared to the amount of material eroded and transported away from the spoil grounds. There are too many unknown parameters involved to quantify the erosion and transport potential during a cyclone throughout the area, and it is thus not possible to quantify the likely erosion/deposition during a cyclone.

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Wheatstone Project
Dredge Spoil Modelling

A P P E N D I X   F F :

Comparison of Net Currents from Onslow and MesoLAPS Wind-Driven Hydrodynamics

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FF COMPARISON OF NET CURRENTS FROM ONSLOW AND MESOLAPS WIND-DRIVEN HYDRODYNAMICS

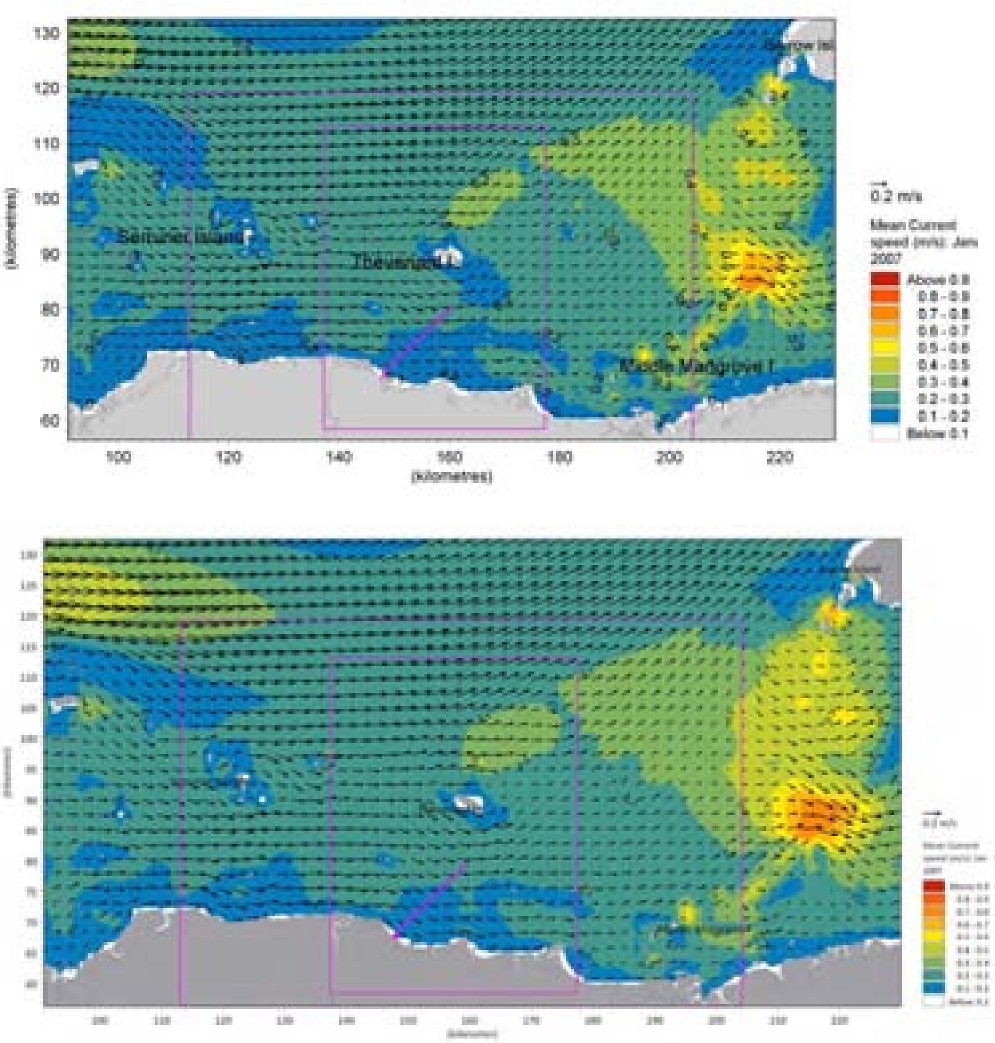

Figure FF.1 Simulated average net currents during January 2007 driven by winds from MesoLAPS (top) and Onslow Met Station (bottom)

FF-2

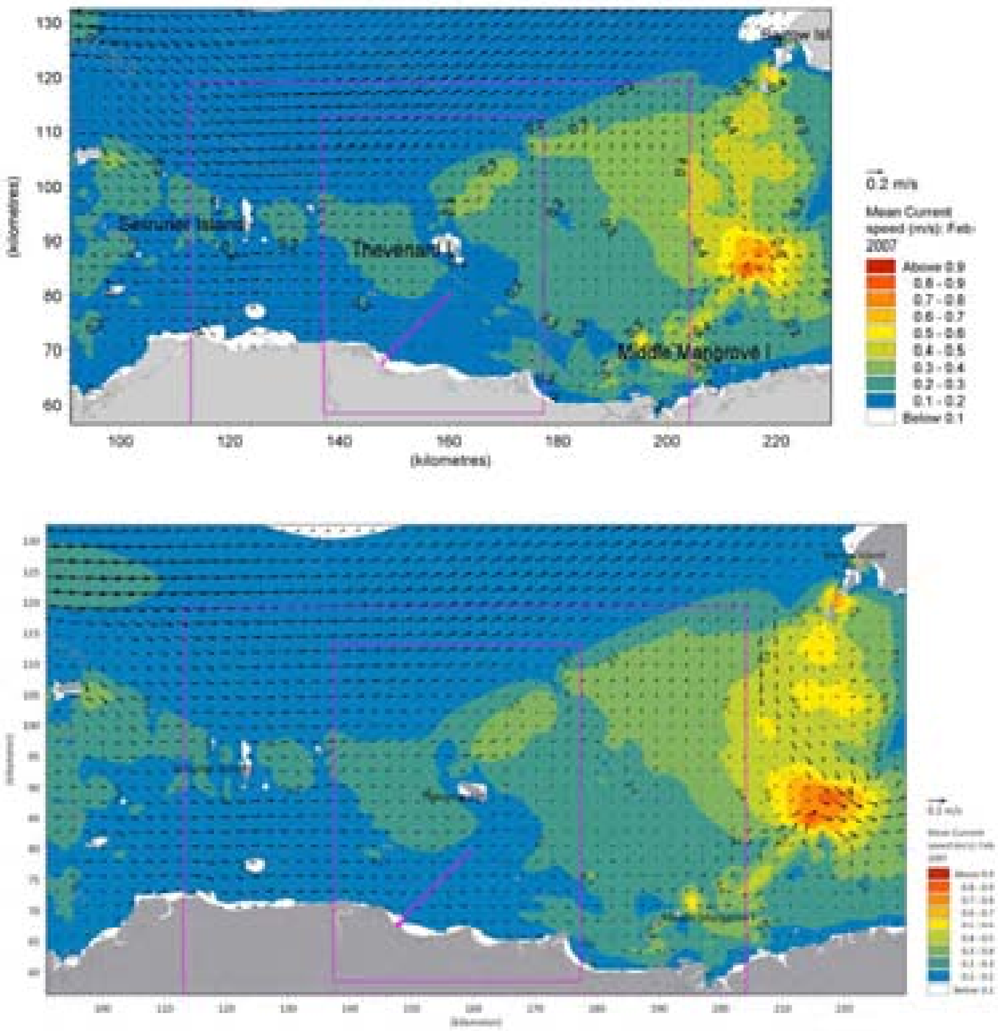

Figure FF.2 Simulated average net currents during February 2007 driven by winds from MesoLAPS (top) and Onslow Met Station (bottom)

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FF-3

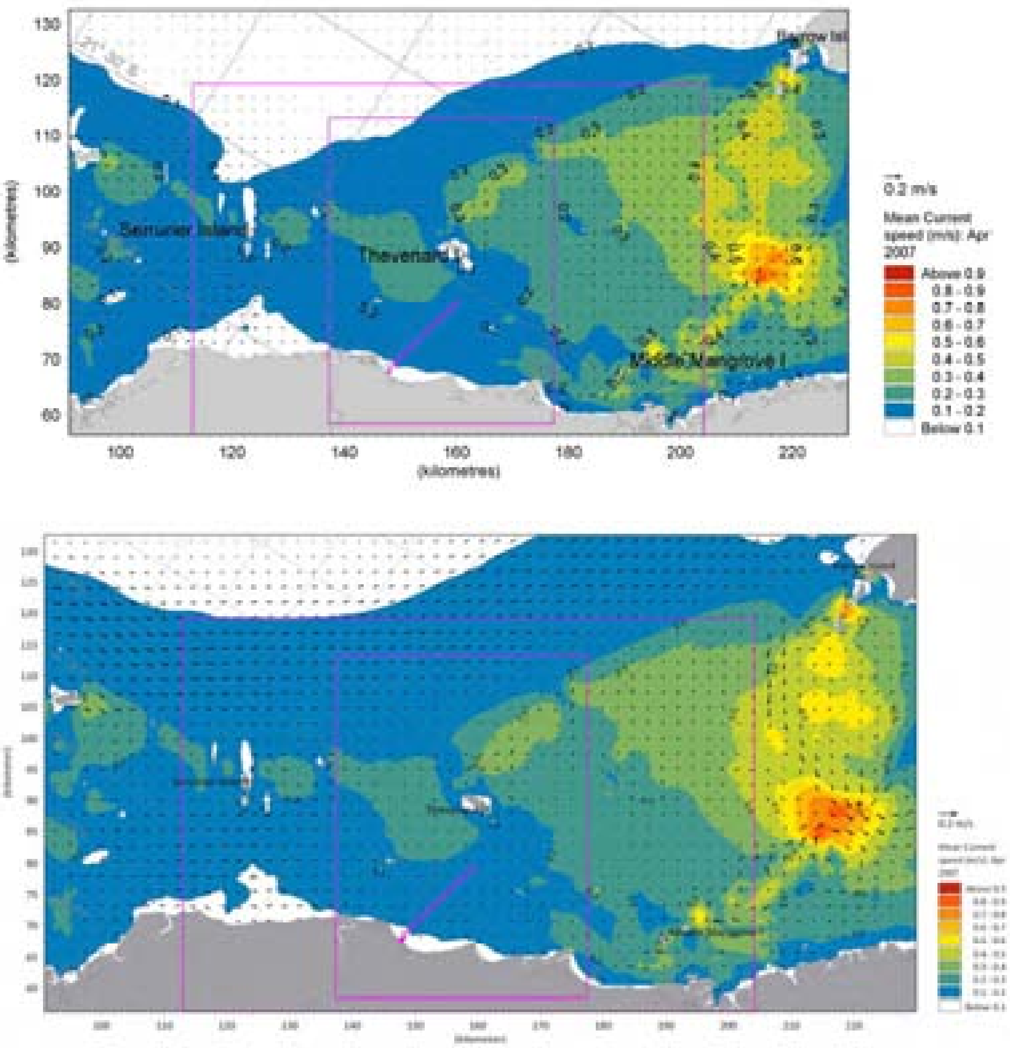

Figure FF.3 Simulated average net currents during April 2007 driven by winds from MesoLAPS (top) and Onslow Met Station (bottom)

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FF-4

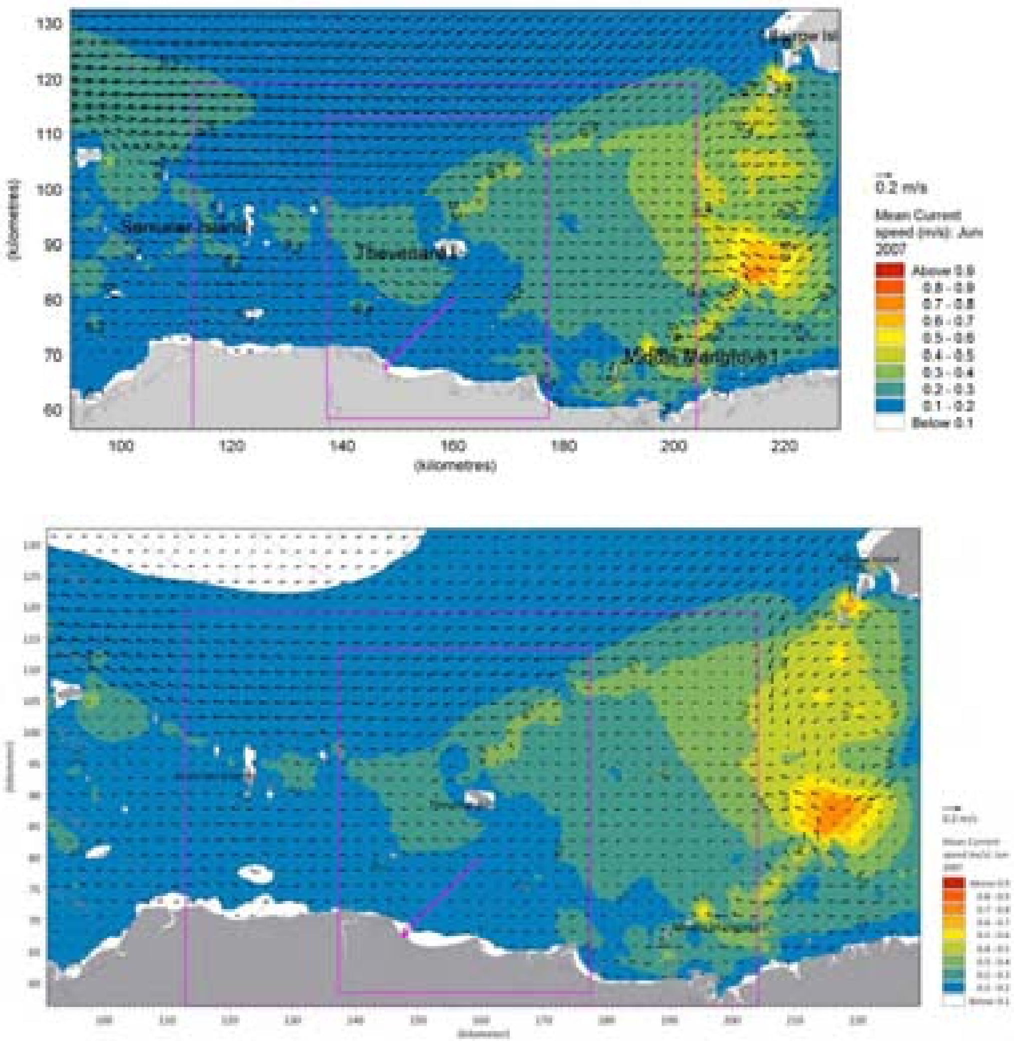

Figure FF.4 Simulated average net currents during June 2007 driven by winds from MesoLAPS (top) and Onslow Met Station (bottom)

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FF-5

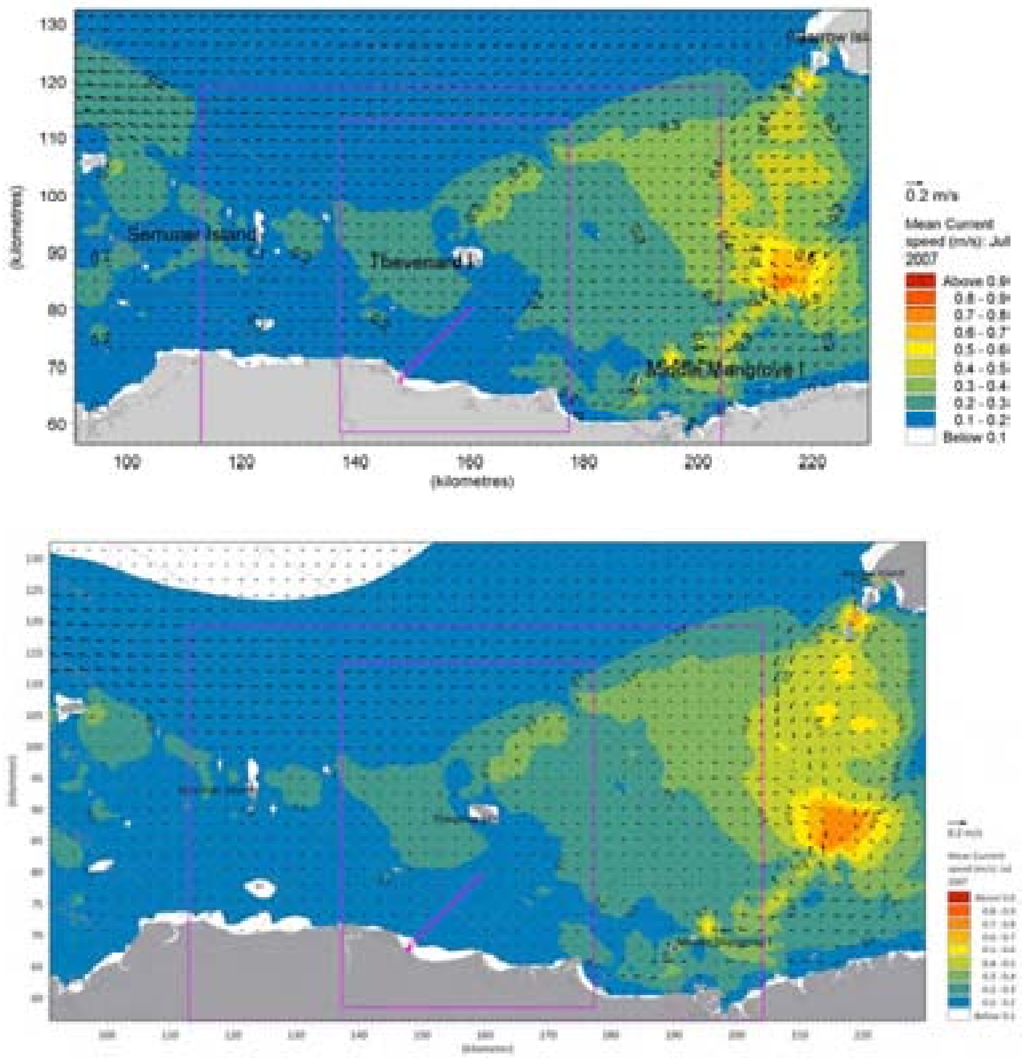

Figure FF.5 Simulated average net currents during July 2007 driven by winds from MesoLAPS (top) and Onslow Met Station (bottom)

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Wheatstone Project
Dredge Spoil Modelling

A P P E N D I X GG :

GEMS Wind, Current and Wave Verification and Analysis

DHI Water & Environment

Global Environmental Modelling Systems
Global Environmental Monitoring Systems

Wheatstone Wind, Currents and Wave Verification and Analysis

Report prepared for Chevron Australia Pty Ltd

APRIL 2010

ABOUT GEMS

Global Environmental Modelling Systems (GEMS), a wholly owned Australian company, has expertise in the development and application of high-resolution computer models to realistically predict atmospheric and oceanographic conditions for use in riverine, coastal and oceanic settings.

The GEMS team is made up of qualified and experienced physical oceanographers, meteorologists, numerical modellers and environmental scientists. GEMS is a leading developer of numerical models in Australia. It has developed a system of validated environmental models and rigorous analytical procedures that provide solutions to a variety of environmental, engineering and operational problems.

CONTACT GEMS

Melbourne Office
Telephone: +61 (0)3 9712 0016
PO Box 149
Warrandyte VIC 3113

Perth Office
Telephone: +61 (0)8 6364 0880
PO Box 1432
Subiaco WA 6097

Dr Graeme D Hubbert
Head of Oceanographic Studies
Mobile: +61 (0)418 36 63 36
Email: graeme.hubbert@gems-aus.com

Steve Oliver
Head of Meteorological and Wave Studies
Mobile: +61 (0)408 81 8702
Email: steve.oliver@gems-aus.com

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V1-2	1 May 2010	Draft to Client	S.Oliver	G.Hubbert

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FIGURES

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SECTION 1. INTRODUCTION

Chevron Australia Pty Ltd proposes to construct and operate a multi-train Liquefied Natural Gas (LNG) plant and a domestic gas (Domgas) plant 12 km south west of Onslow on the Pilbara Coast in Western Australia. The LNG and Domgas plants will initially process gas from fields located approximately 200 km offshore from Onslow in the West Carnarvon Basin and other yet-to-be determined gas fields. The project is referred to as the Wheatstone Project and "Ashburton North" is the proposed site for the LNG and domestic gas plants. The Project will require the installation of gas gathering, export and processing facilities in Commonwealth and State Waters and on land. The LNG plant will have a maximum capacity of 25 Million Tonnes Per Annum (MTPA) of LNG.

The Wheatstone Project has been referred to the State Environmental Protection Authority (EPA) and the Commonwealth Department of Environment, Water, Heritage and the Arts (DEWHA). The investigations outlined in this report have been conducted to support the environmental impact assessment process.

The gas will be brought ashore via trunkline and, after processing, LNG will be shipped from a new port facility at the Ashburton North site. To establish this port a significant dredging program must be undertaken to create a Materials Offload facility (MOF), a navigation channel and turning basin fro the LNG tankers. Up to 45 million cubic metres will need to be dredged over a three year dredging program.

Global Environmental Modelling Systems (GEMS) has been contracted by URS to undertake the following tasks to support environmental studies for the proposed dredging program:

1) Summarize and assess relevant meteorological and oceanographic data available to the project;
2) Simulate the deep ocean wave spectra generated in the Indian Ocean to provide boundary conditions for continental shelf wave modelling conducted by the Danish Hydraulics Institute (DHI);
3) Verify the Indian Ocean wave model predictions against observed data;
4) Compare available atmospheric model output with observations to determine the best atmospheric forcing to be used for ocean modelling;
5) Highlight the key meteorological and oceanographic issues relevant to the project from analysis of the data and general knowledge of the meteorology and oceanography of the region, and
6) Produce this report summarizing the outcomes of the above tasks and documenting the main findings.

The report is structured in separate sections addressing the meteorology, ocean sea levels, ocean currents and ocean waves respectively. A summary of the relevant data available is included within each section.

SECTION 2. WINDS

2.1 OVERVIEW OF THE REGIONAL WIND CLIMATE

2.1.1 Ambient Climate

The Wheatstone study area is located on the fringe of the wet-dry tropics of northern Australia, experiencing two distinct seasons – a 'wet' season from November to March and a 'dry' season from May to September, with transition months that may have the characteristics of either period. Throughout the year, diurnal variations in land temperature cause local land-sea breeze cycles close to the coast, and these result in changed wind speed and directions closer to shore through a twenty-four hour cycle. The effect of these local winds biases the observations at coastal wind stations, such that they cannot be used to accurately describe the offshore winds that are responsible for generating waves and the broader current field.

During the 'dry' season, a belt of high pressure known as the sub-tropical ridge forms over the continent and results in semi-persistent easterly flow across the Pilbara. This flow may weaken and strengthen as individual high pressure centres evolve to the south in response to cold frontal activity. The easterly flow is characterized by low moisture content and stable weather conditions.

Figure 1 shows a synoptic sequence in which a high is initially directing easterly winds across north-west Australia. A cold front pushing northwards from high latitudes then weakens the high but a new high pressure system begins to develop in the wake of the frontal system. The formation of such a new high is often accompanied by a period of stronger easterlies across the Pilbara and Kimberly regions.

Southwards movement of the solar equator following the winter solstice results in warming of the continent and a gradual southward migration of the subtropical ridge. This has a two-fold effect by which the general strength of the easterlies weakens and a persistent 'heat' trough (area of low pressure) forms along or inland from the Pilbara coast.

This broad area of low pressure combines with high-pressure south-westwards over the Indian Ocean to drive persistent southerly winds along the west coast. Figure 2 shows a typical synoptic sequence in January with a heat trough extending southwards from the Pilbara.

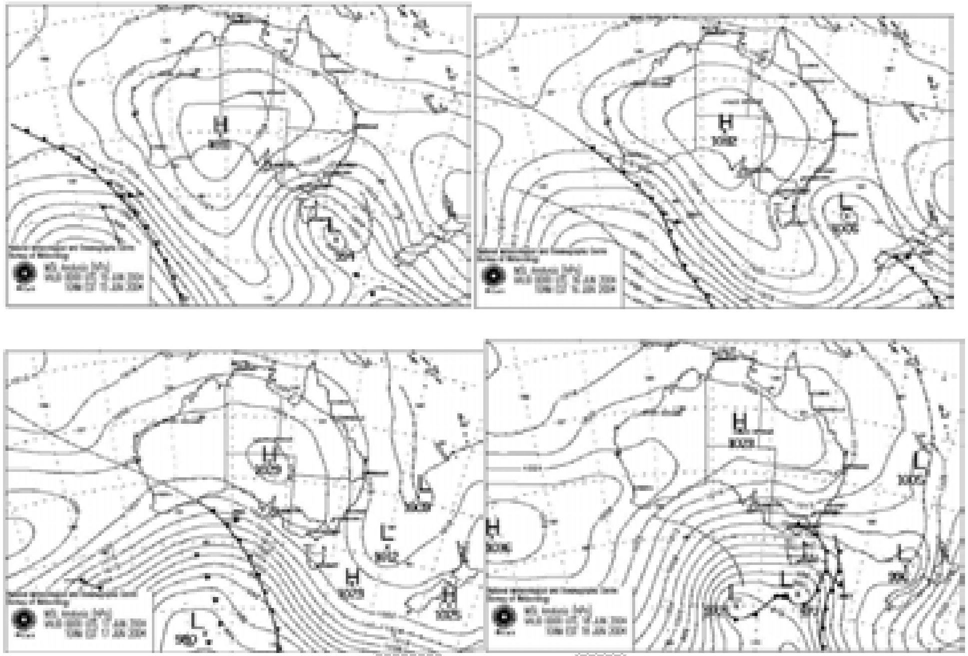


Figure 1. Typical cool-month pattern easterlies across northern Australia, weakening under the influence of front (Panel 3), then beginning to re-establish (Panel 4).

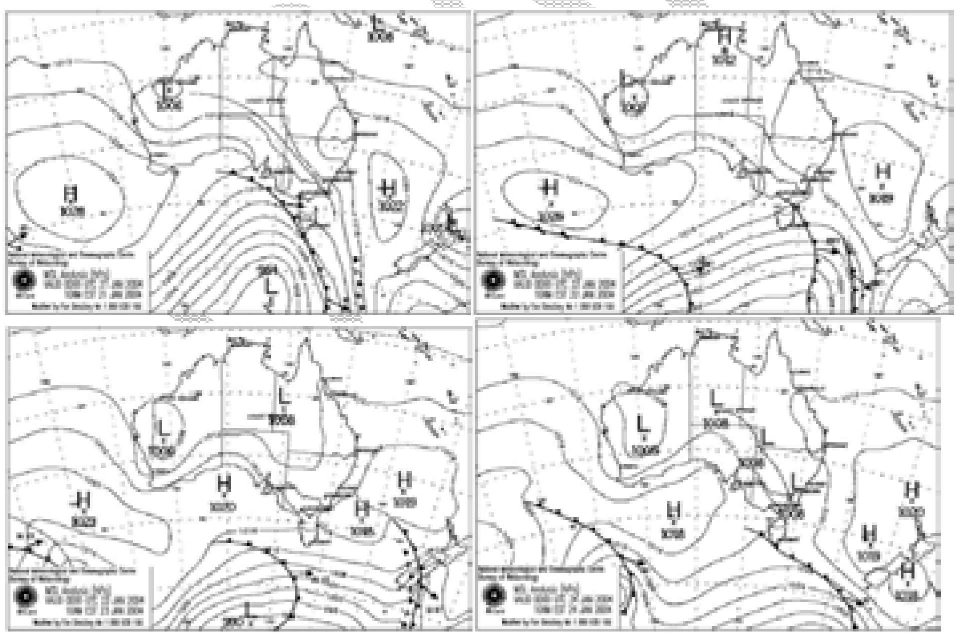


Figure 2. Typical warm-month pattern showing persistence of low pressure through the Pilbara.

2.1.2

2.1.3 Tropical Cyclones

The occurrence of tropical cyclones is relatively high over the north-western Australian region (between Exmouth and Broome), see Figure 3. The occurrence of severe tropical storms and cyclones varies considerably from year-to-year, from none to as many as 16 in the 1960s. Several severe tropical cyclones have occurred since 1976.

Generally, cyclogenesis occurs well to the north where sea temperatures are warmer; storms may then intensify as they track southwards. The direction of movement of the storms is generally controlled by upper atmospheric 'steering' – some storms track to the west under the influence of strong upper easterlies, but others can re-curve towards the Pilbara coast. This situation can be conducive to rapid intensification and acceleration of the cyclones toward the Pilbara coast.

In terms of the assessment of potential environmental impacts from the Wheatstone project, the cyclones are important in terms of:

- Potential re-suspension of deposited sediments, e.g. dredge material placement area(s).
- Backfilling of the dredged channel which would require maintenance dredging.
- Extreme coastal sediment transport and morphology being impacted by the MOF.

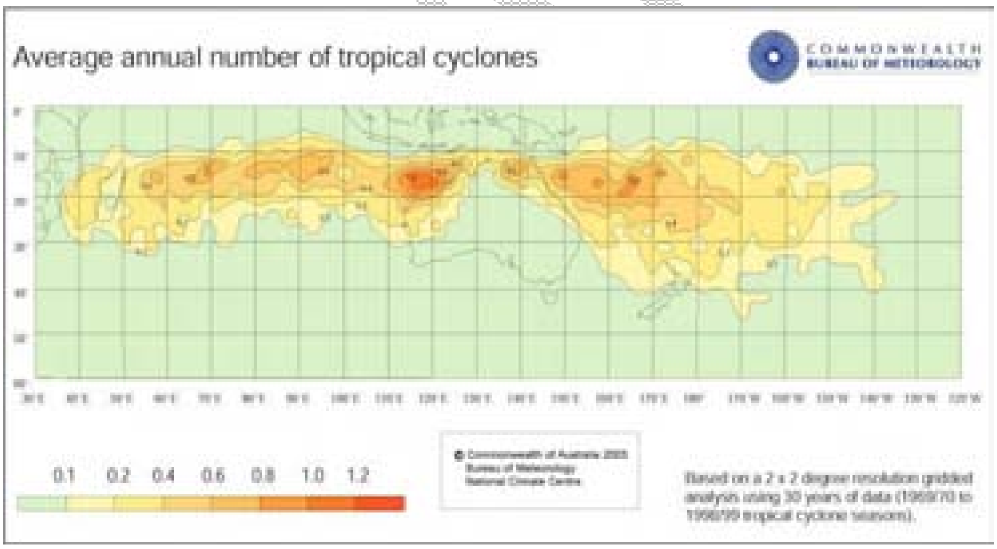


Figure 3. Average occurrence of tropical cyclones in the Australian region (Source BOM)

2.2 DATA SOURCES

2.2.1 Measured Winds

A summary of the meteorological data available to the project is given in Table 1 and the locations are shown in Figure 4.

Of the data in Table 1, two main meteorological observation data sets are available for the region. These are longer term data from the Bureau of Meteorology (BOM) site at Onslow aerodrome and a ten year data set for the Chevron Automatic Weather Station (AWS) site on Thevenard Island.

The BOM site data may be useful for determining long-term climate variability, but the Thevenard Island data will be clearly much more representative of the offshore maritime environment. However, we note that single point winds will generally not adequately represent the spatial variability over the region.

A further shorter term data set is available from an onshore site established for the current project, but this is not considered relevant to the longer term focus for the analysis aims of this report.

Table 1. Summary of meteorological data available to the project

Location	First Data Record	Last Available Data Record	Time Interval
Onslow Airport	*21/11/1997*	*5/05/2009*	*1 hour*
Onslow Township	*01/01/1997*	*5/05/2009*	*3 hours*
Thevenard Island	*12/01/2000*	*20/04/2009*	*1 hour*
RPS logger at Onslow Jetty	*16/12/2008*	*26/02/2009*	*1 minute*
Barrow Island Airport	*23/04/1999*	*30/03/2009*	*1 hour*
Varanus Island	*22/04/1999*	*30/04/2009*	*1 hour*

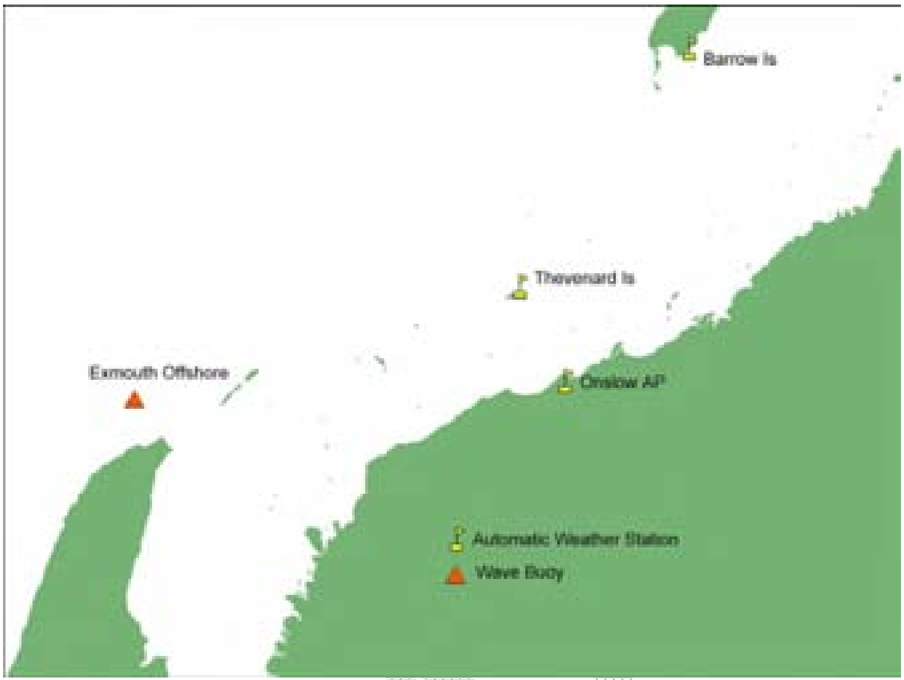


Figure 4. Location of meteorological data available for this report.

2.3 ANALYSIS OF OBSERVED WINDS

The wind analysis in this report (and model validation against observed winds described in following sections) focuses on the longer data sets available from the BOM site at Onslow Airport and the site at Thevenard Island Airport.

Figure 5 shows polar wind diagrams constructed for the period 2000 to 2009 across all available observations for Onslow AP and Thevenard Island respectively. The significant differences between these two diagrams illustrate the major differences in the respective maritime and inland wind climates of the two locations.

While the annual patterns of the winds are broadly similar there is a marked difference in the relevant proportion of south-westerly and north-westerly winds. The offshore environment at Thevenard Island is dominated by south-westerly quadrant winds while Onslow AP is much more subject to north-westerlies (at the expense of the south-westerlies). This inconsistency reflects differences in the diurnal response between the sites and their respective locations within a regional scale sea-breeze circulation that develops along the Pilbara coastline in the warmer months.

The seasonal variation in the two wind climates is presented as monthly polar diagrams in Figure 6 (Onslow AP) and Figure 7 (Thevenard Island). Both diagrams show three main winds regimes – these being:

- Predominant south-west to north-westerlies in the warmest months;
- Lighter, more variable winds within the transition period corresponding to the mid latitude spring; and
- Rapid change to persistent south-westerlies from late August onwards.

In the first three months of the year the presence of the Pilbara heat trough causes a major difference in the predominant wind direction between the two sites.

2.3.1 Applicability of Data from these Sites

The preceding analysis clearly illustrates onshore and offshore differences in the wind climate. These results show that the wind fields employed to drive ocean circulation models over the region must represent these differences in space and time.

Onslow Airport

Thevenard Island

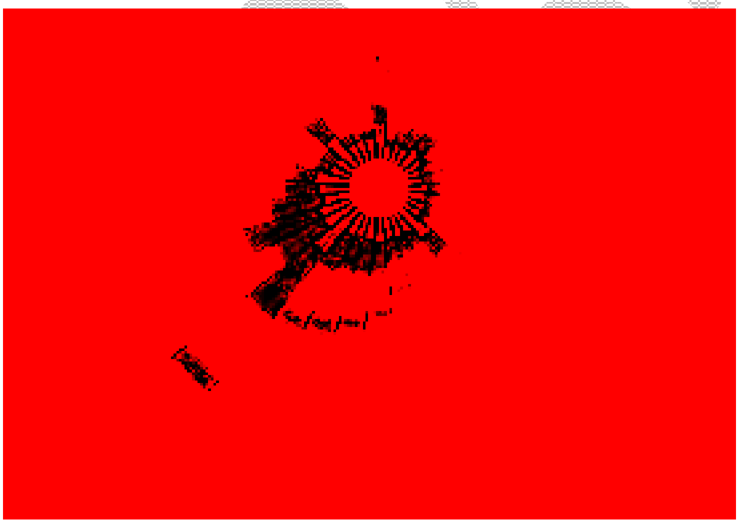


Figure 5. Comparison of polar wind diagrams for Onslow Airport and Thevenard Island based on all data for the 2000-2009 period.

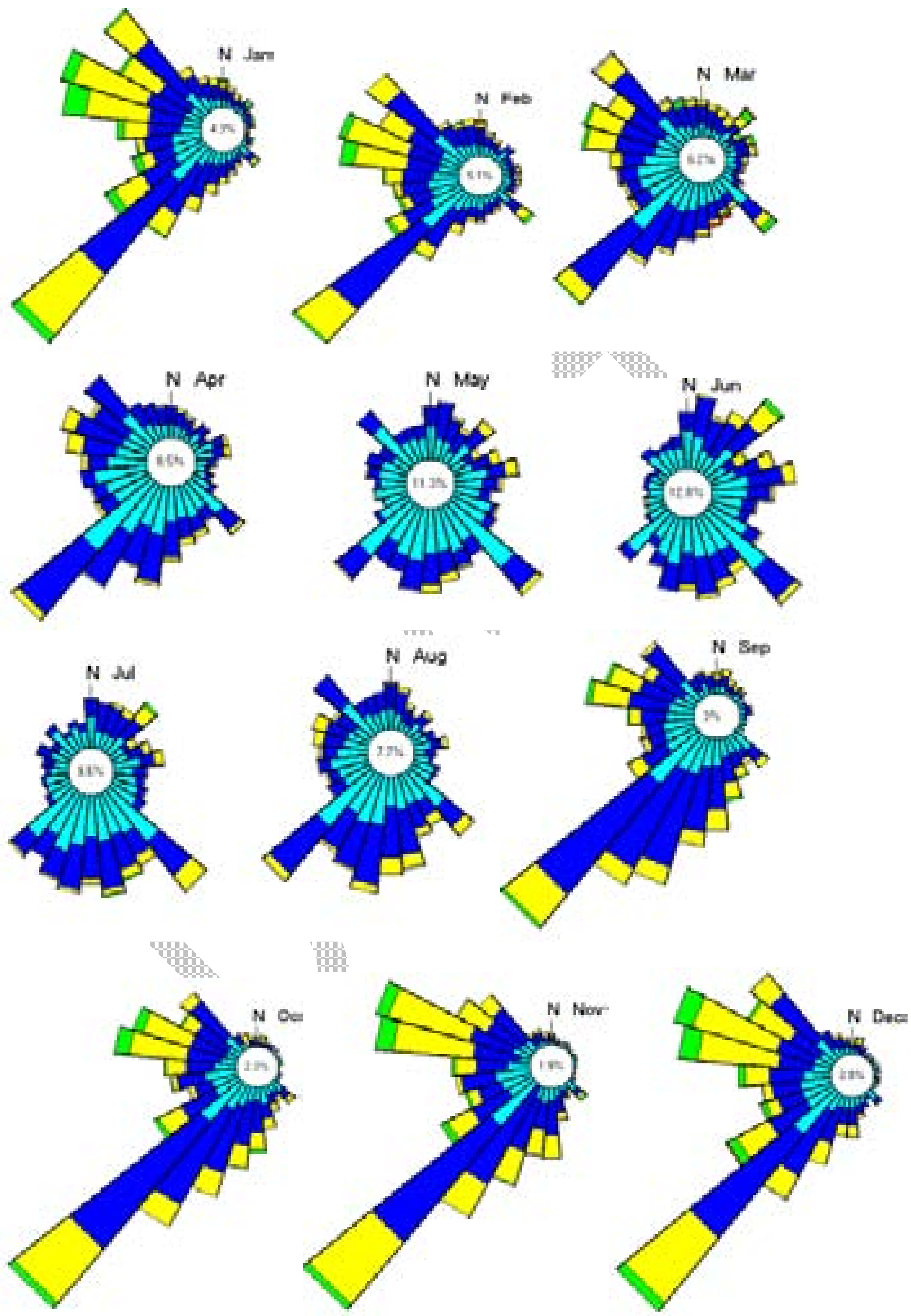


Figure 6. Monthly polar wind diagrams for Onslow Airport.

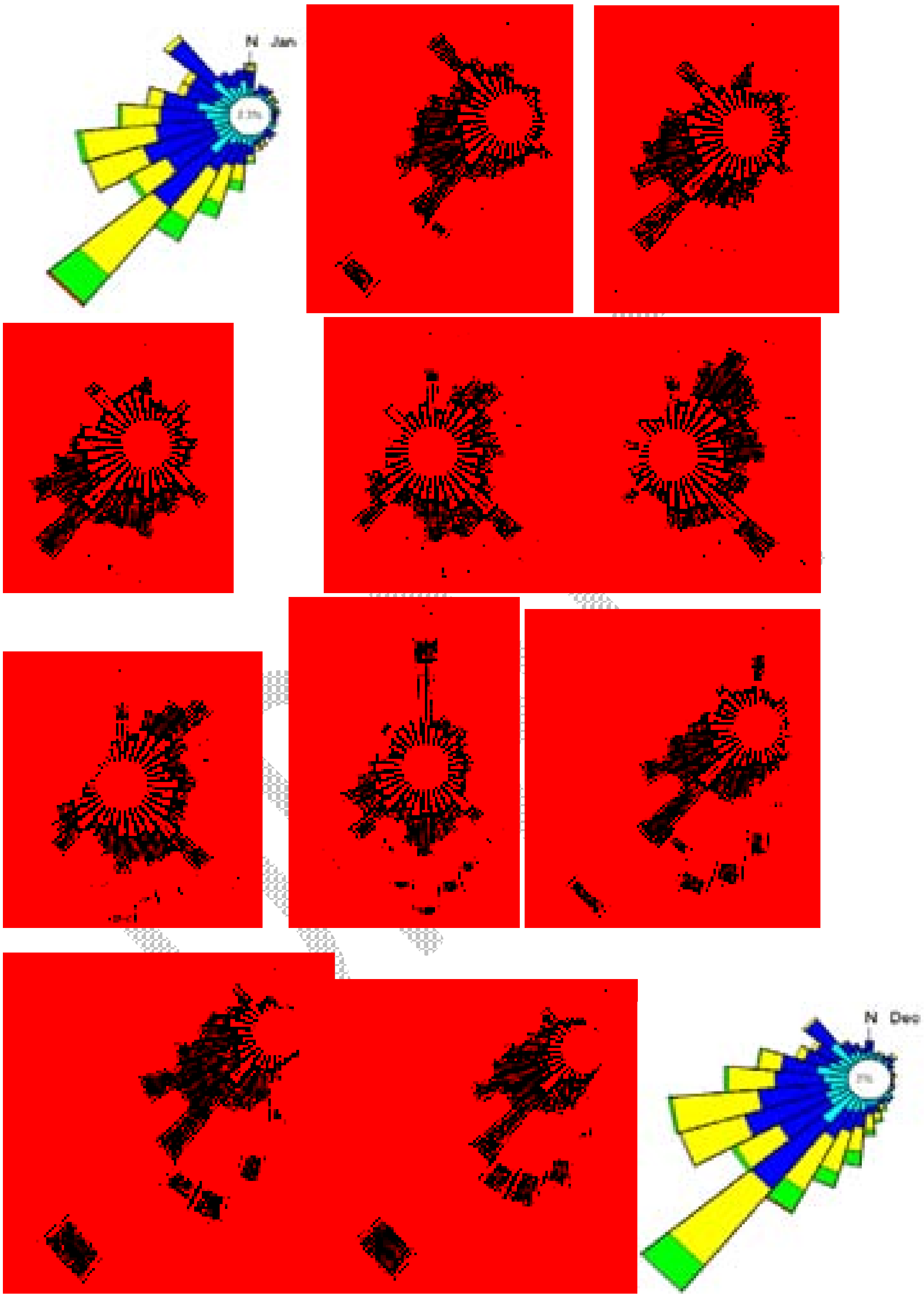


Figure 7. Monthly polar wind diagrams for Thevenard Island.

2.4 Numerical Weather Prediction

Coastal wind observations create a biased representation of the offshore wind patterns due to the formation of local land-sea breeze circulation. In order to adequately describe spatial variation of wind stresses, it is necessary to interpolate the wind field between observation sites. Various numerical wind field products are available, generated from networks of anemometers at a range of spatial scales.

BOM routinely operates a suite of Numerical Weather Prediction (NWP) models at a range of spatial and temporal resolutions. These models are nested in space so that the model system captures a range of atmospheric scales from global through regional (continental) to the local, or meso-scale.

The regional wind fields recommended by GEMS to support regional scale numerical modelling is MesoLAPS, a meso-scale model operated at a spatial resolution of about 10 km operated since 2000 by the Bureau of Meteorology (BOM). The model is nested inside a larger Australia-wide wind field model (LAPS) and runs twice daily producing forecasts out to 48 hours. Wind fields from the analysis cycle (zero hour) and the first eleven hours of forecasts of this model are now routinely downloaded twice daily and archived by GEMS. In effect, this generates 12-hourly interpolated wind fields and a database of hourly meteorological modelled wind fields with the longest forecast time step of eleven hours.

Figure 8 shows 'mean' vector winds fields for selected months based over the meso-LAPS domain. These 'mean' fields should be treated with caution since the averaging process results in a net wind field and eliminated significant day-to-day features of the wind climate.

2.5 Verification of MesoLAPS Winds

Validation of the accuracy of the wind fields for each new study area needs to be undertaken by comparison against observations. Previous studies by GEMS have shown that the MesoLAPS wind fields provide a very good representation of coastal wind regimes.

However, the model winds must be specifically verified for the Wheatstone study area and the results of data comparisons for Onslow AP and Thevenard Island are presented in this section.

Direct comparison of winds over large time scales for data presented at an interval of one hour is problematic. However, inspection of comparison plots provides an excellent qualitative means to evaluate model performance. In contrast quantitative processes, while useful for comparing relative performance such as correlation plots, generally cannot cater for general difference in phase differences between data sets.

A series of selected time series plots is presented to provide an assessment of the performance of the MesoLAPS model. Figures 9 and 10 show comparison of wind speed and direction over the course of three full years (2001, 2005 and 2007); these years having being selected arbitrarily.

Figures 10 and 11 show similar comparisons, but over selected monthly intervals (January, March, July and August), all during 2005.

In general the model does an excellent job in representing wind patterns over both long and short time scales. At Onslow, where the diurnal variation is very pronounced, variations in wind direction is excellent but wind speeds are consistently under-estimated. This underestimation, almost certainly linked to the way the model handles the sea-breeze circulation, is common for coastal terrestrial sites.

At Thevenard Island, both wind directions and wind speed are extremely well represented – the diurnal signal at Thevenard Island is reproduced by the model and wind speeds are more accurate in the maritime environment.

The excellent representation of the maritime winds by the model and its ability to capture the significant spatial variability of winds across the study area mean that the model fields are much more likely to allow proper representation of processes applying across the ocean surface.

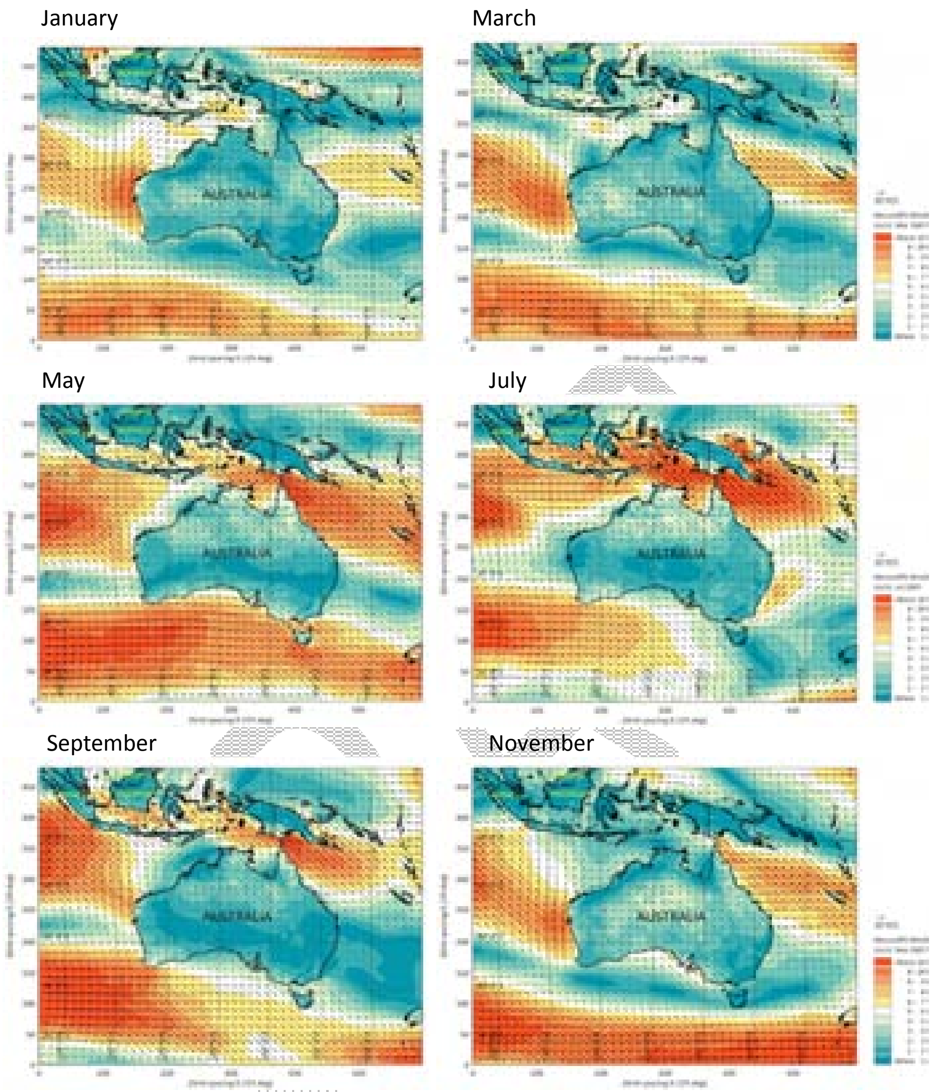


Figure 8. Monthly averaged winds over the Australian continent and surrounding seas sourced from MesoLAPS (selected months).

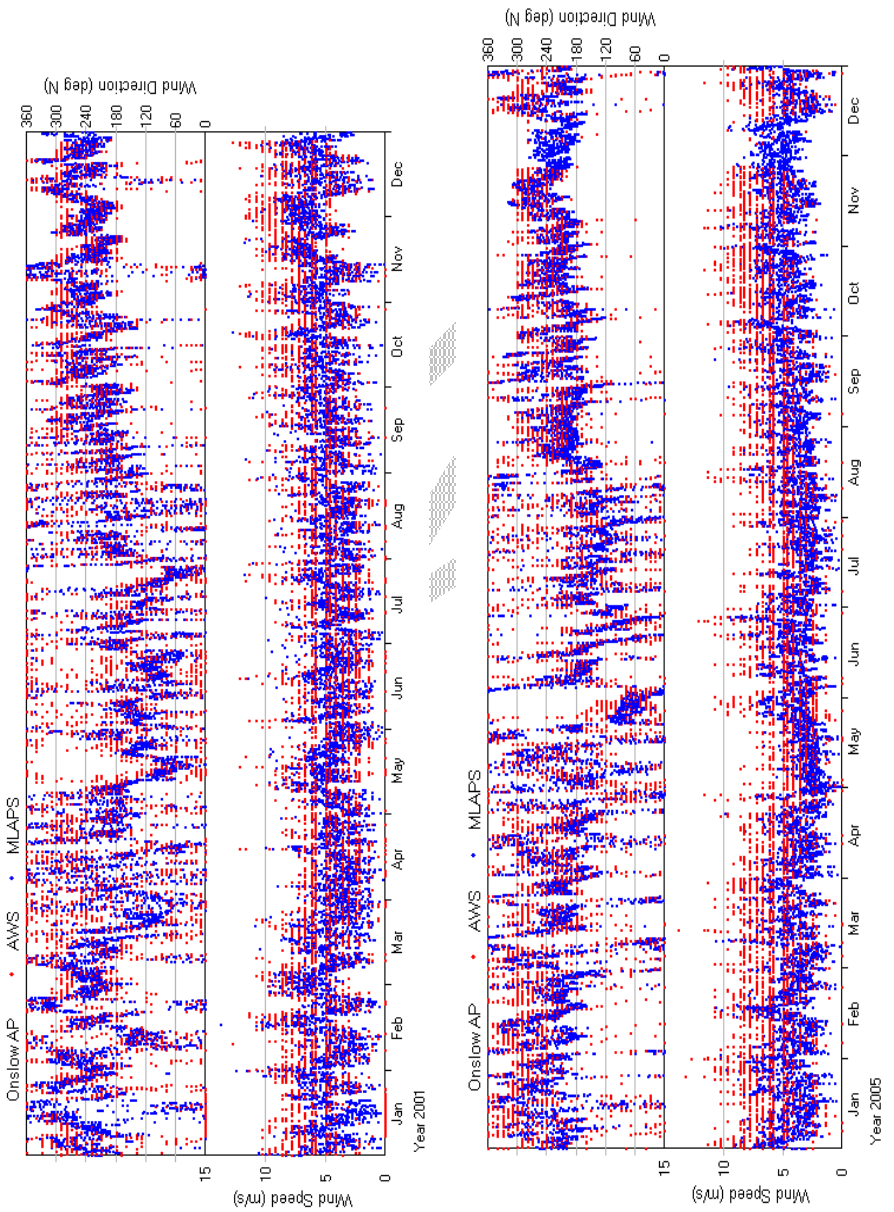


Figure 9. Comparison of observed and modelled winds at Onslow AP for 2001 and 2005.

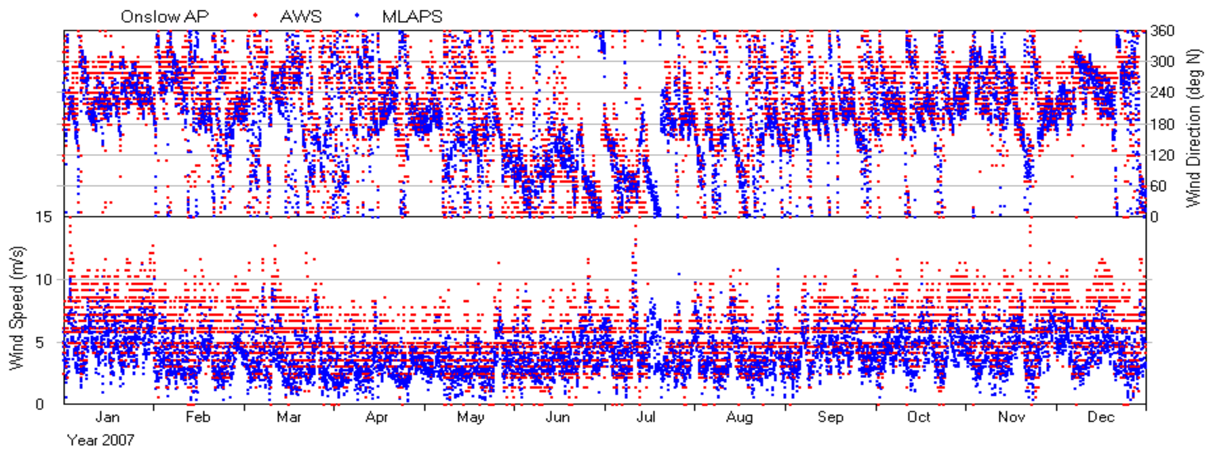


Figure 10. Comparison of observed and modelled winds at Onslow AP for 2007.

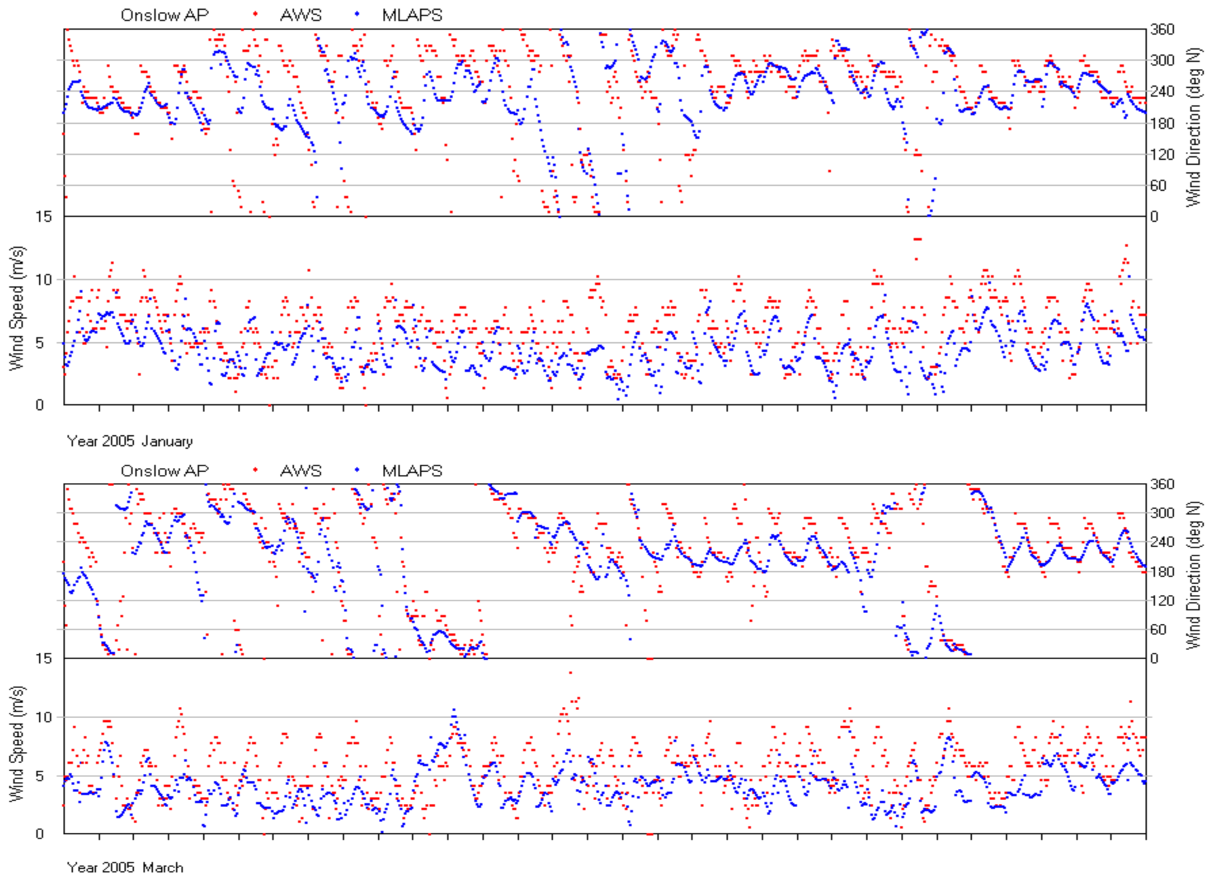


Figure 11. Comparison of observed and modelled winds at Onslow AP for January and March, 2005.

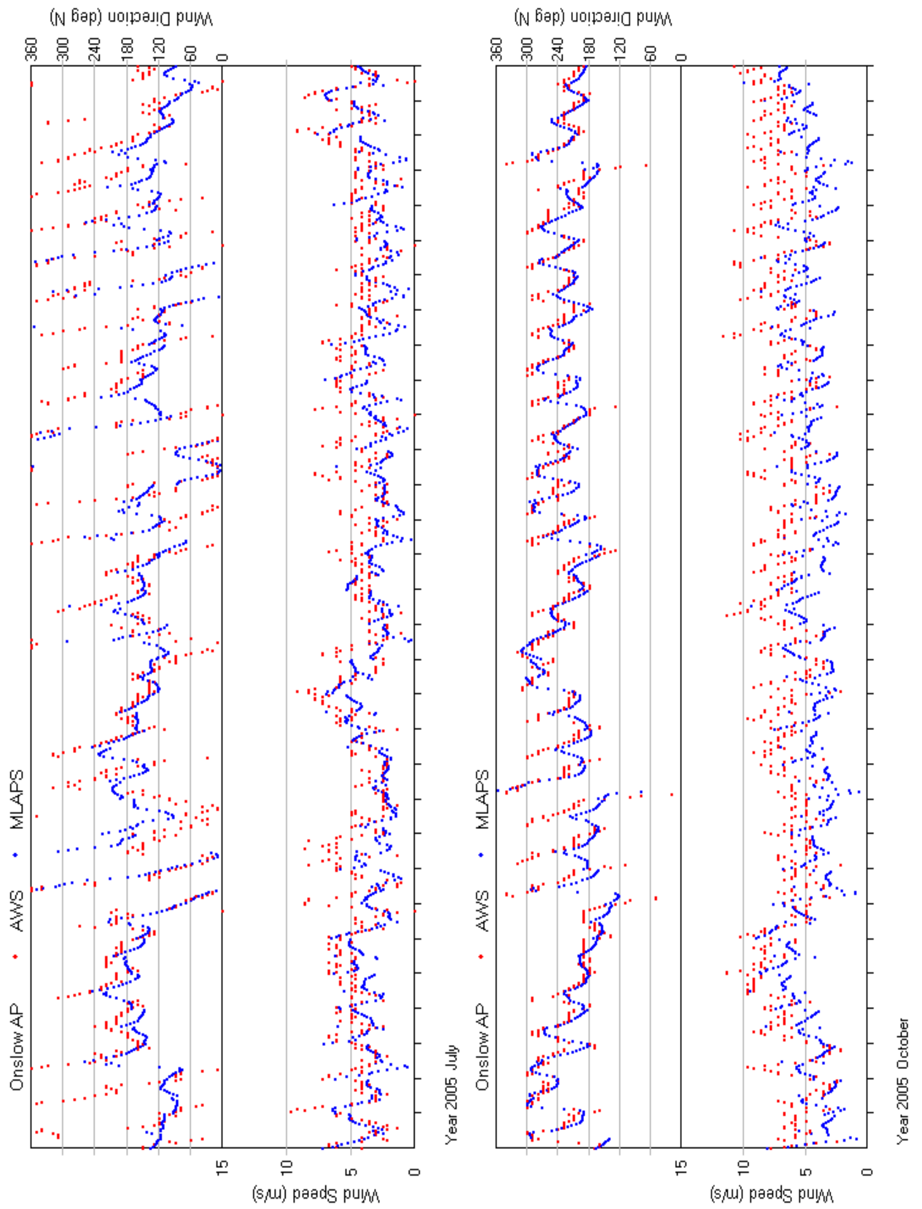


Figure 12. Comparison of observed and modelled winds at Onslow AP for July and October, 2005.

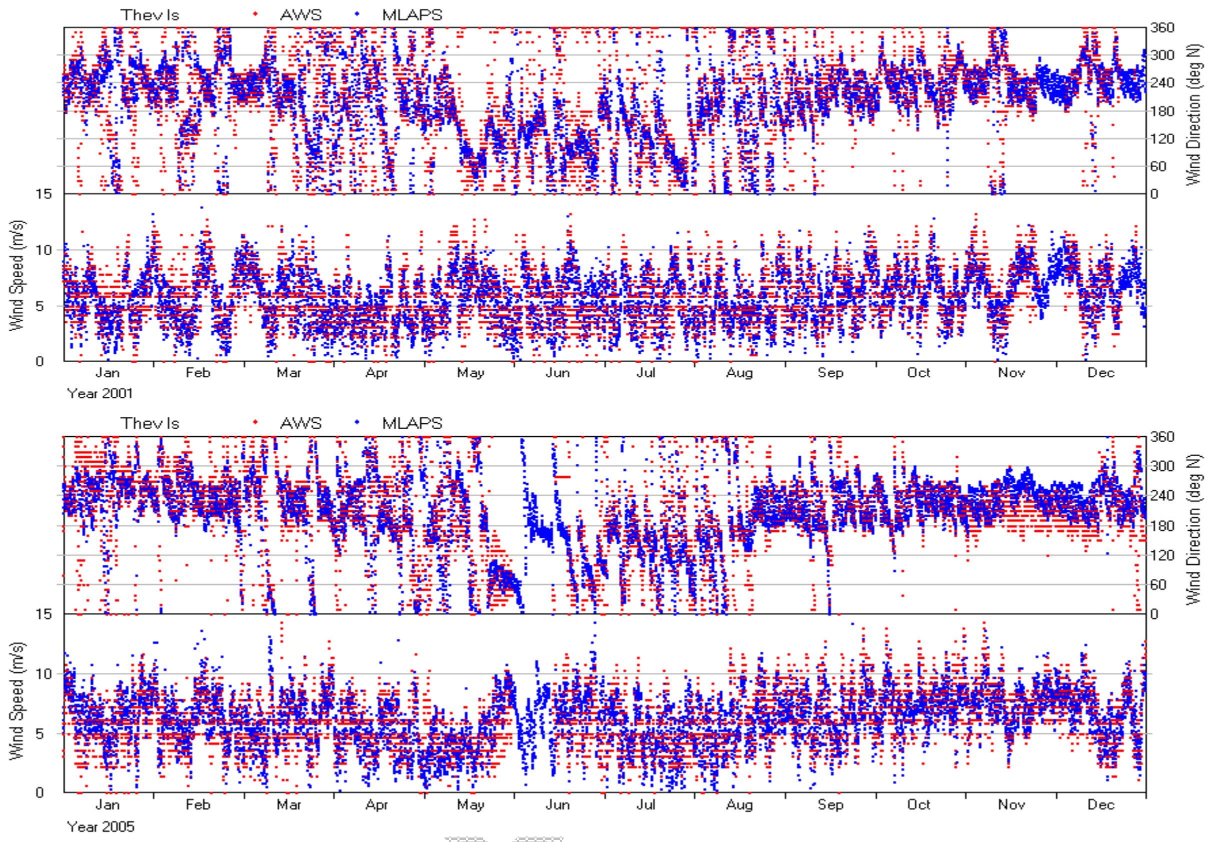


Figure 13. Comparison of observed and modelled winds at Thevenard Island for 2001 and 2005.

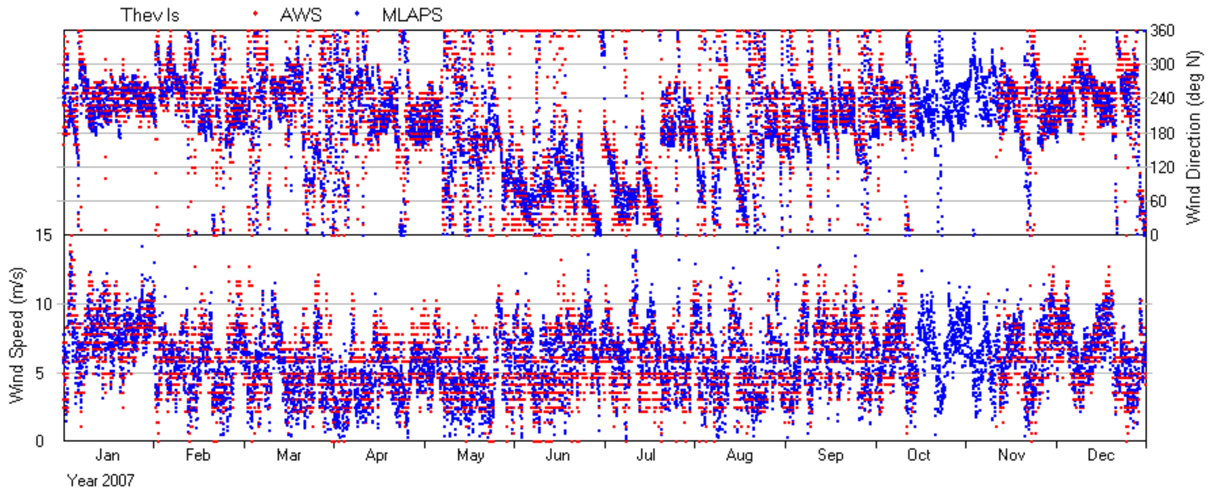


Figure 14. Comparison of observed and modelled winds at Thevenard Island for 2007.

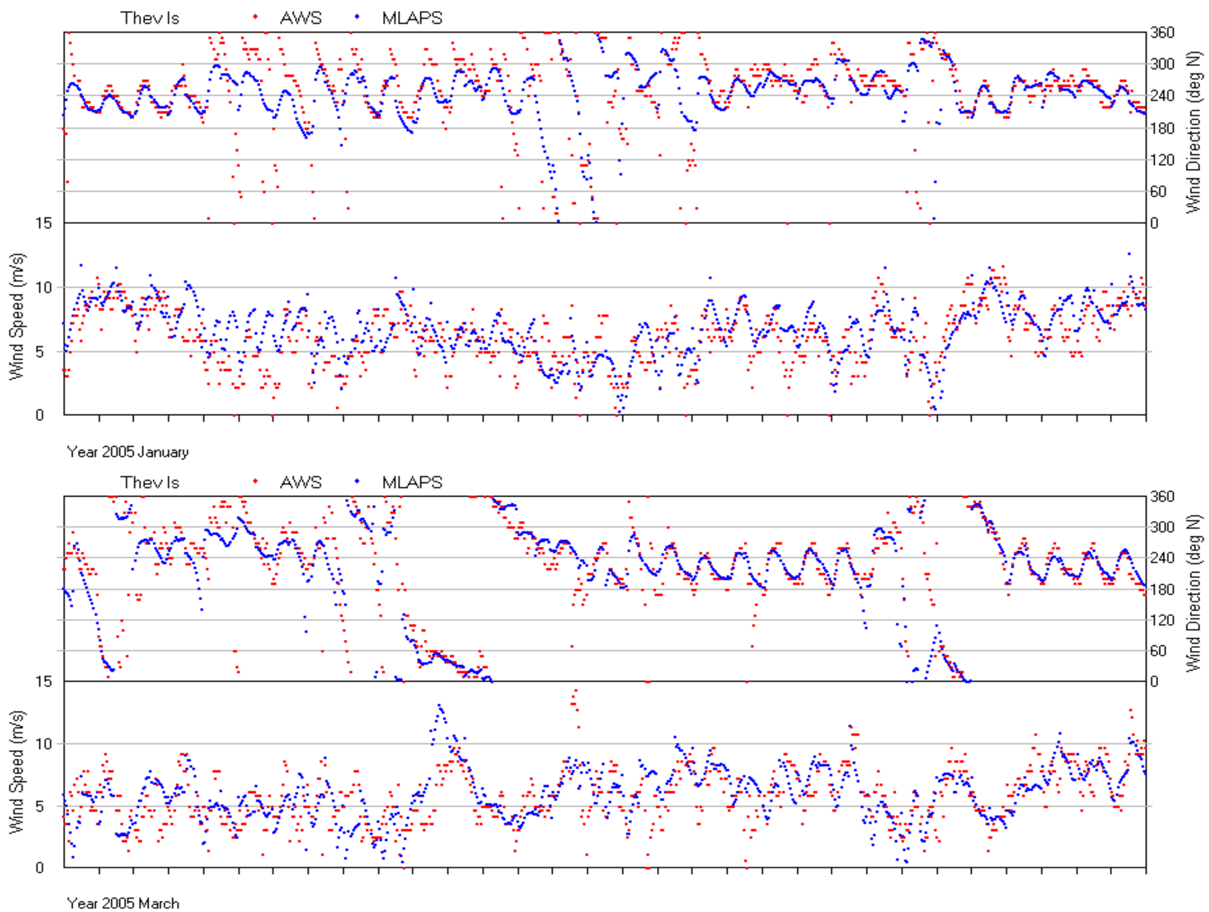


Figure 15. Comparison of observed and modelled winds at Thevenard Island for January and March, 2005.

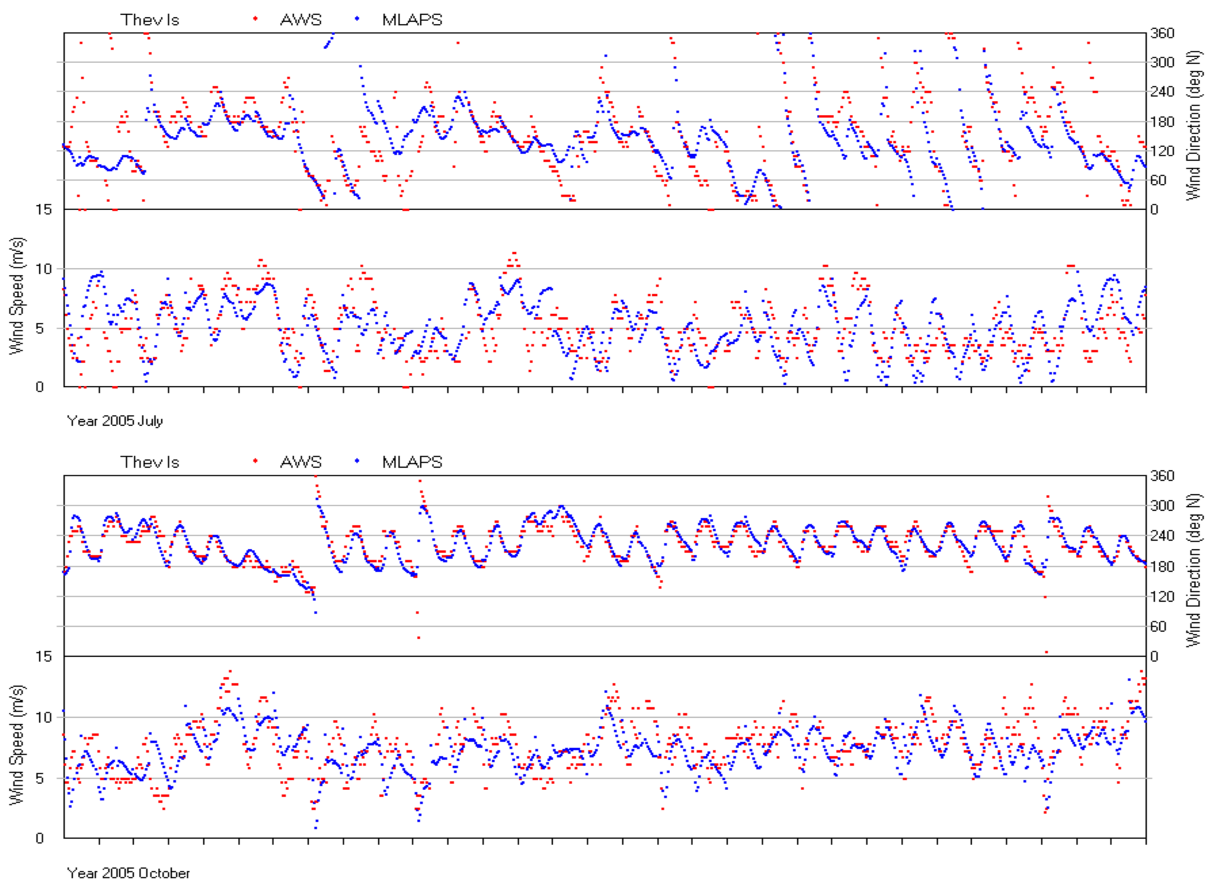


Figure 16. Comparison of observed and modelled winds at Thevenard Island for July and October, 2005.

2.6 INTER-ANNUAL VARIABILITY

The inter-annual variability of winds is an important consideration because representative periods must be selected for the plume modelling. The aim of this selection process is to allow for demonstration of plume fates under both 'average' and more typical outlier climate conditions.

Figure 17 shows a plot of the so-called southern oscillation index (SOI) for the period 1990 to 2009. The SOI is a broad scale indicator of the regional climate. Sustained negative values generally correspond to El Nino conditions and sustained positive values to La Nina.

The effect of these large scale phenomena on regional winds is illustrated in Figure 18. To construct this diagram, hourly winds were extracted from the BOM Meso-LAPS model database for the Wheatstone area for the period 2000 to 2009 inclusive. These data were then subjected to analysis and Figure 18 shows the relative proportion of 'calm winds ' (<5 m/s) , easterly and westerly component winds (with wind speed > 5 m/s), on an annual basis throughout the period. The diagram also shows, in the last column, the corresponding values over this entire period.

There is a period of sustained negative SOI values from 2002 to 2005 and this corresponded to a mild El Nino episode in 2002-3. Winds in this period show a marked westerly anomaly at Wheatstone.

For the period 2007-2009 the SOI is consistently positive, with winds proportionally closer to the mean. However, a weak la Nina episode developed in mid 2007 and there is a corresponding weak easterly anomaly in this period.

The preceding analysis shows that the two periods 2002 to 2004 and 2007 to 2009 represent markedly different states for the wind climate. Accordingly, they were selected as suitable periods to demonstrate dredge outcomes for two different, but representative climate states; the first for the more extreme El Nino anomaly and the second for 'average' conditions but including a mild la Nina.

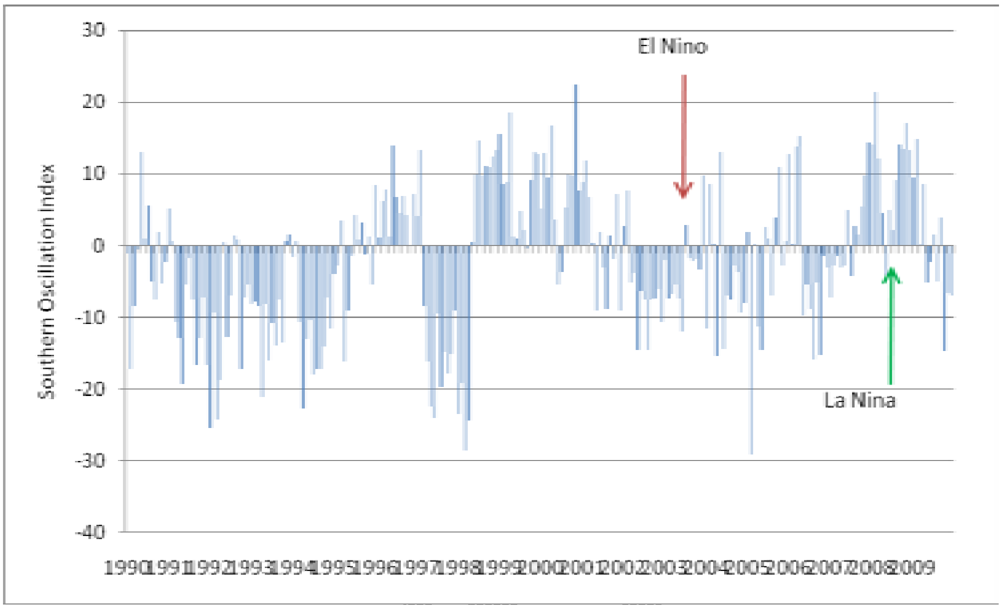


Figure 17. Time series of monthly Southern Oscillation Index (SOI).

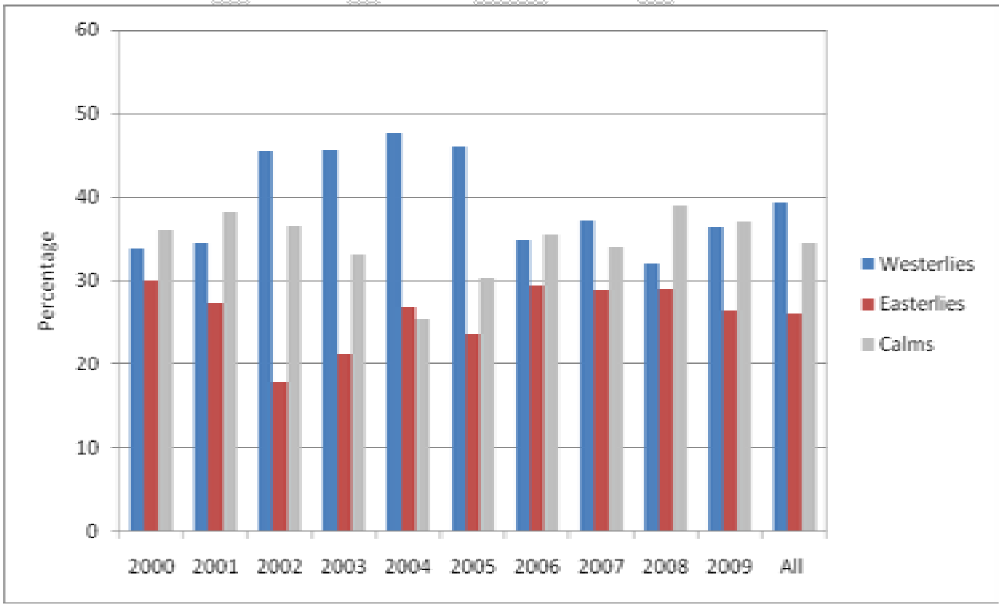


Figure 18. Annual Distribution of westerly, easterly and 'calm' winds for Wheatstone location.

SECTION 3. OCEAN SEA LEVELS

A number of components contribute to observed sea levels including

- Astronomical tides
- Wind and pressure driven setup (on scales from storm surges to variations in mean water levels with seasons)
- Large scale ocean currents
- Wave setup near the coast

For the purpose of sediment plume modelling, the focus is on the net currents and the tidal variations. Net currents will tend to move a turbid plume away from the source whilst the flooding and ebbing tide can cause short term exposure and flushing of plumes from a given location.

To simulate these processes with an ocean model, the tidal levels and any influences of large scale currents are included through the boundary conditions. The wind and pressure driven setup is generated through the application of wind stresses and pressure gradients at the ocean surface.

Wave setup is more relevant to coastal flooding than studies of the movement of plumes, but it can be incorporated in a model simulation by linking a wave model with the ocean model to swap information on water depths and wave radiation stresses.

3.1 Astronomical Tides

The phenomenon of tidal oscillations is the response of the ocean to the combined action of the gravitational forces of the Moon and the Sun acting on the oceans. The tidal regime at any location in the world's oceans consists of a large number of individual waves of different frequencies caused by this combined gravitational forcing. These waves are referred to as "constituents", where each constituent is described with an amplitude and a phase. As these waves behave linearly and do not modify each other, a measured water level record can be decomposed into a series of constituents, which summarise the tidal characteristics of the area.

Tidal predictions for the area may then be made for any time in the past or future by reconstituting a water level time series from the extracted tidal constituents. Locations of tidal stations in the North West Shelf (NWS) area are shown in Figure 19.

Figure 20 shows a sample 8-day prediction of tidal elevations at Onslow, showing that the tidal signal along the coastline of Onslow is semi-diurnal, implying that there will be two high waters and two low waters per day.

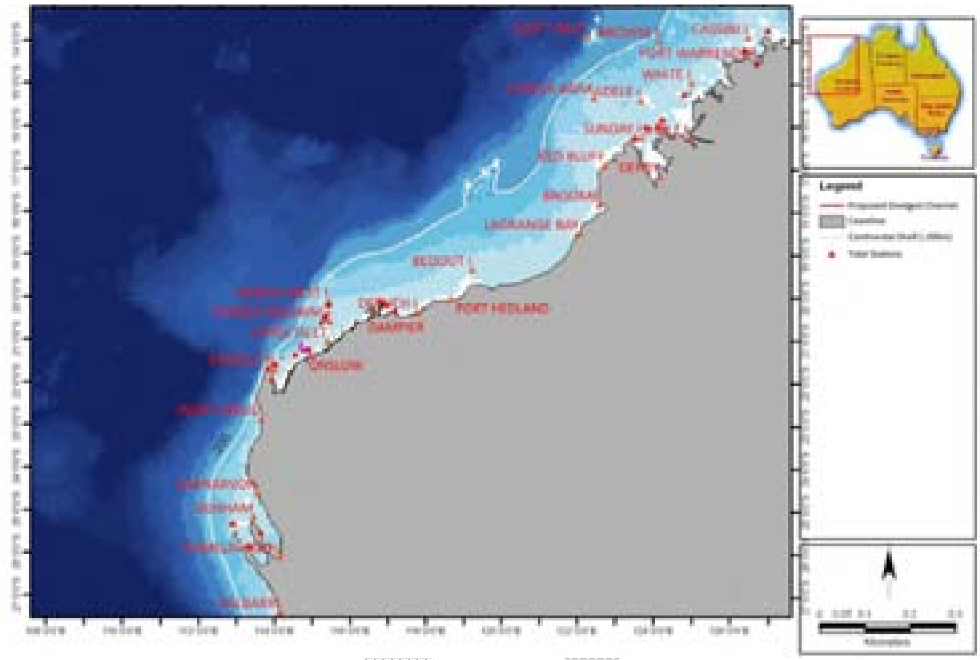


Figure 19. Locations of the tide stations along the North West Shelf (courtesy of DHI).

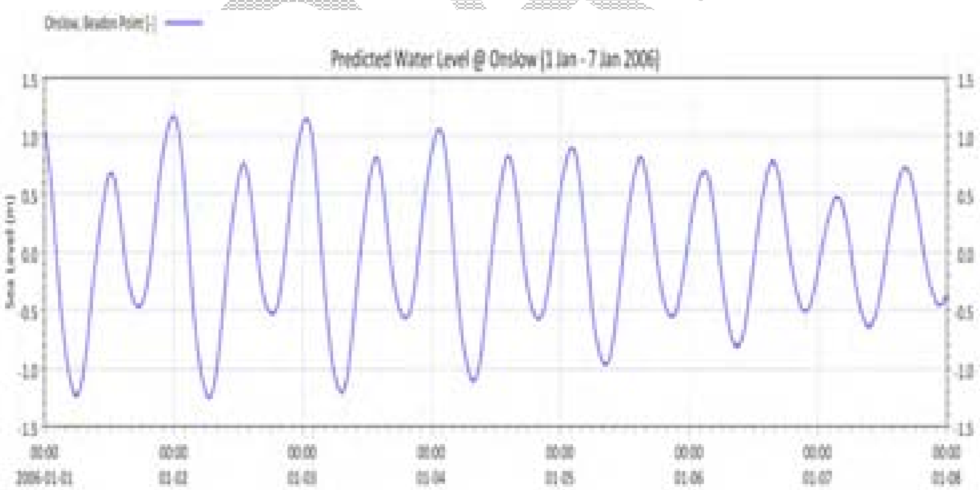


Figure 20. Sample 8 day prediction of the tidal elevation at Onslow, Beadon Point (courtesy of DHI).

3.2 Tidal Dynamics at Onslow

The tidal signal changes progressively along the NWS coastline with increasing tidal ranges from Exmouth to Broome as illustrated in Figure 21, which shows a map of the difference between Chart Datum and Mean Sea Level, which is approximately equal to the maximum tidal amplitude.

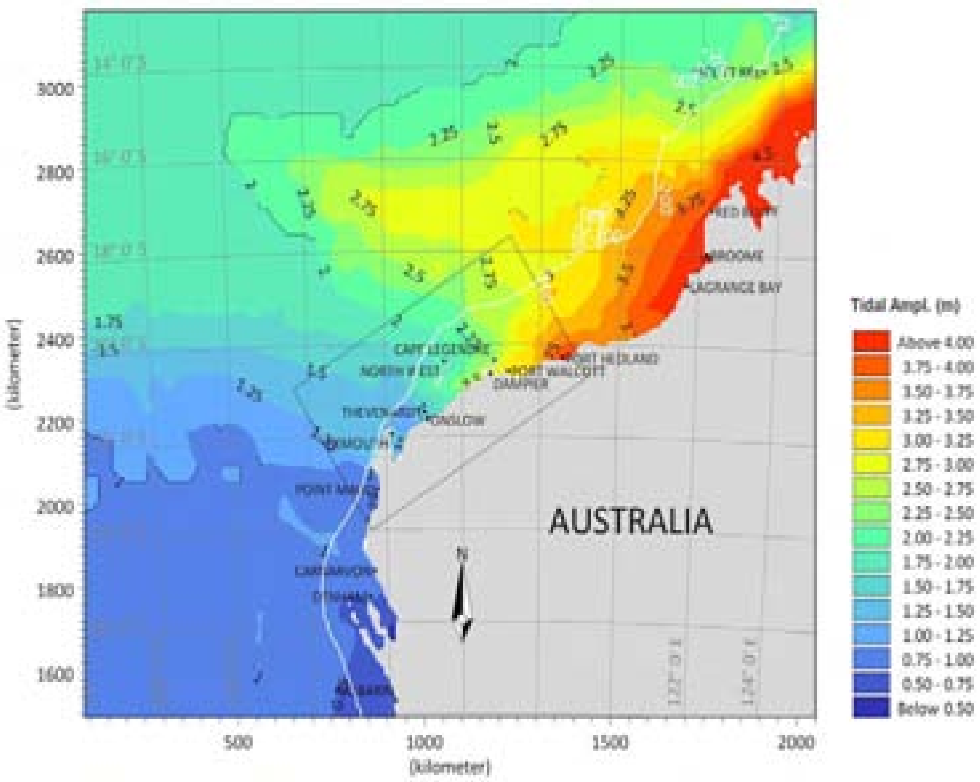


Figure 21. Approximate tidal amplitudes along the north-western coast of Australia (courtesy of DHI).

To illustrate these variations in more detail, the tidal regimes in Exmouth, Onslow and Broome have been sourced from the Admiralty Tide Tables (Table 2), together with the tidal data for Cape Preston which was sourced from previous studies by GEMS (GEMS, 2008).

As Table 2 shows, the mean spring range for Onslow is about 1.9 m whereas less than 150 km away at Cape Preston the mean spring range has almost doubled to 3.4 m whilst at Broome the mean spring tidal range is 7.1 m, which is more than three times the tidal range in Onslow.

The major reason for the significant difference between Onslow and Cape Preston is the mechanism via which the flood tide flows onto the North West Shelf. At Onslow the flood tide flows in from the west with little resistance but due to the shallow regions between Barrow Island and the coast it is unable to fully flow as far as Cape Preston and the Dampier Archipelago.

Instead a large amount of the flood tidal flux is forced to flow seaward of Barrow Island and reach the coast by flowing around the north end of the Montebello Islands and then southward to locations such as Cape Preston. Hence the flood tide reaches Cape Preston and the Dampier Archipelago from a northerly direction with only small tidal fluxes able to flow in from the west.

As a result of these processes the tidal dynamics change dramatically between Onslow and Cape Preston and between Onslow and Barrow Island.

Table 2. Tidal planes for Exmouth, Onslow, Cape Preston and Broome (values are in metres relative to LAT)

Tidal Plane	Acronym	Exmouth	Onslow	Cape Preston	Broome
Highest Astronomical Tide	HAT	2.8	2.9	4.7	9.6
Mean Higher Water Spring	MHWS	2.3	2.5	4.1	8.6
Mean Higher Water Neap	MHWN	1.7	1.8	3.0	5.6
Mean Sea Level	MSL	1.4	1.5	2.4	4.5
Mean Lower Water Neap	MLWN	1.1	1.2	1.8	3.5
Mean Lower Water Spring	MLWS	0.5	0.6	0.7	1.5
Lowest Astronomical Tide	LAT	0.0	0.0	0.0	0.0

SECTION 4. OCEAN CURRENTS

Currents at the site are the dominant factor in determining the spread, deposition and potential re-suspension of the sediment plumes generated through dredging and placement of dredge material. A good understanding of the current regime and patterns and the ability to reproduce these through modelling is critical for the impact assessment. The main application of the current data is to help understand the local and North West Shelf oceanography and to verify the predictions of ocean models used in the study.

Currents at the site are a combination of tidal currents, wind driven currents, wave driven currents, strategy, it is important to assess the relative importance of these components as well as potential stratification and three-dimensionality. The present section includes a basic assessment of the currents based on available data as well as an assessment of the potential impacts from Indian Ocean Currents.

4.1 Current Data Overview

The data base of current measurements available to the project is continuously growing. An overview of current data available to the project as of March, 2010 is provided in Table 2 and the locations are illustrated in Figure 22.

The data consists of the results of two distinct field programs. The first program was carried out for Onslow Salt over a period of 13 months from 25 January 2006 to 21 February 2007 at a number of nearshore locations and one offshore location as follows:

- 1 month of Acoustic Doppler Current Profiler (ADCP) 3D current data at a location north-west of Direction island;
- 1 month of ADCP 3D current data within the Basin just offshore from the Onslow Salt Jetty;
- 13 months of single point current measurements within the Basin just offshore from the Onslow Salt Jetty; and
- 1 month of single point current measurements at the Onslow Salt Jetty.

The second program is being carried out for this project and commenced on January 10, 2009.

Ongoing 3D current measurements are being obtained at:

- The location of the new Product Loading Facility (PLF) (with a gap from June 13 – July 26, 2009);
- Towards the northern end of the new channel (from July 24, 2009); and
- The proposed offshore dredge material placement ground (spoil ground D).

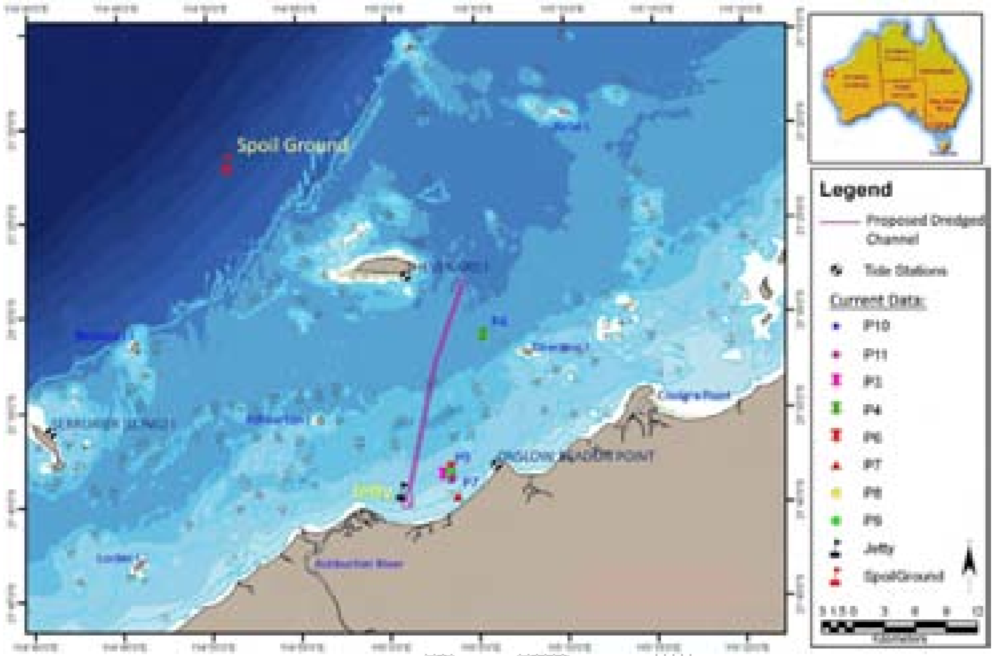
In addition:

- A new ADCP deployment has just occurred at spoil ground C and data will be gathered for the next 12 months;

- 5 satellite tracked surface drifters were released on May 8, 2010 off Onslow at strategic locations along the channel and at spoil ground C – this program will be repeated during winter to sample alternate conditions; and
- 3 months of ADCP data was collected at a location west of the proposed channel in 2009.

Table 3. Overview of available current measurements.

Location	ID	First Data Record	Last Data Record	Water Depth (m)	Longitude	Latitude
NW_Direction Island ADCP	*P4*	*25/01/2006*	*25/02/2006*	*13.5*	*115° 5.330'*	*-21° 31.215'*
Basin ADCP	*P3*	*25/01/2006*	*25/02/2006*	*9.5*	*115° 3.0'*	*-21° 38.525'*
Basin CM	*P6*	*25/01/2006*	*25/02/2006*	*9.5*	*115° 3.457'*	*-21° 38.238'*
Basin CM	*P8*	*26/02/2006*	*22/04/2006*	*11.0*	*115° 3.427'*	*-21° 38.672'*
Basin CM	*P8*	*14/05/2006*	*07/06/2006*	*11.0*	*115° 3.427'*	*-21° 38.672'*
Basin CM	*P9*	*26/02/2006*	*07/06/2006*	*11.0*	*115° 3.420'*	*-21° 38.292'*
Basin CM	*P10*	*08/06/2006*	*20/09/2006*	*8*	*115° 3.468'*	*-21° 38.722'*
Basin CM	*P11*	*21/09/2006*	*01/02/2007*	*8*	*115° 3.533'*	*-21° 38.647'*
Onslow Salt Jetty CM	*P7*	*25/01/2006*	*25/02/2006*	*4.5*	*115° 3.840'*	*-21° 39.618'*
New PLF ADCP		*11/01/2009*	*ongoing*	*8.2*	*115° 0.708'*	*-21° 39.295'*
Spoil Ground_D ADCP		*10/01/2009*	*ongoing*	*51*	*114° 51.113'*	*-21° 21.858'*
New Channel ADCP		*24/07/2009*	*ongoing*	*15*	*115° 2.940'*	*-21° 30.103'*
West of channel ADCP		*19/04/2009*	*15/07/2009*	*16*	*114° 54.898'*	*-21° 31.403'*


Spoil Ground
Legend
Proposed Dredged Channel
Tide Stations
Current Data:
P10
P11
P3
P4
P6
P7
P8
P9
Jetty
SpoilGround

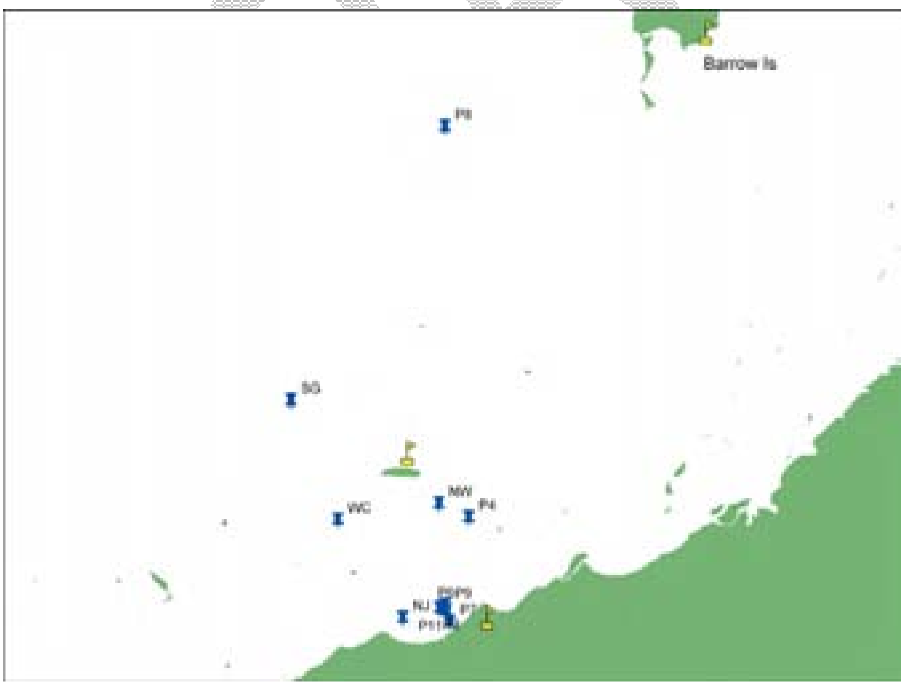

Barrow Is
SG
WC
NW
P4

Figure 22. Locations of current measurements

4.2 2007 Data

The data from the ADCP north-west of Direction Island (P4) in the summer of 2007 is illustrated in Figures 23 and 24. Figure 23 shows time series for the month of data at different levels in the water column. The variations in Figure 23 are difficult to discern, however, so Figure 24 gives the same data in the form of current roses at each of the 8 levels.

Figures 25 and 26 give time series plots of winter and summer data at the Basin site and again to give a different view of the data, Figures 27 to 28 give current roses for sequential periods of the 13 month measurement program at the Basin sites.

The following points arise from these results:

- The ADCP currents north-west of Direction Island (P4) are measured over eight different levels of the water column for one month from 25 January 2006 until 25 February 2006 and show quite distinct differences between surface and bottom currents. The surface currents wind rose is more directionally diffuse whereas the bottom current rose is much more polar. The bottom current rose is also rotated clockwise from the surface current rose and shows much more flow to the south-west than at the surface. These differences are presumably due to the stronger influence of the winds at the surface than at the bottom and the action of the tide against the wind;

- The dominant tidal flow can be seen in all the current roses going in an approximate north-easterly and south-westerly direction with small variations through the water column due to the effects of bottom friction;

- Currents at P3, P6 and P7 are measured over one month for the same period as P4 and are relatively weaker than at P4 but these locations also show predominant flow directions towards the north-east during flood tides and the south-west during ebb tides;

- Overall, flood tide currents flow north-eastward while ebb tide currents flow westerly to south-westerly along the coast;

- A surge in current velocities up to 0.74m/s and 0.69m/s was recorded at P8 and P9 respectively during the end of March 2009. During this period, the peak wind speed of approximately 34.4 m/s was observed at the Onslow Meteorological Station. This was due to Cyclone Glenda which crossed the coast near Onslow at 10pm on 30 March as a marginal category 3 system. One week later around 7 April 2009, Cyclone Hubert hit the area but the impacts were not as significant as Cyclone Glenda and the peak current speeds only reached up to 0.32 m/s at P8 and 0.37 m/s at P9.

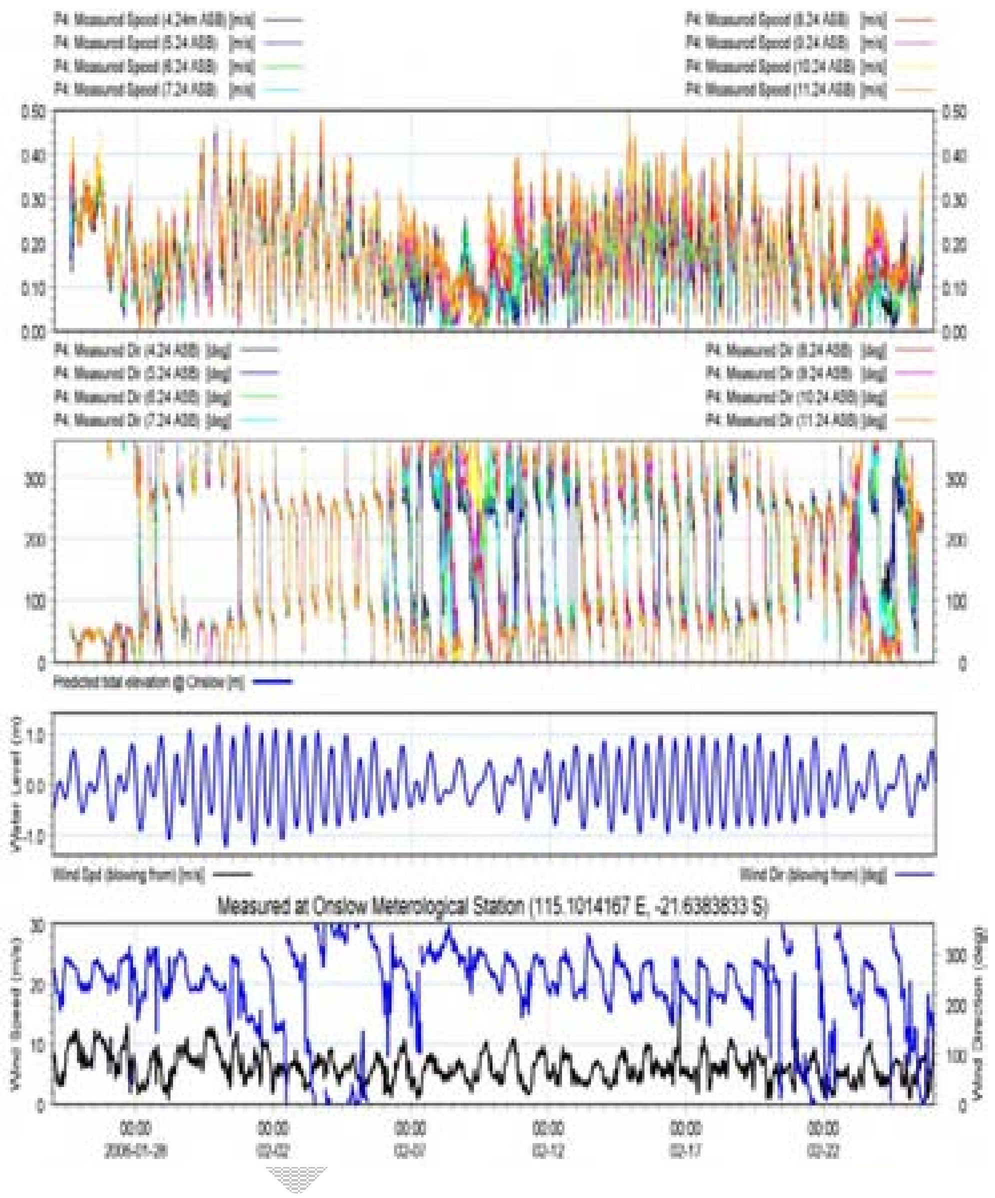


Figure 23. Time series of current speeds and directions measured at the location NW of Direction Island (P4) over 8 different levels of the water column for the period from 25th Jan 2006 until 26th Feb 2006 (courtesy of DHI).

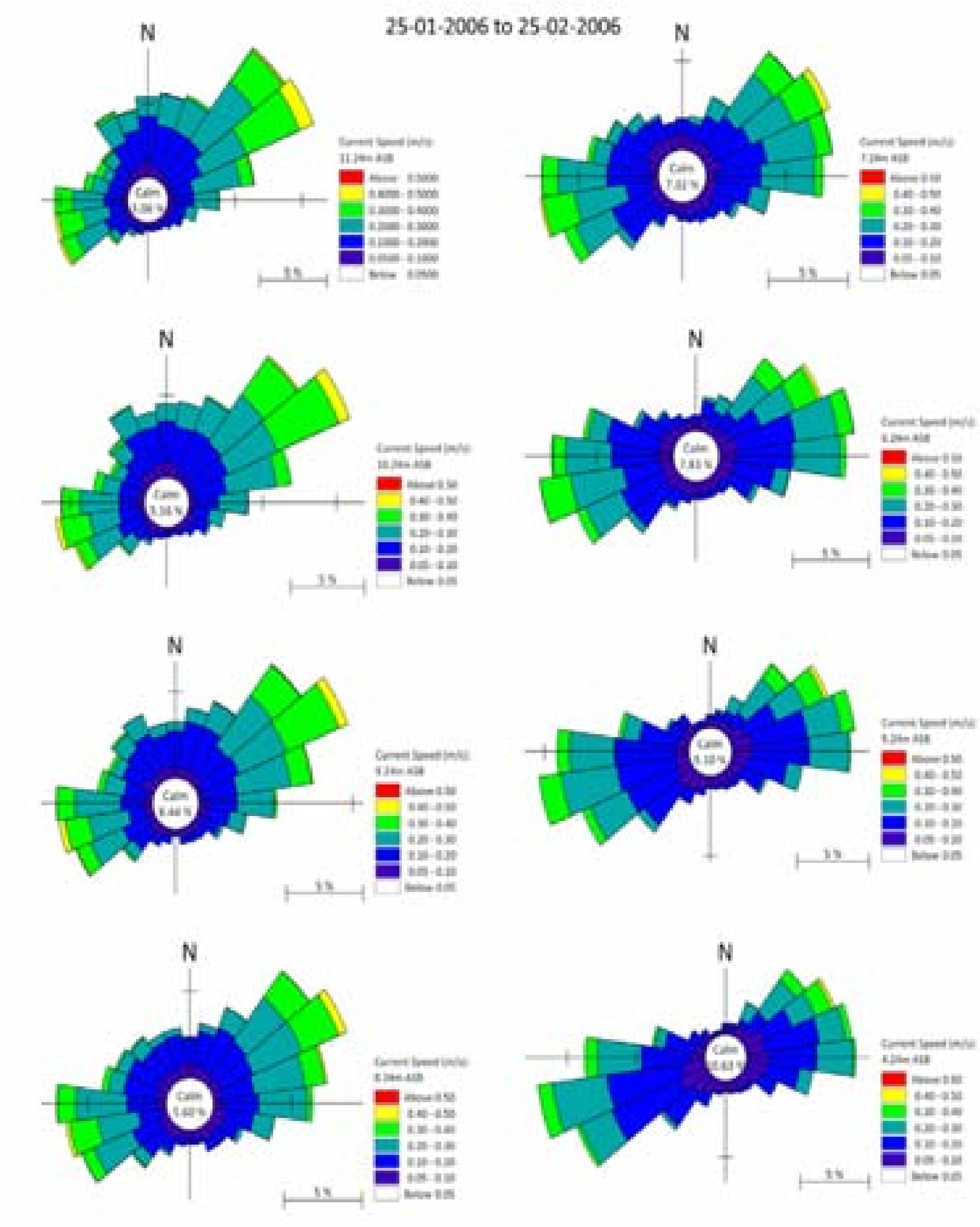


Figure 24. Current roses for measured current data NW of Direction Island (P4) at 8 different levels through the water column from 25th Jan 2006 until 26th Feb 2006 (courtesy of DHI).

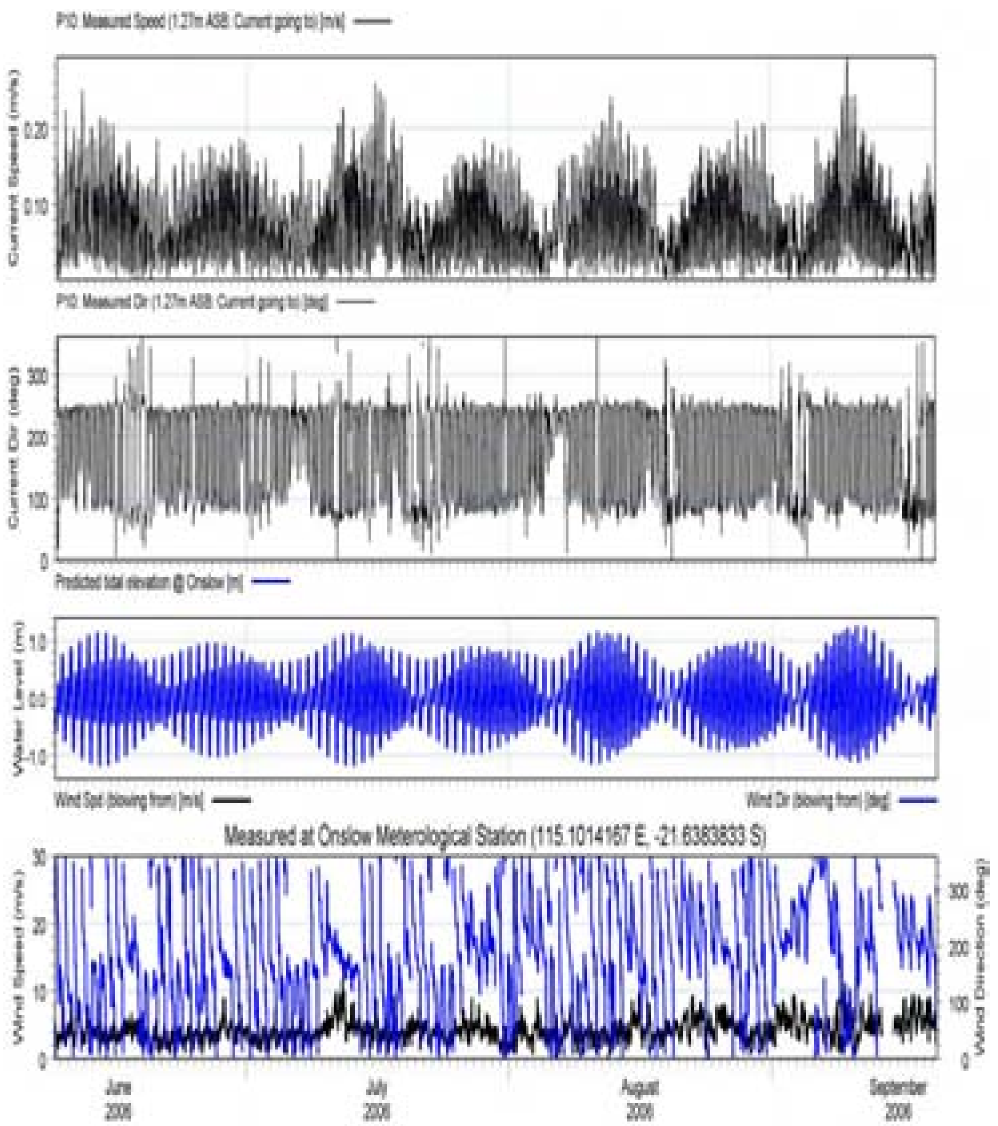


Figure 25. Time series of current speeds and directions measured at P10 (8th June 2006 to 20th September 2006). Predicted tidal elevations at Onslow as well as wind measurements at Onslow Meteorological Station are shown for reference (courtesy of DHI).

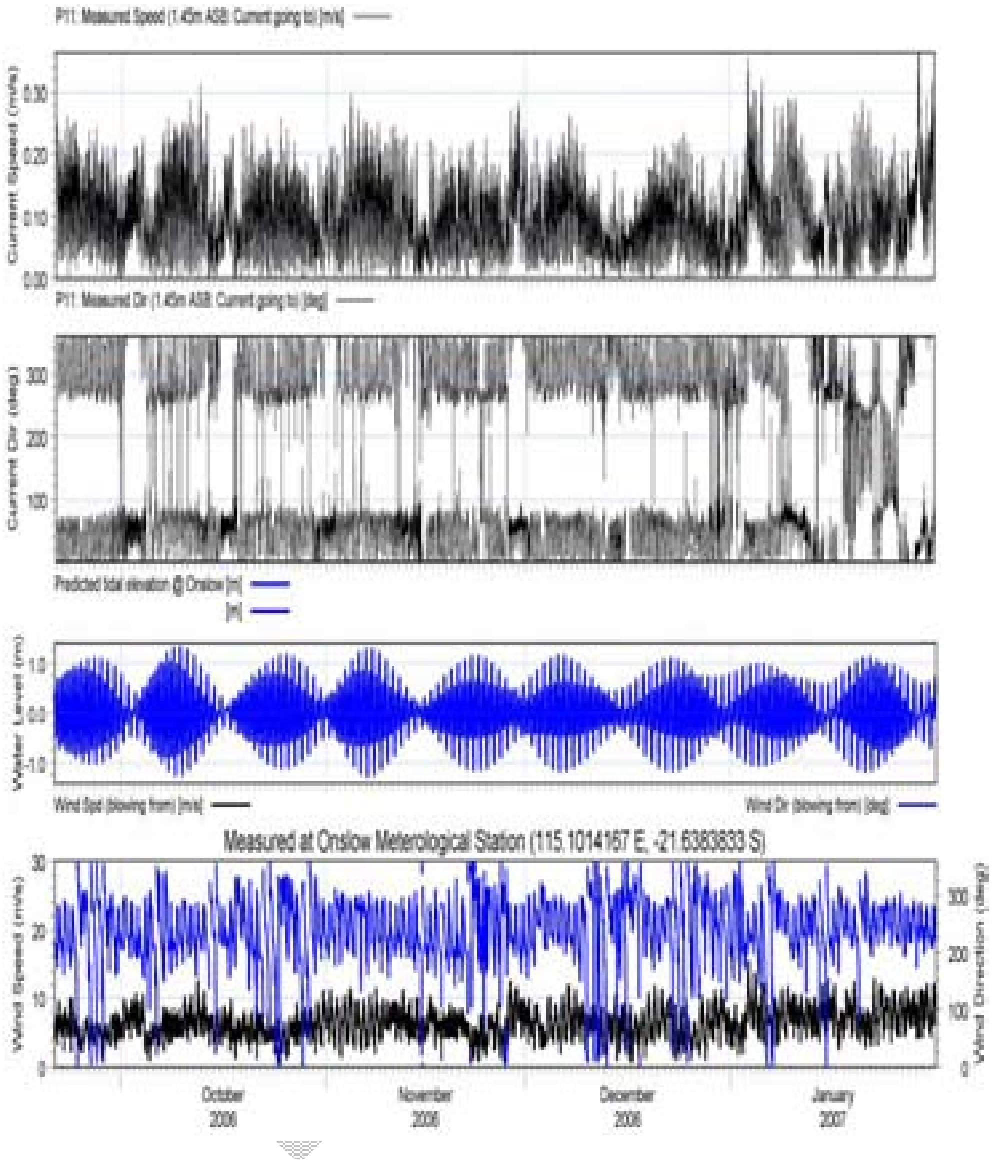


Figure 26. Time series of current speeds and directions measured at P11 (21st September 2006 to 1st February 2007). Predicted tidal elevations at Onslow as well as wind measurements at Onslow Meteorological Station are shown for reference (courtesy of DHI).

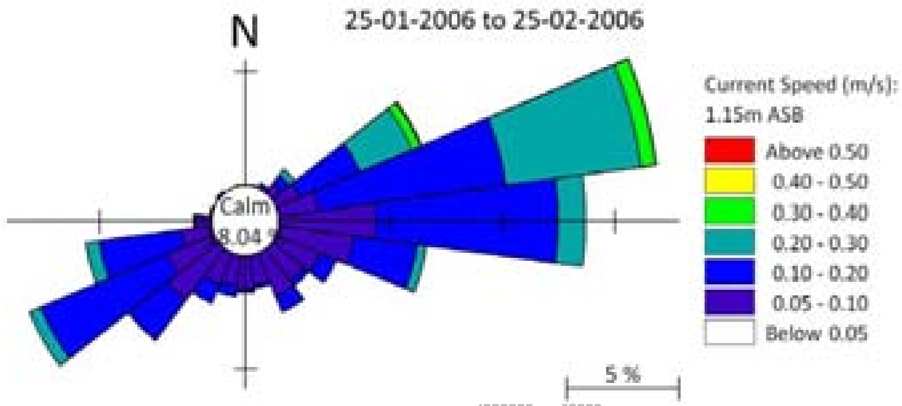


Figure 27. Current rose for measured current data at the Basin (P6)

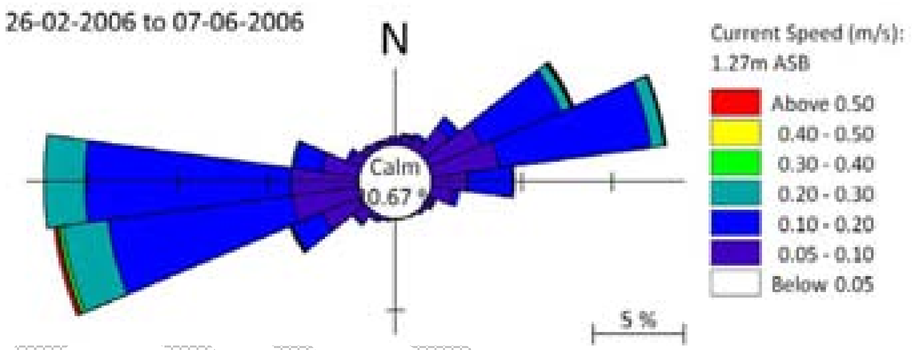


Figure 28. Current rose for measured current data at the Basin (P8) - Missing Data from: 23 Apr 2006 to 13 May 2006.

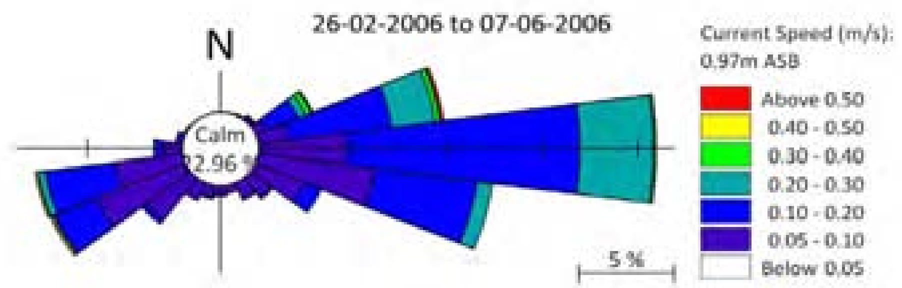


Figure 29. Current rose for measured current data at the Basin (P9)

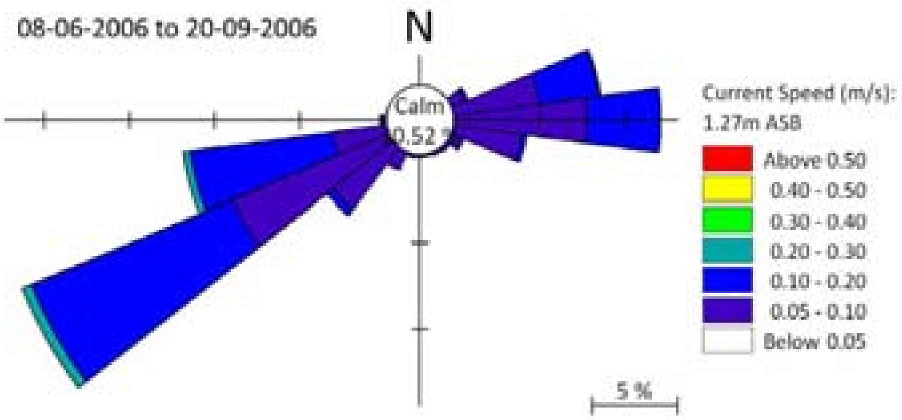


Figure 30. Current rose for measured current data at the Basin (P10).

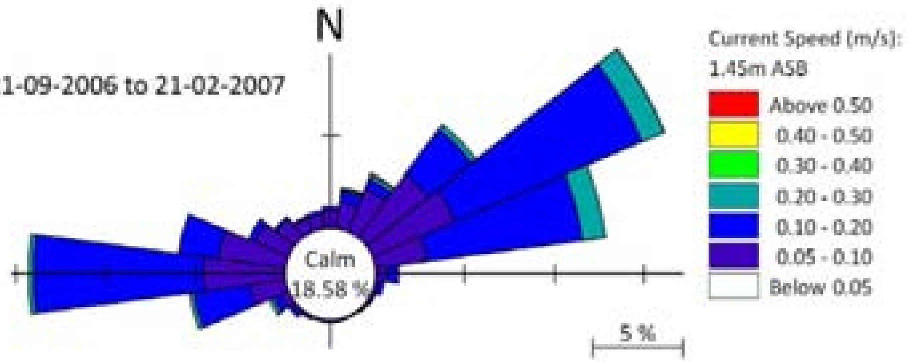


Figure 31. Current rose for measured current data at the Basin CM04p #2 (P11)

4.3 2009 Data

The current measurement campaign dedicated to this project commenced on January 10, 2009 and is being undertaken by RPS. Selected results are presented as follows:

- Figure 32 and 33 show current roses for summer and autumn, 2009 at 11 different depths in the water column at the outer spoil ground (Spoil Ground D);
- Figures 34 and 35 show time series of sea levels at the new PLF location during summer and winter, 2009 respectively;
- Figures 36 and 37 show time series of current speeds near the surface and seabed at the new PLF location during summer and winter, 2009 respectively;
- Figures 38 and 39 show time series of current directions near the surface and seabed at the new PLF location during summer and winter, 2009 respectively;
- Figure 40 shows current speeds near the surface and seabed at the location west of the new channel from April to June, 2009; and
- Figure 41 shows current directions near the surface and seabed at the location west of the new channel from April to June, 2009

The main points arising from these results are:

a) Spoil Ground D
- The current roses in 51m of water show the diminishing effect of the wind with depth and a weaker tidal signal than at the shallower sites;
- The tidal flow at follows (approximately) the continental shelf contours at all depths.

b) The New PLF
- The shallow water currents follow the trend in the 2007 data in the Basin;
- The time series plots show the general dominance of tidal currents, although there are periods with significant influence of wind driven currents;
- The surface currents reach 0.4 m/s on spring tides and are up to 30% stronger than the currents near the seabed; and
- There is only a small variation in current direction with depth.

c) West of the New Channel

- The time series plots again show the general dominance of tidal currents with periods of significant wind driven current events;

- The surface currents reach 0.65 m/s on spring tides and are up to 40% stronger than the currents near the seabed;

- The variation in current direction with depth is more significant than for the nearshore sites with a greater disconnect between surface and bottom current directions.

Time series plots allow us to make qualitative conclusions but it is difficult to quantify differences so a more detailed statistical analysis of the current data presented in the above figures has been undertaken and the results presented in Table 4.

The results in Table 4 confirm the following:

- That the surface currents at the PLF site are, on average, 30% greater than the bottom currents and that at the site west of the new channel this difference increases to 40%;

- That near the shore there is little difference in the current directions from surface to seabed but out along the channel theses variations become larger;

- Near the shore the nett current is towards the east in both summer and winter although it is less than half the strength of the nett currents observed at Cape Preston (also shown in Table 4); and

- In the vicinity of the channel the nett current is slightly stronger than near the shore and is also towards the east in both summer and winter at the surface but near the seabed the nett current in winter is towards the west and opposes the nett current at the surface.

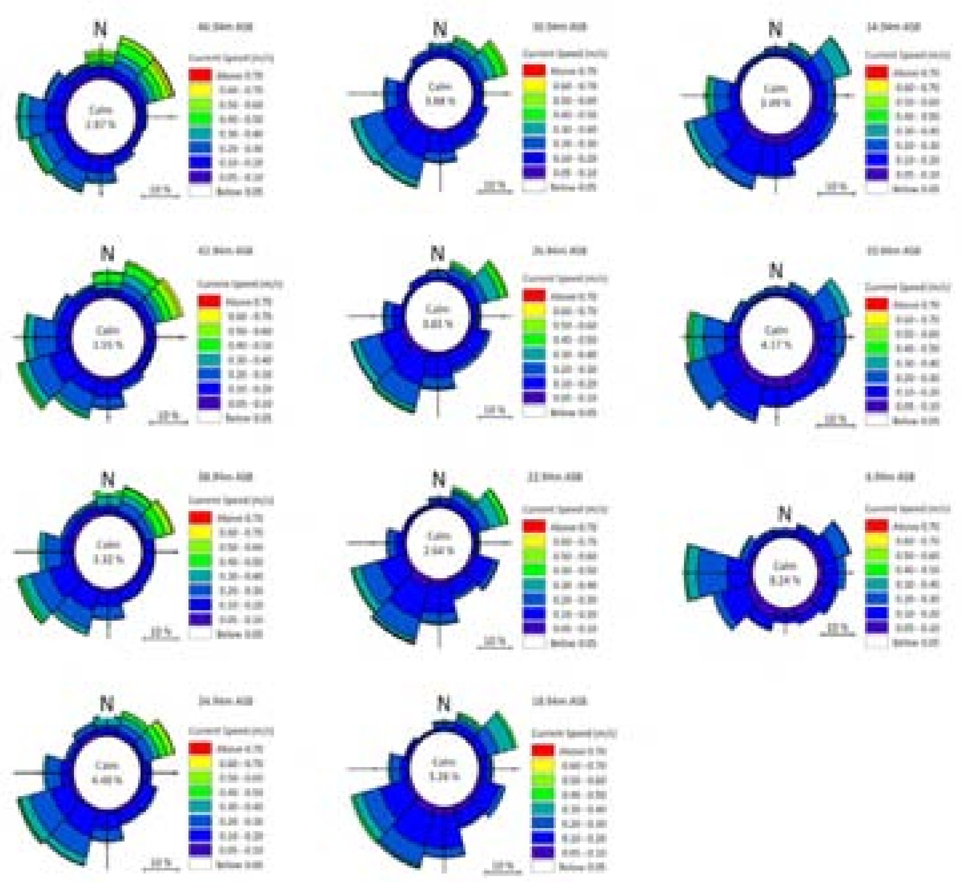


Figure 32. Current roses over different depths around spoil ground D from 10 January – 31 January 2009.

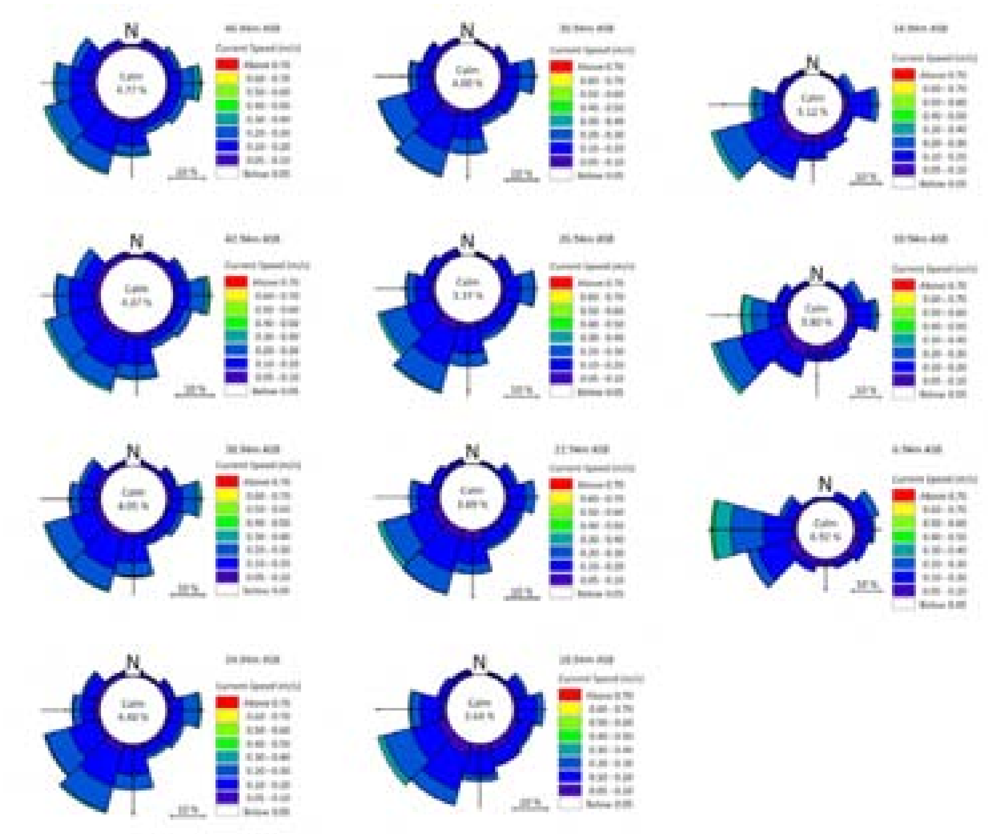


Figure 33. Current roses over different depths around spoil ground D from 1 April - 16 April 2009.

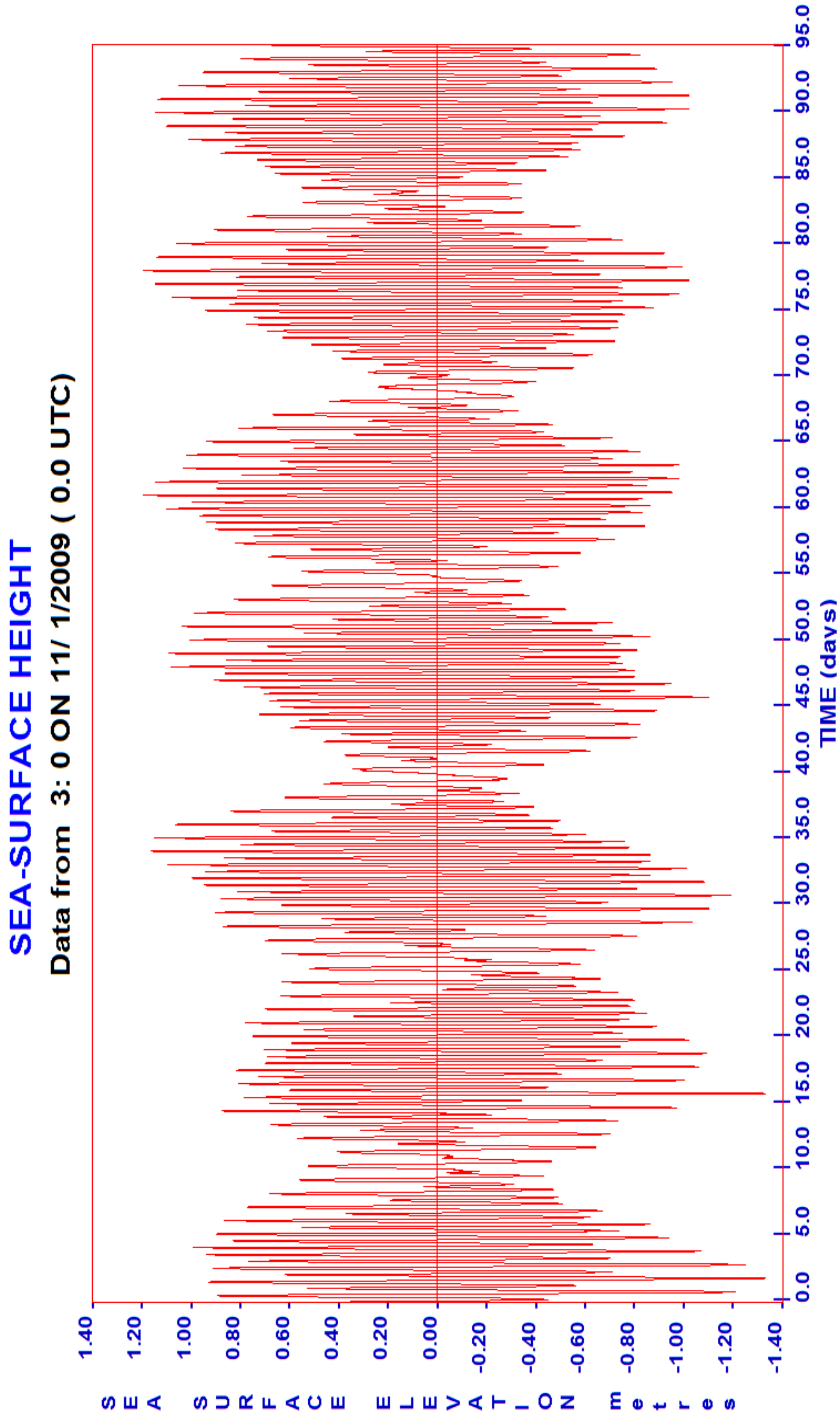


Figure 34. Sea Levels measured at the new PLF location for 95 days from January 11, 2009

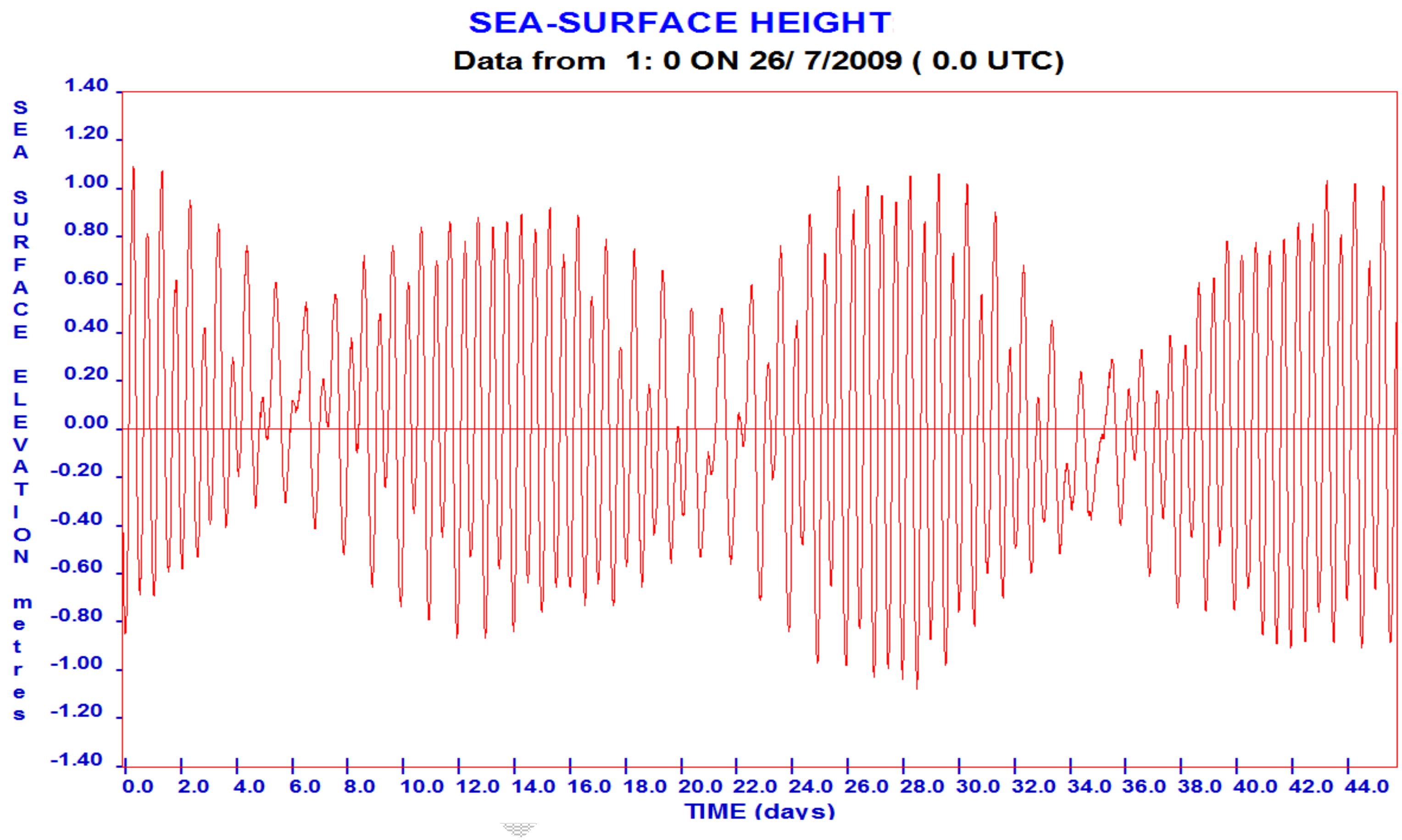


Figure 35. Sea Levels measured at the new PLF location for 45 days from July 26, 2009

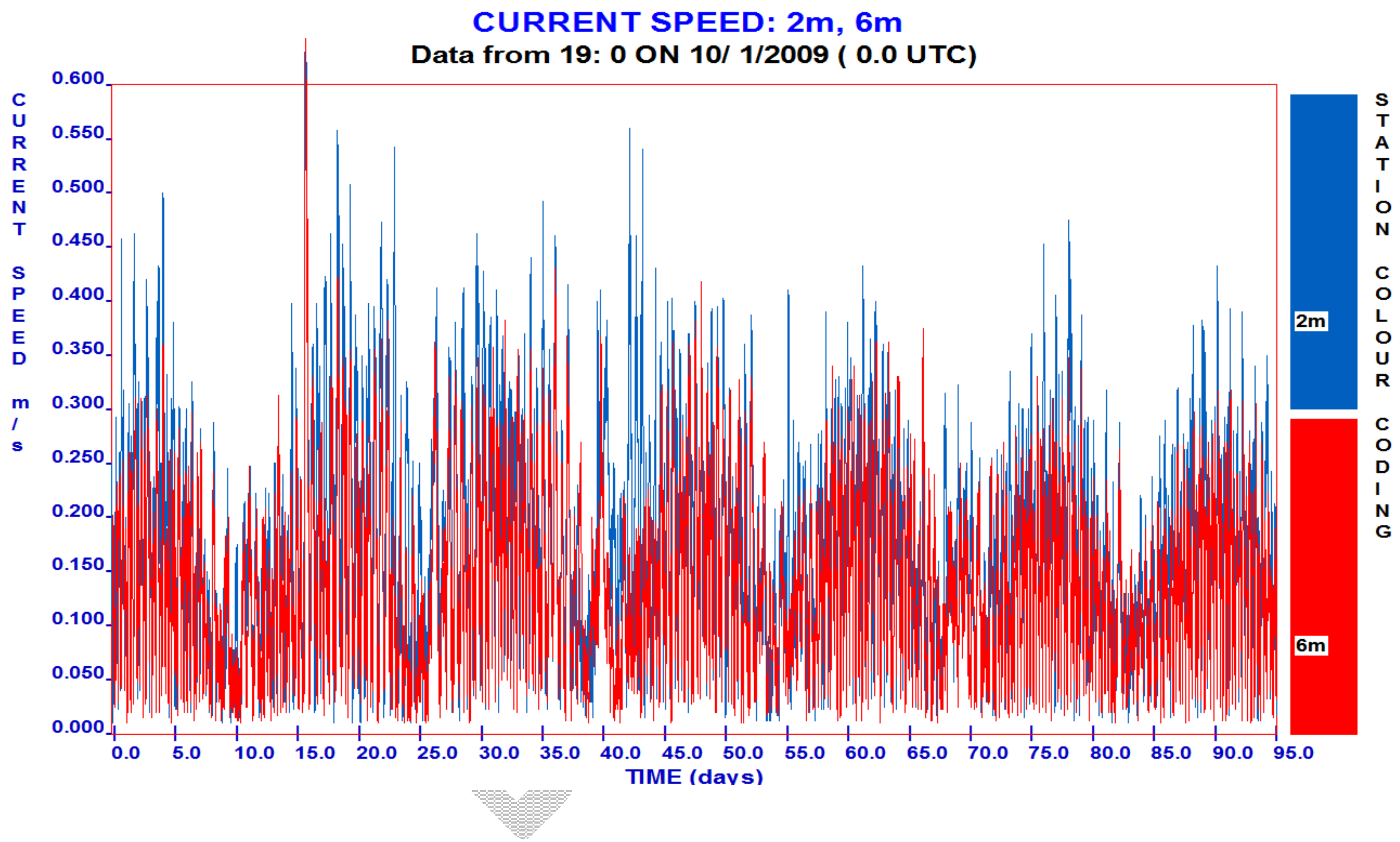


Figure 36. Current speeds measured near the surface (2m) and the seabed (6m) at the new PLF location for 95 days from January 10, 2009

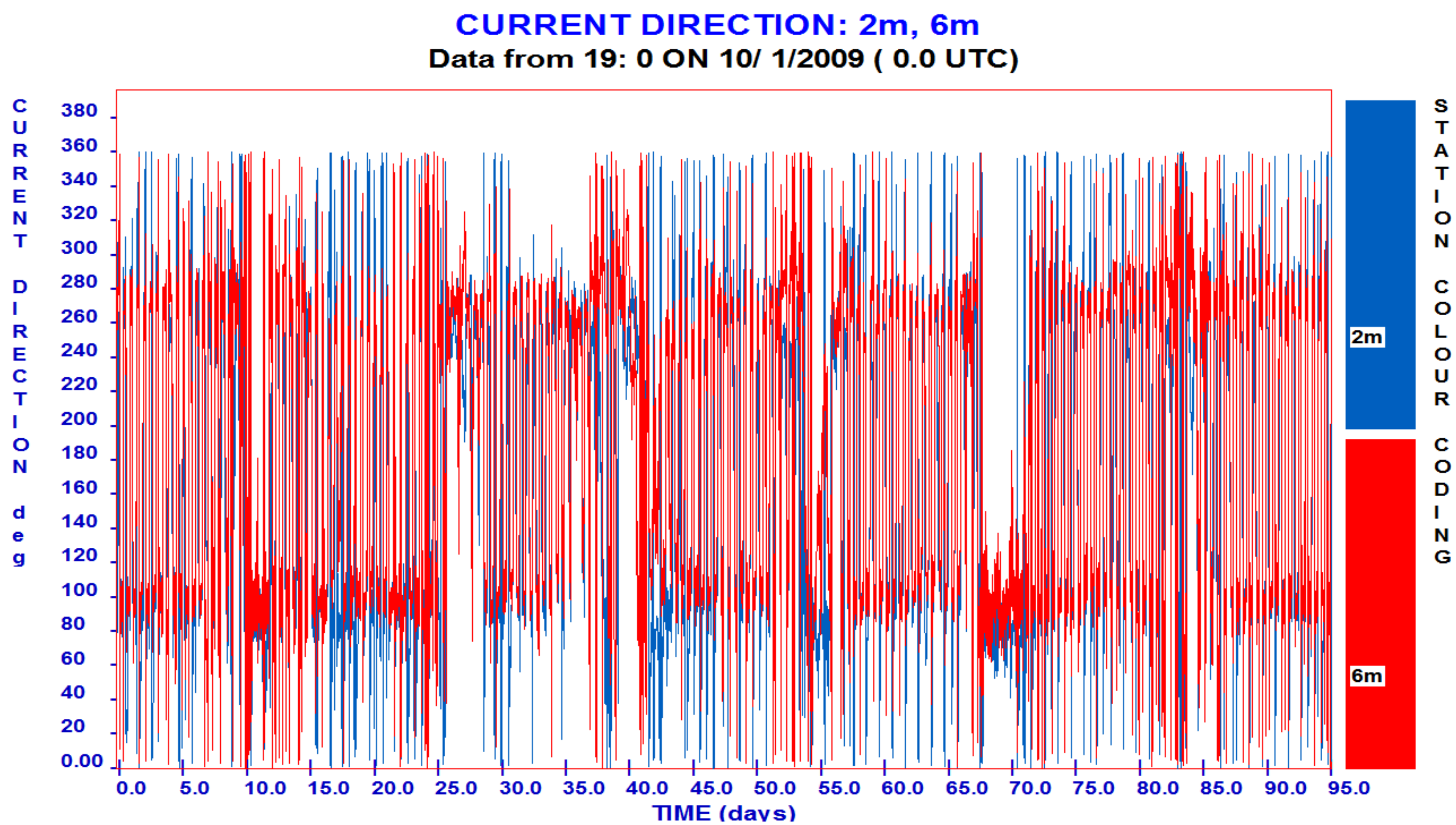


Figure 37. Current directions measured near the surface (2m) and the seabed (6m) at the new PLF location for 95 days from January 10, 2009

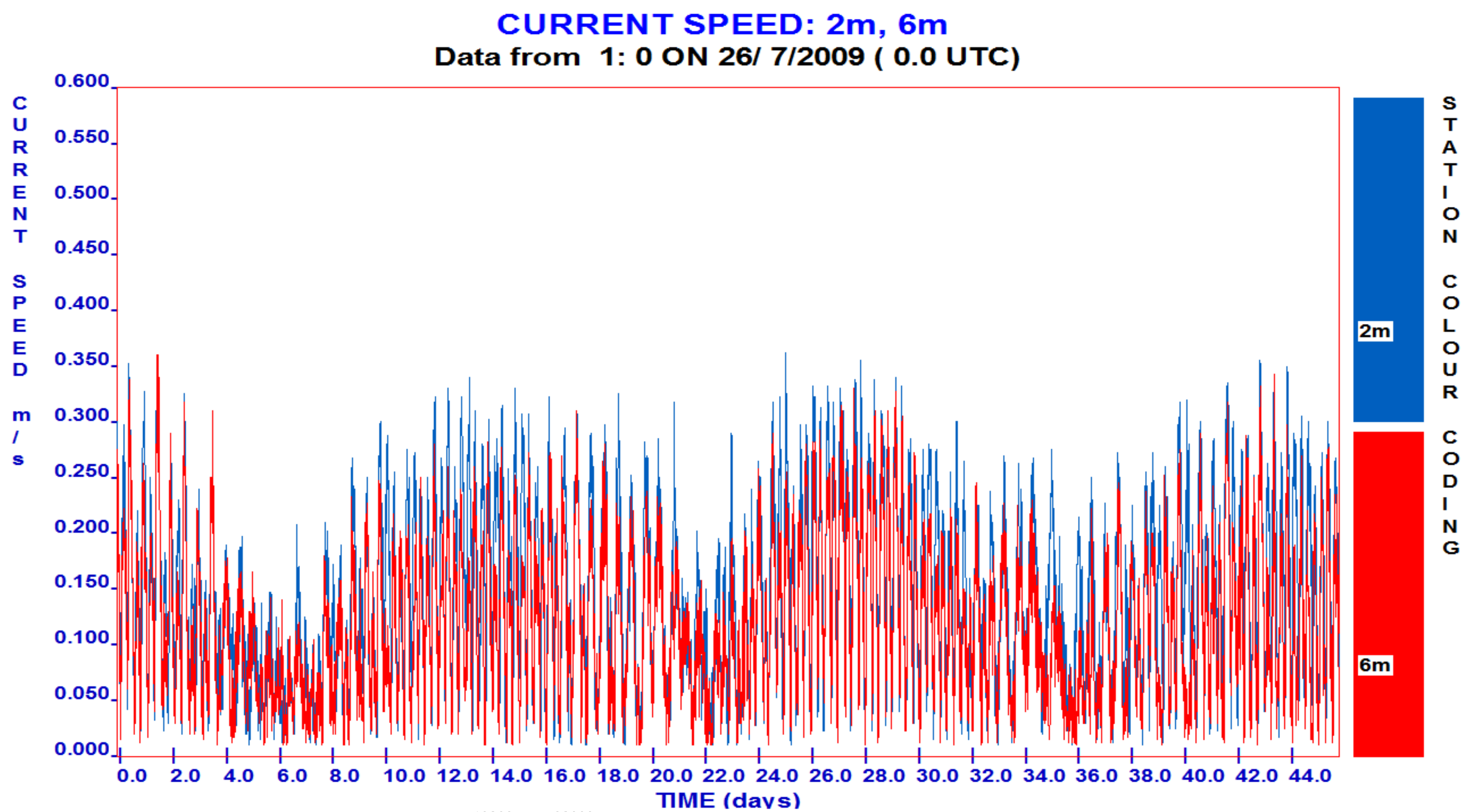


Figure 38. Current speeds measured near the surface (2m) and the seabed (6m) at the new PLF location for 45 days from July 26, 2009.

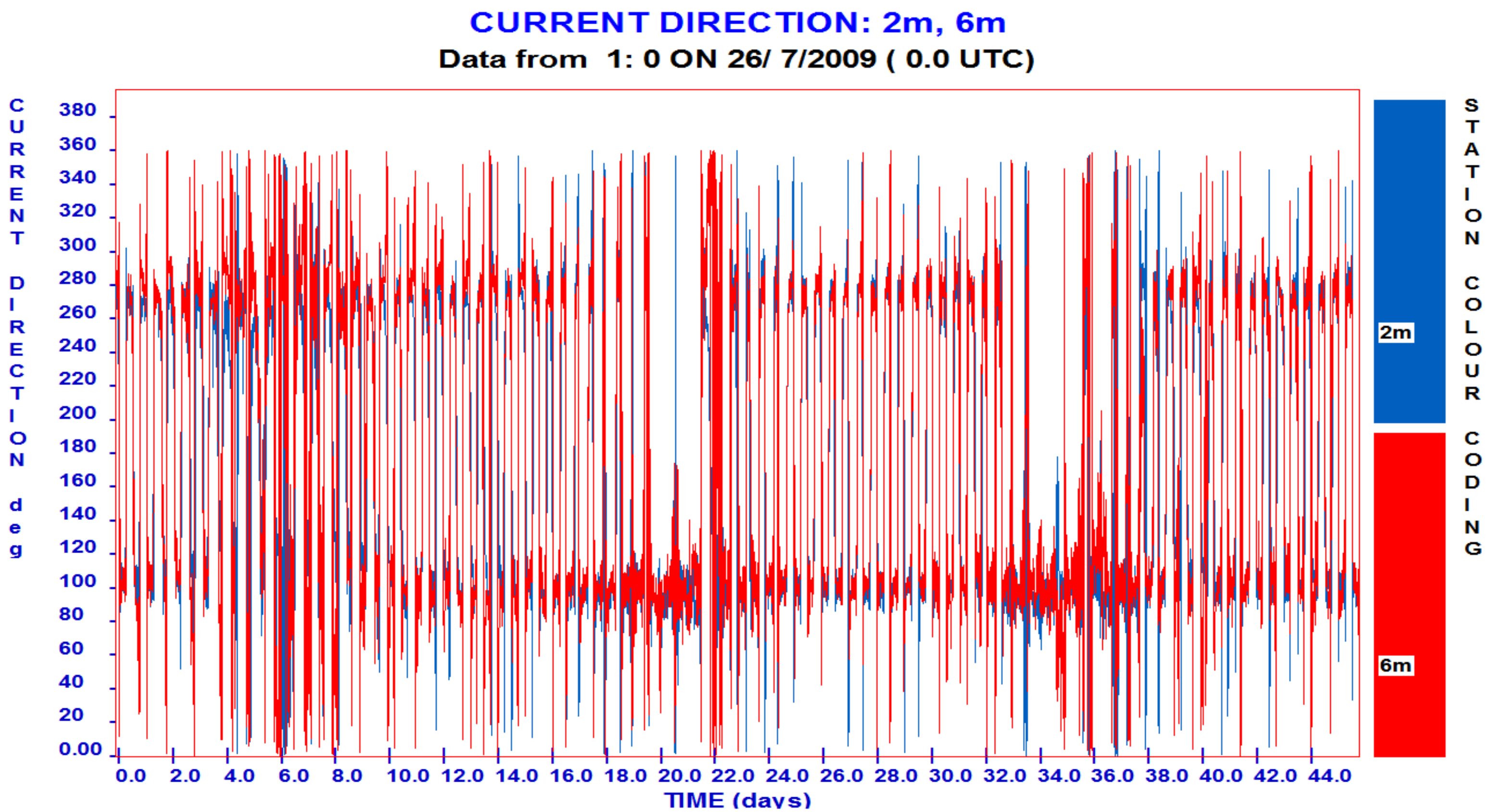


Figure 39. Current directions measured near the surface (2m) and the seabed (6m) at the new PLF location for 45 days from July 26, 2009.

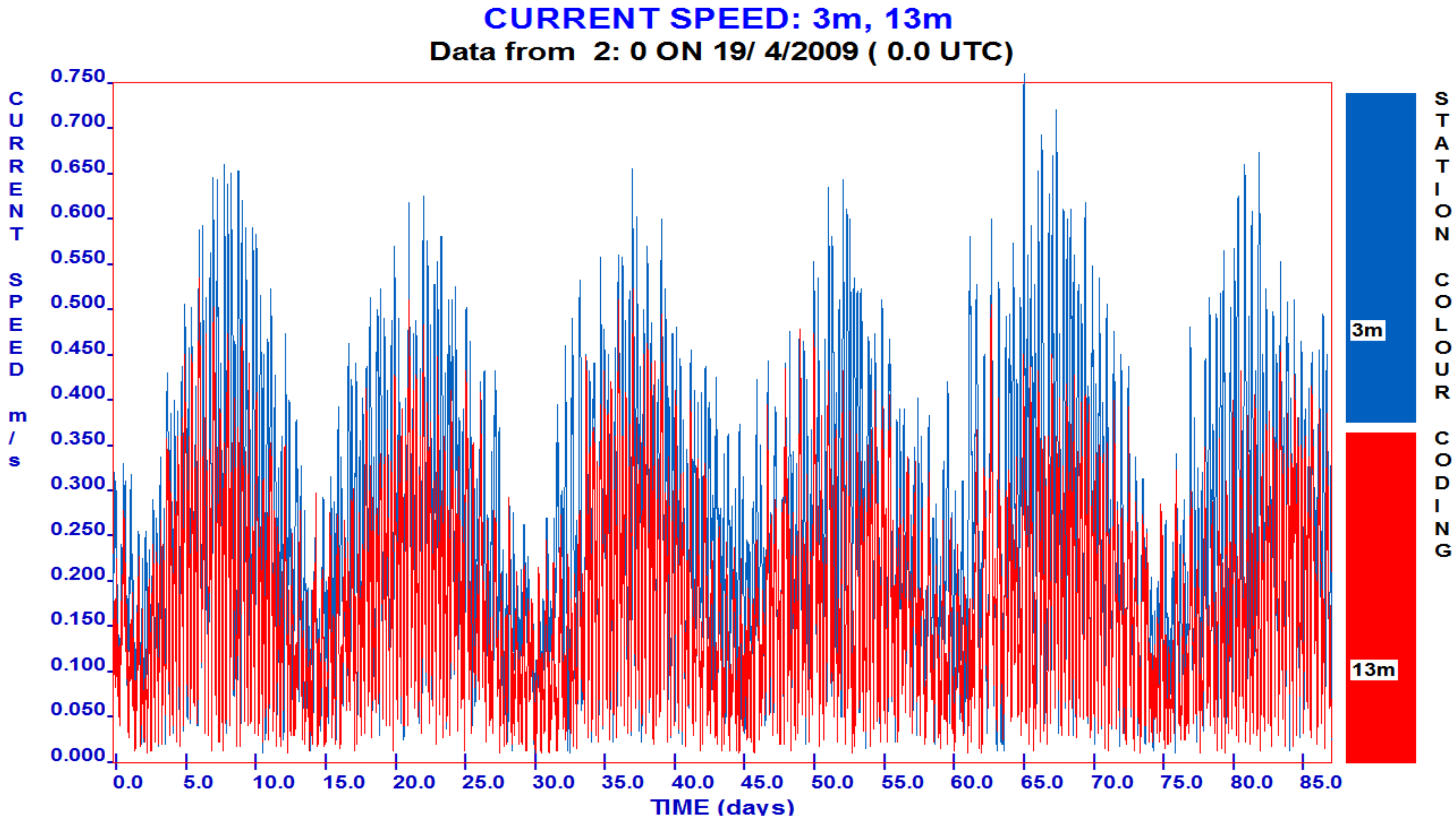


Figure 40. Current speeds measured near the surface (3m) and the seabed (13m) at the location west of the new channel for 85 days from April 19, 2009.

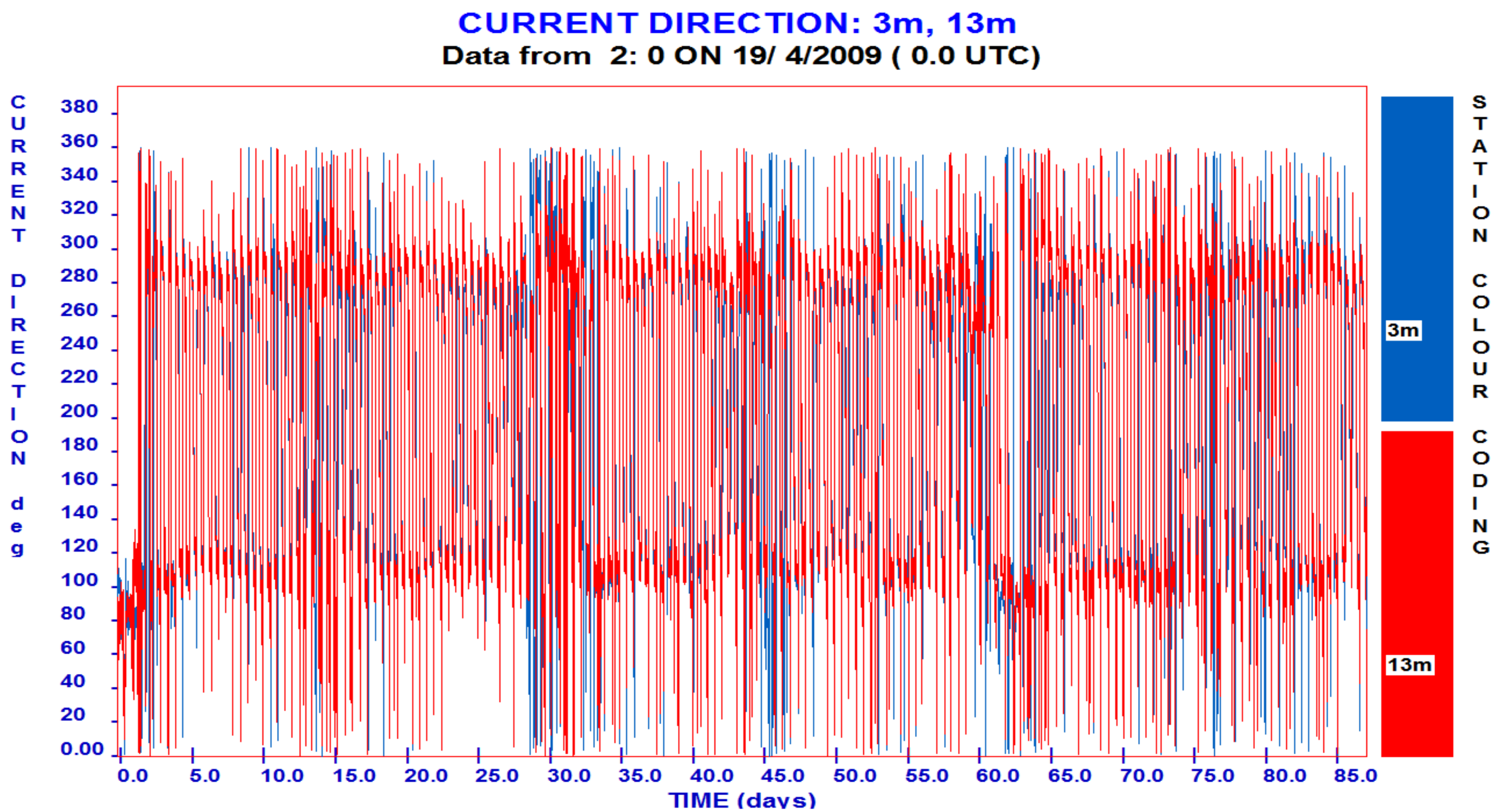


Figure 41. Current directions measured near the surface (3m) and the seabed (13m) at the location west of the new channel for 85 days from April 19, 2009.

Table 4. Current Statistics off Onslow and Cape Preston

Location	Obs Period	Obs Depth (m)	Residual Current Speed (m/s)	Residual Current Direction (deg to)	Mean Hourly Current Speed (m/s)
PLF	Jan-Apr 2009	2	0.03	96	0.18
		6	0.01	90	0.14
	Aug 2009	2	0.03	116	0.15
		6	0.01	113	0.12
Channel West	Apr-May 2009	3	0.04	175	0.25
		13	0.03	281	0.18
	Jun-Jul 2009	3	0.05	143	0.26
		13	0.02	295	0.17
Cape Preston	Jan 2007	3	0.11	66	0.26
		14	0.05	82	0.17
	Jul 2007	3	0.04	206	0.19
		14	0.03	309	0.13

4.4 Large Scale Ocean Currents

A brief overview of the complex ocean current patterns off the North West Shelf area is provided below. Figure 42 and Figure 43 show schematics of the major surface currents in the east-south-east Indian Ocean. The North West Shelf is at the eastern boundary of a major oceanic frontal system and sits within the Indo-Australian Basin, surrounded by the ocean region between the north-west coast of Australia and the Indonesian islands of Java and Sumatra.

The region may be influenced by a number of regional circulation currents including the Indonesian Throughflow to the north: a dominant current flowing through Indonesia into the north-west of Australia; the South Equatorial Currents, the Eastern Gyral Current and the Leeuwin Current.

The North West Shelf region is also known for its high cyclone activities, with the most destructive cyclones frequently occurring in the southern half of the region. Along the shelf break of this region (200m isobath), high internal wave activity can occur.

The narrow and meandering Leeuwin Current flows near the continental shelf break and typically flows southwards off the south-west coast of Australia with varying strength throughout the year, most strongly during the late autumn and winter from May to August when opposing winds are weakest. It is weakest during the summer months from November to March when winds are predominantly blowing strongly from the south-west.

These large scale ocean currents are predominantly found on or seaward of the continental shelf, deeper than the 200m contour. The currents are thus not anticipated to have a significant impact on the current patterns in shallower waters where the dredging will take place.

As discussed earlier in this report, current measurements available to date do not show patterns that have been attributed to large scale ocean currents. It can thus be concluded that the regional ocean currents do not have any significant impact on the spreading and potential impacts from the dredge plumes from the Wheatstone project.

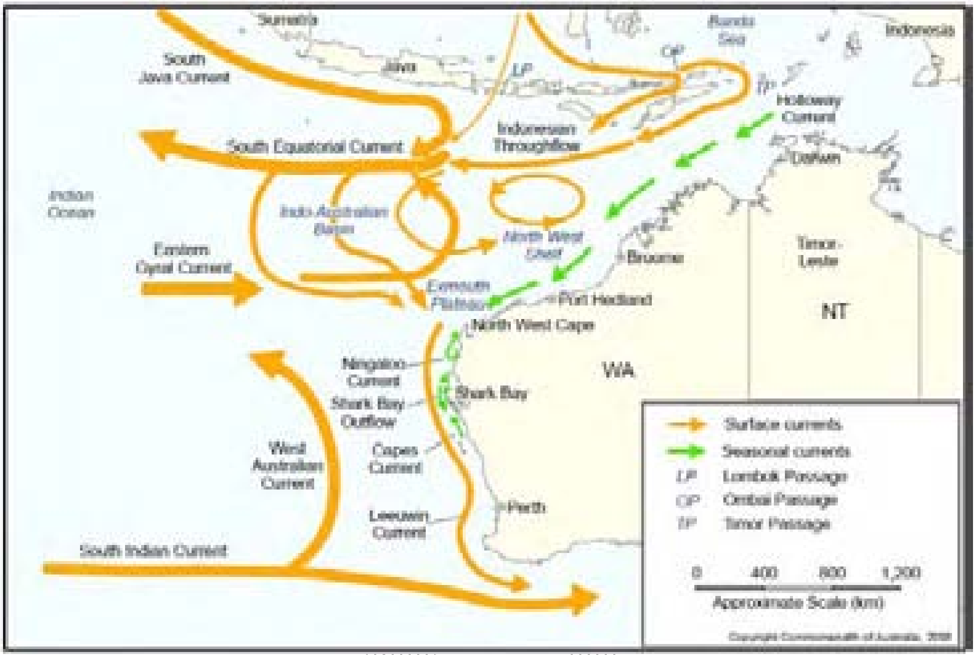


Figure 42. Regional oceanography – surface currents (sourced from Department of the Environment, Water, Heritage and the Arts – DEWHA /6/).

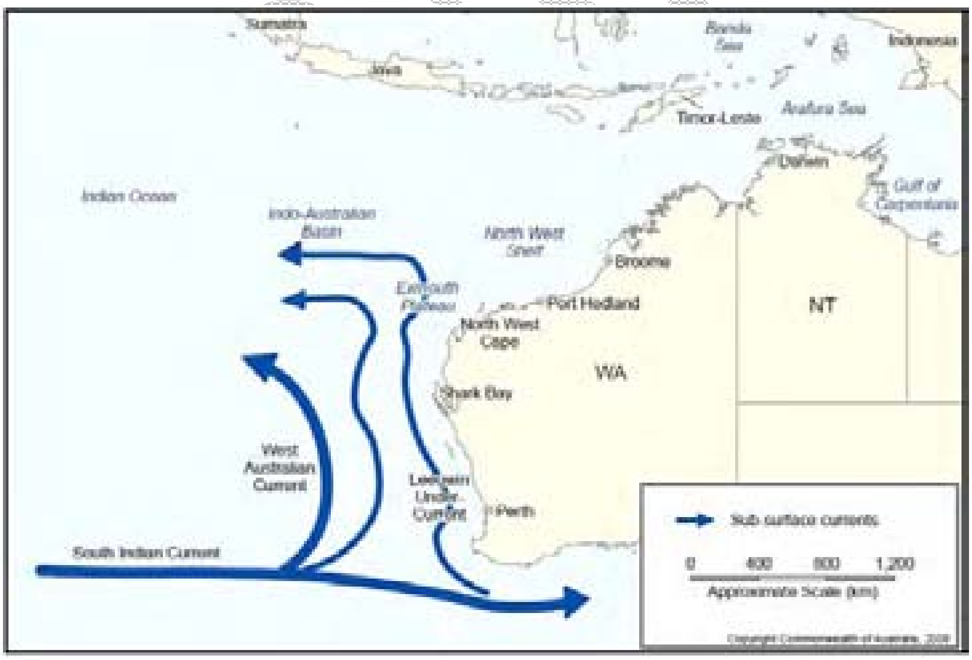


Figure 43. Regional oceanography – sub-surface currents (sourced from Department of the Environment, Water, Heritage and the Arts – DEWHA)

SECTION 5. WAVES

5.1 MODELLING SCOPE

The requirement of the wave modelling program described in this report was to provide wave parameters along an open boundary on an inshore grid defined by the client. The locations of the output points along his boundary are shown in Figure 44.

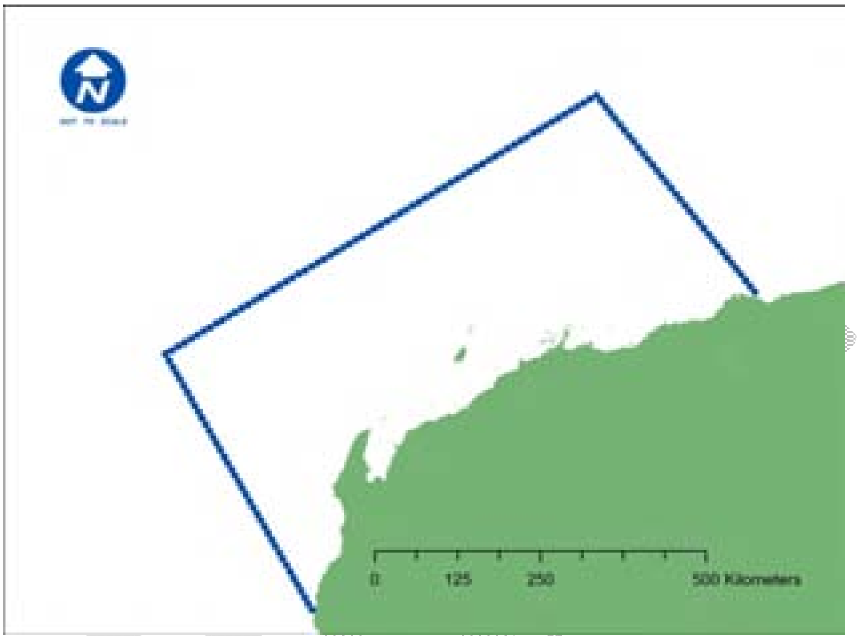


Figure 44. Output locations for wave model boundary conditions.

5.2 MODEL DESCRIPTION

5.2.1 SWAN

SWAN (Booji et al. 1996) is a third-generation wave model for obtaining realistic estimates of wave parameters and can be used on any scale relevant for wind-generated surface gravity waves.

Wave propagation processes represented in SWAN include:

- propagation through geographic space,;
- refraction due to spatial variations in bottom and current,;
- diffraction,;
- shoaling due to spatial variations in bottom and current,;
- blocking and reflections by opposing currents; and
- transmission through, blockage by or reflection against obstacles.

Wave generation and dissipation processes represented include:

- generation by wind,
- dissipation by white-capping,
- dissipation by depth-induced wave breaking,
- dissipation by bottom friction and
- wave-wave interactions in both deep and shallow water

5.2.2 Configuration for Wheatstone

Since the purpose of the current program was to provide boundary offshore boundary conditions, the model was established over two grids, the extent of which are shown in Figure 45. The configuration of the model over these grids is summarized in Tables 5 and 6.

Table 5. SWAN Parameter Settings

SWAN PARAMETER	SETTING
Model Version	40.51
Directional Resolution	10 degrees
Frequency Resolution • No. of bins • Minimum • Maximum • Scale	 35 1 Hz 0.04 Hz Log
Numerical Scheme • Grids 1 to 3 • Grid 4	 Non-Stationary (default) Stationary – max iterations (15)
Physics • Type • Wind • White capping	 Generation 3 Yan Alves Banner
Friction • Grid 1 • Grid 2	 None Default JONSWAP

Table 6. SWAN Grids

MODEL GRID	RESOLUTION	MIN X	MAX X	MIN Y	MAX Y	FRICTION	WINDS
Indian Ocean	0.5 deg	25E	135E	-25S	10N	OFF	GASP
WA Region	0.1 deg	107E	126E	38S	14S	OFF	MESOLAPS

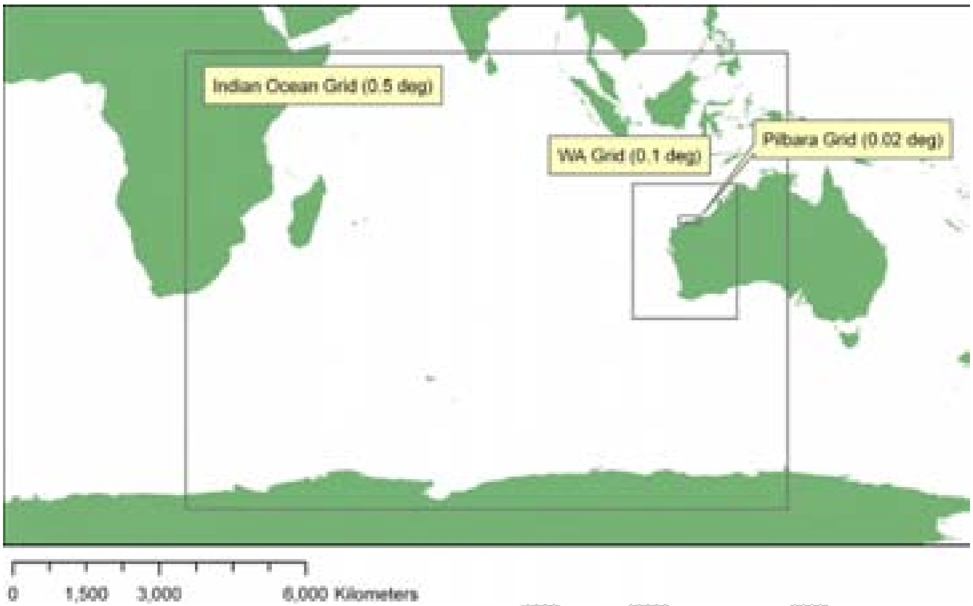


Figure 45. Extent of SWAN model grids.

5.2.3 Wind Input

Winds for the Indian Ocean grid were derived from the BOM GASP database. GASP is the BOM global model, run twice daily. Winds were extracted at three hour intervals at a spatial resolution of approximately 70 km, the latter corresponding to the operational resolution of the model.

For the inner grids, winds from the BOM Meso-LAPS model were extracted at corresponding resolutions of one hour and 12 km respectively.

5.2.4 Model Output

Wave parameters provided at each of the specified output points were:

- Hs
- Peak Period
- Peak Direction
- Mean Direction
- Directional Spreading

These parameters were provided for the total and sea and swell components of the spectrum. The sea-swell cut-off was 9 Hertz. The data were supplied at a temporal resolution of one hour.

Directional spreading is defined as:

$$(\mathrm{DSPR}_{\frac{\pi}{180}})^2 = 2\left(1 - \sqrt{\left[\left(\frac{\int \sin\theta E(\sigma,\theta)d\sigma d\theta}{\int E(\sigma,\theta)d\sigma d\theta}\right)^2 + \left(\frac{\int \cos\theta E(\sigma,\theta)d\sigma d\theta}{\int E(\sigma,\theta)d\sigma d\theta}\right)^2\right]}\right)$$

5.3 VERIFICATION

5.3.1 Measured Waves

The only offshore wave measurements available to the project were from the WA Department of Planning and Infrastructure (DPI) wave rider buoy off Exmouth Gulf (see Figure 3) for the period from October 4, 2006 to August 17, 2009. These data were used to verify the performance of the wave model.

Figure 46 shows wave polar diagrams constructed from the buoy data taken across this period. These diagrams show persistent south-westerly quadrant waves throughout the year. These waves result from the equally persistent south-westerly winds that predominant off the WA central coast for much of the year and from swells propagating into the area from the Indian Ocean.

From May to August, the respective polar diagrams show the presence of waves from out of the north-east. These waves are intermittent and relate to easterly winds blowing offshore for much of this period. However, the presence of these north-east waves will tend to be underestimated in the wave records because the south-west waves are the dominant in the spectrum. Accordingly, inclusion of full wave spectra in the modelling boundary conditions is recommended in order to fully capture all wave processes.

It is noted that if the modelling aim of this work was to compute waves closer to the coast, further model nesting will be required. This task, however, was within the scope of the work described in this report. Accordingly, topographic and resolution limitations are expected have some impact on the accuracy of the model predictions for the buoy site.

Notwithstanding these limitations, the wave model does an excellent job at representing the wave climate as can be seen in the plots presented in Figures 47 to 50 inclusive. Figures 47 and 48 show plots of observed and modelled wave height and peak wave direction for the years 2007 to 2009. Figures 49 and 50 show similar plots limited to selected months in 2008.

All of the figures presented demonstrate close correspondence of model and observed data with the model showing a small, but consistent bias to underestimate wave height.

5.4 WAVES ASSOCIATED WITH TROPICAL CYCLONES

There was no direct representation of a significant tropical cyclone during the validation period although some waves from cyclones in the broader area have been captured within the modelling process.

It is noted that to capture the impact of the more extreme waves associated with tropical cyclones, a much longer period would need to considered. To adequately represent the impact of cyclones on aspects of the project, such as the stability of dredge material placement areas, a cyclone specific modelling study would need to be undertaken. However this is outside the scope of this report.

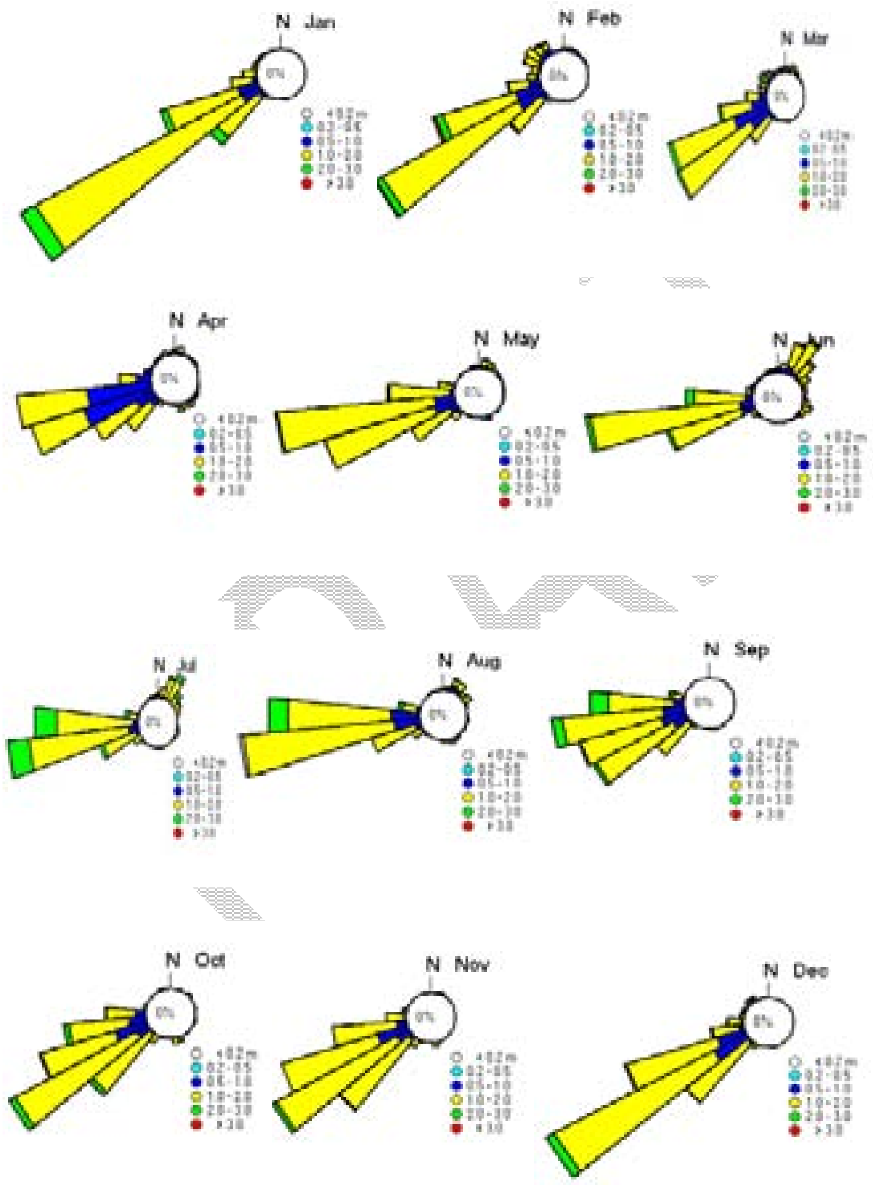


Figure 46. Polar diagrams based on measured significant wave height and peak wave direction at Exmouth Wave Buoy (2007-2009).

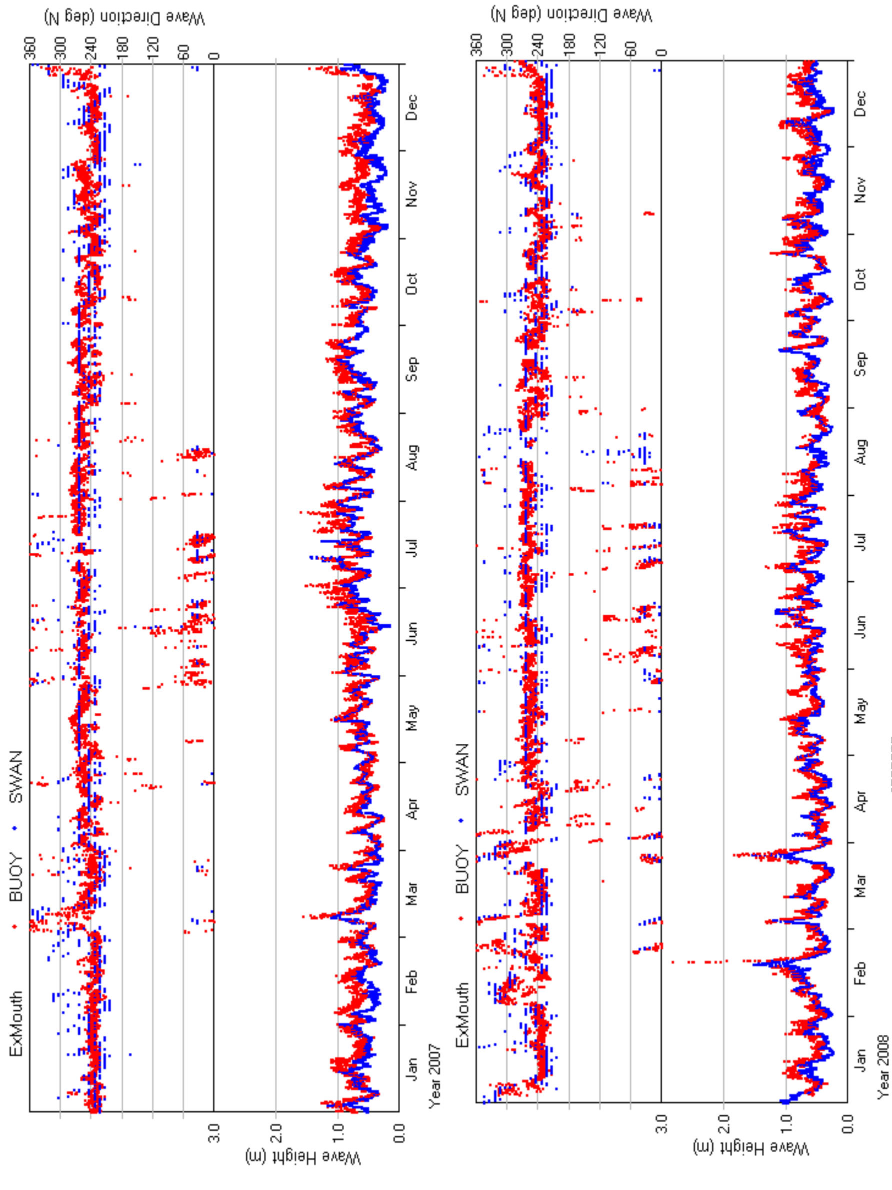


Figure 47. Comparison of observed and modelled waves for the Exmouth Buoy site for 2007 and 2008.

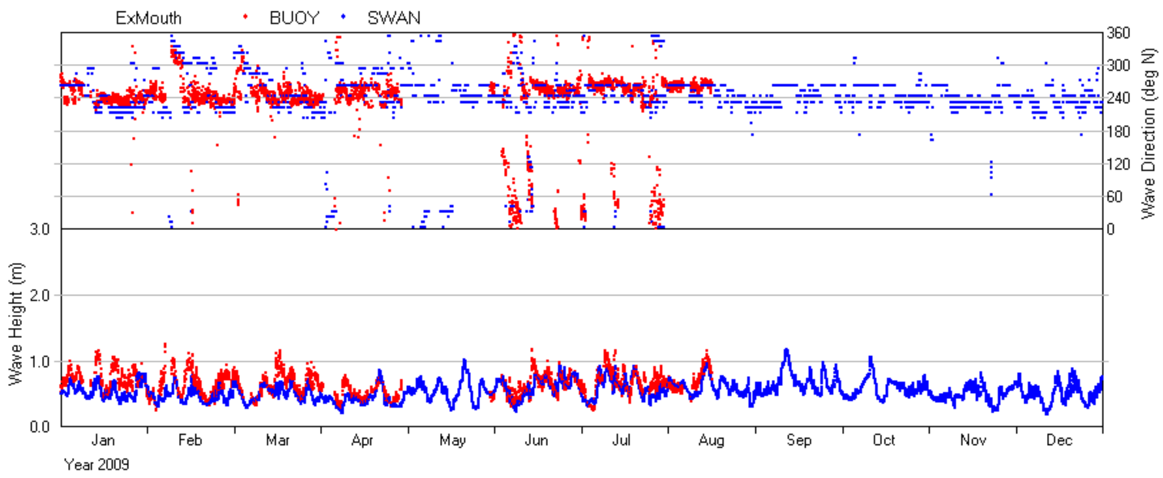


Figure 48. Comparison of observed and modelled waves for the Exmouth Buoy site for 2009.

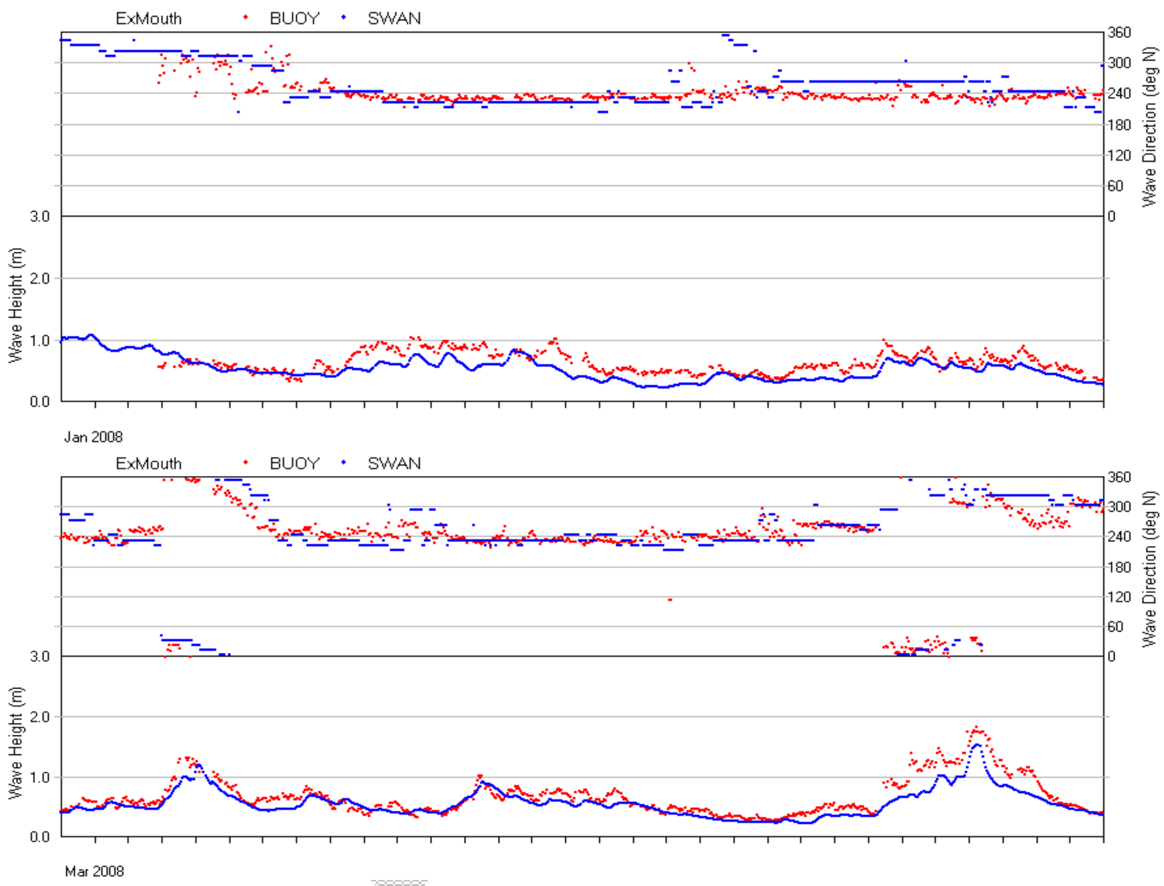


Figure 49. Comparison of observed and modelled waves for the Exmouth Buoy site for January and April, 2008.

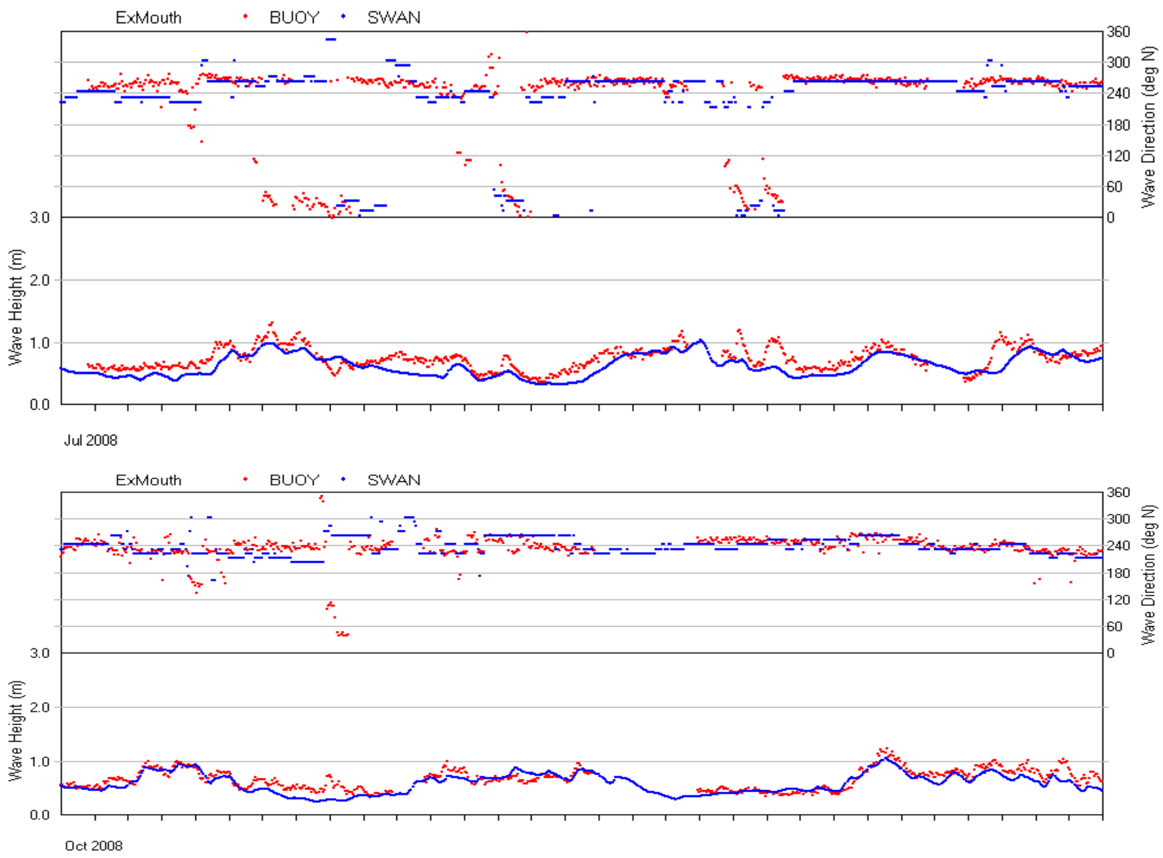


Figure 50. Comparison of observed and modelled waves for the Exmouth Buoy site for July and October, 2008.

SECTION 6. REFERENCES

Booij, N., L.H. Holthuijsen and R.C. Ris, 1996: The ”SWAN” wave model for shallow water, Proc. 25th Int. Conf. Coastal Engng., Orlando, 668-676.

GEMS (2008): Cape Preston Field Data Analysis. Report prepared for Sandwell Australia, April 2008.

Wheatstone Project
Dredge Spoil Modelling

A P P E N D I X HH :

URS Characterisation of the Marine Environment Report

DHI Water & Environment

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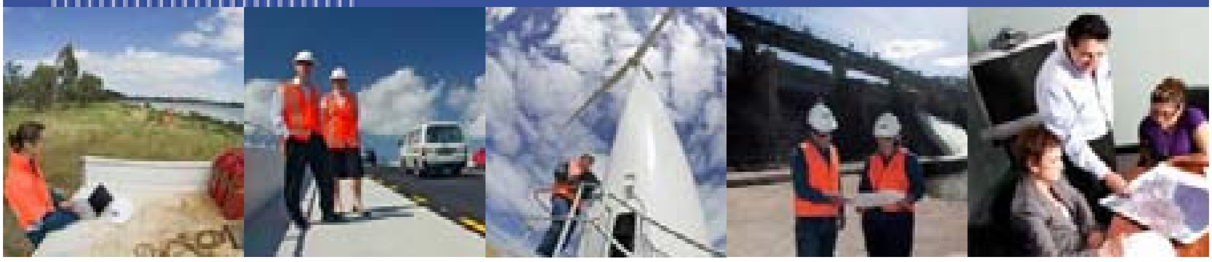

Report

Wheatstone Project - Characterisation of the Marine Environment

10 MAY 2010

Prepared for

Chevron Australia Pty Ltd

QV1 Building
250 St Georges Terrace
Perth, Western Australia
6000

42907466

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Project Manager:

....
Damian Ogburn
Project Manager-
Wheatstone Project

URS Australia Pty Ltd

Level 16, 240 Queen Street
Brisbane, QLD 4000
GPO Box 302, QLD 4001
Australia
T: 61 7 3243 2111
F: 61 7 3243 2199

Project Director:

....
Ian Baxter
Senior Principal Marine
Environmental Scientist

Author:

....
Dr Chris Reed
Senior Project Scientist

Reviewer:

....
Dr Darlene Heuff
Senior Associate Scientist

Date: **10 May 2010**
Reference: 42907466/001/001
Status: Draft

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Appendices

1 Introduction

Chevron Australia Pty Ltd (Chevron) proposes to construct and operate a multi-train Liquefied Natural Gas (LNG) plant and a domestic gas (Domgas) plant 12 km south west of Onslow and 9 km northwest of the Ashburton river outlet on the Pilbara Coast (Figure 1-1). Onslow is situated in the Shire of Ashburton, along the coastal plain of the Pilbara coast of the North West Shelf (NWS)

The LNG and Domgas plants will initially process gas from fields located approximately 200 km offshore from Onslow in the West Carnarvon Basin and future yet-to-be determined gas fields. The project is referred to as the Wheatstone Project and “Ashburton North” is the proposed site for the LNG and Domgas plants. The Project will require the installation of gas gathering, export and processing facilities in Commonwealth and State Waters and on land. The LNG plant will have a maximum capacity of 25 Million Tonnes Per Annum (MTPA) of LNG.

The Wheatstone Project has been referred to the State Environmental Protection Authority (EPA) and the Commonwealth Department of Environment, Water, Heritage and the Arts (DEWHA).

URS Australia Pty Ltd (URS) has been commissioned by Chevron to undertake a review of the available current, temperature, salinity, and wave data and develop an overview of characterisation of the marine environment. This report has been produced in support of the DHI (2010) Dredge Spoil Modelling Report and focuses on those aspects of the marine environment relevant to the Dredge Spoil Modelling study.

1.1 Scope of Works

Data collected in the nearshore and offshore regions in the vicinity of the Wheatstone Platform have been acquired and analysed to characterise the marine environment. The data analysis has focused on information that reveals the vertical structure of the currents. The vertical structure of the water column has been analysed using data from CTD casts and vertical profiles form the World Ocean Atlas (WOA). The vertical structure of the currents has been analysed using current profile data bottom mounted upward looking ADCPS and AWACS. In addition to the vertical profile and current data, wave data and wind data for the area have been summarized.

The measurement and instrument deployment protocols, calibration and other information for the data collection are available in The RPS MetOcean report “Oceanographic and Meteorological Measurements, Wheatstone” submitted to Chevron Australia, Pty Ltd on February 23, 2010.

Analysis of additional data (not included in this report) is reported elsewhere, including (but not limited to):

- DHI (2010): Dredge Spoil Modelling Report. Version 0, May 2010.Prepared for Chevron Australia Pty Ltd in support of the Wheatstone Project EIA.
- GEMS (2010): Wheatstone Wind, Currents and Wave Verification Analysis. Version V1-2, April 2010. Prepared for Chevron Australia Pty Ltd in support of the Wheatstone Project EIA.

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Vertical Current Profiles

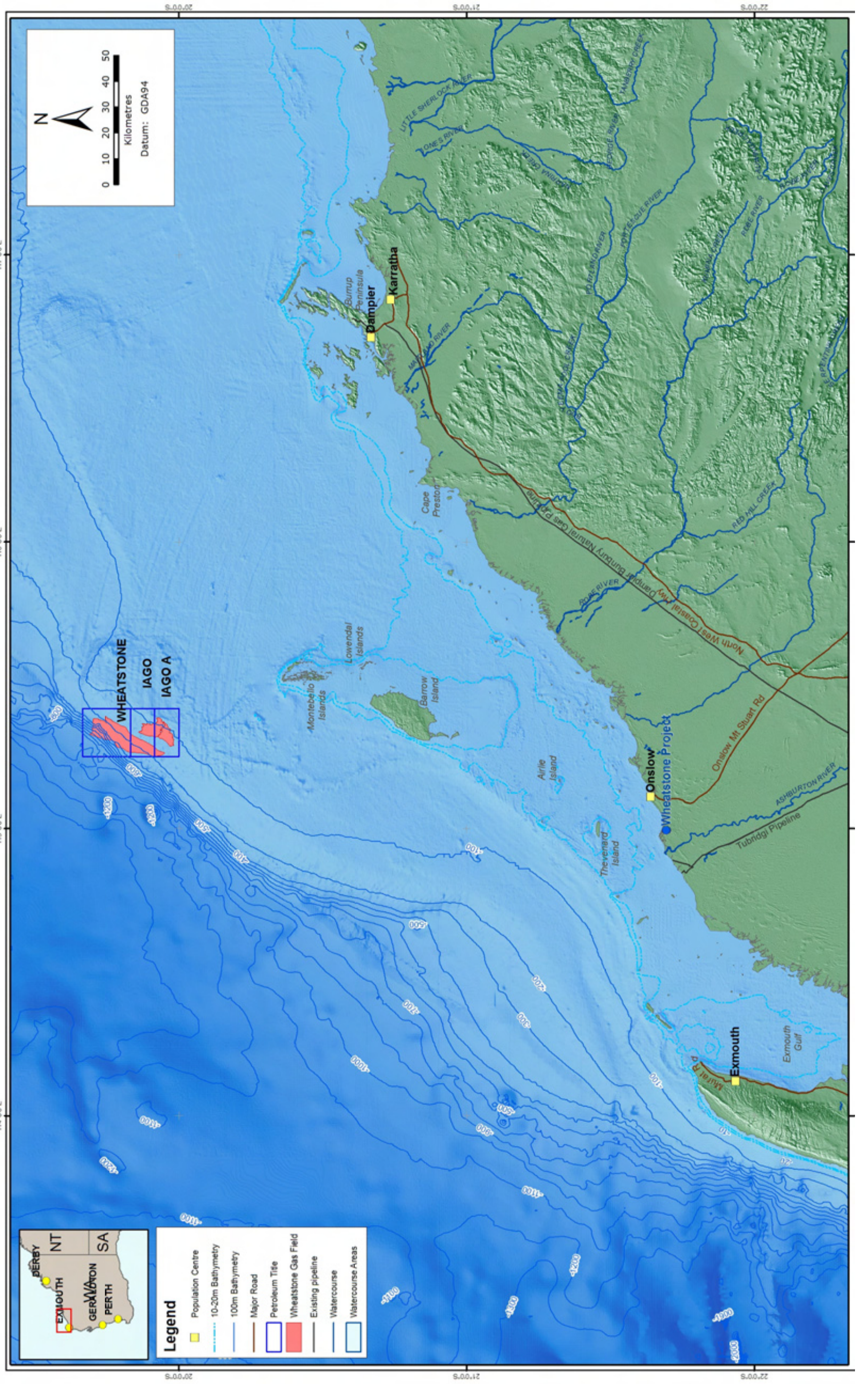

Figure 1-1 Overview of Study Region (Source: URS)

1-1

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2 Monitoring Locations

2.1 Temperature, Salinity and Density Data

This section presents a summary of the temperature, salinity and density data obtained from CTD casts and the World Ocean Atlas.

2.1.1 CTD Monitoring Locations

Vertical casts were obtained at 10 station locations at various data and times. The locations and times are listed in Table 2-1 and the locations are shown in Figure 2-1.

Table 2-1 Station Locations and Deployment Dates for CTD Casts

Location and Water Depth	Water Depth (m)	Date	Time
Ashburton Island	11	13-Dec-2009	11:11
		30-Jan-2010	12:34
Channel	15	17-Apr-2009	15:34
		24-Jul-2009	13:35
		13-Sep-2009	14:25
		29-Oct-2009	10:42
		31-Jan-2010	14:10
Direction Island	12	17-Apr-2009	14:54
		6-May-2009	14:12
		24-Jul-2009	15:07
		13-Sep-2009	16:15
		25-Oct-2009	11:29
Dredge Route	15	18-Apr-2009	9:03
		27-Apr-2009	9:02
		29-Oct-2009	12:29
		31-Jan-2010	11:54
Jetty	6	17-Apr-2009	12:34
		5-Jun-2009	11:54
		26-Jul-2009	7:52
		10-Sep-2009	13:45
		25-Oct-2009	9:55
		13-Dec-2009	11:49
		2-Jan-2010	12:49
Paroo Shoal	11	17-Apr-2009	13:15
		5-Jun-2009	12:51
		24-Jul-2009	10:27
		10-Sep-2009	16:27
Thevenard Island	11	29-Oct-2009	10:00
		11-Dec-2009	14:28
Ward Reef	7	13-Sep-2009	13:00
		25-Oct-2009	9:16
		12-Dec-2009	13:10
		31-Jan-2010	14:51

Location and Water Depth	Water Depth (m)	Date	Time
West Thevenard Island	11	31-Jan-2010	9:34
Spoil Ground	52	16-Apr-2009	11:10
		25-Jul-2009	18:02
		29-Nov-2009	13:09
		31-Jan-2010	10:05

2.1.2 World Ocean Atlas Data

The National Oceanic and Atmospheric Association (NOAA) publish salinity and temperature data for the world's oceans on a 1 degree grid available in the WOA Database. Data from three WOA stations in the vicinity of the site have been acquired. The station locations are show in Figure 2.1 and the geographic coordinates and water depths for each station are listed in Table 2-2. A time line of the casts for each station are shown in Table 2-6.

Table 2-2 WOA Station Locations

Station Reference ID	Location (lat/long)	Water Depth (m)
Point 1	-21.5 / 114.5	15
Point 2	-20.5 / 115.5	55
Point 3	-19.5 / 115.5	1050

2.2 Current Monitoring Locations

Current vertical profile data was collected using Acoustic Doppler Current Profilers (ADCP) at seven locations for the periods indicated in Table 2-3. Three of the stations were selected for detailed analysis of the vertical current structure, representing near-shore location (Jetty), a mid-depth station (Spoil Ground) and the deep-water station at the Wheatstone platform.

Table 2-3 Current (ADCP) Monitoring Locations and Recording Periods

Location	Depth (m)	Start Date	End Date	Frequency
Bank	11.24	25-Jan-2006 14:00:08	25-Feb-2006 14:40:08	10 min
		25-Jan-2006 14:01:17	25-Feb-2006 15:31:17	10 min
		24-Jan-2006 10:00:00	25-Feb-2006 14:00:00	10 min
		26-Feb-2006 12:00:00	7-Jun-2006 12:00:00	10 min
		26-Feb-2006 12:00:00	7-Jun-2006 12:00:00	10 min
		8-Jun-2006 10:00:00	20-Sep-2006 13:30:00	10 min
		21-Sep-2006 06:50:00	5-Nov-2006 18:52:00	1 min
Channel	12.41	24-Jul-2009 15:00:00	12-Sep-2009 11:30:00	10 min
		9-Dec-2009 14:40	29-Oct-2009 10:50	10 min
Dredge Route	13.44	17-Apr-2009 9:20	15-Jul-2009 15:00	10 min
		29-Oct-2009 14:00	31-Jan-2010 11:50	10-20 min
Jetty	6.77	11-Jan-2009 10:19:30	16-Apr-2009 16:19:30	10-20 min
		17-Apr-2009 13:00:00	13-Sep-2009 18:00:00	10-20 min
		26-Jul-2009 17:00:00	10-Sep-2009 14:00:00	10-20 min
		10-Sep-2009 14:00:00	25-Oct-2009 10:00	10-20 min
		14-Dec-2009 8:30	1-Feb-2010 12:50	10-20 min

Vertical Current Profiles

Location	Depth (m)	Start Date	End Date	Frequency
		26-Oct-2009 11:00:00	13-Dec-2009 12:00:00	10-20 min
		25-Jan-2006 10:00:00	25-Feb-2006 14:00:00	10 min
Spoil Ground	46.94	10-Jan-2009 16:40:00	16-Apr-2009 10:40:00	10 min
		16-Apr-2009 11:40	22-Jul-2009 10:30	10 min
		22-Jul-2009 13:00	29-Oct-2009 14:00	10 min
		29-Oct-2009 18:40	31-Jan-2010 10:00	10 min
		10-Jan-2009 16:40:00	16-Apr-2009 10:40:00	10 min
Ward Reef	7.12	10-Sep-2009 10:21	24-Oct-2009 15:12	10 min
		25-Oct-2009 9:50	12-Dec-2009 13:27	10 min
		13-Dec-2009 9:30	1-Feb-2010 9:09	10 min
Wheatstone Platform	66.84	5-May-2009 12:20:00	10-Nov-2009 9:29:59	10 min

2.3 Wave Monitoring Locations

Wave data has been collected at 7 station locations. The deployments for each station are listed in Table 2-4 and a time line of available data is shown in Table 2-9.

Table 2-4 Wave Monitoring Data

location	depth (m)	start date	end date	freq
		01/25/06	02/25/06	10 min
		01/25/06	02/25/06	10 min
		01/25/06	02/25/06	10 min
		02/26/06	06/07/06	10 min
		02/26/06	06/07/06	10 min
		06/08/06	09/20/06	10 min
Bank ADCP	11.24	09/21/06	11/05/06	1 min
		07/24/09	09/12/09	10 min
Channel	12.41	09/12/09	10/29/09	10 min
		04/19/09	07/15/09	10 min
Dredge Route	13.44	10/29/09	01/31/10	10-20 min
		01/11/09	04/16/09	10-20 min
		04/17/09	06/13/09	10-20 min
		07/26/09	09/10/09	10-20 min
		09/10/09	10/25/09	10-20 min
		12/14/09	02/01/10	10-20 min
		10/26/09	12/13/09	10-20 min
Jetty	6.77	01/25/06	02/25/06	10 min
Spoil Ground	46.94	01/10/09	04/16/09	10 min
		04/16/09	07/22/09	10 min
		07/22/09	10/29/09	10 min
		10/29/09	01/31/10	10 min

location	depth (m)	start date	end date	freq
		01/10/09	04/16/09	10 min
Ward Reef	7.12	09/10/09	10/24/09	10 minutes
		10/25/09	12/12/09	10 minutes
		12/13/09	02/01/10	10 minutes
Wheatstone Platform	66.84	05/05/09	11/10/09	10 min

2.4 Wind Speed and Wind Direction Monitoring Locations

Wave data has been collected at 5 station locations. The deployments for each station are listed in Table 2-4 and a time line of available data is shown in Table 2-5.

Table 2-5 Wind Speed and Wind Direction Data

location	height (m)	start date	end date	freq
Barrow Island		1-Jan-2001	19-Jan-2001	1 hr
		23-Jan-2001	25-Jul-2001	1 hr
		16-Aug-2001	28-Dec-2001	1 hr
		1-Jan-2001	14-Jan-2006	1 hr
		17-Jan-2006	29-Mar-2006	1 hr
		1-Apr-2006	23-Dec-2006	1 hr
		28-Dec-2006	5-Jan-2007	1 hr
		9-Jan-2007	11-Jan-2008	1 hr
		30-Jan-2008	30-Mar-2009	1 hr
Thevenard		1-Jan-2001	25-Nov-2001	1 hr
		5-Dec-2001	24-Dec-2001	1 hr
		1-Jan-2002	15-Feb-2002	1 hr
		9-Mar-2002	12-May-2002	1 hr
		16-May-2002	7-Dec-2002	1 hr
		5-Feb-2003	28-Feb-2004	1 hr
		4-Mar-2004	14-Nov-2004	1 hr
		15-Dec-2004	1-Jun-2005	1 hr
		5-Jun-2005	8-Jan-2006	1 hr
		11-Jan-2006	20-Jan-2006	1 hr
		23-Jan-2006	16-Feb-2006	1 hr
		21-Feb-2006	29-Mar-2006	1 hr
		1-Apr-2006	6-Apr-2006	1 hr
		10-Apr-2006	15-Oct-2007	1 hr
		13-Nov-2007	22-May-2008	1 hr
		24-Jun-2008	15-Jul-2008	1 hr
		18-Jul-2008	25-Jul-2008	1 hr
		29-Jul-2008	12-Aug-2008	1 hr

Vertical Current Profiles

location	height (m)	start date	end date	freq
		18-Aug-2008	30-Sep-2008	1 hr
		21-Nov-2008	20-Apr-2009	1 hr
Onslow Town		1-Jan-2001	16-Apr-2004	0,3,6,9,12,15,18 hour
		17-Apr-2004	14-Mar-2005	6,9,12,15,18 hour
		15-Mar-2005	4-Mar-2009	6,9,15 hour or 5,8,14 hour
Onslow_Airport	10	1-Jan-2001	4-Mar-2009	1 hour
Onslow	3	30-Dec-2005	31-Dec-2005	1 min
		1-Jan-2006	31-Dec-2006	1 min
		1-Jan-2007	11-Apr-2007	1 min
		16-Apr-2007	31-Aug-2007	1 min
		17-Dec-2008	31-Jan-2009	1 min
		31-Jan-2009	25-Feb-2009	1 min

2.5 Summary of Monitoring Data

Depicted in Figure 2-1 are the locations of the monitoring sites for which data has been reviewed in this report.

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Vertical Current Profiles

Table 2-6 CTD Casts

	1/1/2009	1/16/2009	1/31/2009	2/15/2009	3/2/2009	3/17/2009	4/1/2009	4/16/2009	5/1/2009	5/16/2009	5/31/2009	6/15/2009	6/30/2009	7/15/2009	7/30/2009	8/14/2009	8/29/2009	9/13/2009	9/28/2009	10/13/2009	10/28/2009	11/12/2009	11/27/2009	12/12/2009	12/27/2009	1/11/2010	1/26/2010	2/10/2010
Ashburton Island																								■			■	
Channel								■						■				■			■						■	
Direction Island								■	■					■				■			■							
Dredge Route								■	■												■						■	
Jetty								■			■			■			■			■							■	■
Paroo Shoal								■			■			■			■											
TVI																					■							■
Ward Reef																		■		■							■	
West TVI																											■	
Spoil Ground								■						■													■	

Table 2-7 Current Data

	1-Jan-06	16-Jan-06	31-Jan-06	15-Feb-06	2-Mar-06	17-Mar-06	1-Apr-06	16-Apr-06	1-May-06	16-May-06	31-May-06	15-Jun-06	30-Jun-06	15-Jul-06	30-Jul-06	14-Aug-06	29-Aug-06	13-Sep-06	28-Sep-06	13-Oct-06	28-Oct-06	12-Nov-06	27-Nov-06	12-Dec-06	27-Dec-06	11-Jan-07	26-Jan-07
Bank ADCP				■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■					
Channel																											
Dredge Route																											
Jetty			■	■																							
Spoil Ground																											
Ward Reef																											
Wheatstone Platform																											

Table 2-8 Current Data (Continued)

	1-Jan-2009	16-Jan-2009	31-Jan-2009	15-Feb-2009	2-Mar-2009	17-Mar-2009	1-Apr-2009	16-Apr-2009	1-May-2009	16-May-2009	31-May-2009	15-Jun-2009	30-Jun-2009	15-Jul-2009	30-Jul-2009	14-Aug-2009	29-Aug-2009	13-Sep-2009	28-Sep-2009	13-Oct-2009	28-Oct-2009	12-Nov-2009	27-Nov-2009	12-Dec-2009	27-Dec-2009	11-Jan-2010	26-Jan-2010
Bank ADCP																											
Channel														■	■	■	■	■	■	■	■						
Dredge Route								■	■	■	■	■	■	■							■	■	■	■	■	■	■
Jetty		■	■	■	■	■	■	■	■	■	■				■	■	■	■	■	■	■			■	■	■	■
Spoil Ground	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Ward Reef																	■	■	■	■	■	■	■	■	■	■	■
Wheatstone Platform									■	■	■	■	■	■	■	■	■	■	■	■	■						

Table 2-9 Wave Data

	1-Jan-09	16-Jan-09	31-Jan-09	15-Feb-09	2-Mar-09	17-Mar-09	1-Apr-09	16-Apr-09	1-May-09	16-May-09	31-May-09	15-Jun-09	30-Jun-09	15-Jul-09	30-Jul-09	14-Aug-09	29-Aug-09	13-Sep-09	28-Sep-09	13-Oct-09	28-Oct-09	12-Nov-09	27-Nov-09	12-Dec-09	27-Dec-09	11-Jan-10	26-Jan-10	10-Feb-10	25-Feb-10
Channel														■	■	■	■	■	■	■	■								
Dredge								■	■	■	■	■	■	■	■						■	■	■	■	■	■	■		
Jetty	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	
Offshore										■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Spoil Gnd	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■				

■ Data Available
None or Incomplete data

Table 2-10 Wind Data

	Jan-01	Feb-01	Mar-01	Apr-01	May-01	Jun-01	Jul-01	Aug-01	Sep-01	Oct-01	Nov-01	Dec-01	Jan-02	Feb-02	Mar-02	Apr-02	May-02	Jun-02	Jul-02	Aug-02	Sep-02	Oct-02	Nov-02	Dec-02
BarrowIsland																								
Thevenard																								
Onslow Town																								
Onslow_AP																								
Onslow																								

Table 2-11 Wind Data (continued)

	Jan-03	Feb-03	Mar-03	Apr-03	May-03	Jun-03	Jul-03	Aug-03	Sep-03	Oct-03	Nov-03	Dec-03	Jan-04	Feb-04	Mar-04	Apr-04	May-04	Jun-04	Jul-04	Aug-04	Sep-04	Oct-04	Nov-04	Dec-04
BarrowIsland																								
Thevenard																								
Onslow Town																								
Onslow_AP																								
Onslow																								

Table 2-12 Wind Data (continued)

	Jan-05	Feb-05	Mar-05	Apr-05	May-05	Jun-05	Jul-05	Aug-05	Sep-05	Oct-05	Nov-05	Dec-05	Jan-06	Feb-06	Mar-06	Apr-06	May-06	Jun-06	Jul-06	Aug-06	Sep-06	Oct-06	Nov-06	Dec-06
BarrowIsland																								
Thevenard																								
Onslow Town																								
Onslow_AP																								
Onslow																								

Table 2-13 Wind Data (continued)

	Jan-07	Feb-07	Mar-07	Apr-07	May-07	Jun-07	Jul-07	Aug-07	Sep-07	Oct-07	Nov-07	Dec-07	Jan-08	Feb-08	Mar-08	Apr-08	May-08	Jun-08	Jul-08	Aug-08	Sep-08	Oct-08	Nov-08	Dec-08
BarrowIsland																								
Thevenard																								
Onslow Town																								
Onslow_AP																								
Onslow																								

Table 2-14 Wind Data (continued)

	Jan-09	Feb-09	Mar-09	Apr-09	May-09	Jun-09	Jul-09	Aug-09	Sep-09	Oct-09	Nov-09	Dec-09	Jan-10	Feb-10	Mar-10	Apr-10	May-10	Jun-10	Jul-10	Aug-10	Sep-10	Oct-10	Nov-10	Dec-10
BarrowIsland																								
Thevenard																								
Onslow																								
Onslow_AP																								
Onslow																								

Data Available

None or Incomplete data

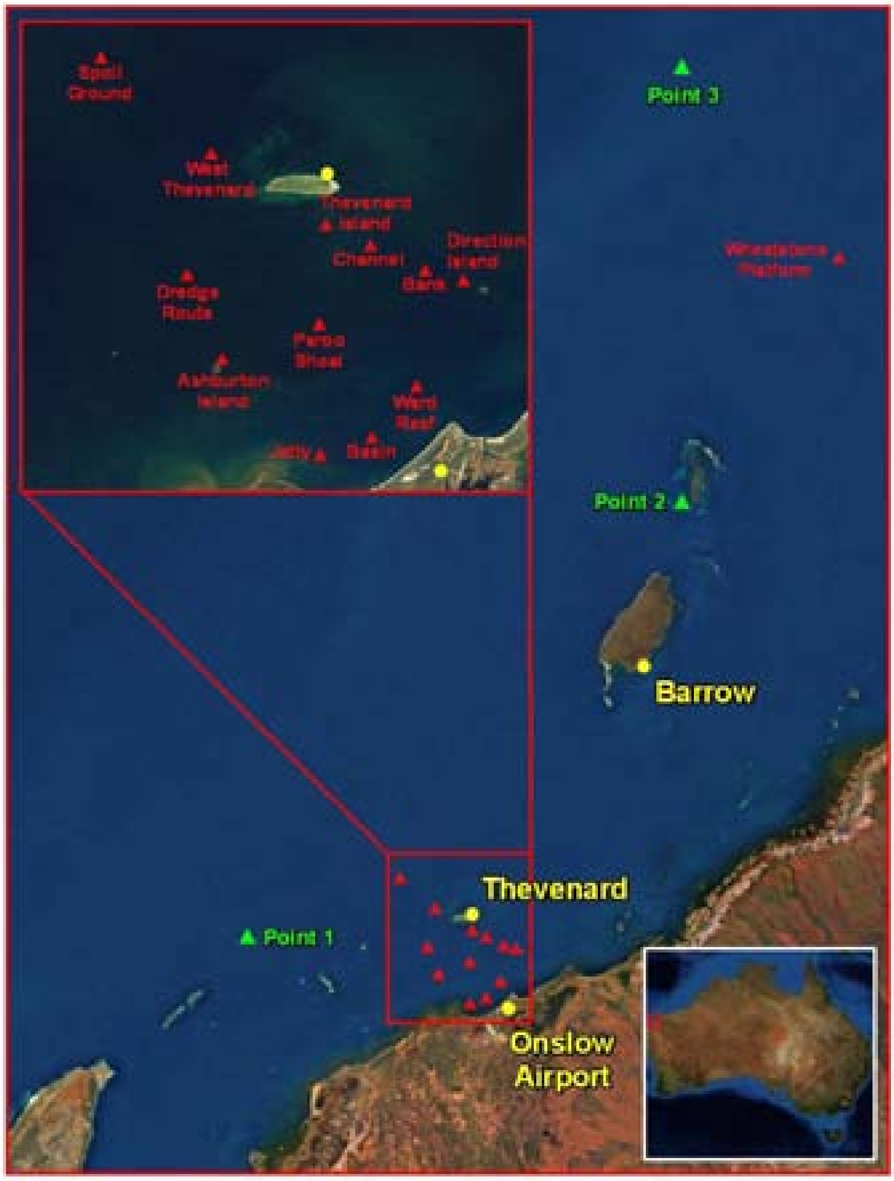

Figure 2-1 Station Location Map

3 Data Analysis and Results

3.1 Temperature Salinity and Density Data

3.1.1 CTD Data

The vertical profiles are shown in Appendix A. The data include temperature, salinity and density measurements. A general summary of the data indicate that the salinity and temperature levels vary temporally, but they are essentially uniform over the water column at each station. Typically the salinity varies by only 0.5 ppt or less over the vertical profile. Only once, at the spoil ground location, did the vertical structure indicate some stratification. For the data collected on October 31, 2009, the temperature increased over 52 meter the water depth from 21.0 ^{oC} C to 24 oC. However, the salinity profiles were uniform, and the density profiled indicated very little density stratification.

It can be concluded from these data that the water column in the near-shore area is not stratified and therefore the vertical density profile does not have significant impact on the current profiles.

3.1.2 World Ocean Atlas Data

Vertical plots of the monthly average temperature and salinity data from the 2005 WOA data base are shown in Appendix B. The data are consistent with the data from the CTD casts, but also reveal some of the deep water vertical structure that was not covered in the CTD data. The salinity data at the Point 1 and Point 2 locations show similar characteristics. The salinity vertical range and seasonal range do not vary significantly. At both locations, the salinities are nominally 35.0 ppt, and vary by less than 0.5 ppt over the depth and seasonally. The temperature data at the shallowest station, Point 1, indicates a vertically missed water column, with the expected seasonal summer and winter variation in water temperatures. Peak summer temperatures are on the order of 28 ^{o}C, and the winter low temperature is just below 23 ^{o}C. At the 55 m station, Point 2, the same seasonal variation occurs, with slightly higher summer maximum and winter low (29 ^{o}C and 23.2 ^{o}C). The vertical profile data and Point 2 indicate that the near bottom water does not warm as much as the surface water and remain lower than the surface temperatures by about 2 to 3 ^{o}C.

For the deep water station, Point 3, the vertical profile of salinity indicates an increasing salinity with depths to about 200 meters, and then a decreasing profile below. The maximum seasonal variation occurs at about 200 meters water depth, and is on the order of 2 ppt. The near surface waters (< 100 meters) show a seasonal variation of less than 1 ppt. The thermocline is evident in the temperature vertical profile, which extends from about 100 meters depth to the sea bottom. Seasonal variations in temperature are limited to the upper 100 meters, ranging from 24 ^{o}C in the winter to 29 ^{o}C in the summer. In the thermocline the seasonal range is less than 2 ^{o}C.

3.2 Currents

The current data was analysed to determine the characteristics of the vertical current profile, with a focus on the flow direction variation in the vertical. Data from three stations were used, from the Jetty station location, representing shallow/near-shore conditions, the Platform station, representing deep/offshore conditions, and the Channel station, representing intermediate depth conditions. The data fro the period 5-May-2009 through 10-Sept-2009 were used, which represents a period within which data were available from all three stations. In order to provide some insight into this structure the data difference in the bottom current and near-surface currents at each station were calculated. This calculation was done for each of the 10 minute (or 20 minute) records. The data were processed so that the angle difference was positive and ranged between 0 and 180 degrees. The data was further processed by considering the flow speed and the range of turning. For each station, the data were sorted by depth-average flow speed, and grouped into slow, medium and high speed ranges based on the 25th and 75th speed percentiles. For each group, the data were sorted by the direction difference between the top and bottom velocity bins to determine the frequency of the current turning in the vertical. The frequency distribution of the angle difference for each flow speed is presented in Figure 3-1 through Figure 3-3 for each of the three stations.

The data indicate that the vertical structure of the current direction is more uniform for the shallower near-stations, with increasing variation in the current direction over the vertical at stations with larger water depths. The median vertical variation in current at the shallow Jetty location is about 14 degrees. At the medium depth Channel Location, the median vertical variation in current is 16 degrees, and at the Wheatstone Platform it is 32 degrees.

The data also show that the vertical variation in current is much higher when the depth-average currents speeds are lower. These results suggest that the larger vertical variation in current occur during neap tides, when the tidal currents are not dominant, or during flow reversals associated with slack tide conditions. When the current speeds are larger, and transport lengths are higher, the surface and bottom currents tend to be more aligned. At the Jetty location, the median vertical variation in current is about 7 degrees for the higher speed ranges. It is about 14 degrees for the medium speed ranges, and about 53 degrees for the slower speed ranges. Similar patterns are evident at the Channel Location and the Wheatstone Platform.

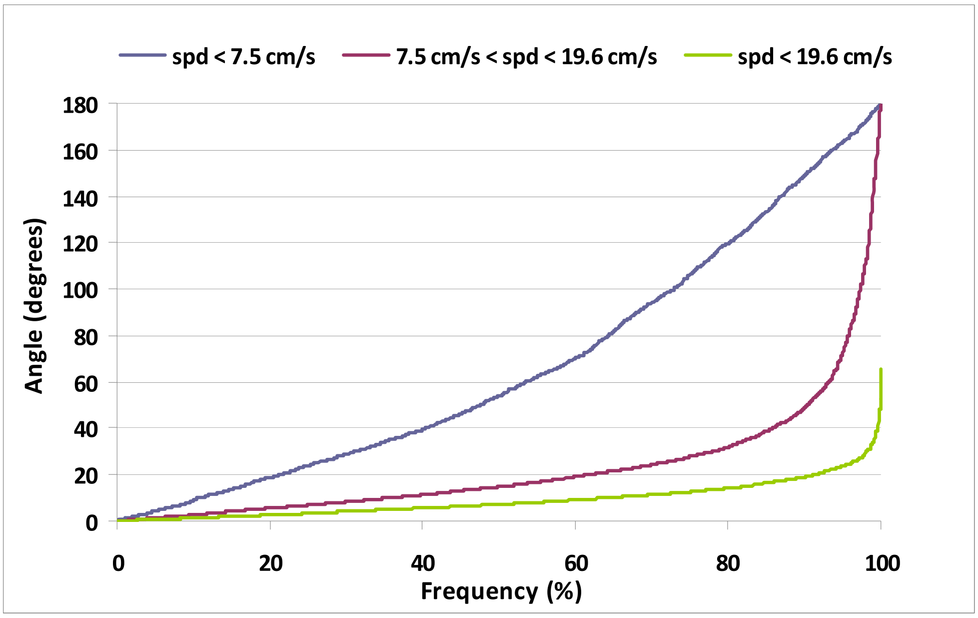

Figure 3-1 Distribution of the Current Vertical Directional Variation for slow, medium and high speed ranges at the Jetty Station (see Figure 2.1 for station locations)

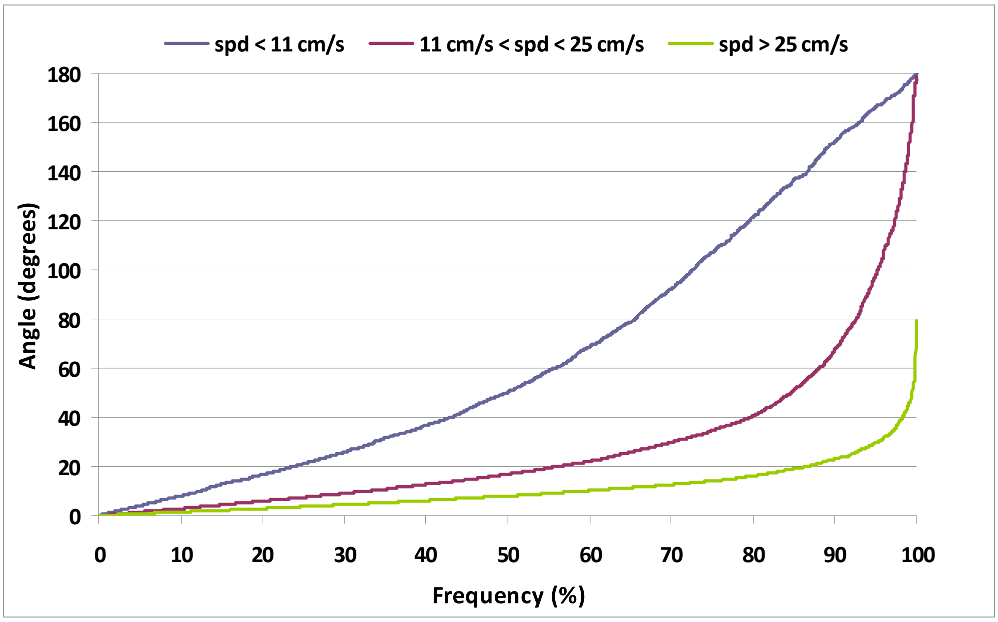

Figure 3-2 Distribution of the Current Vertical Directional Variation for slow, medium and high speed ranges at the Channel Station (see Figure 2.1 for station locations)

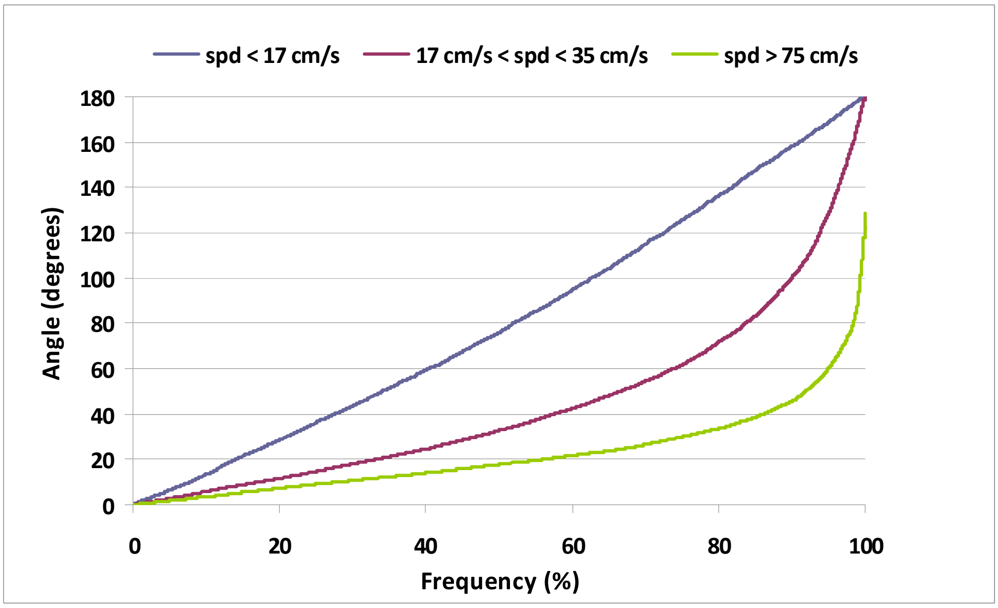

Figure 3-3 Distribution of the Current Vertical Directional Variation for slow, medium and high speed ranges at the Wheatstone Platform (see Figure 2.1 for station locations)

Additional plots of the current data for the three stations are shown in Appendix C. The time series show approximately one week of current speed and direction for the surface and bottom layers, and for the middle layer at the Platform station.

An example of the vertical profile of the currents at the Channel stations is also provided for two tide cycles occurring on September 21, 2009. The current speed and direction were transformed to an along-tide axis and across-tide axis component prior to plotting. The tide axis was determined from analysis of the direction data and was approximately 72 degrees (clockwise from North).

3.3 Wave Fields

Wave roses have been generated for four stations during the period of May 5, 2009 through June 13, 2009. The four stations represent increasing distances from the coastline and were selected because they have concurrent wave measurements (Jetty, Channel, Spoil Ground, Platform). The wave data for these stations were processed into sea and swell components using a period of 9 seconds (0.111 hz) to divide the spectral energy into sea and swell components. The concurrent wave rose plots are shown in Appendix D and represent the significant wave height and mean direction. For the early winter period the swell, which appears to be originating from the Southwest based on the Platform wave rose, is turned successively more shoreward at each of the inshore stations. The swell wave heights tend to decrease with increasing proximity to the coastline (note the scale change for the Platform wave rose). The turning pattern and wave height trends are consistent with expected shoaling patterns for long period waves diffracting around Northwest Cape.

The seas for the concurrent period are not as well correlated. Seas at the platform indicate a southwest propagation direction, and at the two inshore stations, Jetty and Dredge Route, the seas are propagating more shoreward with a larger spread in the direction. The wave data at the Spoil Ground location appear to be inconsistent with wave data from the other three stations.

Wave roses for the period of record for each station are also shown in Appendix D. For each station, the period of record varies and there are differing data gaps within each period. Therefore it is important to review the time line data available in Table 2-9 When reviewing the wave rose date for each period of record.

3.4 Wind Fields

Presented in Figure 3-4 through Figure 3-6 are the wind roses for the Onlsow Airport, Thevenard Island and Barrow Island meteorological monitoring sites for the period from 2000-2009. The increase in frequency of elevated wind speeds with distance offshore is evident. The predominance of strong winds from the southwest quadrant is noted at all locations with more frequent strong easterlies recorded at the Barrow Island site than at the Thevenard Island or Onslow locations. Seasonal wind roses and wind roses by hour of day are presented in Appendix E.

Vertical Current Profiles

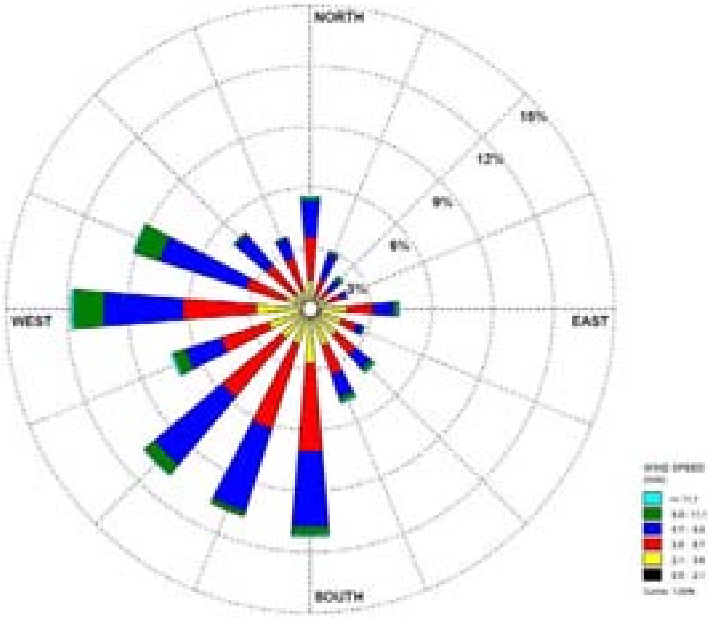

Figure 3-4 Onslow, 2000-2009

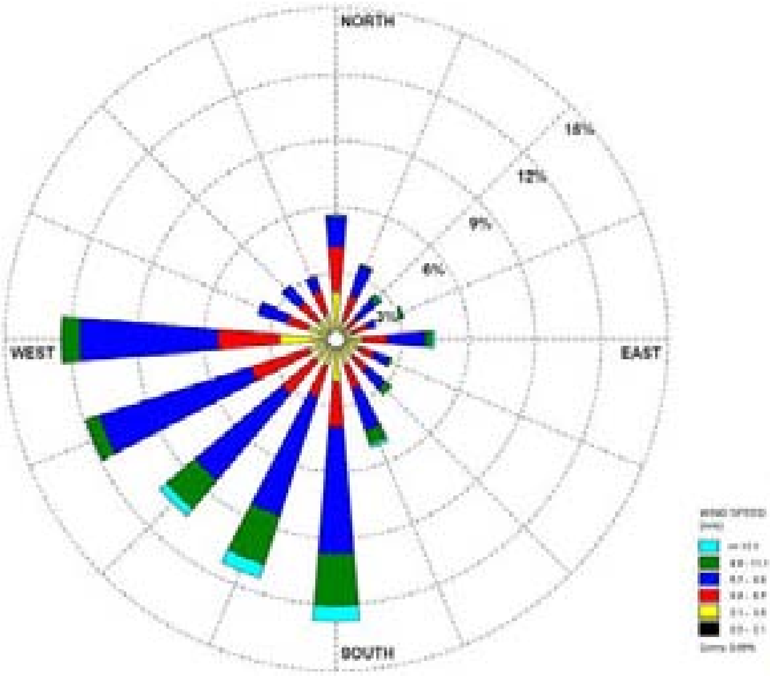

Figure 3-5 Thevenard Island, 2000-2009

Vertical Current Profiles

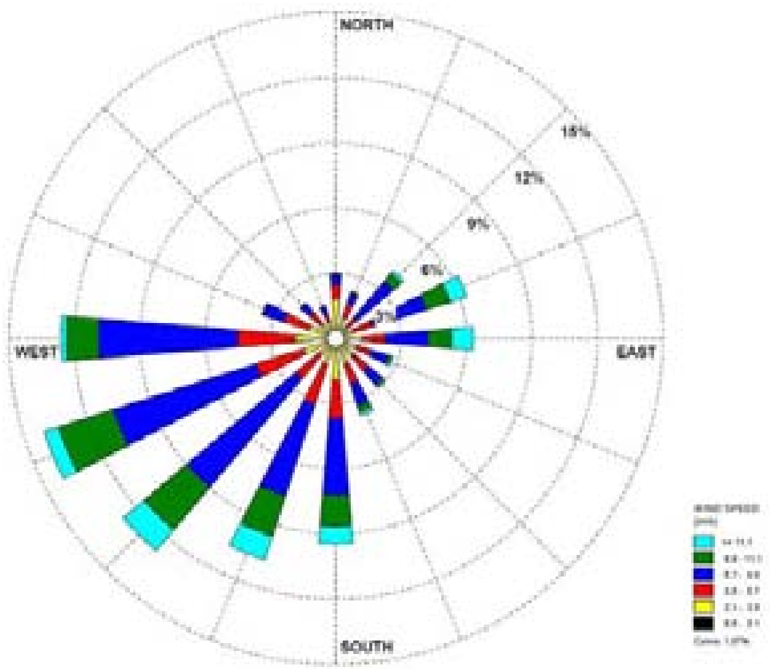

Figure 3-6 Barrow Island, 2000-2009

4 Limitations

URS Australia Pty Ltd (URS) has prepared this report in accordance with the usual care and thoroughness of the consulting profession for the use of Chevron Australia Pty Ltd and only those third parties who have been authorised in writing by URS to rely on the report. It is based on generally accepted practices and standards at the time it was prepared. No other warranty, expressed or implied, is made as to the professional advice included in this report.

The methodology adopted and sources of information used by URS are outlined in this report. URS has made no independent verification of this information beyond the agreed scope of works and URS assumes no responsibility for any inaccuracies or omissions. No indications were found during our investigations that information contained in this report as provided to URS was false.

This report was prepared between 3 May 2010 and 10 May 2010 and is based on the conditions encountered and information reviewed at the time of preparation. URS disclaims responsibility for any changes that may have occurred after this time.

This report should be read in full. No responsibility is accepted for use of any part of this report in any other context or for any other purpose or by third parties. This report does not purport to give legal advice. Legal advice can only be given by qualified legal practitioners.

Appendix A CTD Vertical Profiles

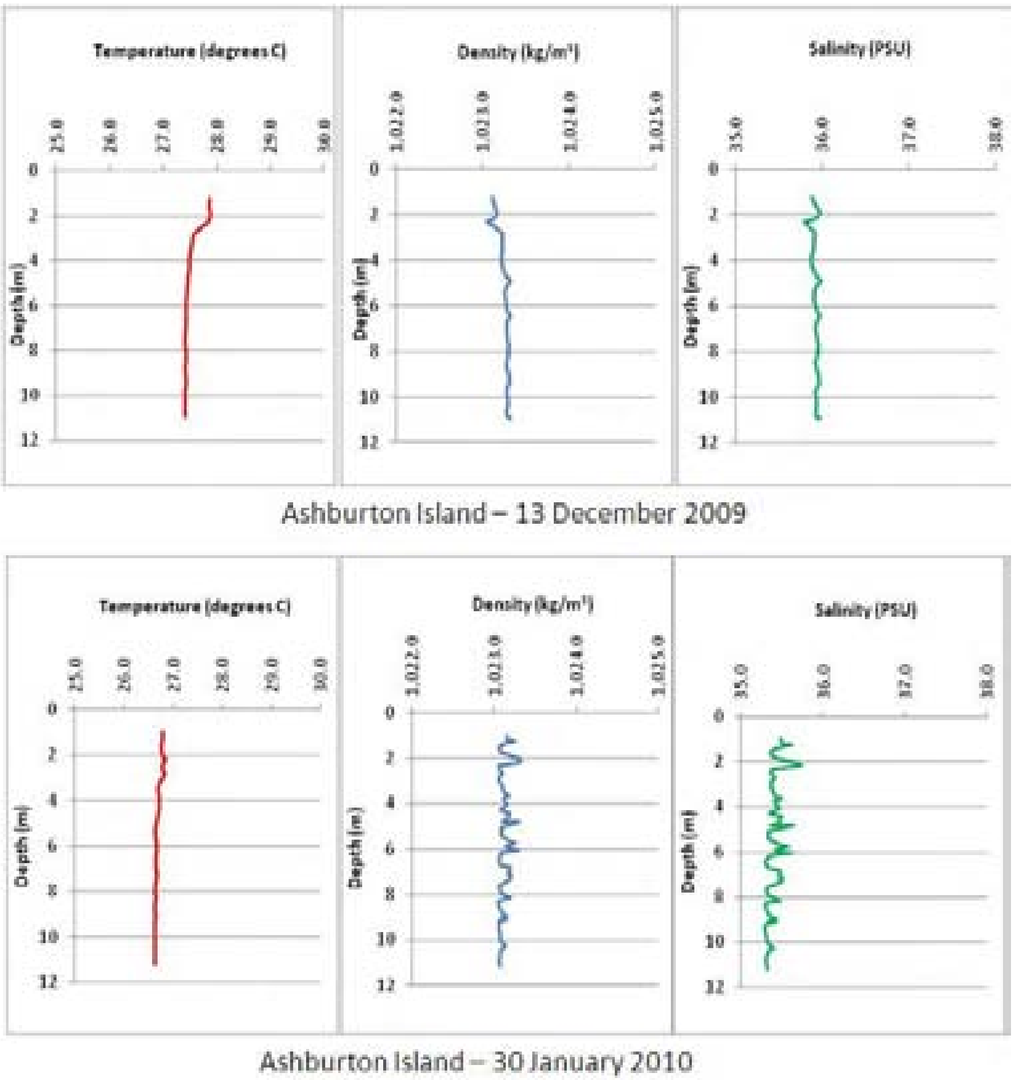

Figure A-1 Ashburton Island- Vertical Profiles of Salinity, Temperature and Density

Vertical Current Profiles

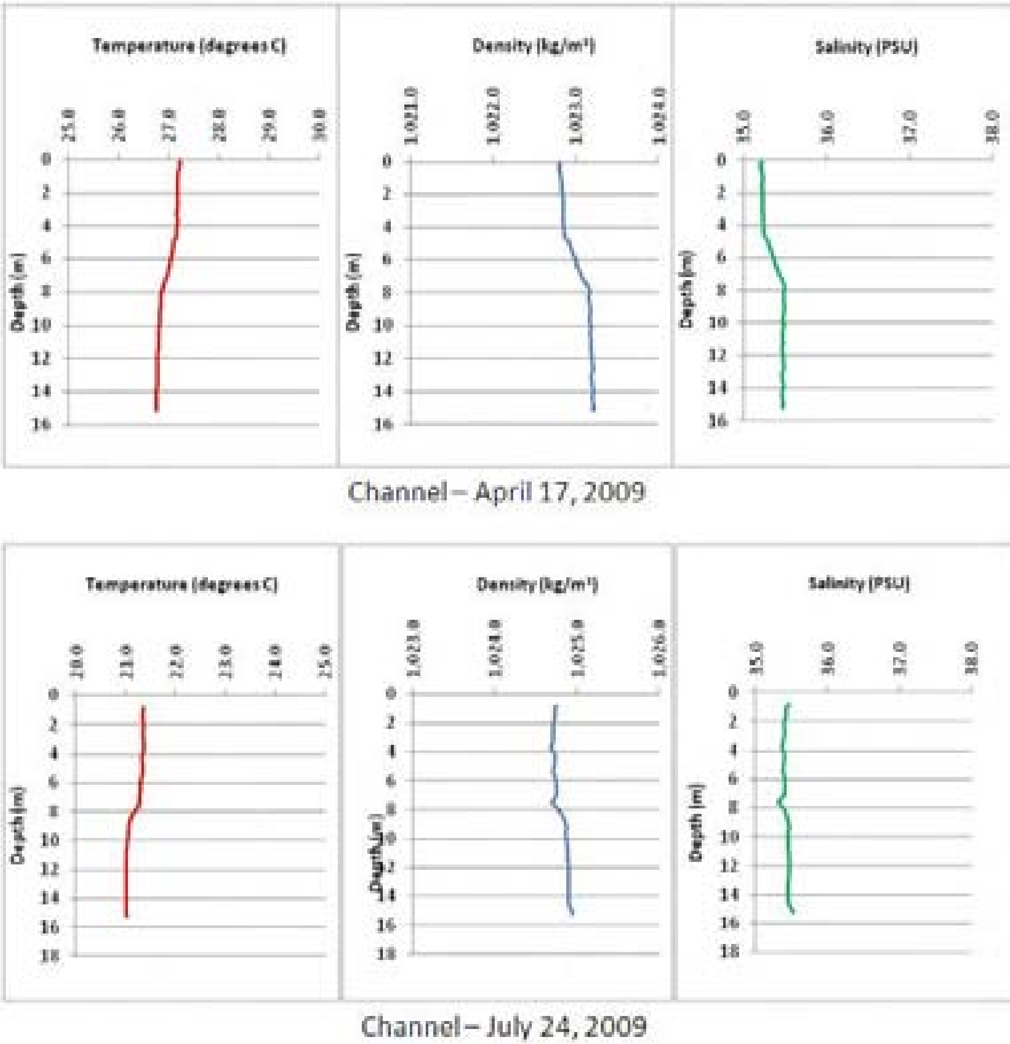

Figure A-2 Channel- Vertical Profiles of Salinity, Temperature and Density

Vertical Current Profiles

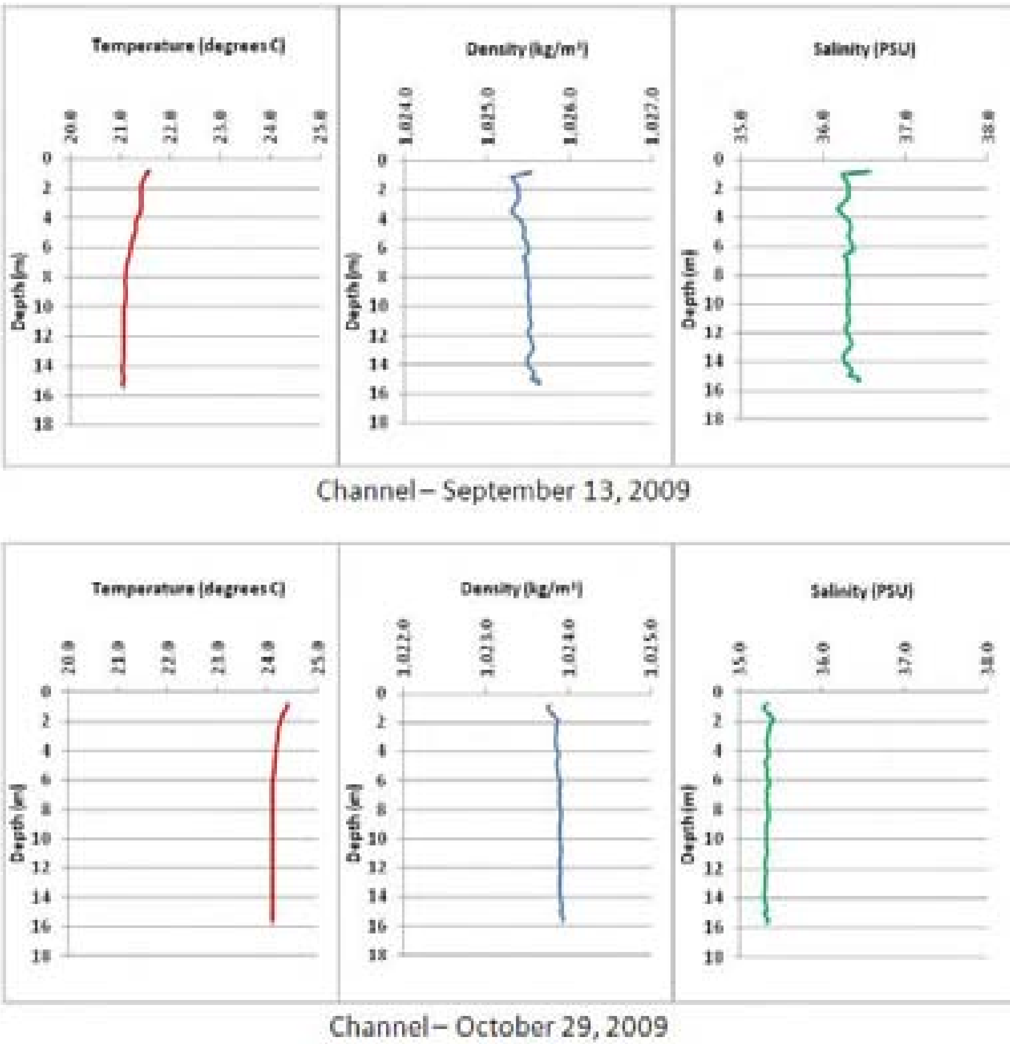

Figure A-3 Channel- Vertical Profiles of Salinity, Temperature and Density

Vertical Current Profiles

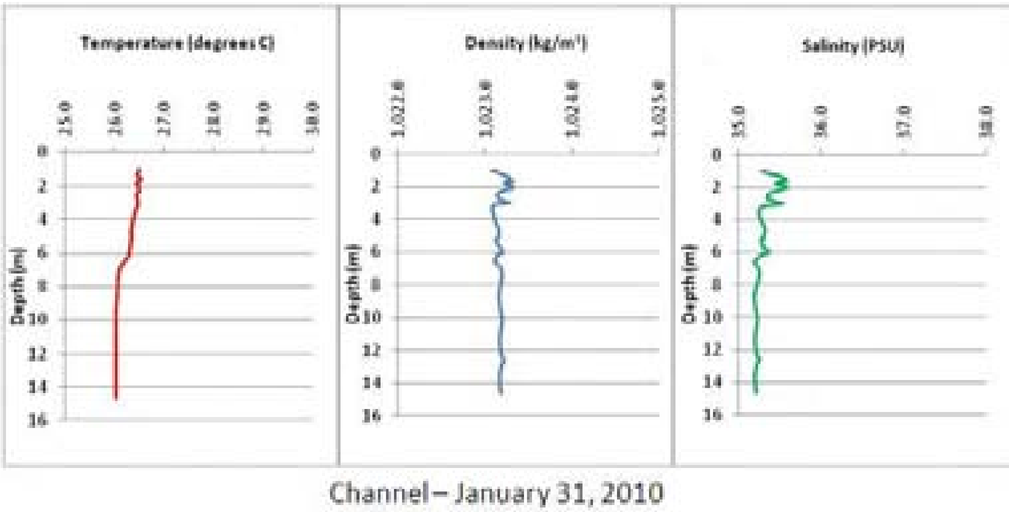

Figure A-4 Channel- Vertical Profiles of Salinity, Temperature and Density

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Vertical Current Profiles

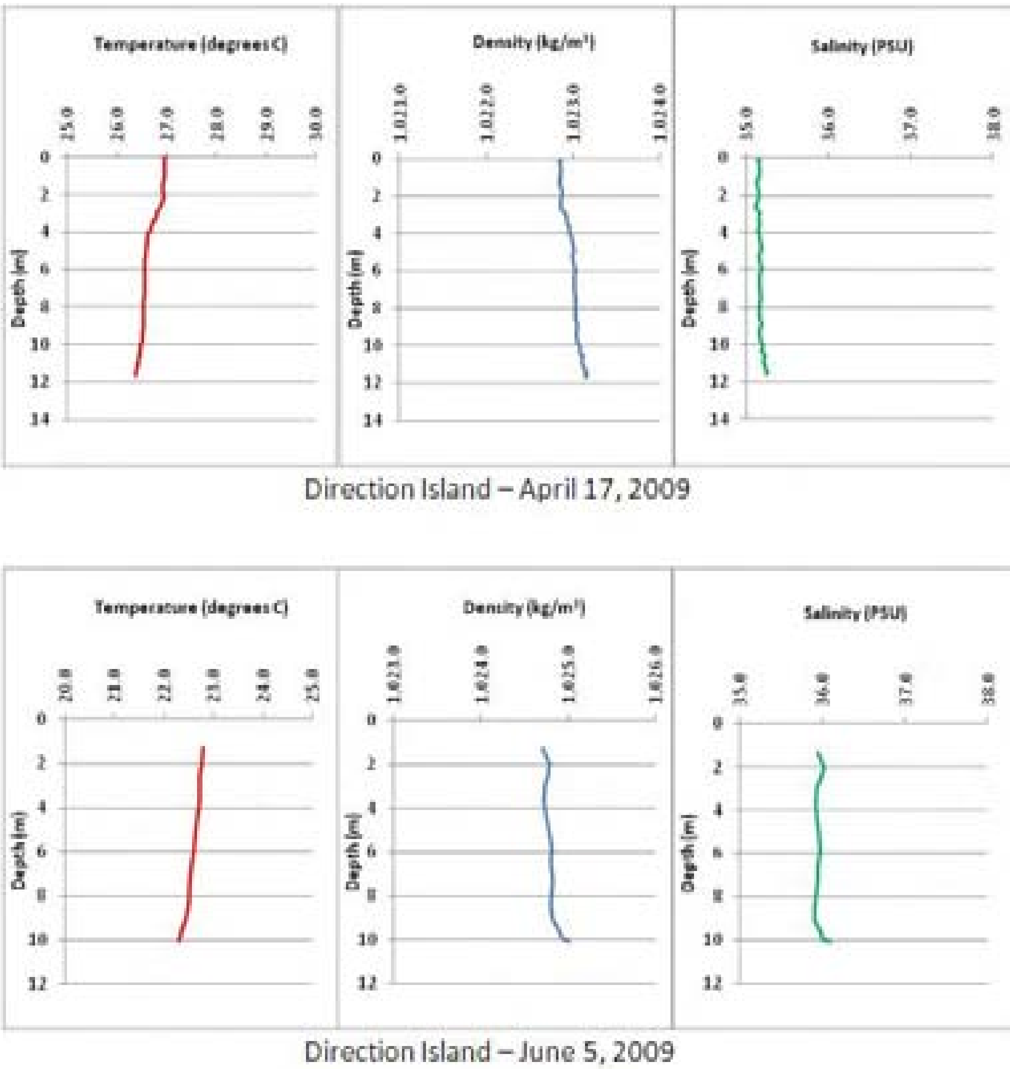


Figure A-5 Direction Island- Vertical Profiles of Salinity, Temperature and Density

Vertical Current Profiles

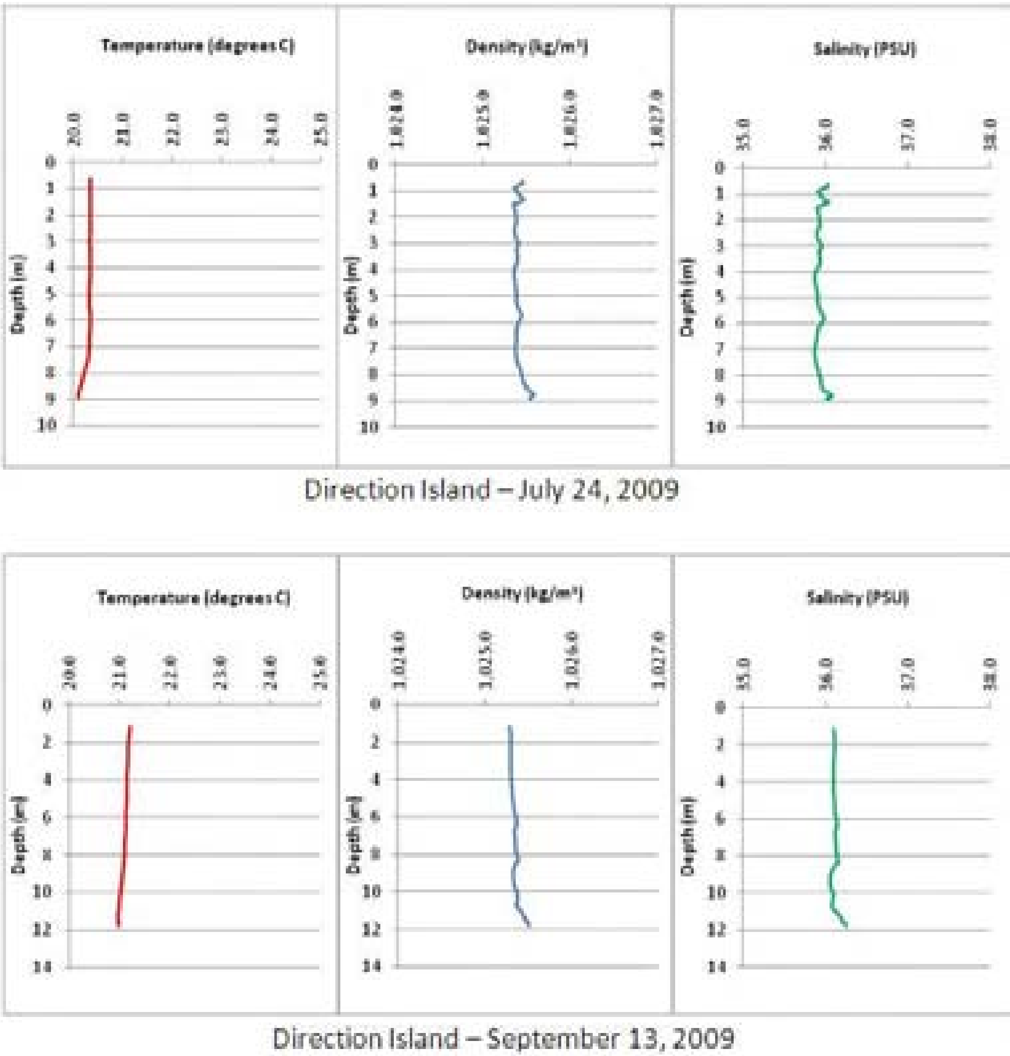


Figure A-6 Direction Island- Vertical Profiles of Salinity, Temperature and Density

Vertical Current Profiles

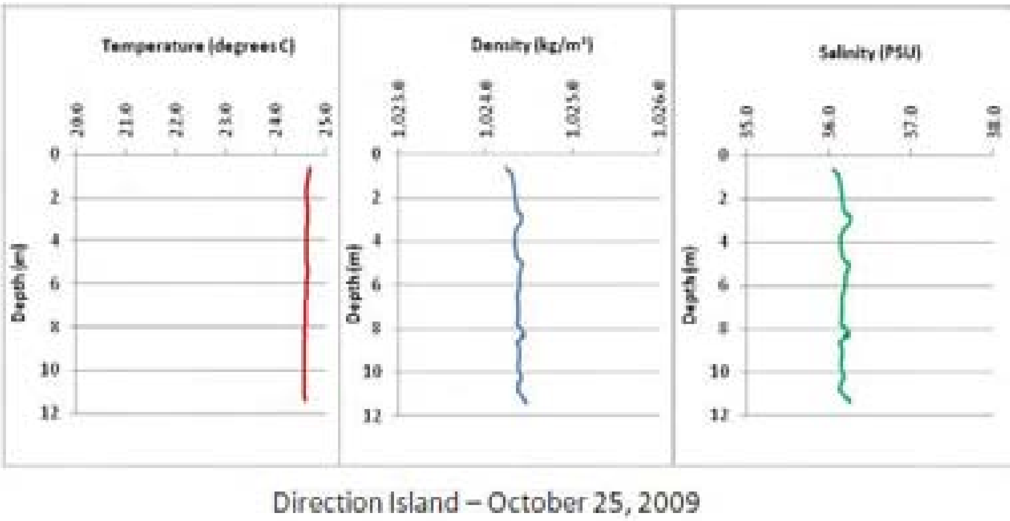


Figure A-7 Direction Island- Vertical Profiles of Salinity, Temperature and Density

Vertical Current Profiles

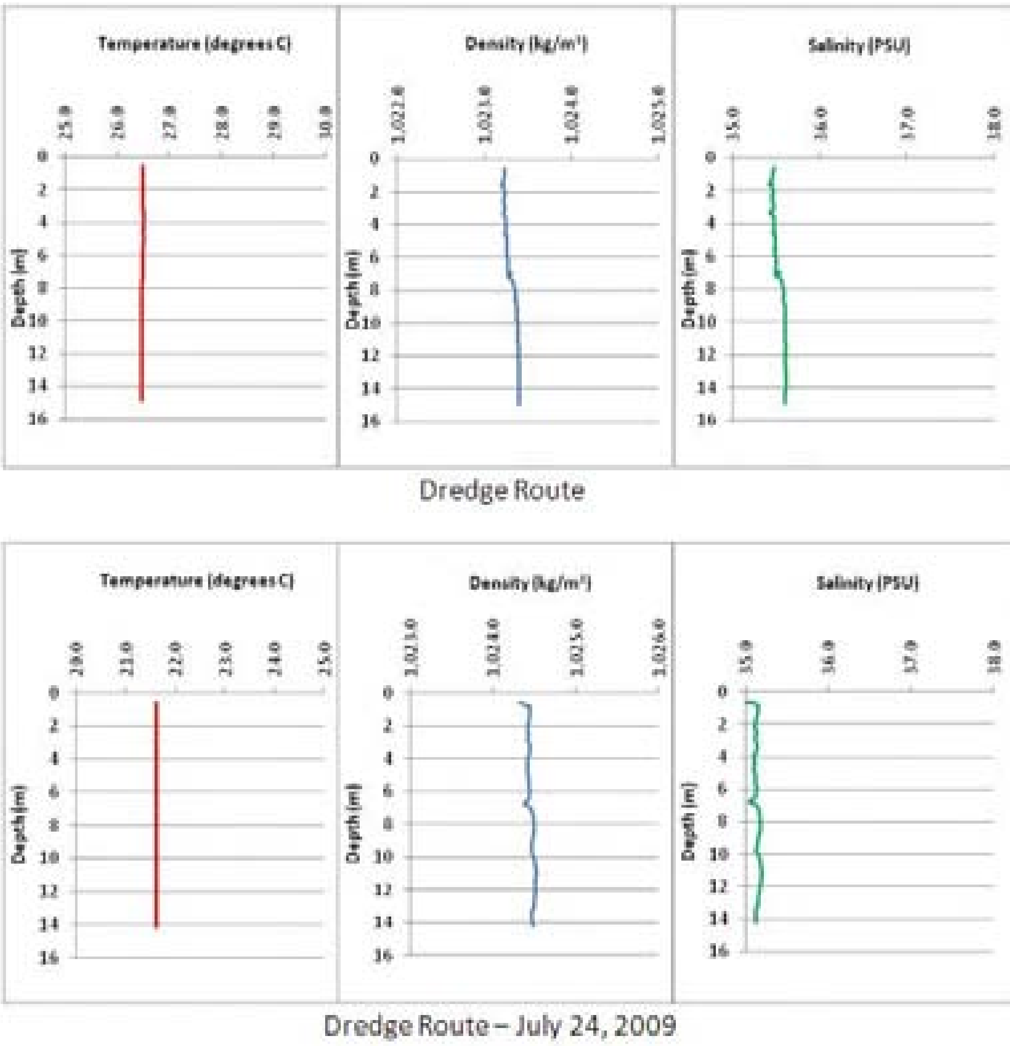


Figure A-8 Dredge Route- Vertical Profiles of Salinity, Temperature and Density

Vertical Current Profiles

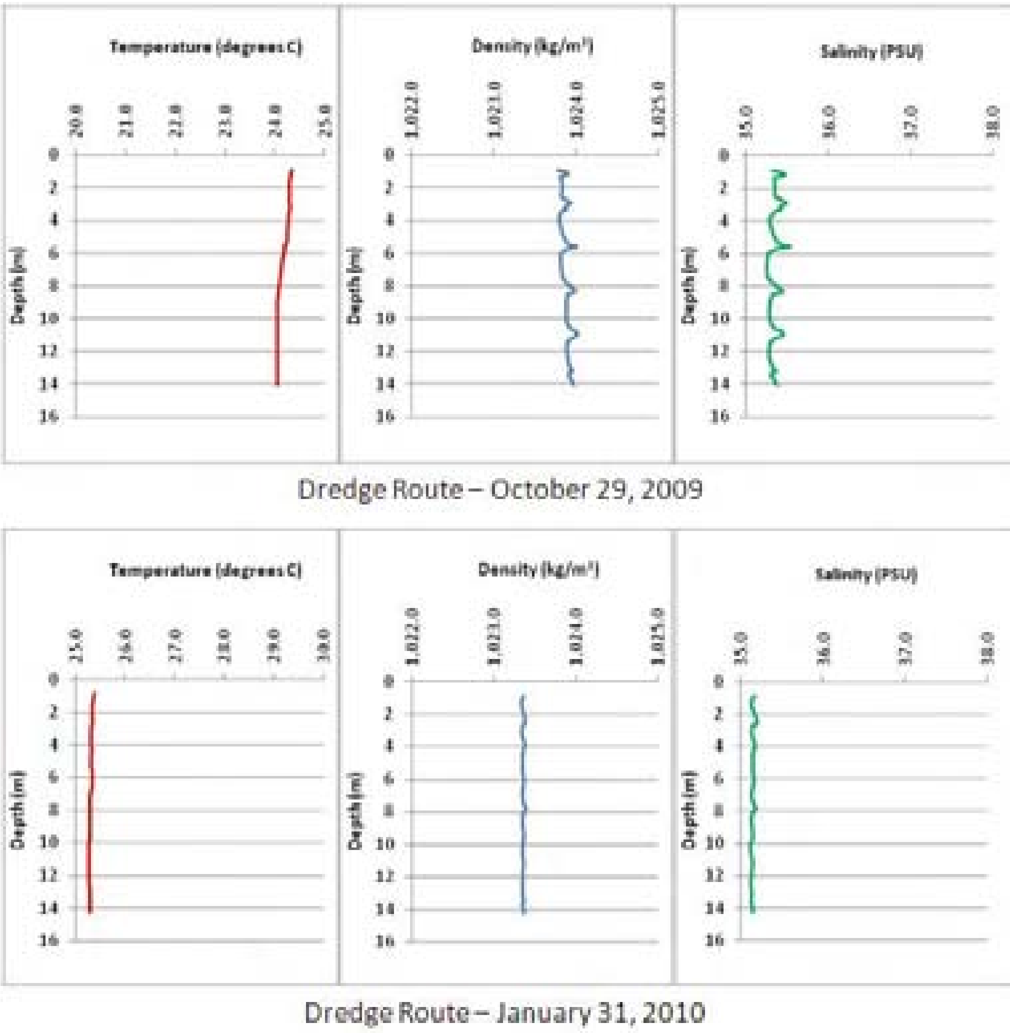


Figure A-9 Dredge Route- Vertical Profiles of Salinity, Temperature and Density

Vertical Current Profiles

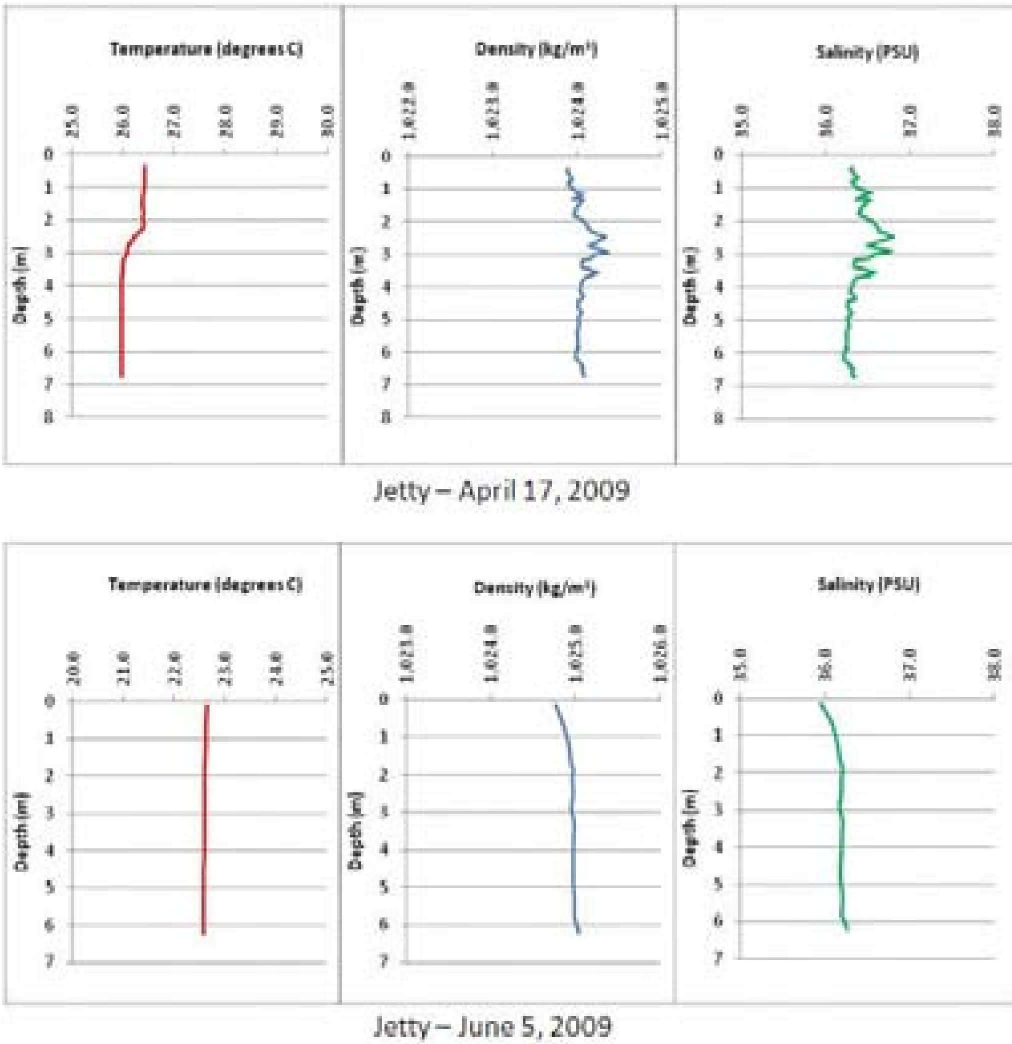


Figure A-10 Jetty- Vertical Profiles of Salinity, Temperature and Density

Vertical Current Profiles

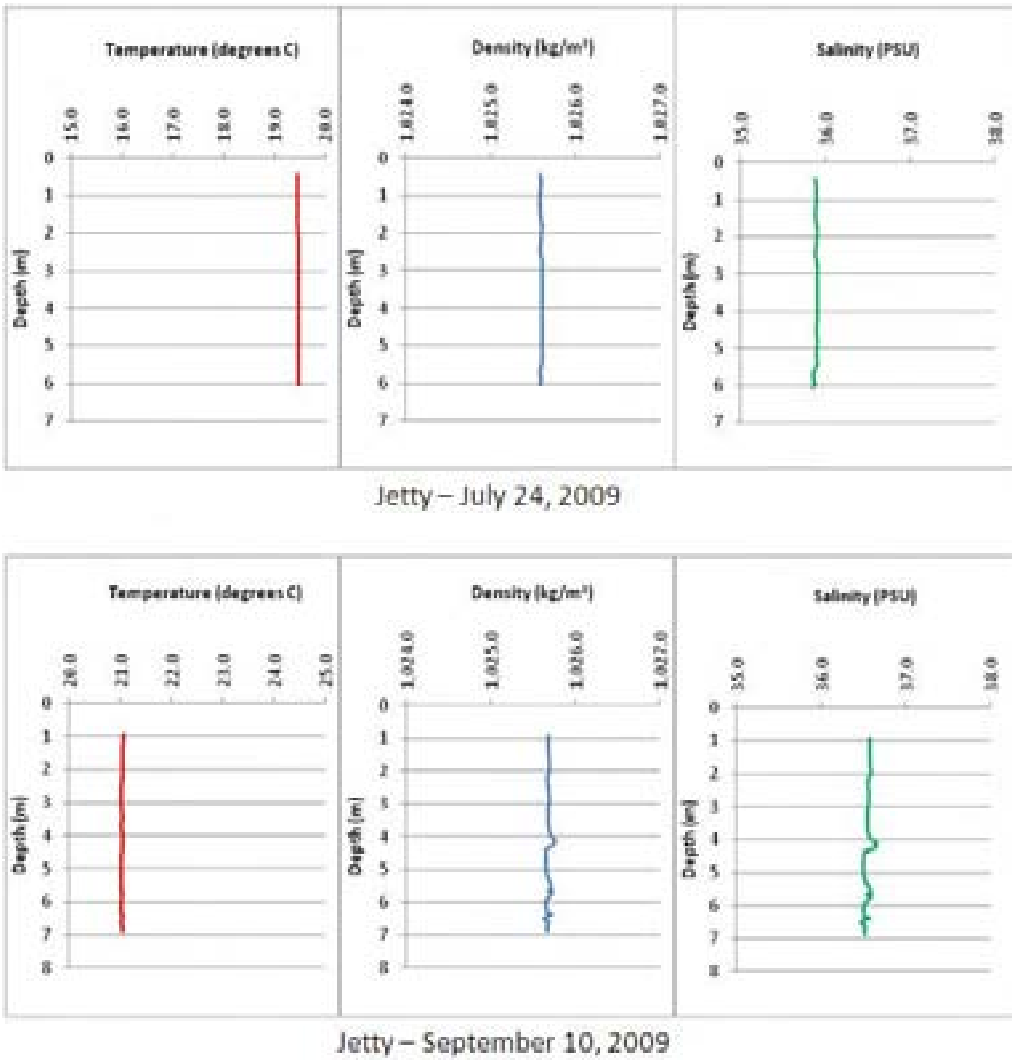
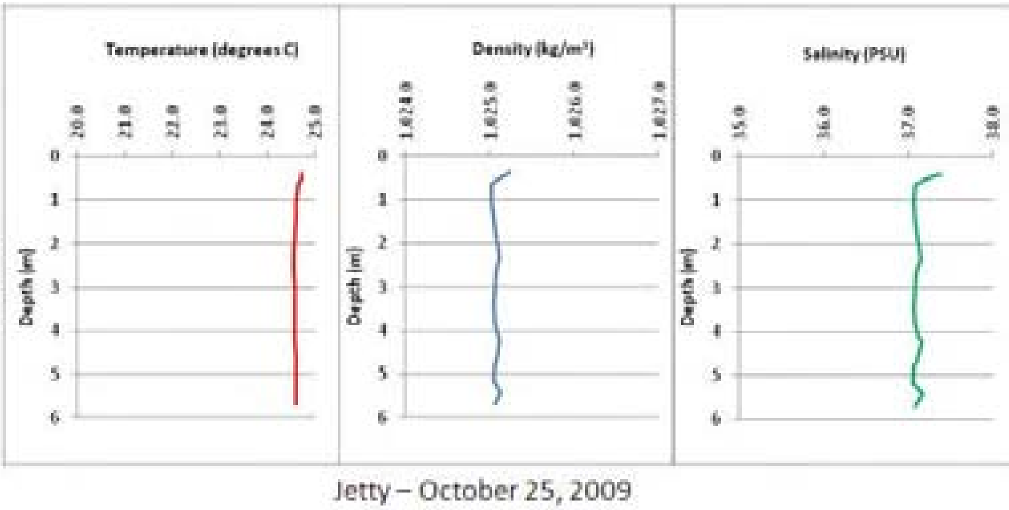


Figure A-11 Jetty- Vertical Profiles of Salinity, Temperature and Density

Vertical Current Profiles



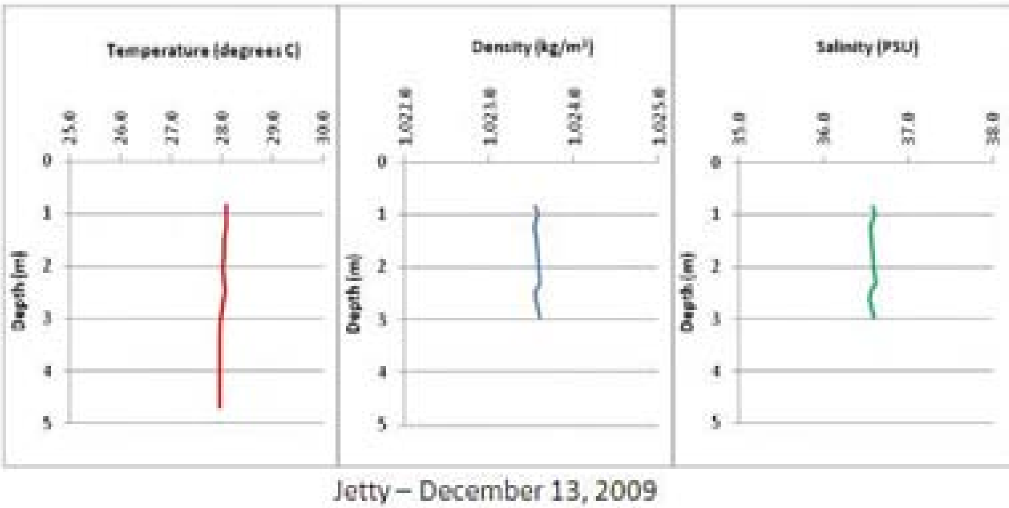


Figure A-12 Jetty- Vertical Profiles of Salinity, Temperature and Density

Vertical Current Profiles

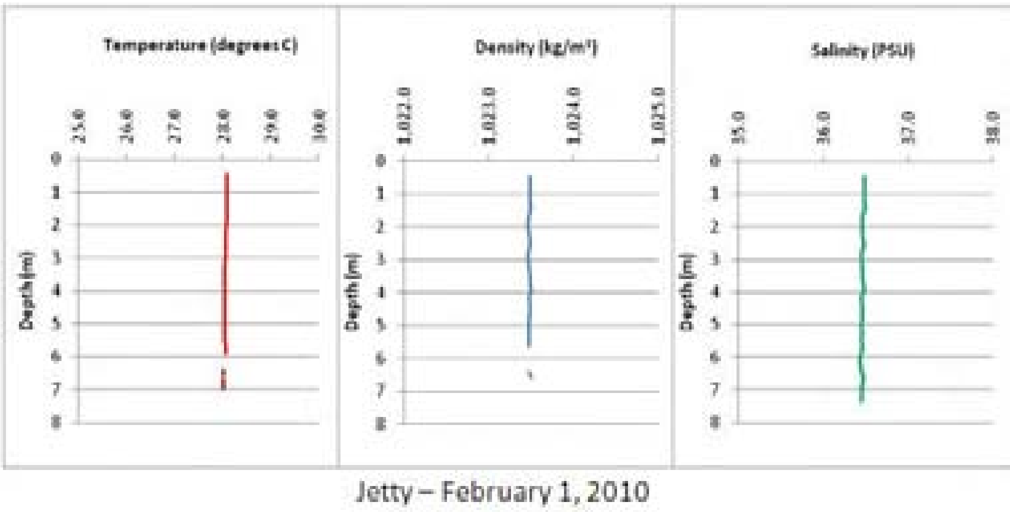


Figure A-13 Jetty- Vertical Profiles of Salinity, Temperature and Density

Vertical Current Profiles

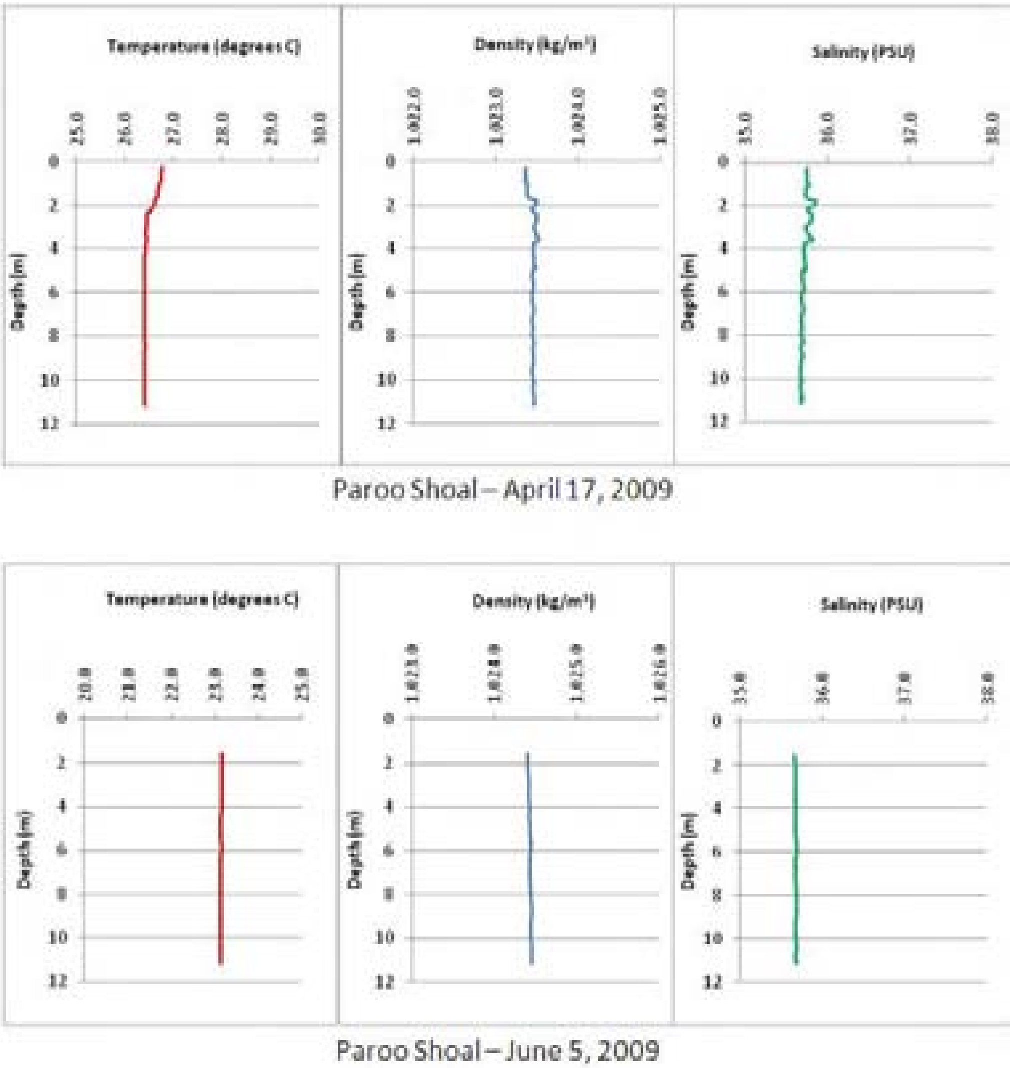


Figure A-14 Paroo Shoal- Vertical Profiles of Salinity, Temperature and Density

Vertical Current Profiles

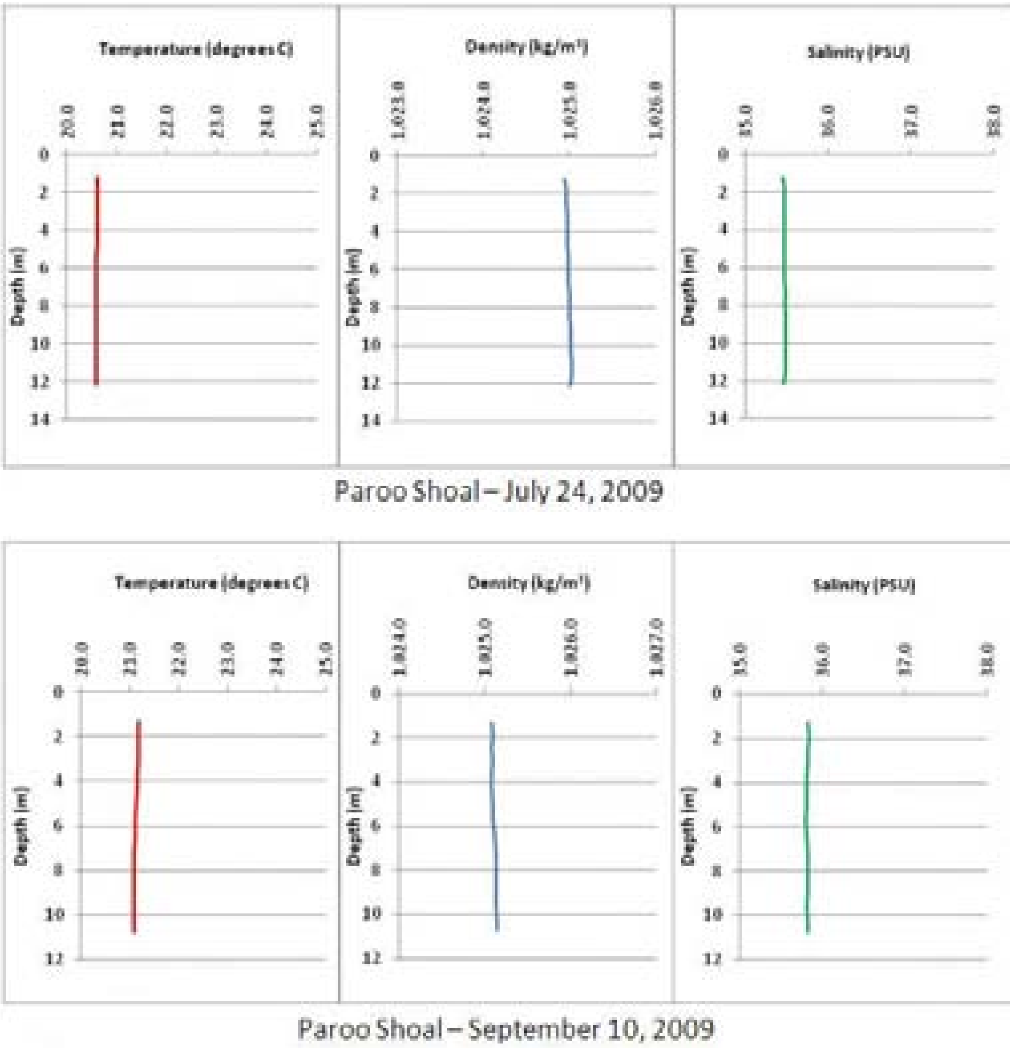


Figure A-15 Paroo Shoal- Vertical Profiles of Salinity, Temperature and Density

Vertical Current Profiles

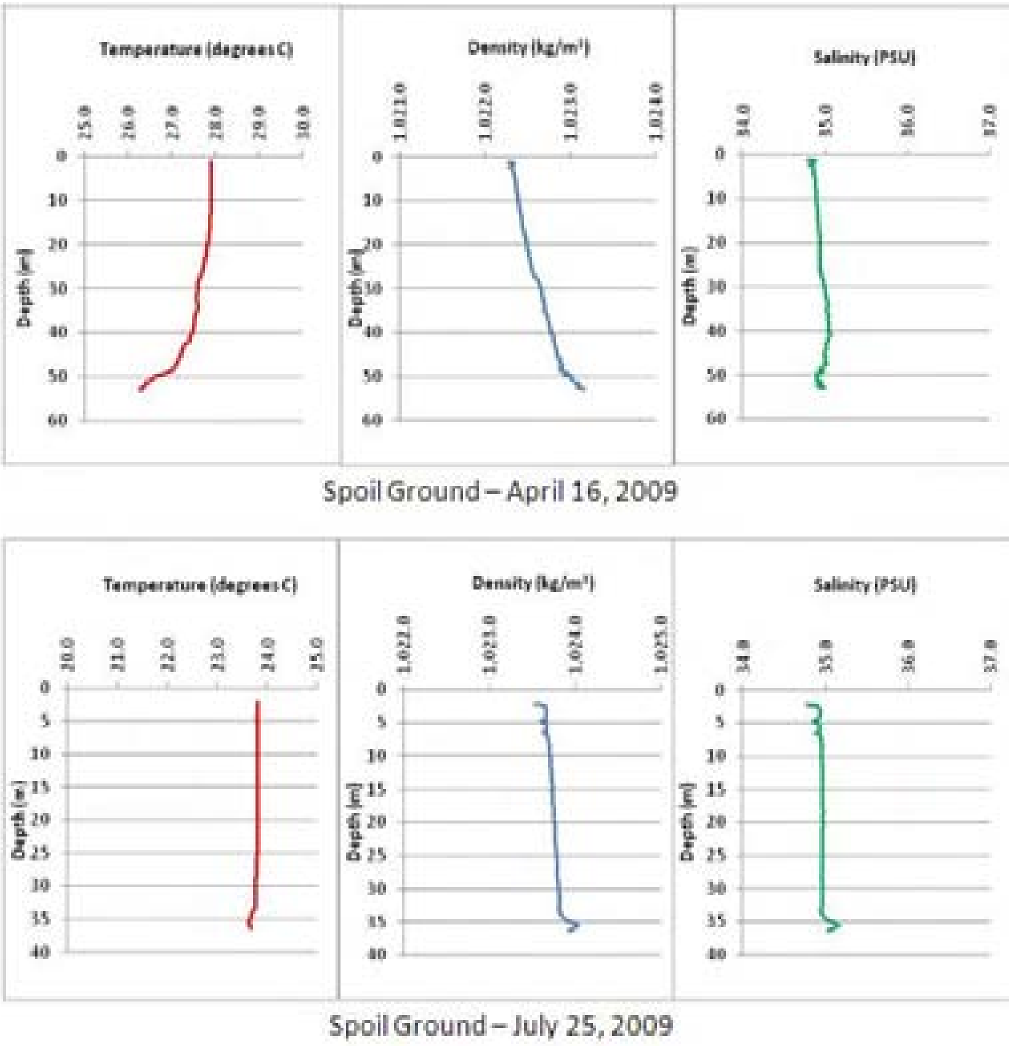


Figure A-16 Spoil Ground- Vertical Profiles of Salinity, Temperature and Density

Vertical Current Profiles

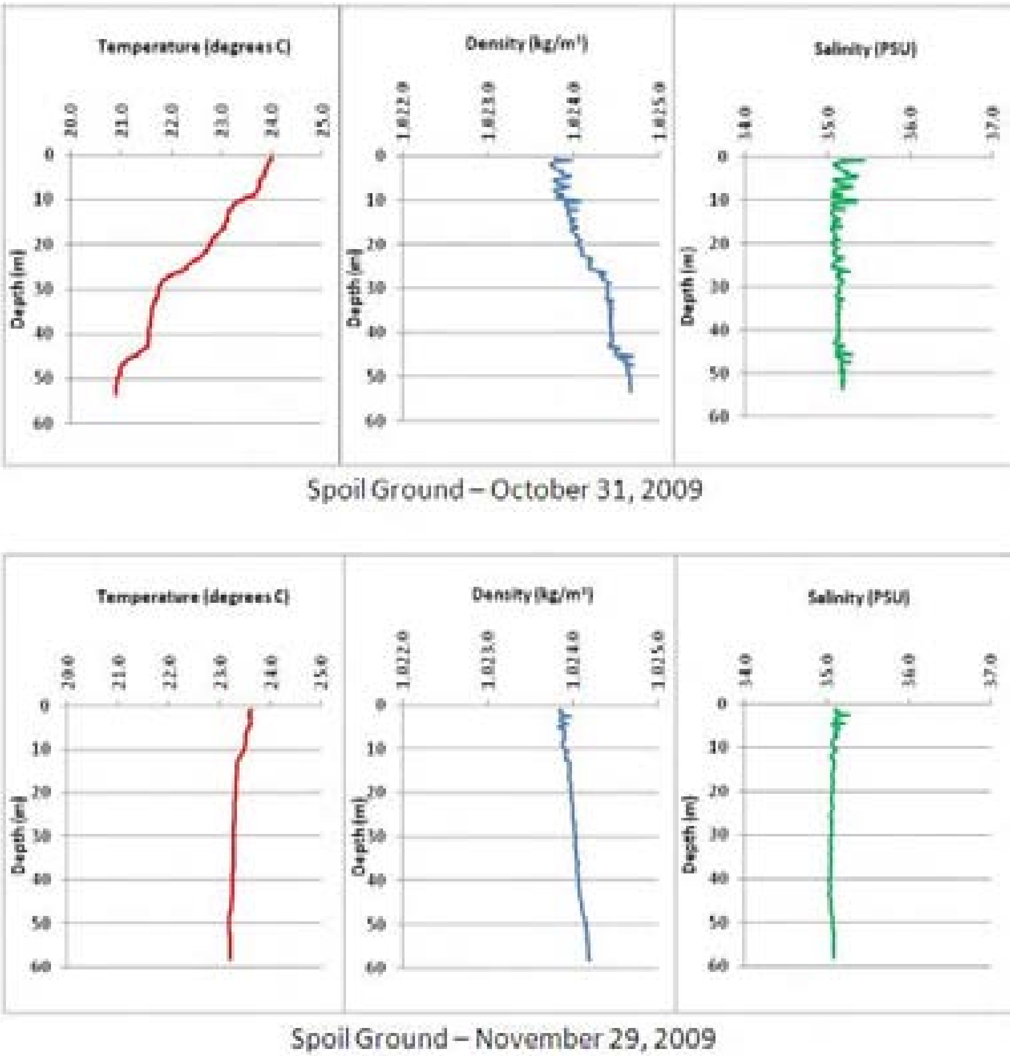


Figure A-17 Spoil Ground- Vertical Profiles of Salinity, Temperature and Density

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Vertical Current Profiles

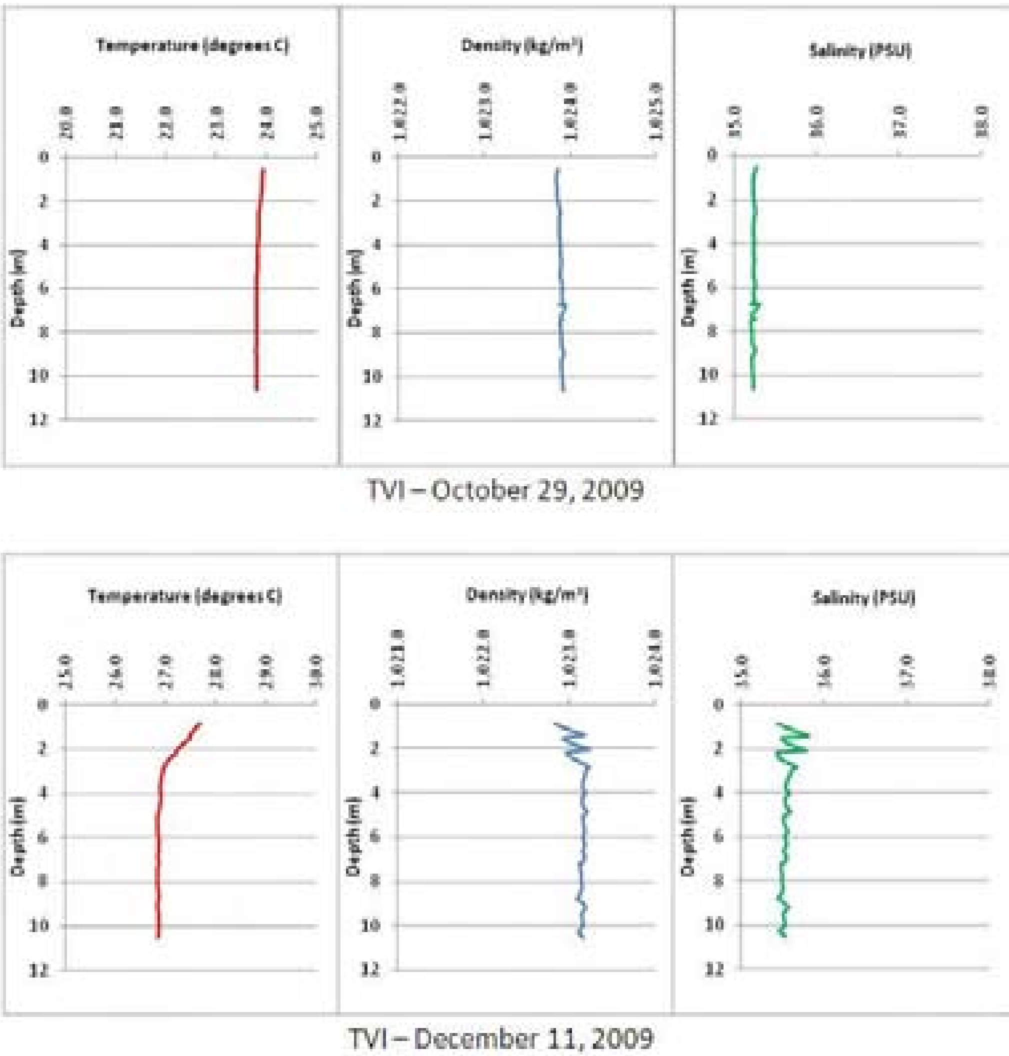

Figure A-18 Thevenard Island- Vertical Profiles of Salinity, Temperature and Density

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Vertical Current Profiles

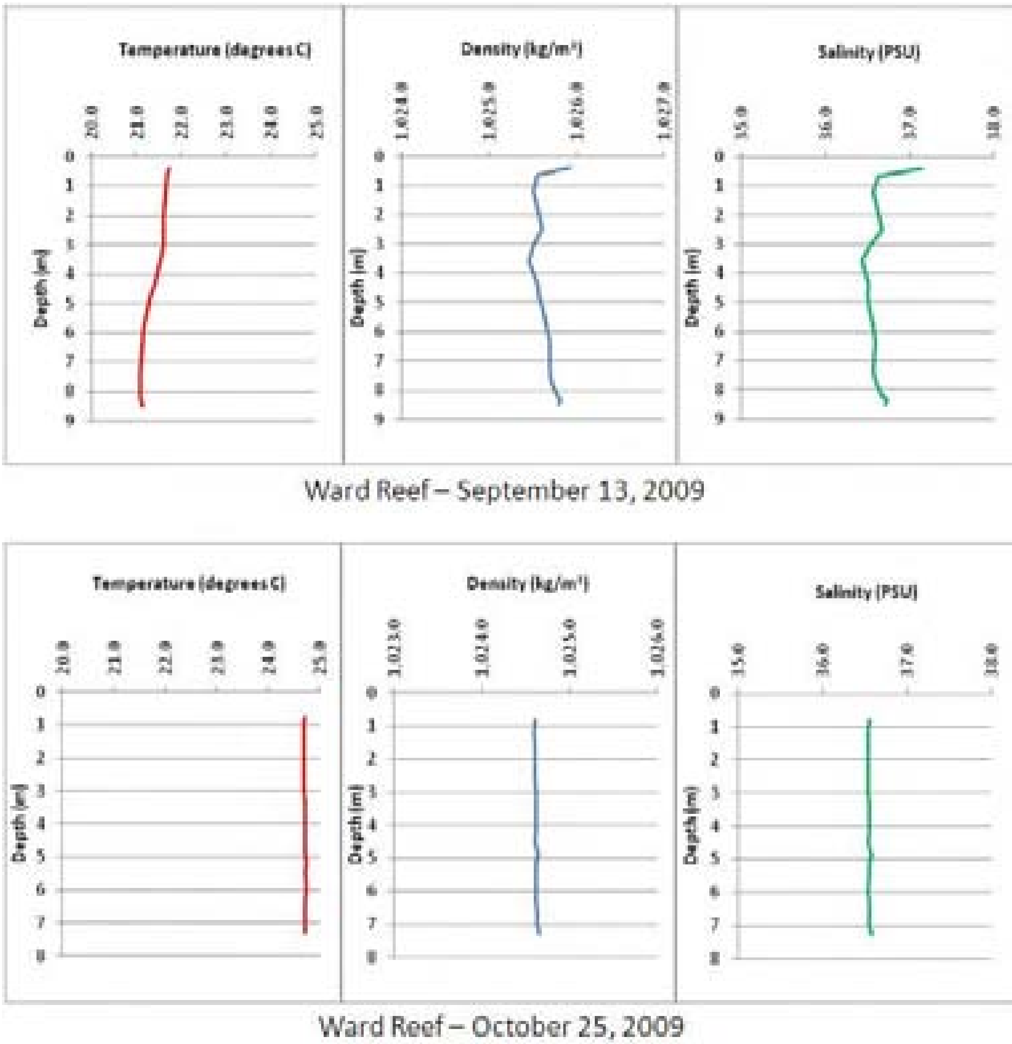

Figure A-19 Ward Reef- Vertical Profiles of Salinity, Temperature and Density

Vertical Current Profiles

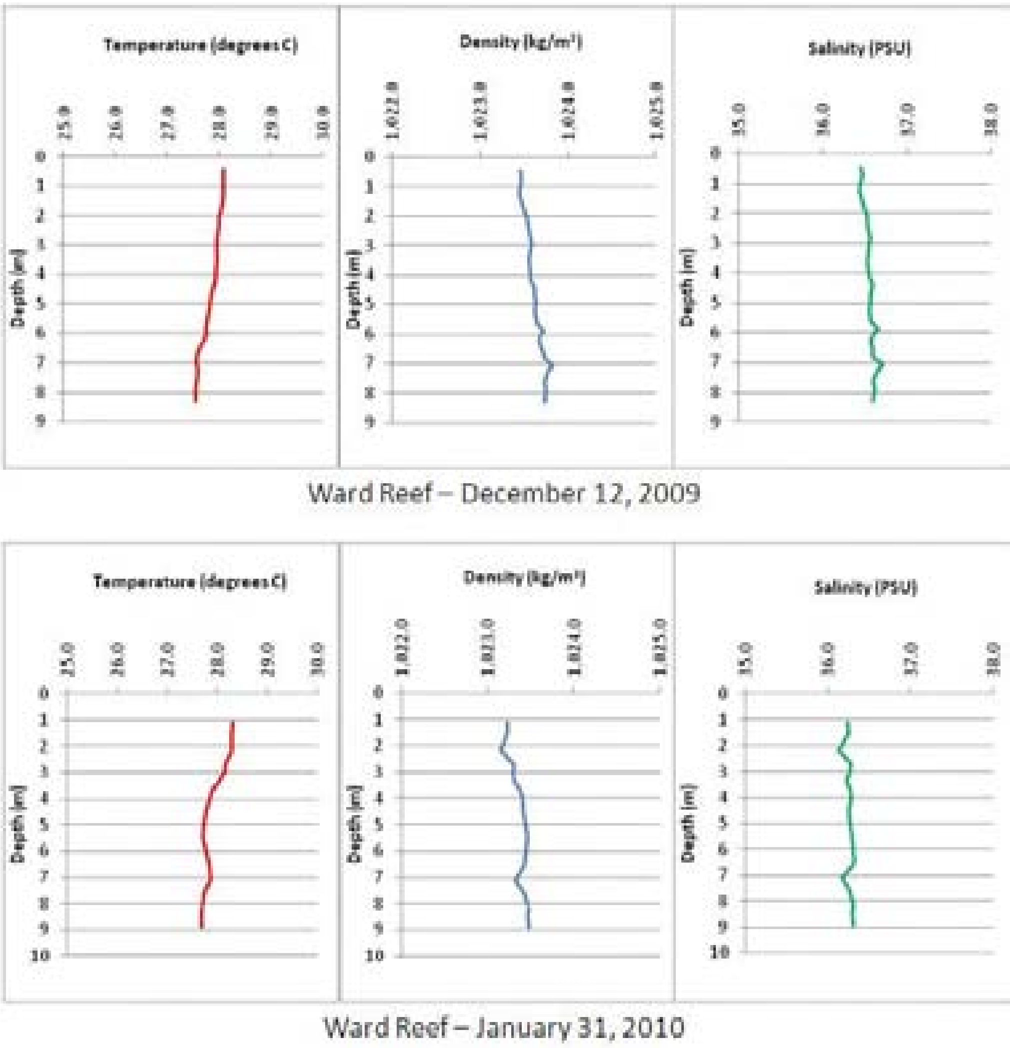

Figure A-20 Ward Reef- Vertical Profiles of Salinity, Temperature and Density

Vertical Current Profiles

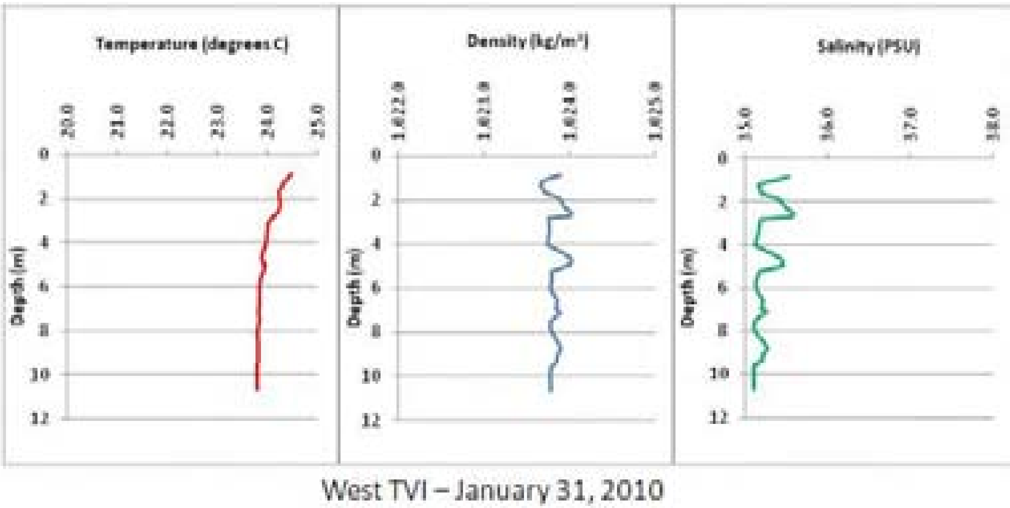

Figure A-21 West Thevenard Island- Vertical Profiles of Salinity, Temperature and Density

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Appendix B World Ocean Atlas Temperature and Salinity Data

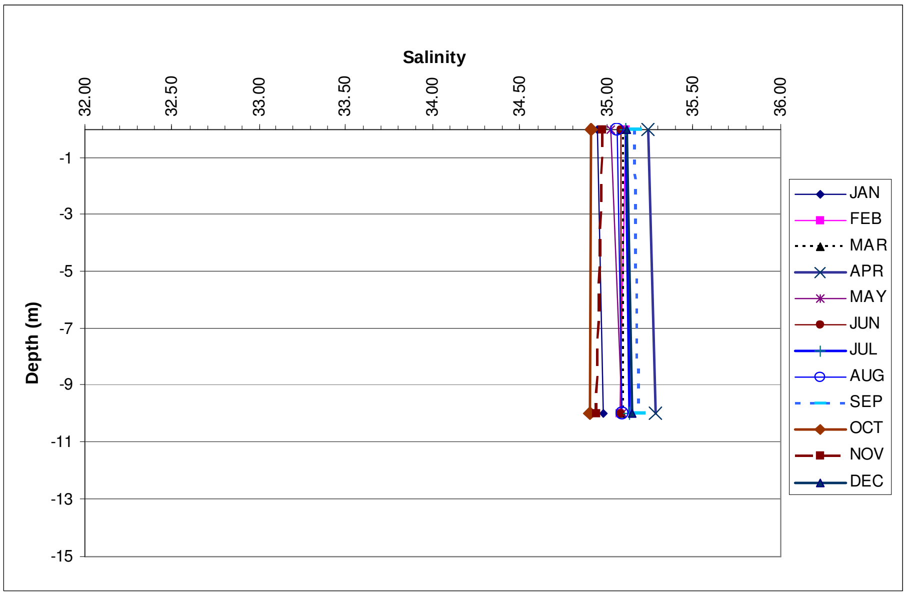

Figure A-22 Variation of mean salinity at point 1

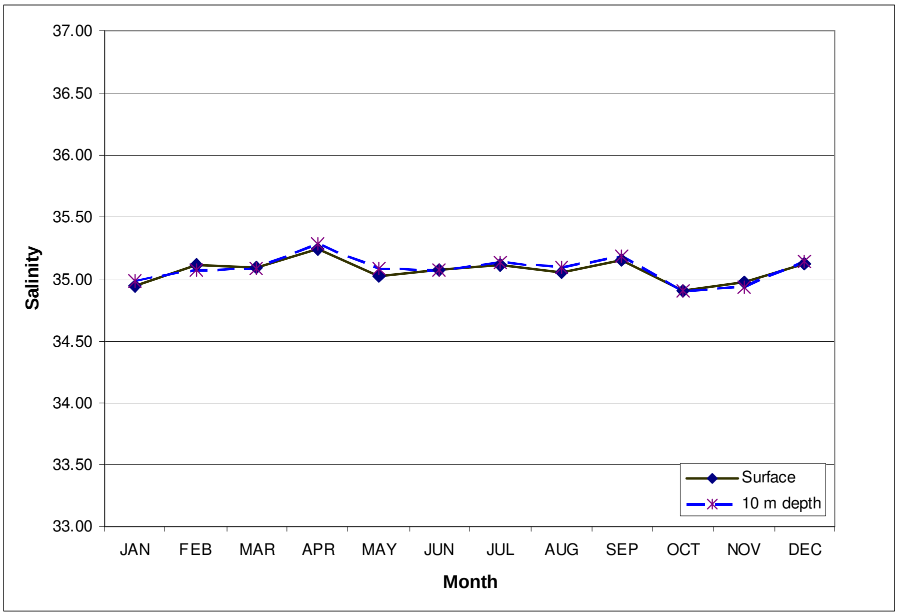

Figure A-23 Monthly variation of mean salinity at point 1

Vertical Current Profiles

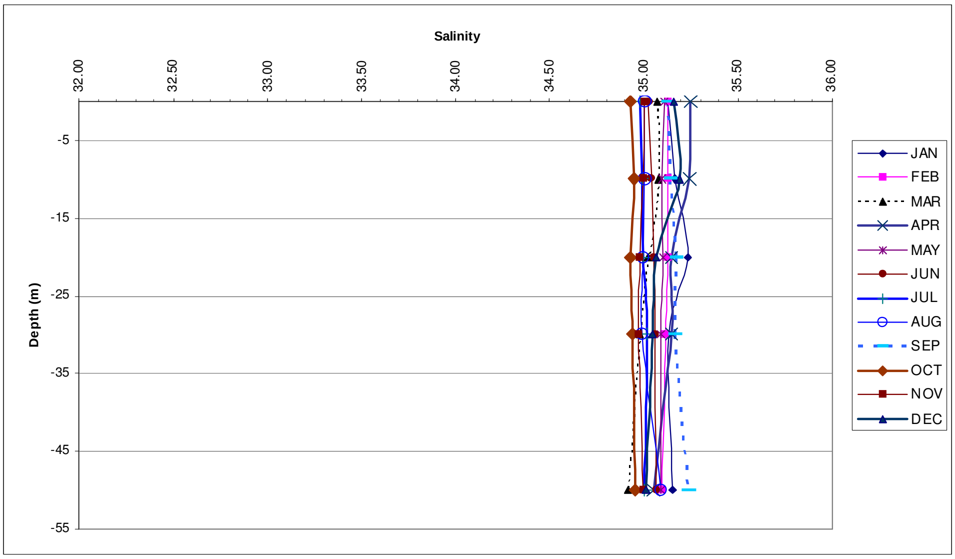

Figure A-24 Variation of mean salinity at point 2

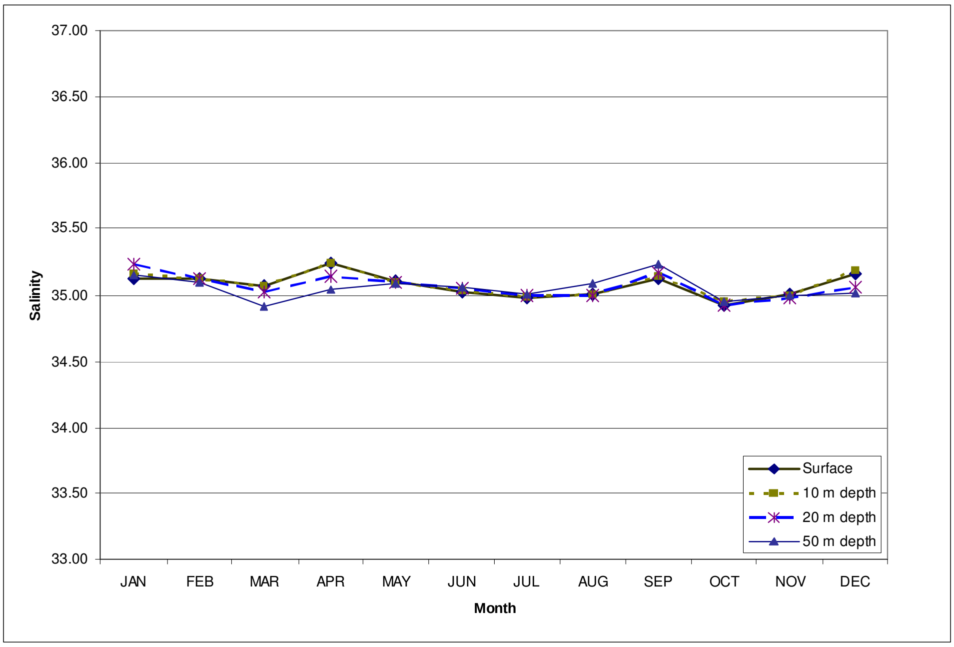

Figure A-25 Monthly variation of mean salinity at point 2

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Vertical Current Profiles

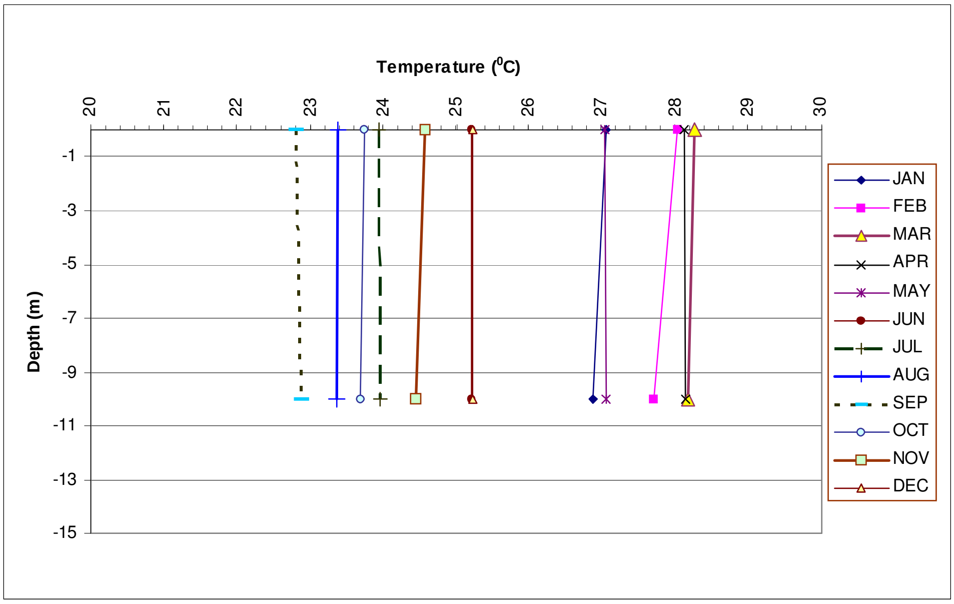

Figure A-26 Variation of mean temperature at point 1

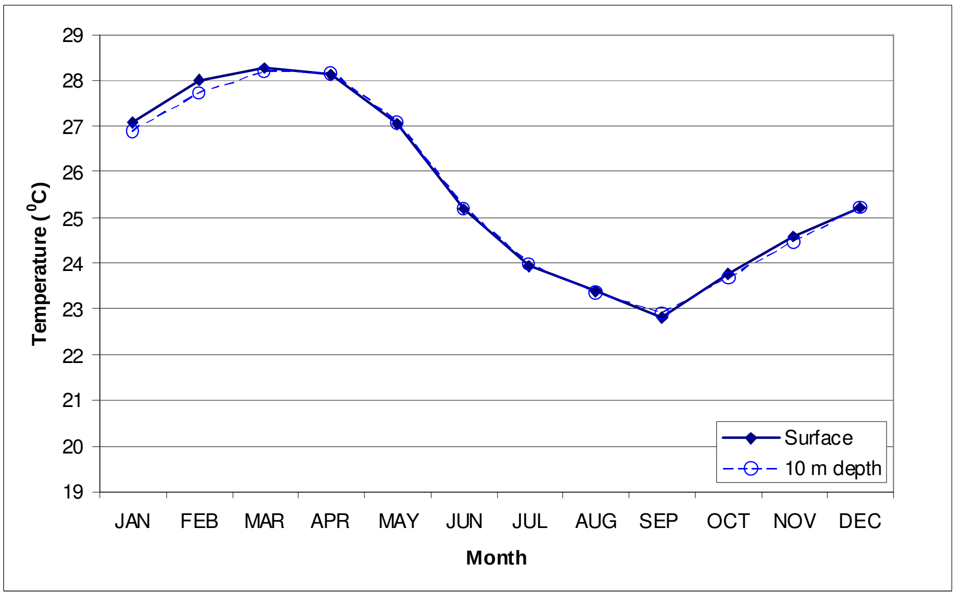

Figure A-27 Monthly variation of mean temperature at point 1

Vertical Current Profiles

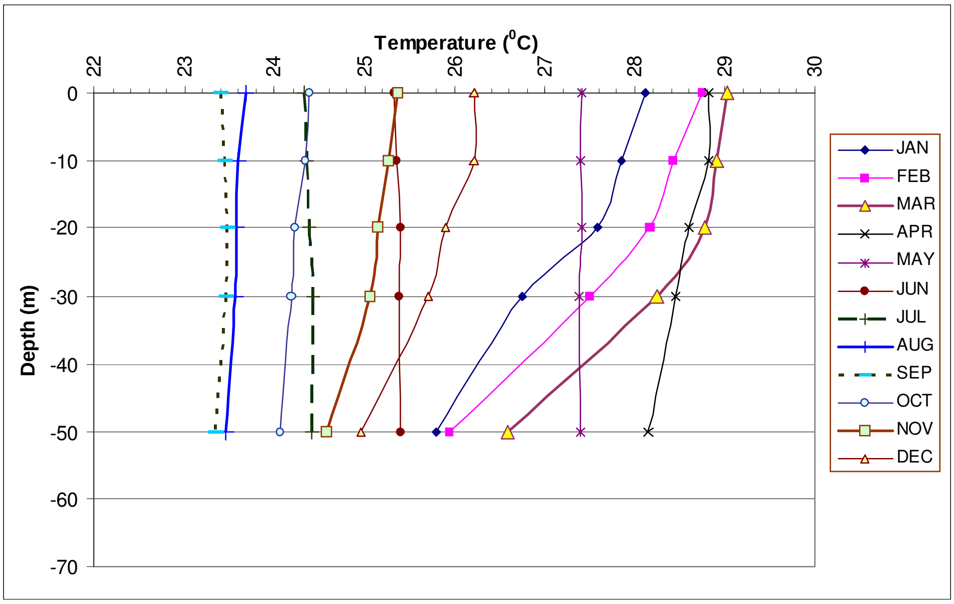

Figure A-28 Variation of mean temperature at point 2

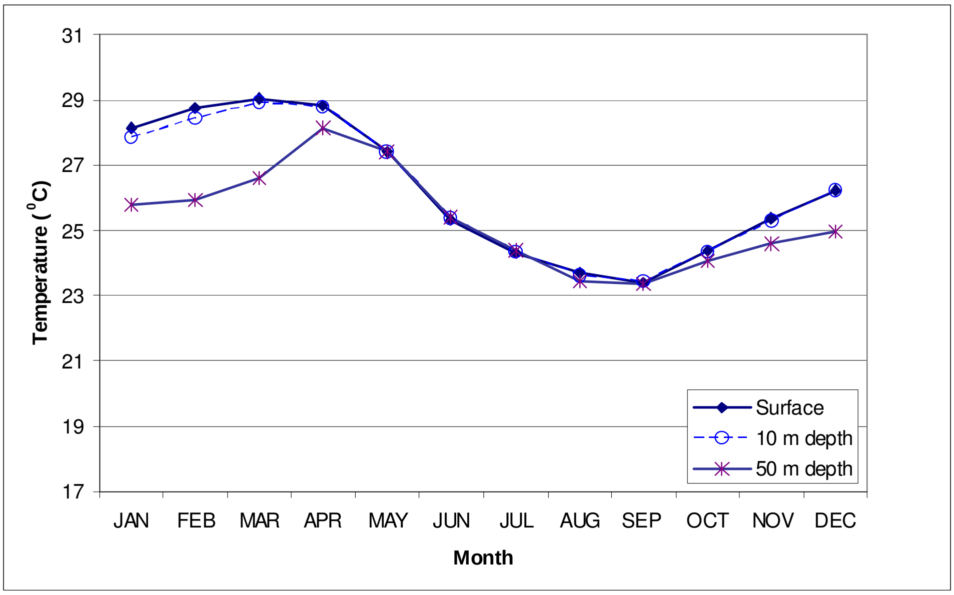

Figure A-29 Monthly variation of mean temperature at point 2

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Vertical Current Profiles

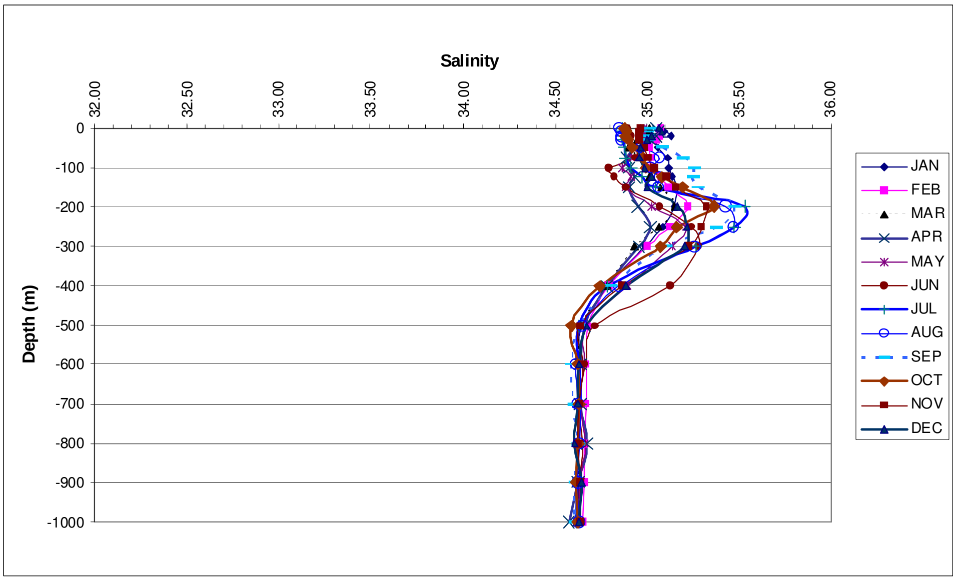

Figure A-30 Variation of mean salinity at point 3

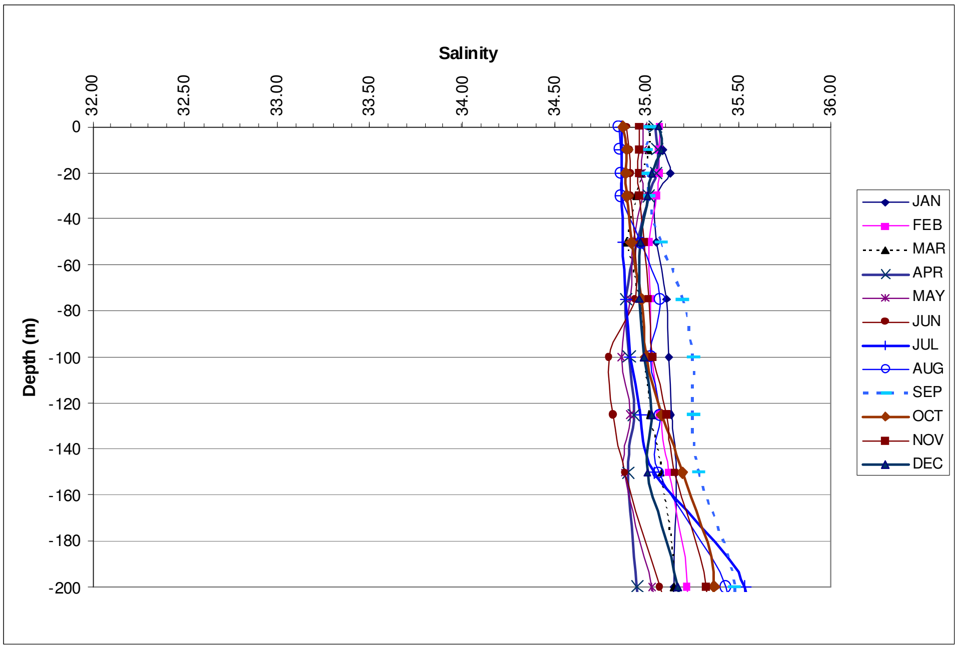

Figure A-31 Variation of mean salinity at point 3 (top 200m of Figure B-26)

Vertical Current Profiles

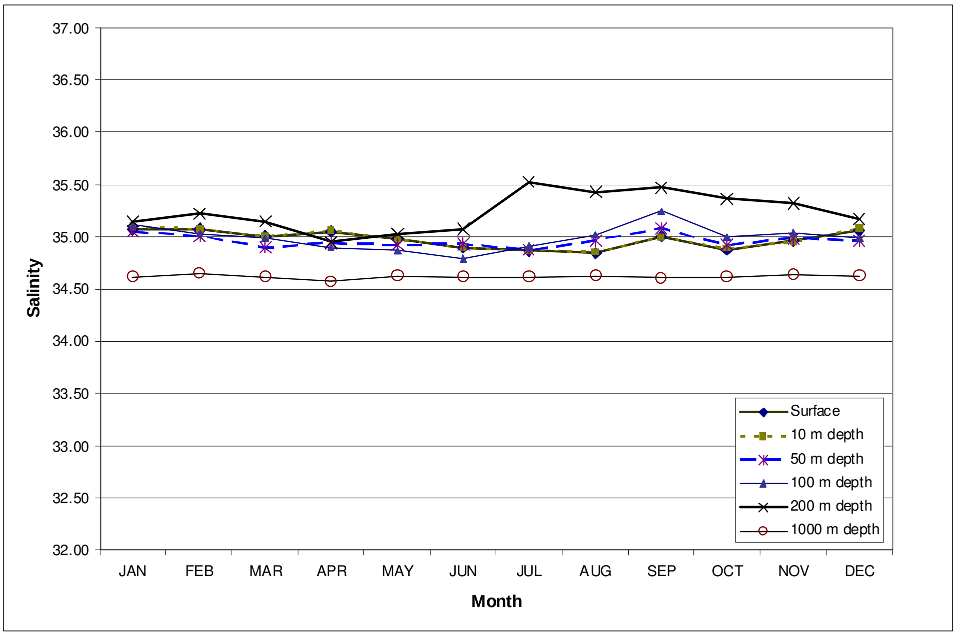

Figure A-32 Monthly variation of mean salinity at point 3

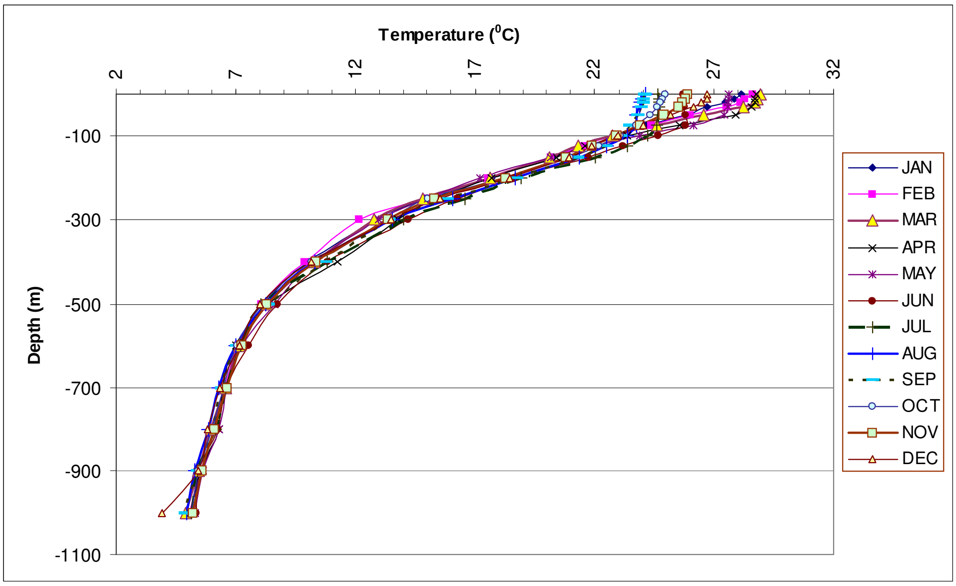

Figure A-33 Variation of mean temperature at point 3

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Vertical Current Profiles

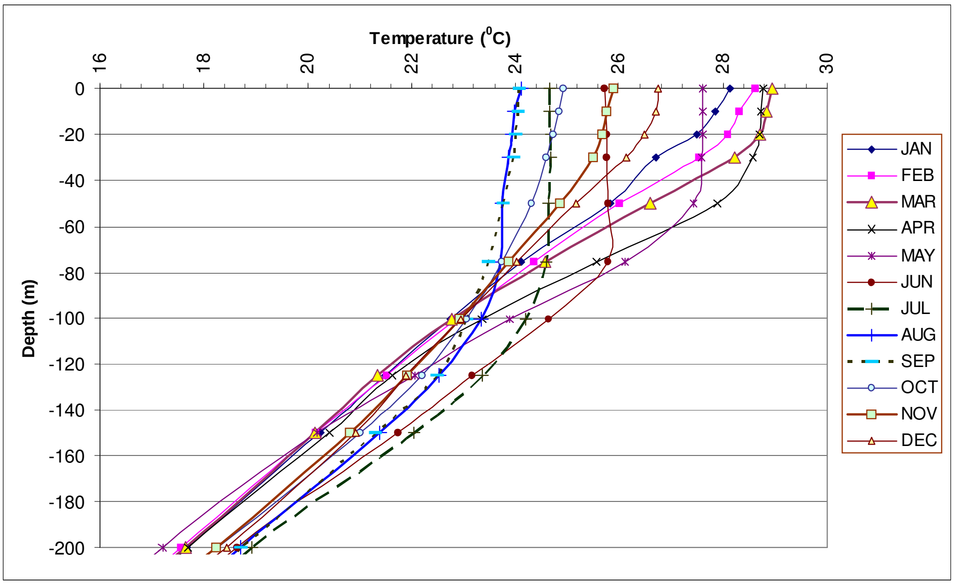

Figure A-34 Variation of mean temperature at point 3 (top 200m of Figure B-33)

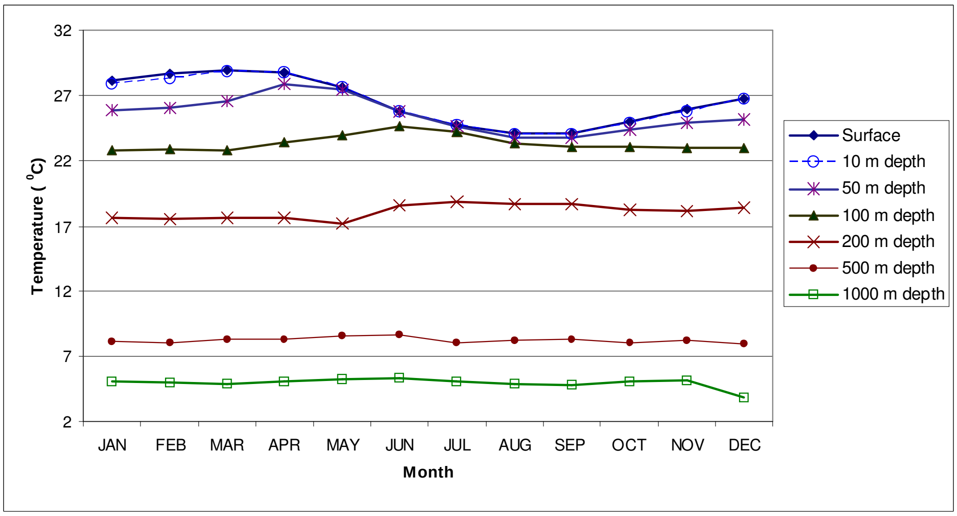

Figure A-35 Monthly variation of mean temperature at point 3

42907466/001/001

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Vertical Current Profiles

C

Appendix C Currents

C.1 Timeseries

C.1.1 Jetty

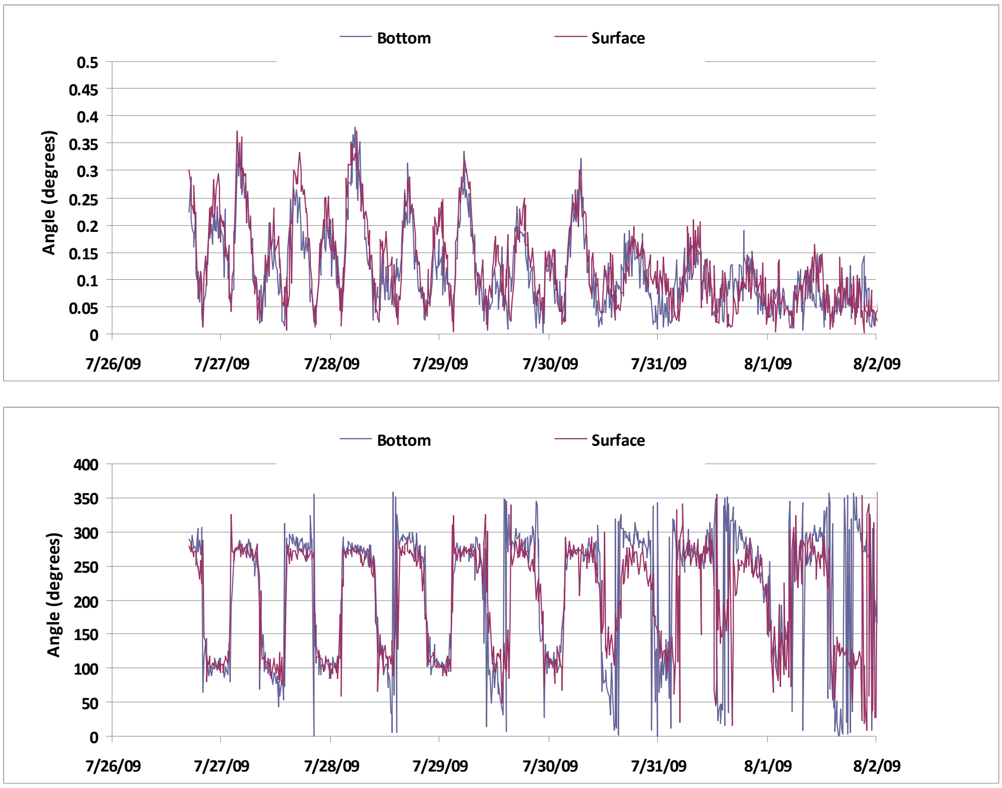
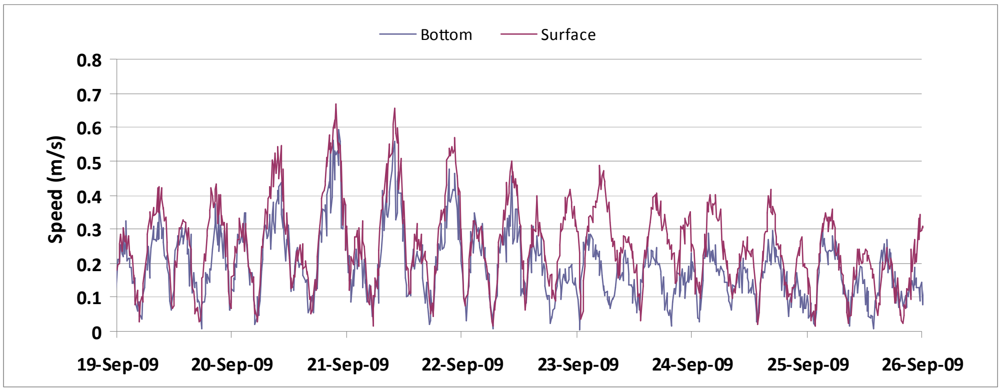


Figure 4-1 Timeseries of current speed (upper) and direction (lower) at the jetty.

C.1.2 Channel



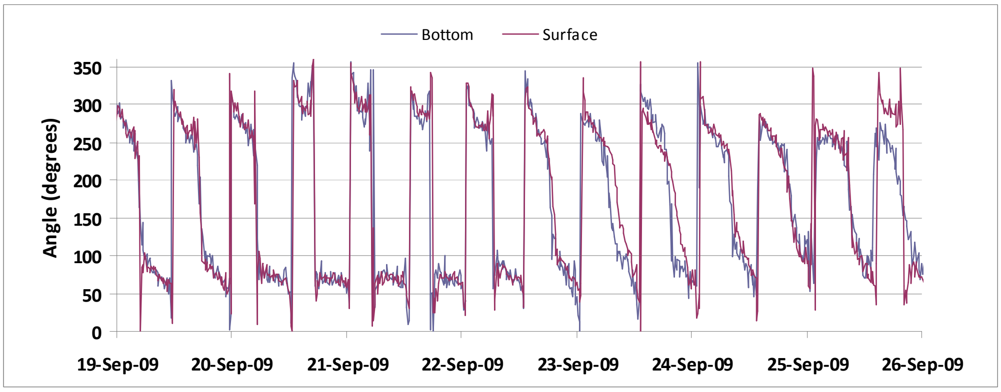
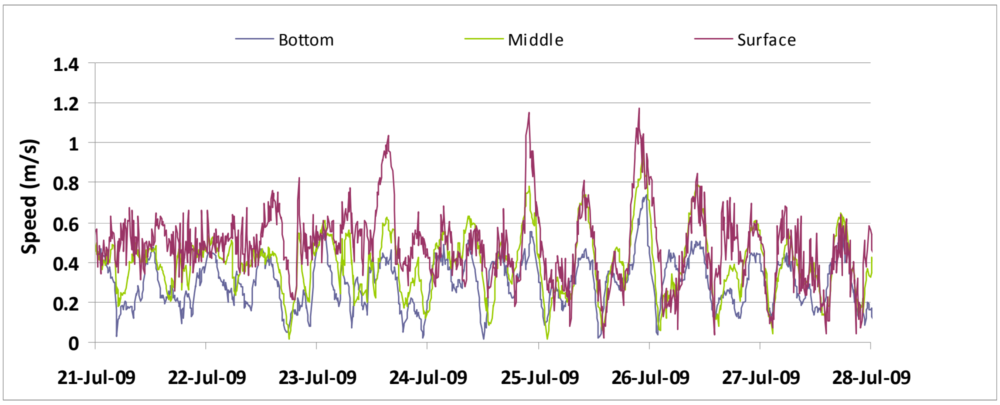


Figure 4-2 Timeseries of current speed (upper) and direction (lower) at the channel

C.1.3 Platform



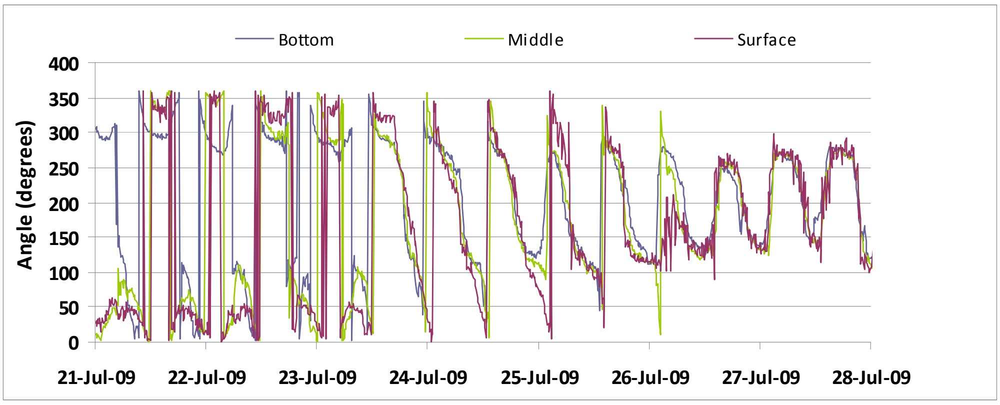


Figure 4-3 Timeseries of current speed (upper) and direction (lower) at the platform.

C.2 Vertical Current Profiles - Channel

C.2.1 Along-Tide Axis

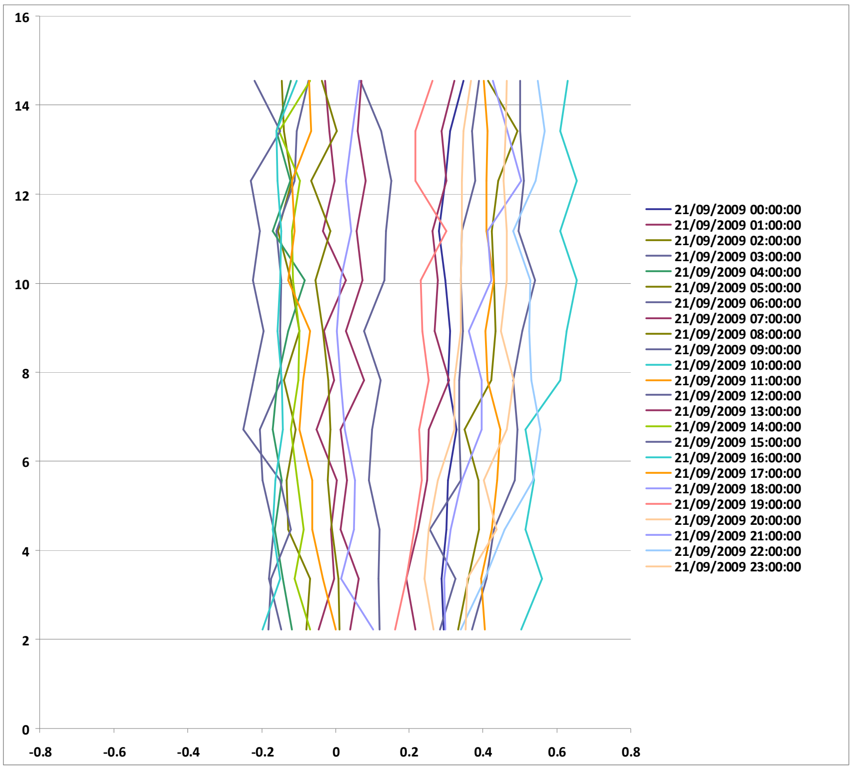


Figure 4-4 Vertical current profiles for September 21, 2009

Vertical Current Profiles

C.2.2 Across-Tide Axis

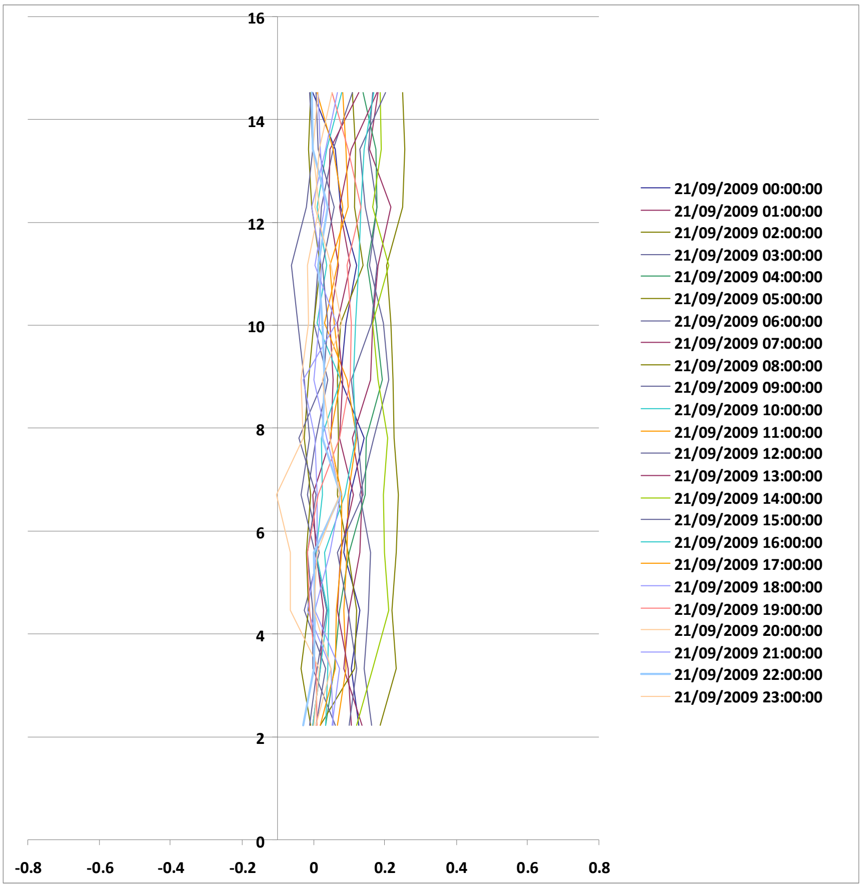


Figure 4-5 Vertical current profiles for September 21, 2009

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Appendix D Wave Roses

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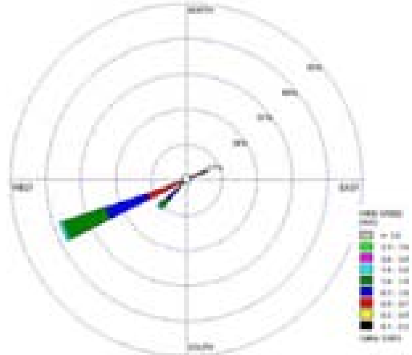
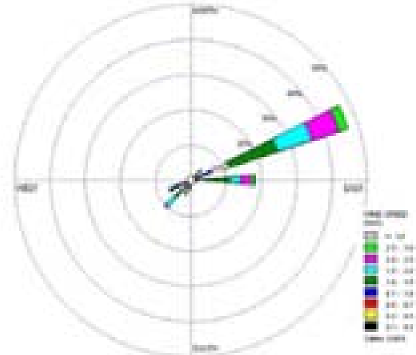
Platform (Swell) 5th May 2009 – 13th Jun 2009



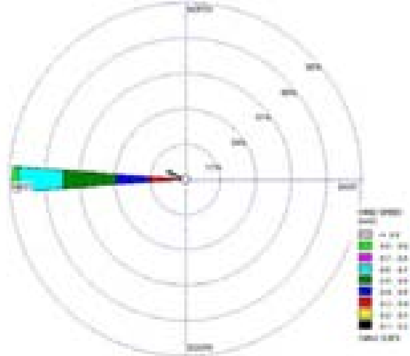
Note: The wind classes for Platform wind rose are different than other wind roses.

Platform (Sea) 5th May 2009 – 13th Jun 2009

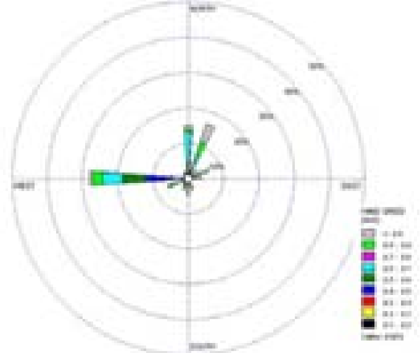


Note: The wind classes for Platform wind rose are different than other wind roses.

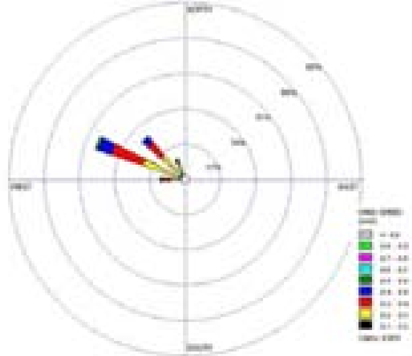
Spoil Ground (Swell) 5th May 2009 – 13th Jun 2009



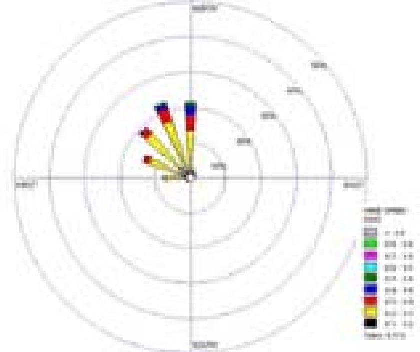
Spoil Ground (Sea) 5th May 2009 – 13th Jun 2009



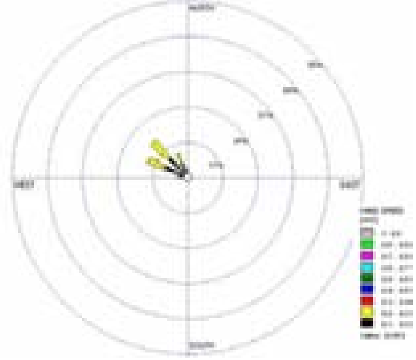
Dredge Route (Swell) 5th May 2009 – 13th Jun 2009



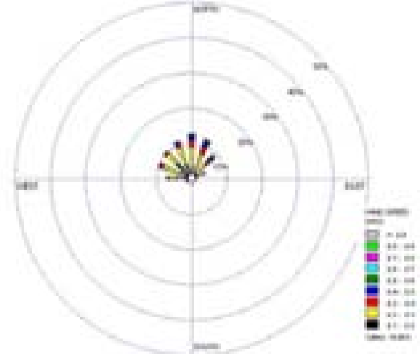
Dredge Route (Sea) 5th May 2009 – 13th Jun 2009



Jetty (Swell) 5th May 2009 – 13th Jun 2009

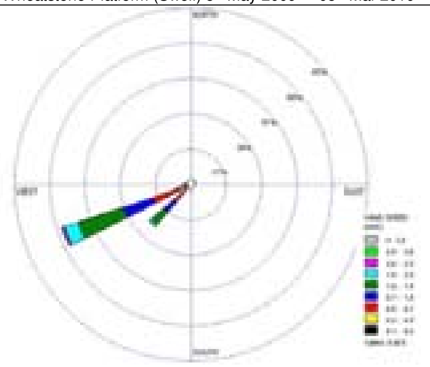


Jetty (Sea) 5th May 2009 – 13th Jun 2009



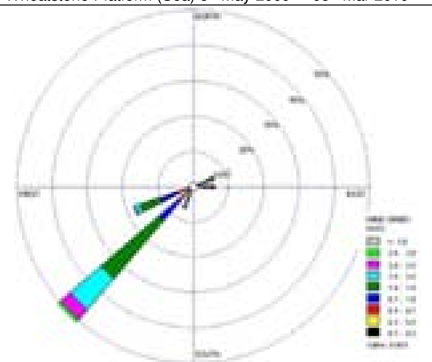
Vertical Current Profiles

Wheatstone Platform (Swell) 5th May 2009 – 05th Mar 2010



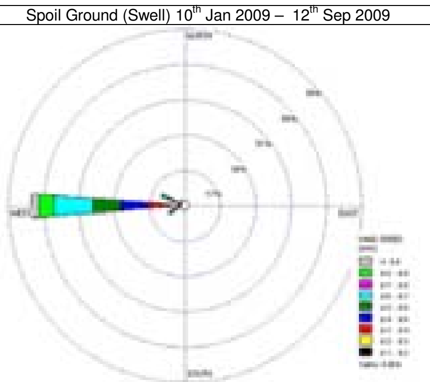
Note: the ring scale for Platform wind rose is different than other wind roses.

Wheatstone Platform (Sea) 5th May 2009 – 05th Mar 2010

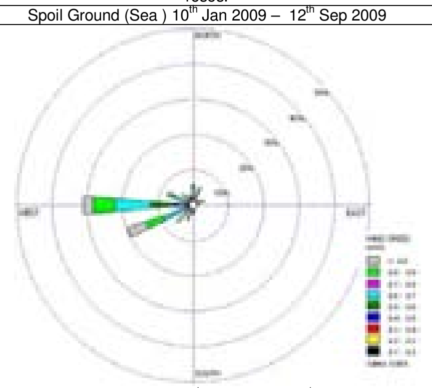


Note: the ring scale for Platform wind rose is different than other wind roses.

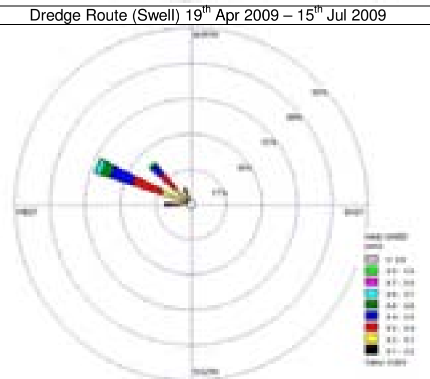
Spoil Ground (Swell) 10th Jan 2009 – 12th Sep 2009



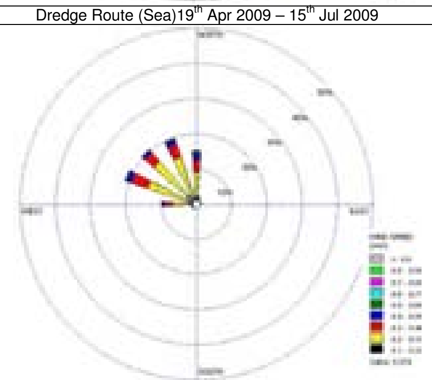
Spoil Ground (Sea) 10th Jan 2009 – 12th Sep 2009



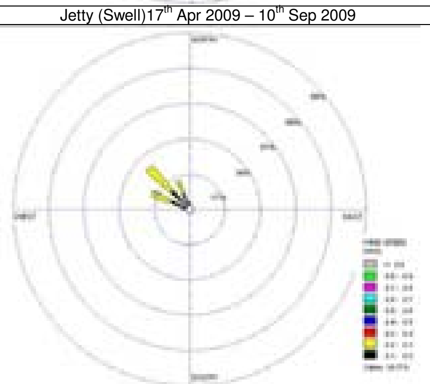
Dredge Route (Swell) 19th Apr 2009 – 15th Jul 2009



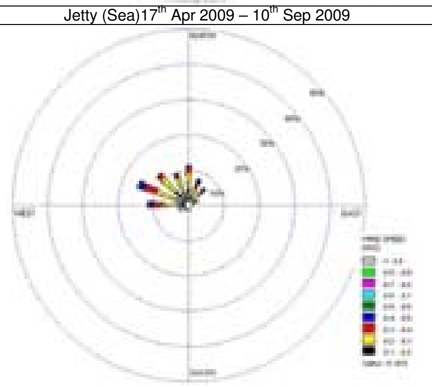
Dredge Route (Sea)19th Apr 2009 – 15th Jul 2009



Jetty (Swell)17th Apr 2009 – 10th Sep 2009



Jetty (Sea)17th Apr 2009 – 10th Sep 2009



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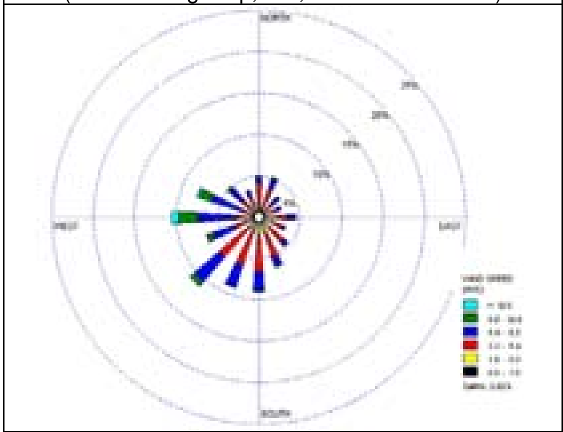
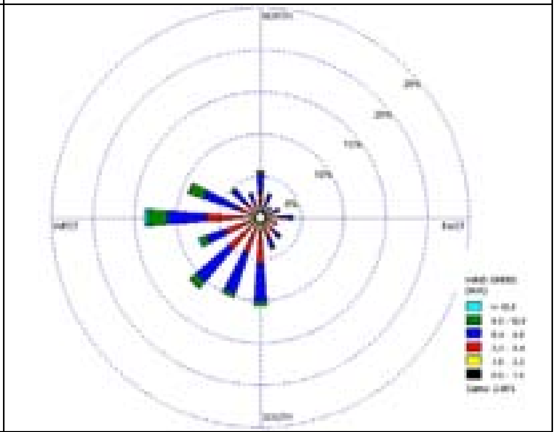
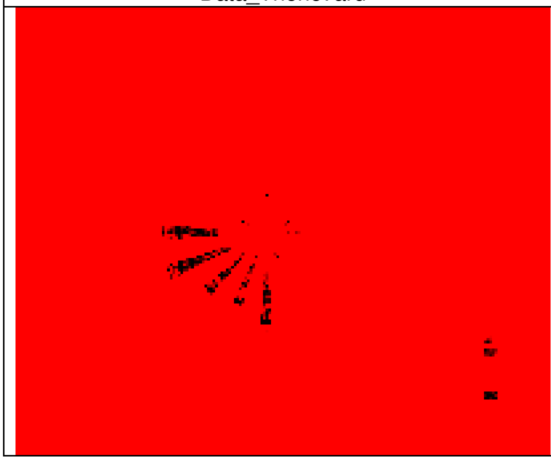
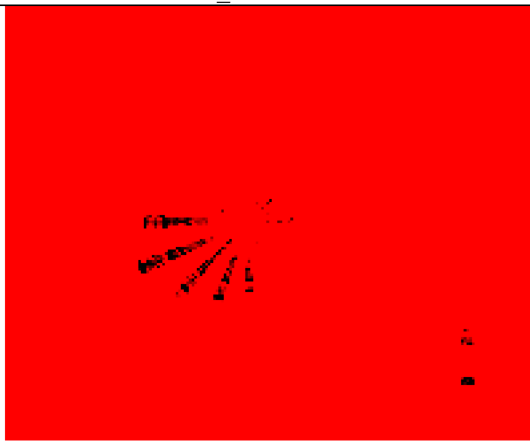
E

Appendix E Wind Roses, 2007

4.1 Annual Wind Roses, 2007

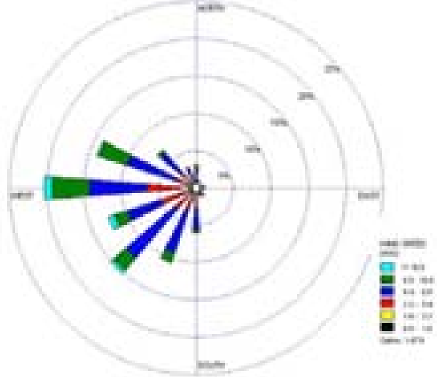
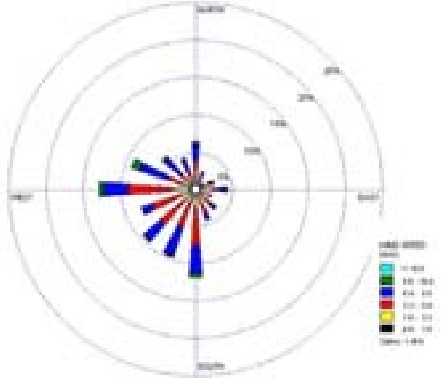
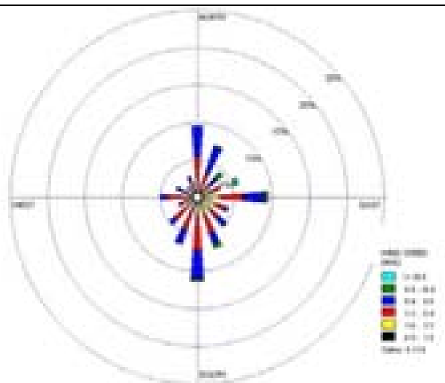
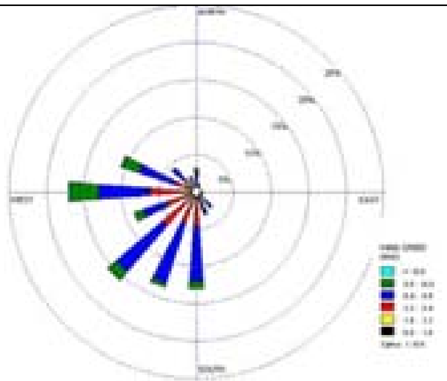
4.1.1 Onslow, Barrow Island and Thevenard

Data_Onslow (Data missing: Sep, Oct, Nov and Dec 2007)	Data_OnslowAirport
	
Data_Thenevard	Data_Barrow Island
	

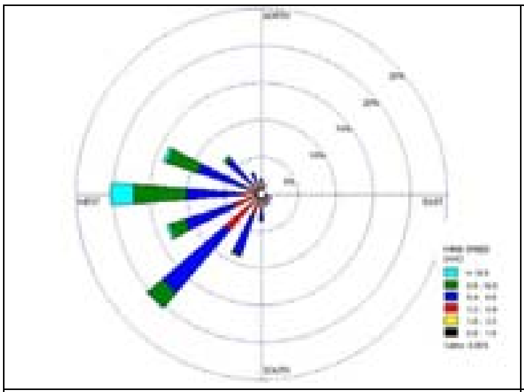
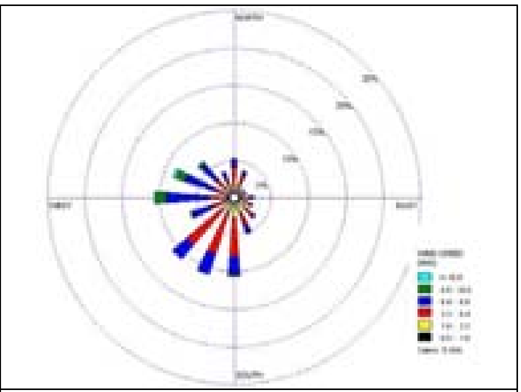
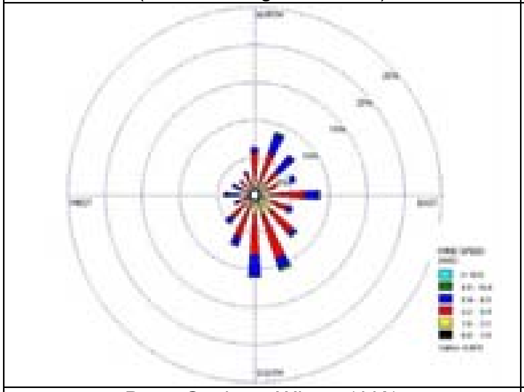
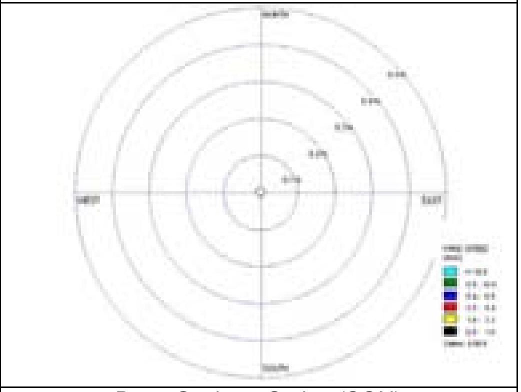
Vertical Current Profiles

4.2 Seasonal WIndRoses, 2007

4.2.1 Onslow

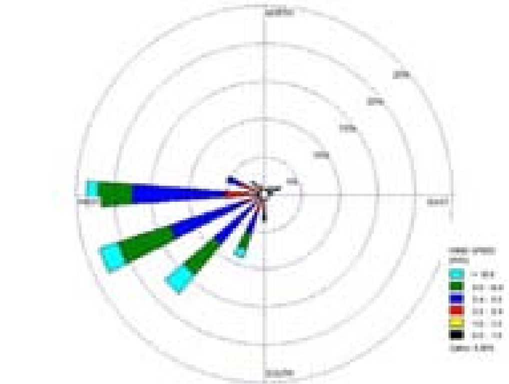
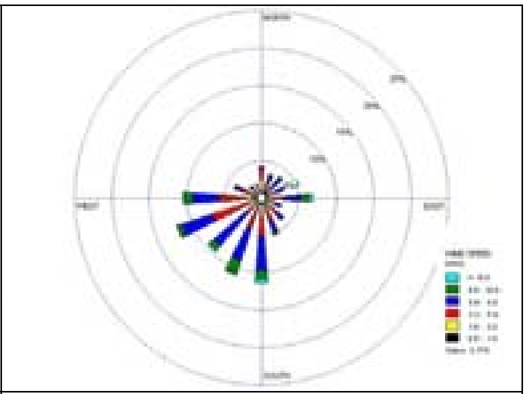
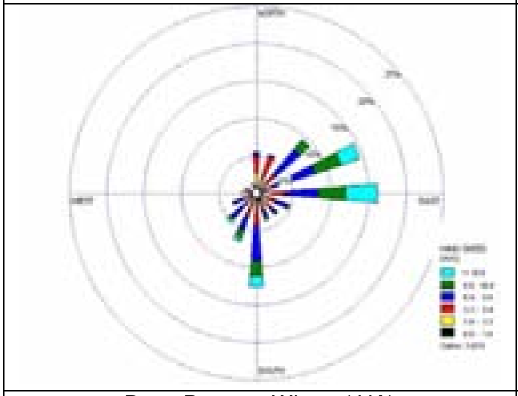
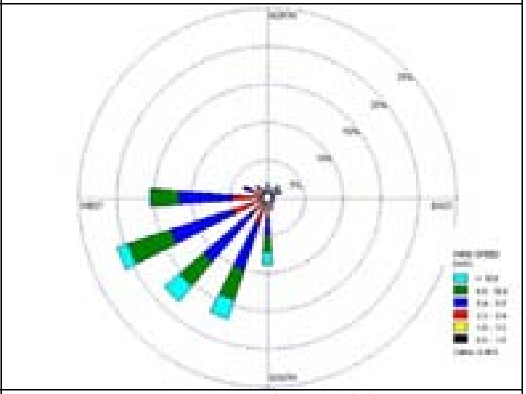
	
Data_Onslow_airport_Summer (DJF)	Data_Onslow_airport _Autumn (MAM)
	
Data_Onslow_airport _Winter (JJA)	Data_Onslow_airport _Spring (SON)

Vertical Current Profiles

	
Data_Onslow_Summer (DJF) (Data missing: Dec 2007)	Data_Onslow _Autumn (MAM)
	
Data_Onslow _Winter (JJA)	Data_Onslow _Spring (SON) (Data missing: Sep, Oct and Nov 2007)

Vertical Current Profiles

4.2.2 Barrow Island

	
Data_Barrow_Summer (DJF)	Data_Barrow _Autumn (MAM)
	
Data_Barrow _Winter (JJA)	Data_Barrow _Spring (SON)

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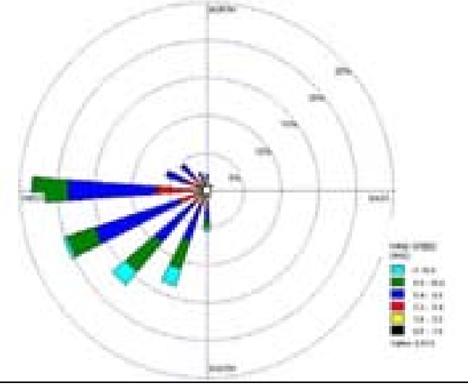
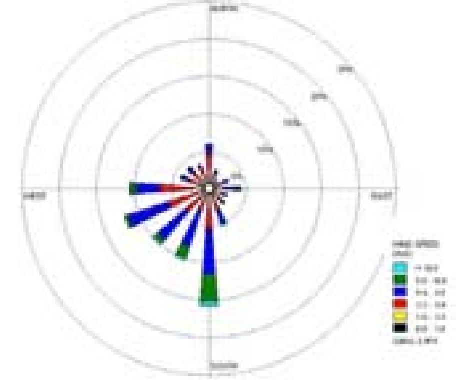
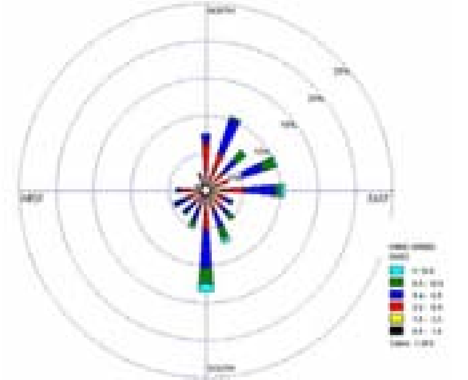
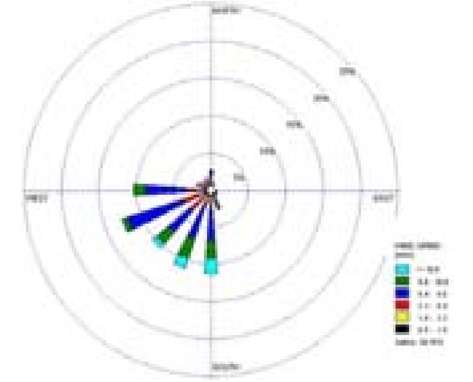
Vertical Current Profiles

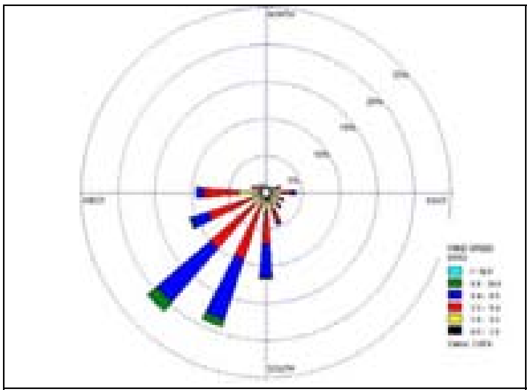
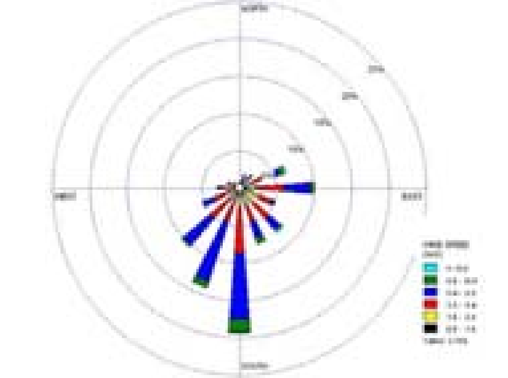
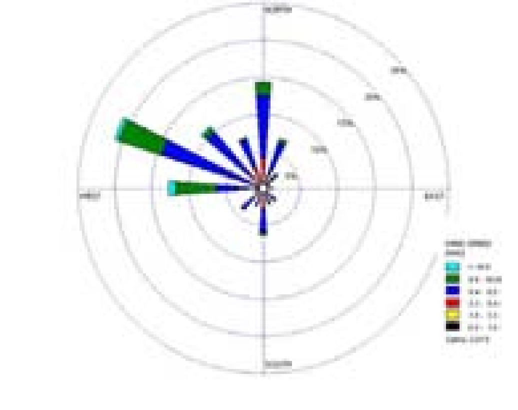
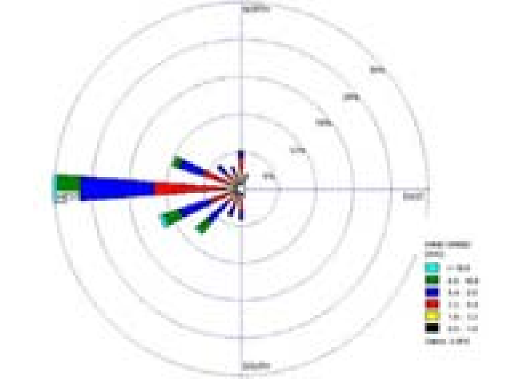
4.2.3 Thevenard Island

	
Data_Thevenard_Summer (DJF)	Data_Thevenard _Autumn (MAM)
	
Data_Thevenard _Winter (JJA)	Data_Thevenard _Spring (SON)

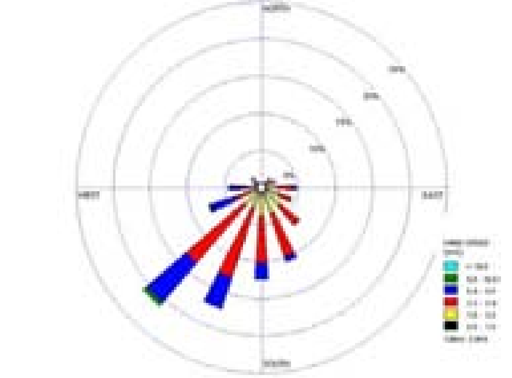
URS

4.3 Hour of Day WIndroses, 2007

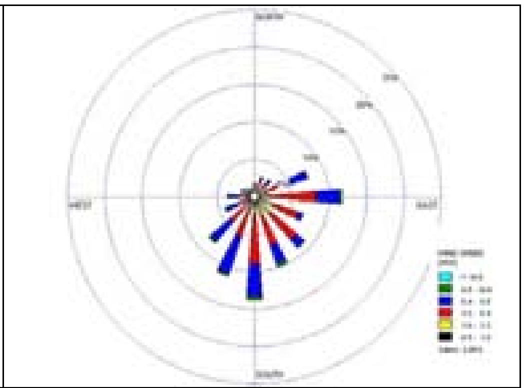
4.3.1 Onslow

	
Data_Onslow_airport _01 – 06 hours	Data_Onslow_airport _07 – 12 hours
	 Note: The ring scale is 0% - 30% compared to 0% - 25% for all other wind rose in this Appendix.
Data_Onslow_airport _13 – 18 hours	Data_Onslow_airport _19 – 00 hours

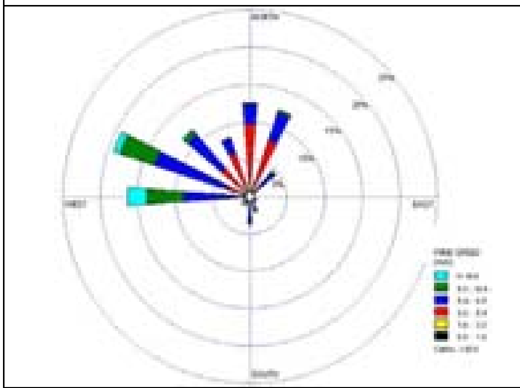
Vertical Current Profiles



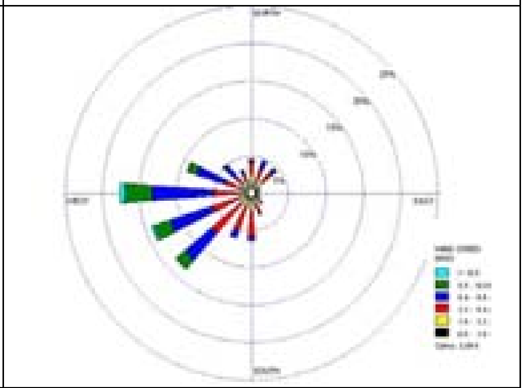
Data_Onslow _01 – 06 hours
(Data missing: Sep, Oct, Nov and Dec 2007)



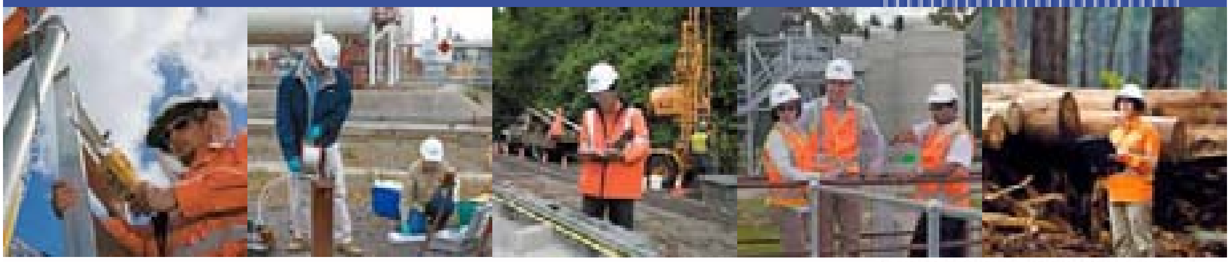
Data_Onslow _07 – 12 hours
(Data missing: Sep, Oct, Nov and Dec 2007)



Data_Onslow _13 – 18 hours
(Data missing: Sep, Oct, Nov and Dec 2007)



Data_Onslow _19 – 00 hours
(Data missing: Sep, Oct, Nov and Dec 2007)



URS Australia Pty Ltd
Level 16, 240 Queen Street
Brisbane, QLD 4000
GPO Box 302, QLD 4001
Australia
T: 61 7 3243 2111
F: 61 7 3243 2199
www.ap.urscorp.com

APPENDIX II:

HR Wallingford Review of Modelling Approach

DHI Water & Environment

HR Wallingford

17 March 2010

Our reference EBR4454-0308-CL01

Ms Rhonda Redwine
Downstream Project Manager
Chevron
Wheatstone Project LNG Plant
1600 Smith Street
Houston, Texas 77002

Dear Ms Redwine

DREDGE SPOIL MODELLING

Introduction

HR Wallingford (working with Lanier Associates, as Lanier Wallingford International (LWI)" has been asked to comment upon the approach to the dredge spoil modelling undertaken by DHI in support of the EIA for the Wheatstone Project.

Background

LWI has provided input to the marine engineering design and development of the Wheatstone Project. This has required consideration of the potential environmental effects of elements of the marine construction programme. The most significant component of the marine engineering works in terms of potential environmental impact is the dredging activity. Dredging and placement of dredged material will result in direct impacts on the seabed and the release of fine material into the water column and onto the seabed which will then be subjected to the transportation forces of the prevailing metocean conditions.

HR Wallingford Preliminary plume dispersion modelling

HR Wallingford has developed the dredging and disposal plan for the Wheatstone Project. This identifies the type of dredging plant likely to undertake the works based on the soil conditions and characteristics of the site. The associated dredge cycle times, production rates and sediment release rates for the dredging plant have been estimated by HR Wallingford (EBR4454/230-002). A programme for the dredging works has been developed. The dredging and disposal plan for the works has evolved with consideration of the potential environmental impacts of the proposed works.

Preliminary modelling of plumes from dredging and disposal was undertaken by HR Wallingford to inform the development of the dredging plan. The key outcome of this preliminary modelling was demonstration that for the main part of the dredging (the

[illegible]

HR Wallingford

deepening of the PLF Approach Channel) it would be potential to define zones of no overflow for parts of the approach channel from where dispersion might directly influence adjacent coral reefs (e.g. Paroo Shoal, Hastings Shoal and Ward Reef). Furthermore the preliminary plume modelling indicated that nearshore disposal sites (Sites A, B and C) appeared to be viable in terms of the potential for dispersion of fine material from these sites during placement or subsequent reworking of sediment to directly impact sensitive coral receptors.

The HR Wallingford modelling approach utilised 2D flow models with representations of summer and winter flow conditions. Sensitivity tests to settling velocity and representation of initial plume formation were undertaken (LWI Report EBR4454.0240/002). This drew upon work undertaken by HR Wallingford with the Dutch Dredging Contractors on the monitoring and prediction of plume formation by trailer suction hopper dredgers (TSHD) (Aarninkhof et al[1], 2010). Sensitivity tests to dynamic plume formation by TSHD and the use of the green valve to limit aeration during overflow showed that only small percentages of the mass of material lost in the overflow from TSHD would be expected to be released into the water column at the time of dredging. The majority of the material would rapidly descend to the seabed and remain there as a near bed high concentration layer. During the early stages of the dredging works before the dredging will have lowered the existing seabed by a few metres or more these layers might be subject to resuspension by propeller wash or prevailing metocean conditions. Once the seabed was lowered the risks of resuspension would reduce. In our experience the greatest sources of fines to the marine environment arise during the overflow of barges and TSHDs and these are the key sources that must be considered in the environmental assessment. At Wheatstone prevailing metocean conditions are such that the risk of resuspension of fines from the bed in the dredged areas is low. The focus is thus on the release of fines into the water column that are then available to be dispersed from the dredge location at the time of dredging.

Examination of the potential for extreme far field impacts was undertaken by HR Wallingford by considering the simple scenario of plume transport whereby there was no settlement of fines from the plume. This approach maximises the rates of advection of material away from the dredging zone and gives an indication of the pathways over which such transport to the far-field will occur. This element of the preliminary work indicated that under conditions of limited settling of fines (i.e. strong wind-wave agitation in nearshore waters) fine material could be dispersed towards the Mangrove Islands under summer conditions.

DHI plume dispersion modelling to inform the EIA

In parallel to this pilot modelling associated with the development of the dredge plan DHI were developing their detailed modelling approach to support the EIA of the Wheatstone Project. In October 2009 DHI and HR Wallingford reviewed one another's initial modelling results at a workshop in Wallingford and found them to be broadly consistent. This was an important finding in the development of the Dredging and Disposal Plan (DDP) which has evolved since October 2009 with outputs from the DHI modelling being used to guide the DDP in terms of avoiding adverse environmental impact.

[1] Reference

Aarninkhof, S.G.J., Spearman, J.R., de Heer, A.F.M. and van Koningsveld, M. 2010. Dredging-induced turbidity in a natural context, status and future perspective of the TASS program. In: Proc. WODCON XIX 2010 World Dredging Congress, Beijing.

HR Wallingford

<u>Modelling approach of HR Wallingford and DHI</u>

Both DHI and HR Wallingford utilised scenario testing approaches for the plume dispersion modelling. This is the most efficient way of identifying aspects of the dredging work that may present high risk to the environment. It also allows for early development of the approaches to monitoring, mitigating and managing the risks to the environment of the dredging. In our view more complex longer term modelling at this early stage would be unnecessary and misguided in the absence of a final DDP.

Both DHI and HR Wallingford utilised 2D flow modelling for the plume dispersion modelling because based on the available data this was an appropriate way in which to represent the flow fields at Wheatstone. In the area of the proposed dredging and nearshore disposal (Sites A, B and C) all in less than 15m of water the flow can reasonably be classified as being well mixed. That is not to say that wind shear does not occur and cause a differential in transport direction from surface to bed under some conditions but this type of effect is of secondary importance and in our view a depth averaged modelling approach will provide a good basis from which to plan, assess, mitigate and manage the environmental effects of the dredging.

The proposed DDP is a viable basis for the development of the Wheatstone Project. It has developed on the basis of scenario testing, knowledge of the soils to be dredged and has incorporated mitigation measures where appropriate to reduce risk to the environment. A monitoring and management plan has been developed for the works and this plan takes the results of the scenario testing to identify where real-time feedback monitoring can be undertaken to further reduce risk to sensitive receptors that may be affected by the works if the plume simulation results underestimated plume concentrations. The risks of uncertainty in the predicted impact arise from the modelling assumptions and source term definition. These risks are offset by the chosen approach to monitoring and management of the dredging that does not rely on ongoing modelling.

Further more complex modelling (for example the use of a 3D flow model, improved validation of the model for all meteorological conditions or greater resolution of the source term during its formation at the time of overflow) would improve the model predictions and add valuable insight into plume generation and dispersion at Wheatstone. However, in our opinion further simulation and assessment will not make stepwise changes to the environmental assessment of impact of the scheme or the approach to monitoring and managing the environmental risk.

Accordingly it our view that the approach of 2D plume dispersion modelling to inform the dredge plan, environmental assessment and development of monitoring, mitigation and management plans is entirely appropriate

Yours sincerely

MIKE DEARNALEY
Director

Wheatstone Project
Dredge Spoil Modelling

APPENDIX JJ:

Des Mills Closeout Review & DHI Response

DHI Water & Environment

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Des Mills Marine Environmental Reviews

REVIEW OF DHI REPORT

WHEATSTONE PROJECT
DREDGE SPOIL MODELING REPORT

DOCUMENT: WHST-STU-EM-RPT-0139

DHI REPORT: MY 5527-0 –DREDGE SPOIL MODELING

10 MAY 2010

PREPARED FOR URS BY
DR DES MILLS

DES MILLS MARINE ENVIRONMENTAL REVIEWS

Des Mills Marine Environmental Reviews

8 JUNE 2010

Des Mills Marine Environmental Reviews

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EXECUTIVE SUMMARY

This document provides an independent review of the modeling approaches and methodologies applied by DHI Water and Environment (DHI) to predict the intensity and spatial coverage of sediment plumes that could potentially be generated by the proposed three-year dredging campaign for the Chevron Wheatstone Project. These dredge plume predictions have been used to in conjunction with defined ecological tolerance limits to identify key marine habitats and communities at risk.

At the stage of environmental impact assessment studies there are typically large project uncertainties. To encompass these uncertainties the dredge plume modeling approach needs to include a wide range of plume simulations for the various possible combinations of dredging activities, spill rates and climatic conditions. In this way the overall spatial envelope and intensity of the dredge plumes can be conservatively estimated and the marine habitats and biological communities at risk fully identified.

DHI has chosen to apply two-dimensional, short term scenario modeling as its primary approach for predicting the extent and intensity of the dredge plumes. Each short term scenario simulation is of fourteen days duration and represents the outcome of a particular set of dredging activities, defined sediment spill rates and seasonal wind conditions. Relevant dredge plume statistics are extracted from these simulations, effectively providing fourteen-day duration “exposure images” of the plume distribution. The plume distributions from many different scenarios can then superposed to derive a composite representation of the plume. For example, the envelope of extent and intensity of plumes resulting from all stages and activities of the dredge program, each conducted over a range of seasonal climatic scenarios can be derived.

While in principle a three-dimensional modeling approach appears more suited to representing the detailed dispersion of the dredge plumes, it is also subject to the project uncertainties outlined above and is more computationally-intensive, potentially limiting the range of dredging and climatic conditions that can be simulated.

DHI has sought to demonstrate that, for the purposes of environmental impact assessment of the Wheatstone dredging project, the two-dimensional modeling system can be calibrated to produce results which are generally similar to, or more conservative than, those from the three-dimensional modeling. Where the model represents a dredge plume that consists of fine sediments that are vertically well-mixed throughout the water column then a two-dimensional approach can be justified.

However, if it is important that the model also represent coarser silt fractions of the plume (with higher settling velocities), then the validity of the selected modeling approach would require further justification. These coarser fractions would have more pronounced, but quite variable vertical suspended sediment concentration (SSC) profiles which may not be well represented by a two-dimensional dredge plume model, even one augmented by an assumed vertical SSC profile form. These coarser silt fractions will settle and deposit more rapidly when bed shear stress is below its critical value. If, compared to the fines, the rates of horizontal transport of these coarser silt fractions is significantly lower (since they form intermittent bed deposits more readily) then the 14 day time-scale of the short term scenarios would also need to be re-examined.

Section 3 of this review provides a more comprehensive overview of the modeling approach adopted by DHI and raises several issues in relation to its application to the Wheatstone Project.

Section 4 reviews the implementation of the Mike21 HD hydrodynamic model to simulate unsteady, two-dimensional (depth-averaged) flows for input to the dredge plume transport model. The model was forced by tides at its open boundaries and by wind across the model domain.

While tidal currents were adequately represented it was found that no single source of available wind data was able to force the hydrodynamic model so as to satisfactorily represent the net (tidally-averaged) currents right across the project area and for all important seasonal meteorological conditions.

For the purposes of environmental impact assessment this problem was satisfactorily addressed by merging dredge plume simulation results derived from separate hydrodynamic model flows driven by Onslow and MesoLAPS winds, respectively. This produced broader spatial representations of the plume, since use of the Onslow winds gave higher simulated net currents and plume excursions for eastward drift (mainly in summer), while use of the MesoLAPS winds gave higher simulated net currents and plume excursions for westward drift (mainly in winter).

Section 5 reviews the wave modeling. Waves are important for dredged sediment plume behaviour in shallow water as they generate additional bed shear stress and turbulence that may hinder deposition of suspended sediment or enhance resuspension of sediment from the bed. The dredge plume model receives inputs from a wave model (Mike21 SW) that simulates locally-generated wind waves and transmission of ocean swell waves to the site.

The wave model has been validated for inshore, sheltered locations and also for outer, more exposed locations within the project area. The validations include summer, winter and transitional seasonal conditions. Hence it may be concluded that the model is appropriately simulating the seasonal and spatial variability of the wave climate (and the attenuation of ocean swell) throughout the dredging project area.

The dominance of short period wind-driven waves across the project area (as demonstrated by the wave measurements) explains why the simulation results are relatively insensitive to the wave specification applied at the open boundaries of the model.

Section 6 reviews the implementation of the two-dimensional sediment transport model (Mike21 MT) for the Wheatstone dredge plume simulations. The model simulates the transport behavior of several sediment size fractions subject to erosion, advection, dispersion and settling/deposition processes for mud or sand/mud mixtures under the action of currents and waves and is driven by the outputs of the two-dimensional hydrodynamic and wave models and by sediment source terms representing the release of dredged sediments.

DHI has made “low (realistic)” and “high” estimates of dredged sediment mass spill rates for each major activity and phase of the proposed dredging campaign. Six sediment fractions were defined in the model, each with a specified settling velocity. Values were assigned for various model parameters representing processes of erosion, deposition and horizontal diffusion.

There are no dredge plume field data sets from the Onslow area that could be used to calibrate and validate the dredge plume model. The dredge plume simulation model requires a considerable range of data inputs and parameter values. Selection of many of these values relies on professional judgements based on very limited information from the site combined with the consultants’ dredge monitoring experience from elsewhere. The task of the modeler is therefore to tailor the model settings to obtain conservative predictions of typical and worst case impacts related to the dredge plume. The model inputs, settings and assumptions need to be *carefully explained and justified* to demonstrate that the final simulation results and predicted impacts are likely to be conservative.

Conclusions

A strong and practical advantage of DHI’s chosen strategy is its ability to accommodate uncertainties at the environmental impact assessment stage of the project. The short computer run times for each scenario allows for finer horizontal resolution and a wider range of combinations (of seasonal condition, dredge activity and spill rate) to be simulated under different sets of assumptions. The results from these multiple dredge plume scenario simulations can be superimposed to derive an outer envelope and maximum intensity distribution for all the scenarios, and this will help to provide a broader, more conservative estimate of where the dredge plume could occur as a result of the entire dredging campaign.

This review identifies (in Section 3) several questions relating to the application of this methodology to the Wheatstone Project. It is recommended that these issues be addressed promptly and supplementary input provided to the environmental impact assessment process.

1. BACKGROUND

Chevron Australia Pty. Ltd. (Chevron) proposes to construct a multi-train Liquefied Natural Gas (LNG) plant and export terminal and a domestic gas (Domgas) plant approximately 12 km southwest of Onslow on the Pilbara coast in north-west Western Australia. The LNG and Domgas plants will initially process gas from fields located approximately 200 km offshore from Onslow in the West Carnarvon basin and future yet-to-be determined gas fields. The LNG plant will have a maximum capacity of 25 million tonnes per annum (MTPA) of LNG. The project is referred to as the Wheatstone Project.

Construction of the Wheatstone Project includes the dredging of approximately 40 million m^3 of material for installation of berths and turning basins at an inshore Materials Offloading Facility (MOF) and a Product Loading Facility (PLF) as well as access to these through an approximately 15 km long navigation channel. Dredged material will be placed at designated offshore sites.

Chevron is seeking environmental approvals for the Wheatstone Project. Dredge plume impacts have been rated as a key environmental risk for the project. DHI Water and Environment (DHI) has been commissioned by Chevron via a sub-contract with URS Australia Pty. Ltd. (URS) to provide a numerical modeling study to support environmental impact assessment of the proposed dredging and dredged material disposal.

Chevron in conjunction with URS requested Dr Des Mills of Des Mills Marine Environmental Reviews (MER) to conduct an independent review of the DHI modeling study and prepare a closeout report prior to submission of the proponent's modeling study report to the WA Environmental Protection Authority (EPA).

This closeout report is based on a review of the document entitled "Wheatstone Project - Dredge Spoil Modelling Report" (DHI, 10 May, 2010) and its accompanying set of technical Appendices.

2. PURPOSE

The main purpose of this review is to assess the modeling approaches and methodologies to determine whether the modeling is fit for purpose, soundly based and would underpin conservative estimates of the dredge plume and associated impacts of the proposed dredging. The following tasks were undertaken:

- Review the modeling strategy and comment on its applicability to the Wheatstone Project for predictions of the dredge plumes and their associated environmental impacts;
- Review the characterization of the physical environment (and data presented) in terms of its ability to support the selection, setup and performance testing of the hydrodynamic, wave and dredge plume models;
- Review the hydrodynamic and wave modeling, including comparisons against recently measured data, and comment on the capability of the models used to adequately represent current and wave conditions in the area of the proposed dredging activities;
- Review the dredge plume model setup and comment on the capability of the model to adequately represent the dispersion and fate of materials released by the proposed dredging and spoil disposal activities.

3. MODELING STRATEGY AND APPROACH

Dredge Plume Modeling Strategy

A primary goal of the dredge plume environmental impact assessment studies is to predict the spatial extent and severity of marine ecological impacts (and physical influence) that could result from the proposed dredging campaign. Dredge plume modeling is used to predict the levels of exposure of key marine habitats and organisms to dredging-induced stressors. These exposure levels are then compared against ecological stressor thresholds (tolerance limits) to predict the potential extent and severity of ecological impacts that could occur.

At the stage of environmental impact assessment studies there are typically large project uncertainties in relation to:

- final contractor dredging plans;
- the eventual sequence and timing of the dredging project stages;
- the precise wind, current and wave conditions that will be encountered at each stage of the dredging, and
- material types, their locations and the dredge spill characteristics that will be generated.

To encompass these uncertainties the dredge plume modeling approach needs to include a wide range of plume simulations for the various possible combinations of dredging activities, spill rates and climatic conditions. In this way the overall spatial envelope and intensity of the dredge plumes can be conservatively estimated and the marine habitats and biological communities potentially at risk identified.

DHI has chosen to apply two-dimensional, short term scenario modeling as its primary approach for predicting the extent and intensity of the dredge plumes and their associated environmental impacts. Each short term scenario simulation is of fourteen days duration and represents the outcome of a particular combination of dredging activities, defined sediment spill rates and seasonal wind conditions. After an initial simulation period to allow for full development of the plume the results from each scenario simulation period are processed (relevant plume statistics are derived) to give fourteen-day duration “exposure images” of the plume.

The report provides a discussion of the relative merits of alternative modeling approaches, including consideration of:

- two-dimensional (depth-averaged) versus three-dimensional modeling;
- use of short term scenario versus long term (full dredge campaign) simulations.

Whichever approach is adopted, it is essential to establish confidence in the hydrodynamic and wave model simulations for the region and project area, since these simulations provide critical drivers and inputs for the dredge plume model.

Furthermore, it is essential to justify the sediment-related settings and parameter values in the dredge plume model in terms of the attainment of conservative results which will fully represent the potential envelope of extent and intensity of the plumes. This justification of inputs is particularly important since, currently, there are no dredge plume data for the project area which can be used to directly calibrate and validate the dredge plume model.

A practical advantage of DHI’s chosen strategy is the short computer run times for each scenario which allows for finer horizontal resolution and a wider range of combinations (of seasonal condition, dredge activity and spill rate) to be simulated under different sets of assumptions. The results from these multiple dredge plume scenario simulations can be superimposed to derive an outer envelope and maximum intensity distribution for all the scenarios, and this will provide a broader, more conservative estimate of where the dredge plume could occur as a result of the entire dredging campaign.

Six short-term seasonal climatic scenarios were selected for application to the dredge plume modeling to develop an envelope of possible impacts. Wind data from carefully selected periods were used to represent two summer, two winter and two transitional climatic scenarios, and were applied to produce the hydrodynamic and wave simulations for input to the dredge plume model.

Field measurements and modeling have demonstrated that short period waves dominate the wave climate throughout the project area. A strong correlation between local wind and wave conditions is therefore expected and so it is appropriate that simulated wave data driven by winds from the selected periods be included as part of the seasonal climatic scenarios.

The study defined seven base case dredging scenarios and an impact mitigation dredging scenario, each representing a particular stage in the construction of the berths, turning basins and channels for access to the MOF and PLF. Likewise, two dredging scenarios for the installation of the subsea pipeline were identified due to their location and potential to impact on coral and seagrass habitats. Each dredging scenario was defined over a 14 day period and specifies the dredge plant, dredging location, the spoil placement site and the dredging cycle time.

The report acknowledges that there is considerable uncertainty attaching to estimates of mass spill rates and also to the particle size (or settling velocity) distributions associated with the spills. For each of the dredging scenarios the study defines "low" (typical) and "high" (worst case) mass spill rate estimates.

The report demonstrates how the simulated dredge plume statistics from each short term scenario can be superimposed on a cell-by-cell basis across the model grid. For each statistical measure required by the tolerance limits (e.g. percent exceedance of 25 mg/L SSC) the highest percent exceedance outcome from the scenarios can be determined and then compared with the ecological tolerance limits to map out the distribution of different levels of ecological impact. This enables a conservative assessment to be made of the envelope of extent and intensity of impacts that could occur over the range of scenarios selected. For example, the envelope of effect and influence resulting from the combination of all stages and activities of the dredge program, each conducted over a full range of seasonal climatic scenarios could be derived. This would identify ecological receptors potentially at risk from the dredging campaign, but would produce a more extensive envelope than would any single realization of the dredging program.

The report shows comparisons between simulations of dredge scenario plumes as derived from the two-dimensional models and from depth-averaging of the three-dimensional simulation results. The higher SSC concentrations in the plumes generally tend to spread slightly further for the two-dimensional simulations. The lower SSC concentrations spread significantly further in the two-dimensional model for summer conditions, but slightly less for winter conditions. The simulated net sedimentation fields are generally similar in both the two- and three-dimensional models.

Issues

This review has identified several issues and questions in the application of the DHI chosen approach for modeling dredged sediment plumes for the Wheatstone Project. These issues are briefly summarized below:

- While flow conditions in the shallower parts of the project area have limited vertical structure, this is not the case for measurements from near the outer portion of the proposed shipping channel which show current directions varying with depth, being most frequently to the northeast in the upper water column and most frequently to the southwest in the lower water column. A two-dimensional, depth-averaged model, based on the assumption of well-mixed flow conditions, cannot reproduce this behavior.

- Both the two- and three-dimensional hydrodynamic models applied to this study have difficulties in accurately simulating wind-driven net current flows which drive large-scale plume excursions. For both models this is largely because of the lack of an entirely satisfactory and representative source of wind forcing data for the project area and surrounding region.

  For the purposes of environmental impact assessment this uncertainty has been mitigated by merging dredge plume simulation results derived separately from the two-dimensional hydrodynamic model flows driven by OMS and MesoLAPS winds. This produces a broader spatial representation of the plume, since use of the OMS winds leads to higher simulated net currents and plume excursions when movement is to the east (mainly in summer), whereas use of the MesoLAPS winds leads to higher simulated net currents and plume excursions when movement is to the west (mainly in winter).

- It is important to understand whether the wind forcing data applied to model for each of the seasonal climatic scenarios produces “strong”, “weak” or “typical” net currents compared to long-term averages for these seasonal climatic types. This will have a bearing on the spatial extent and concentration/sedimentation of the simulated plume and is relevant to the provision of conservative estimates of the plume. Some discussion of this aspect was provided in draft versions of this report but has not been included in the final report.

- Augmenting the depth-averaged dredge plume model with an assumed form for the vertical SSC profile, taken from the work of Teeter (1986), is of potential concern. The Teeter profile is based on underlying assumptions (e.g. constant bed shear stress) which may be inappropriate in the context of modeling dredge plumes in a dynamic marine environment. As a consequence, it is possible, under some circumstances, that the model may misrepresent sediment deposition rates which in turn may result in misrepresentation of suspended sediment concentration gradients along the dredge plume axis. This is discussed in more detail in Section 7 of this review.

- The sediment settling velocity (~ particle size) distributions of dredge spill sediments from sources other than overflow have not been specified. These sediment distributions should be documented for the various types and sources of spill and the range of expected transport behaviors should be explained. A more comprehensive justification should be provided for the number of sediment fractions (with defined settling velocities and percentage mass) *and the overall range of particle sizes* (settling velocities) represented in the model.

  Sediment fractions presently included in the model have been assigned settling velocities of 1 mm/s or less. These fractions are expected to be fairly well-mixed (vertically) in suspension (Rouse number << 1) for much of the time and only to deposit relatively slowly when bed shear stress levels are sub-critical. In order to better represent the dredge plumes and their impacts, the model may require additional silt fractions (including settling velocities of about 3 or 4 mm/s) which are in incipient rather than full suspension for much of the time (Rouse number value of about 1) with more pronounced vertical SSC profiles, and which deposit more rapidly when bed shear stress for deposition is below critical value.

  As the sediment fraction settling velocity increases the vertical profile of SSC will become less uniform and the application of a two-dimensional model less appropriate. For a typical water depth (10 m) and sediment settling velocity of 3 mm/s the settling time scale is about 1 hour and over this time period the bed stress can vary significantly during the acceleration and deceleration of the ebb and flood tidal currents, contrary to assumptions on which the Teeter profile is based.

- The report identifies “significant and repeated resuspension of [dredged] material” by currents and waves which can regenerate plumes far from the dredge location. This has the potential to redistribute dredged sediment material (e.g. migration of areas of net sedimentation) over time-scales considerably *greater than 14 days*, which cannot be represented by the short-term scenario simulations.

  DHI has tested the model for this effect and found that, with the present settings for the sediment fractions, there is negligible migration of the SSC footprint or net sedimentation areas over an extended simulation period. This may be because the sediment fractions specified in the model are expected to remain in full suspension for most of the time under the range of current and wave conditions encountered in the Wheatstone area.

  By contrast, coarser silts fractions with settling velocities of 3 or 4 mm/s are likely to experience greater deposition rates when bed stress levels are sub-critical. The transport of these intermittently suspended coarser silt fractions is likely to differ (in rate and possibly direction) from the transport of the finer fractions represented in the model, and may not be fully represented within a fourteen day simulation period.

The modeling strategy adopted by DHI for the Wheatstone study is able to accommodate a broad range of uncertainties about the project definition and eventual execution that exist at the environmental impact assessment stage. This review has raised a number of technical issues about the adopted modeling strategy and its implementation for the Wheatstone project. If these issues can be resolved by DHI, then the modeling methodology can be deemed appropriate to support the assessment of dredge plume environmental impact analysis for the Wheatstone Project.

Stability of Dredged Material Disposed to Placement Sites

The stability of dredged material at the placement sites after completion of dredging is considered on the basis of modelled bed shear stress exceedance, bottom shear stress maps (cyclonic and non-cyclonic conditions), stable sediment grain size and the effects of consolidation and cohesive forces. Changes in the bed shear stress due to bed level changes as a result of disposal are taken into consideration. It is noted that dredge sites A, B and C are located in a bed shear stress shadow area (see Appendix EE) which is likely to limit mobility compared to other areas outside of the shadow area. However the broad conclusions that there will be some initial winnowing of very fine particles and ongoing mobility of fine sand material away from the placement site appears justified.

Other Issues

It is recommended that the scope of this study be extended to evaluate the sediment suspension and plume generation caused by shipping operations (for the project operating at capacity), including when large vessels (with tug boats) are manoeuvring onto or off berths.

4. CHARACTERISATION OF THE PHYSICAL ENVIRONMENT

The report presents relevant information and data on the bathymetry, climate, meteorology and oceanography of the region and project area. Wind, water level, current and wave data are analysed in some detail since these are required to set up and run the hydrodynamic, wave and dredge plume models in order to simulate the transport and fate of dredged sediments.

A bathymetric database for input to the hydrodynamic, wave and dredge plume models was developed by combining available regional and local (more spatially intensive) data sets. Satellite imagery was processed and calibrated to estimate the bathymetry in three poorly surveyed sub-areas. The overall coverage and spatial resolution of the bathymetric data are considered adequate for application to this study.

From an analysis of available wind data the report has identified characteristic regional wind patterns for summer, winter and transitional seasons.

There are significant differences between winds measured at mainland coastal versus offshore locations. The land-sea breeze cycle is strongest for nearshore areas, reinforcing daytime westerly winds during summer. Wind speeds during the winter months tend to be significantly higher at locations further offshore, particularly for easterly winds.

Two main sources of wind data were used to force the hydrodynamic model: single point winds from the Onslow Meteorological Station (OMS) and MesoLAPS winds.

The MesoLAPS model (part of the Australian Bureau of Meteorology numerical weather prediction system) provides analysis and prediction of wind and surface pressure fields across the region at a 12.5 km spatial resolution. Following an assessment of MesoLAPS winds against measured wind data from the region, DHI accessed hourly and six-hourly MesoLAPS outputs to force the hydrodynamic and wave models, respectively.

Long-term (9 year) wind records have been used to develop wind roses to describe the *average* progression of wind characteristics throughout the year. However the long term records should also have been used to address the issue of *inter-annual variability.* It should be demonstrated whether wind records used to drive the models for the seasonal climate scenarios are typical or atypical of those seasons.

The report provides an adequate description of the astronomical tides of the region but there is little discussion of other drivers which may influence water level in the project area.

The report identifies surface wind stress and tide as the main drivers of currents that would transport the dredged sediment plume and concludes that "net currents driven by local winds usually will dominate net currents in shallower water such as at the site for the proposed navigation channel". This is a reasonable general conclusion for water depths of less than 15 m, noting that this is where the dredging will occur and that the trajectories of the dredge plumes will be predominantly shore parallel. However a quantification of the forcing terms in the momentum conservation equations demonstrates that other forcings (e.g. atmospheric pressure gradients or regional sea level gradients) may at times be of the same order as the wind forcing terms.

The report concludes that "no significant three-dimensional current processes are observed in the nearshore waters". This conclusion appears justified for the shallower parts of the project area. However, current direction shearing in the water column has been measured on occasions at the P4 location, near the outer end of the proposed channel. There is an upper and a lower portion of the water column (in all about 50% of it for station P4) that is not sampled by the ADCP current meters, and so current shearing over the full water column may be greater than indicated by the available data. Current direction shearing with depth through the water column could result in differences for the transport and fate of different sediment fractions if they are preferentially present in different portions of the water column.

Wave measurements at several locations indicate the dominance of short period wind-driven waves across the project area and for the various seasons.

Core samples were collected along the proposed channel and berthing corridors to provide information on the soil and rock types present and a general idea of where they may be encountered during the dredging operations.

Seabed sediments have been assessed through grab sampling campaigns. Mean grain size within and surrounding the project area is variable but predominantly sandy material. The primary offshore spoil grounds proposed for this project are predominantly composed of sand or coarser material, but particles less than 75 μm may account for up to about 30-40 % by mass.

Very little work appears to have been conducted *in situ* to predict the characteristics and subsequent transport behavior of sediment spills released from the dredging processes, although it is acknowledged that both DHI and Lanier Wallingford International (LWI) have drawn on their extensive international experience in dredge plume monitoring and analysis in this regard. Apart from some data from measurements of dredge overflow samples, little information has been provided on settling velocity distributions associated with different types and sources of dredge spill. This is critical information to justify the setup of the dredge plume model and its representation of sediment fractions.

5. HYDRODYNAMIC MODEL SETUP AND CALIBRATION

Hydrodynamic modeling is required to simulate water movements in the project area for input to the dredge plume simulations.

The study used the Mike21 HD model to simulate unsteady, two-dimensional (depth-averaged) flows for input to the environmental impact analysis of the dredge plumes. A three-dimensional hydrodynamic model, Mike3 HD, was used mainly to demonstrate comparisons in performance between the two- and three-dimensional modeling approaches.

The two-dimensional hydrodynamic model was applied to a broad region of the North West Shelf and was used to drive embedded two- and three-dimensional models with finer spatial resolution, which covered the project area and the potential areas of dredge plume influence.

The Mike21 HD model is based on the assumption that the waters are well-mixed and without significant vertical structure in the current field. The Mike3 HD model is run under the assumption that there is no vertical density stratification. Available current meter data suggests the vertical flow structure is only minor for shallower waters of the project area, becoming more important near the outer portion of the proposed shipping channel in waters greater than 10 m depth. Widespread significant and persistent vertical density stratification is not normally expected in the area, except after occasional, high river outflows associated with cyclonic activity.

The entire regional model domain incorporates four nested grids with horizontal resolutions of 3645m, 1215m, 405m and 135m, respectively. The overall extent of the model domain, location of the open boundaries, nested grid refinement factor of 3 and horizontal resolution of the model grids is appropriate for the intended application of the models.

The dredge plume model operates on the same grid. The long-shore extent of the more finely resolved model sub-domains needs to be matched to the extent of potential impacts of the dredge plume. This is to avoid excessive “numerical diffusion” which would result in under-prediction of the plume concentrations.

The regional hydrodynamic model was tidally forced at its open boundaries by specifying tidal elevation data derived from DHI’s global tidal system (KMS). Water levels from regional model simulations (with tidal forcing only) compare favourably with tidal predictions for 16 primary tidal stations throughout the region. This confirms that the tidal data applied at the open boundaries of the model are reliable and that, at a regional scale, the model adequately represents the tidal wave dynamics. However, it should not be assumed that a hydrodynamic model which accurately simulates tidal water levels will necessarily be able to accurately simulate tidal or wind-driven currents.

Analysis of available wind data showed the importance of the land-sea breeze cycle for nearshore areas, strengthening westerly winds during summer, and that wind speeds tend to be significantly higher at locations further offshore for easterly winds which occur more often during the winter months.

A critical step in the model setup and calibration was to determine the best available source of wind data to force the model and optimise model performance. Trial simulations were conducted for each of the available sources of wind data. On the basis of these trials two sources of wind data were selected for ongoing use. These were the single point wind measurements from the Onslow Meteorological Station (OMS) and hourly regional wind field (and barometric pressure field) data derived from the Australian Bureau of Meteorology Weather Forecasting System MesoLAPS model.

No single source of available wind data was able to force the hydrodynamic model so as to satisfactorily represent the measured currents right across the project area and for all important seasonal meteorological conditions. It was critical that the hydrodynamic model should deliver realistic or conservative (in terms of the impact assessment) representations of the:

- wind-driven net currents which determine the larger scale horizontal excursions of the dredge plumes over periods of days to weeks;
- tidal currents which influence the local scale horizontal excursions of the dredge plumes over periods of hours, and
- instantaneous current speeds which influence bed shear stress and the flux of dredged sediments to and from the seabed, through deposition and resuspension processes.

A review of comparisons between the model simulations and measured current meter data from the 2006 and 2009 data sets provided evidence that:

- for eastward net (tidally-averaged) current events which are more common in summer, the model simulations driven by OMS winds tend to overestimate the measured net currents;
- for westward net (tidally-averaged) current events which are more common in winter, the model simulations driven by the MesoLAPS wind fields tend to overestimate the measured net currents;
- on balance, for both OMS and MesoLAPS wind data, the model is reasonably able to represent the tidal currents and the instantaneous peak current speeds.

Each of the two sets of hydrodynamic simulations (one driven by OMS wind data and the other by MesoLAPS wind field data) have been used to prepare separate dredge plume simulations. The separate dredge plume simulations have then been superposed to derive a composite representation of the dredge plumes. Compared to the use of any single wind forcing data source, this composite approach provides a broader and more concentrated representation of the dredge plume envelope and therefore a more conservative assessment of the extent of ecological impact and physical influence of the dredge plume.

6. WAVE MODEL SETUP AND CALIBRATION

Waves are important for dredged sediment plume behaviour in shallow water as they generate additional bed shear stress and turbulence that may hinder deposition of suspended sediment or enhance resuspension of sediment from the bed. The dredge plume model receives inputs from a wave model (Mike21 SW) that simulates locally-generated wind waves and transmission of ocean swell waves to the site.

Mike21 SW is a spectral wind wave model that simulates the growth, decay and transformation of wind generated waves and swells in offshore and coastal areas. The model uses an unstructured (spatially varying) finite element grid across the computational domain so that regional and local scale topographic and bathymetric features may be readily incorporated. Mike21 SW is driven by off-shore wave conditions, tidal elevations and specified wind fields.

The variable-resolution model grid adopted for this study appears able to resolve areas across which there is significant change in bathymetry or wave characteristics. The range of model grid sizes should be stated.

The wave model domain extends beyond the continental shelf but does not encompass oceanic scales over which deep ocean waves are generated. It therefore requires that ocean wave data are specified around the open boundaries of the model.

Beside ocean wave inputs at the open boundaries, MesoLAPS (6 hourly) wind field data and Onslow tidal elevation predictions were the other forcings used to drive the Mike21 SW model for this application.

Monthly median significant wave height statistics and "main direction" were available for the calendar months January to December from the "Wheatstone" location (offshore of the Montebello Islands in 100 m water depth). The temporal coverage of the data from which these statistics were derived is not given. The wave model was forced with these wave statistics applied at the open boundaries and with MesoLAPS wind fields. The wave simulation results were compared with measurements at the "Basin DWR" location (water depth 10 m) and at the "Jetty" location (water depth 8.2 m). The model demonstrated an acceptable level of agreement for significant wave heights and mean wave directions at these two inshore sites. Measurement and simulation results indicate that the wave regime at these locations is dominated by wind-driven short period sea waves.

Further wave simulations were forced with directional wave time-series data from a location off the North West Cape (water depth 50 m) applied at the model open boundaries and with MesoLAPS wind fields applied across the model domain. Good agreement was found between simulated and measured significant wave height, mean wave direction and mean wave period at each of the "Spoil Ground" (water depth 52 m), "Channel" (water depth 15 m) and "Jetty" (water depth 8.2 m) locations. The measured waves at the "Channel" and "Jetty" locations have mean periods predominantly in the range 3 – 8 seconds and significant wave heights with strong diurnal variation. This signals the importance of winds in directly driving the wave regime experienced in the project area and suggests that longer swell waves from the open ocean are substantially attenuated by the time they reach areas where dredge plumes are likely to be encountered.

The wave model has been validated for inshore, sheltered locations and also for outer, more exposed locations within the project area. The validations include summer, winter and transitional seasonal conditions. Hence it may be concluded that the model is appropriately simulating the seasonal and spatial variability of the wave climate (and the attenuation of ocean swell) throughout the dredging project area.

The dominance of short period wind-driven waves across the project area (as demonstrated by the wave measurements) explains why the simulation results are relatively insensitive to the wave specification applied at the open boundaries of the model.

7. DREDGE PLUME MODEL SETUP

The study applies the two-dimensional sediment transport model (Mike21 MT) for the Wheatstone dredge plume simulations. A three-dimensional sediment transport model (Mike31 MT) is also used to demonstrate comparisons in performance between the two- and three- dimensional modeling approaches.

Mike21 MT is a depth-averaged finite-difference model which simulates the transport behavior of several sediment size fractions subject to erosion, advection, dispersion and settling/deposition processes for mud or sand/mud mixtures under the action of currents and waves. Mike21 MT is established on the same grid system and gridded bathymetry configuration as used for the two-dimensional hydrodynamic model. Mike21 MT is driven by the outputs of the two-dimensional hydrodynamic and wave models and by sediment source terms representing the release of dredged sediments.

The focus of the modeling is on the transport of those fractions of dredged material which move beyond the immediate vicinity of the dredging activity and form passive plumes (no significant density effects) governed primarily by ambient currents and waves, and by particle settling, deposition and resuspension.

The model deals only with the transport of dredged sediment material and does not account for the transport of ambient seabed sediments or sediments released from other activities unrelated to the dredging. The model therefore only simulates the "excess" contributions to the total suspended sediment concentrations and deposition rates (i.e. the contributions that are specifically caused by the dredger operations).

The reviewer has concerns about the use of the Teeter (vertical suspended sediment concentration) profile to estimate sediment deposition rates in the Mike21 MT model. Error or uncertainty in modeled deposition rates will lead to error or uncertainty in the rates of change of suspended sediment concentrations along the dredge plume axis.

The rate of deposition calculation in Mike21 MT involves $\mathbf{c_b}$ which is the suspended sediment concentration close to the bed. Since Mike21 MT is a depth-averaged model it can only calculate $\hat{\mathbf{c}}$, the depth-averaged suspended sediment concentration, not $\mathbf{c_b}$. In an attempt to overcome this problem an assumed form for the vertical SSC profile, taken from the work of Teeter (1986), is added into Mike21 MT. The assumed form of the Teeter profile is used to calculate $\mathbf{c_b}$ from $\hat{\mathbf{c}}$ and, on this basis, the sediment deposition rates are evaluated.

However, the form of the Teeter SSC profile is derived from an analysis which assumes:

- one-dimensionality (i.e. all dynamic and physical variables are uniform in all horizontal directions), and that
- vertical diffusivity and probability of deposition are constant with time (the latter effectively corresponding to an assumption of constant bed shear stress).

These underlying assumptions may be inappropriate in the context of modeling dredge plumes in a dynamic marine environment (with high spatial and temporal variability).

DHI state that the sensitivity of plume simulations to the inclusion or exclusion of the Teeter vertical SSC profile is small compared to the sensitivity of the model to varying other parameters such as the critical shear stress for erosion. This may be so. However no information has been provided on whether the Teeter profiles are reasonably representing *actual* (measured) SSC profiles across a range of sediment fractions and hydrodynamic conditions relevant to the Wheatstone dredging application.

If the dredged sediment spills are all fines in suspension that are vertically well mixed throughout the water column then this may not be a significant issue. However if the spills include silt sizes with greater settling velocities (e.g. 3 or 4 mm/s) that are more intermittently suspended these sediment fractions are likely to develop stronger vertical SSC profiles and the validity of using two-dimensional modeling augmented with the Teeter profile would need to be questioned.

Sediment losses from dredging operations can be highly variable, depending on the material dredged, the dredge plant and activity, the mode of sediment loss and the metocean conditions. Estimating loss rates at the environmental impact assessment stage of a project has a significant degree of uncertainty. The loss estimates are based on monitoring of dredging projects elsewhere in areas which are comparable to the project area. The dredge-induced sediment loss terms, include:

- mass rates of loss;
- distribution of these loss rates across the range of sediment particle sizes/settling velocities, and
- timing and location of the dredging activities.

DHI in collaboration with LWI have made "low (realistic)" and "high" estimates of dredged sediment mass spill rates for each major activity and phase of the proposed dredging campaign. The "low" spill rates are considered by DHI to be the best estimated representative spill rates for extended periods of dredging. The "high" spill rates may occasionally occur during individual dredge cycles but are considered highly conservative when maintained for extended periods of time.

DHI has compiled a data base of settling velocities obtained from monitoring various dredging projects. The sediment (settling velocity) distributions for most dredging sources *other* than overflow (e.g. drag head action and propeller wash) are not detailed. The report shows settling velocity distributions from *overflow* samples for dredging of silty sand material with bed silt/clay content in the 10-30 % range (Figure G.1). While the bed sediments in the Wheatstone project area have similar silt/clay content (Table 2.2), the description (Section 2.2.2) of the in situ material to be dredged suggests that its fines content may be significantly higher.

Six sediment fractions (Table G.1) were specified in the dredge plume model to represent a measured settling velocity distribution derived from *overflow* for dredging of silty sand material (Figure G.1). A different settling velocity was assigned for each of these fractions ranging up to a maximum of 1 mm/s. All of these fractions would be expected to be present in fairly well-mixed suspension for most of the time under the range of current and wave conditions encountered in the Wheatstone area. This may be why increasing the number and resolution of the sediment fractions (across the same overall size/settling velocity range) did not lead to significant changes in the spatial extent or mean concentration of the simulated plume representations.

Table 2.3 presents an assumed particle size distribution for material to be disposed at placement sites. Of the total "fines" (< 80 μm) present in this material 48% by weight are assumed to be particles less than 20 μm, 33% in the range 20 to 60 μm and 19 % in the range 60 to 80 μm. By way of reference, particles of size 70 μm have settling velocities of around 4-5 mm/s and particles of size 50 μm have settling velocities of around 2 mm/s. The coarsest sediment fraction defined in the model (Table G.1) has a representative settling velocity of only 1 mm/s, corresponding to a particle size of around 35 μm. It does not appear that the sediment fraction settings, as presently specified in the model, can represent the distribution or transport of fines assumed to be released from dredge spoil dumping activities.

Further investigation is recommended to determine if additional coarser silt fraction(s) (e.g. with settling velocities of 3 or 4 mm/s) should be included in the model to improve representation of the sediment losses from the various sources of spill (e.g. drag head action, propeller wash and spoil ground disposal). In nature, these fractions are likely to be transported in an incipient or transitional state between resuspension and deposition for much of the time and only remain suspended for the stronger current and wave conditions encountered in the project area. The rate (and possibly direction) of transport and the vertical SSC profiles of these fractions are expected to be different compared to the finer fractions already represented in the model. The contributions of these additional silt fractions to the total dredge spill and to the environmental impact of the dredge plume should be discussed. If these contributions are significant then the implications of including these fractions on the chosen modeling strategy should be discussed.

Critical shear stresses for erosion and deposition play a key role in determining the spatial extent of the sediment plume. Values chosen for these critical shear stresses were derived from DHI experience and the literature, but the literature also demonstrates that these values can vary considerably with the size, composition and nature of the sediments. For this reason it would have been appropriate to identify realistic ranges of these parameter values, demonstrate the sensitivity of the sediment plume model to these parameters and make the case that the values chosen were conservative.

The value chosen for the horizontal dispersion coefficient (1.5 m^2/s) is in the expected range for wastewater plumes from major ocean outfall diffusers and has been independently derived by calibrating the model against satellite imagery of dispersing dredge plumes.

There are no dredge plume field data sets from the Onslow area that could be used to calibrate and validate the dredge plume model. The dredge plume simulation model requires a range of data inputs and parameter values. Some of these can be derived directly from data or from well-calibrated hydrodynamic and wave model simulations; others rely on professional judgements and the extensive field measurement and modeling experience of DHI. The task of the modeler is therefore to come up with conservative predictions of typical and worst case impacts related to the dredge plume. The model inputs, settings and assumptions need to be *carefully explained and justified* to demonstrate that the final simulation results and predicted impacts are likely to be conservative.

9. REFERENCES

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Teeter, A. M. (1986). Vertical transport in fine-grained suspension and newly deposited sediment. *Estuarine Cohesive Sediment Dynamics*, A. J. Mehta, ed., Lecture Notes on Estuarine and Coastal Studies Vol. 14, Springer-Verlag, Berlin, FRG, 170-191.

Wheatstone Project

Wheatstone Project - Dredge Spoil Modelling Response to Independent Peer Review Comments of 8th June, 2010.

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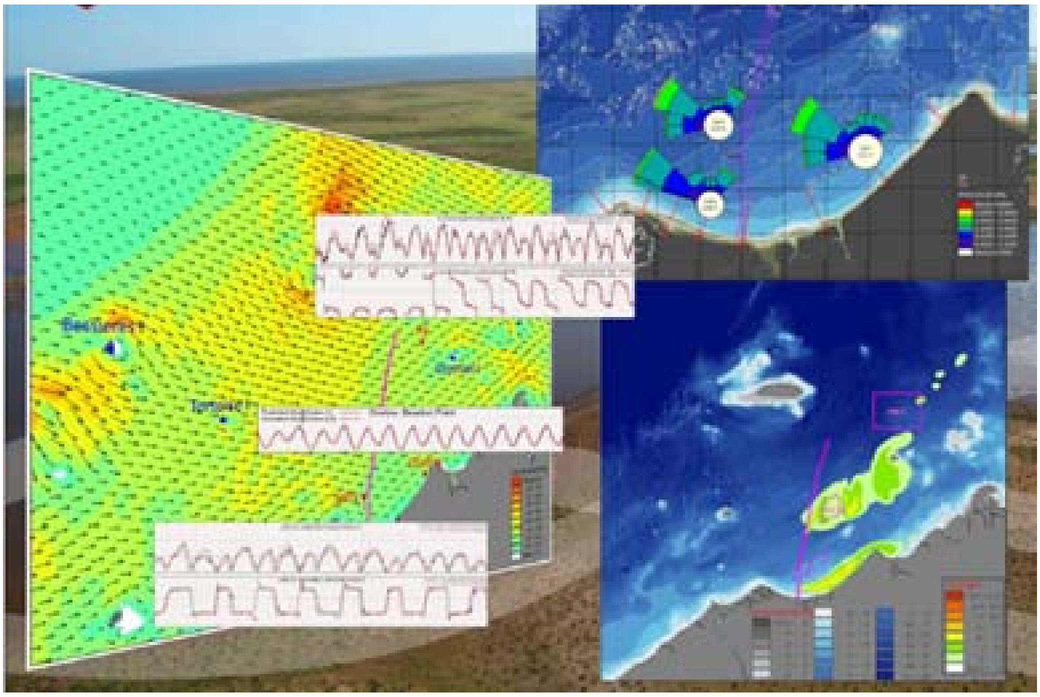
Wheatstone Project - Dredge Spoil Modelling

Response to Independent Peer Review Comments of 8th June, 2010.

Chevron Australia P/L



June 2010

Technical Note

Wheatstone Project - Dredge Spoil Modelling

Response to Independent Peer Review Comments of 8th June, 2010.

June 2010

11th Floor, Hill-View Side
Wisma Perindustrian
Jalan Istiadat, Likas
88400 Kota Kinabalu

Tel: +60 88 260 780
Fax: +60 88 260 781
e-mail: dhikk@tm.net.my
Web: www.dhi.com.my

Client	Client's representative
Chevron Australia	Mr. Ceri Morgan

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Authors	**Date**
Amy Ling Cesar Rocha Dr. Claus Pedersen	10 May 2010
	Approved by Dr. Claus Pedersen

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CONTENTS

1 INTRODUCTION

A report, Mills (2010), dated 8 June 2010 was submitted by Dr. Mills of Des Mills Marine Environmental Reviews (DMMER) outlining the findings of the independent peer review (IPR) of the DHI report "Dredge Spoil Modelling" of 10th May, 2010.

This technical note constitutes DHI's response and outlines additional work being undertaken to further address the issues raised in the review comments by Dr. Mills. In addition to the present response, additional supporting modelling and assessments will be included in an addendum submission to the EIA.

2 REVIEWER ISSUES AND RESPONSES

The IPR report constitutes a comprehensive review of the modelling strategies and methodologies applied by DHI for the dredge plume modelling carried out for the Wheatstone project.

The review purpose is stated in Mills (2010):

The main purpose of this review is to assess the modelling approaches and methodologies to determine whether the modelling is fit for purpose, soundly based and would underpin conservative estimates of the dredge plume and associated impacts of the proposed dredging.

The conclusions in the Executive Summary of the review report states:

A strong and practical advantage of DHI's chosen strategy is its ability to accommodate uncertainties at the environmental impact assessment stage of the project. The short computer run times for each scenario allows for finer horizontal resolution and a wider range of combinations (of seasonal condition, dredge activity and spill rate) to be simulated under different sets of assumptions. The results from these multiple dredge plume scenario simulations can be superimposed to derive an outer envelope and maximum intensity distribution for all the scenarios, and this will help to provide a broader, more conservative estimate of where the dredge plume could occur as a result of the entire dredging campaign.

This review identifies (in Section 3) several questions relating to the application of this methodology to the Wheatstone Project. It is recommended that these issues be addressed promptly and supplementary input provided to the environmental impact assessment process.

The present technical note is the first pass response to the questions raised by Dr. Mills. Each of the 6 bullet points under "issues" in Section 3 of the report, Mills (2010), are reproduced in the following subsections, and annotated with DHI's initial response and proposed further works .

2.1 3D Effects

2.1.1 Issue per Mills (2010):

While flow conditions in the shallower parts of the project area have limited vertical structure, this is not the case for measurements from near the outer portion of the proposed shipping channel which show current directions varying with depth, being most frequently to the northeast in the upper water column and most frequently to the southwest in the lower water column. A two-dimensional, depth-averaged model, based on the assumption of well-mixed flow conditions, cannot reproduce this behaviour.

2.1.2 DHI Response:

As pointed out by Dr. Mills, there is at times a tendency for higher frequency of north-easterly currents at the upper compared to the lower water column. This is caused by friction on the surface by the predominant south-westerly winds. This is for instance seen in the "old" dataset of current roses from P4, see Figure 2. This effect varies with location and seems less noticeable for the locations with similar depth to the outer channel from the ongoing field campaign, see Figure 3 to Figure 5. It is noted that this primarily occurs during neap tide when the wind driven currents are more dominant, and thus generally for weaker currents. This was documented in the characterisation of the ambient environment, Appendix HH, of the reviewed document, and is further illustrated in time series of currents at 3 layers of the water column shown in Figure 6 to Figure 14 for the three locations with current roses. The 3D effects are generally weak compared to the overall current regime.

Whereas DHI agrees that there are wind driven (and other) 3D effects present at the site which a 2D model cannot resolve, it is our firm belief that the combination of a 2D model and the scenario approach generally will lead to a conservative envelope of possible impacts. This is described for a "line source" in Appendix E to the reviewed modelling report. 3D current structures in essence increase dispersion in the horizontal plane, which leads to lower depth-averaged concentrations within the plume. Generally speaking, a 2D model will thus lead to higher concentrations stretching further from the site in the current direction.

In the case of a "line source" such as dredging along the channel with currents perpendicular to the channel, this will lead to the impact zone stretching further from the channel as illustrated in Appendix E. For a point source, a similar effect is present in the direction(s) of the currents. For a combination of climatic scenarios, this will generally lead to larger 2D impact zones in all the dominant current directions for the various climatic scenarios, while the 3D effects may lead to extended impact zones in other directions if the 3D effects consistently carry the plume in directions not covered by the 2D tidal and wind driven currents. For point sources in the vicinity of sensitive receptors, it can thus be critical to include 3D effects.

For the present case, the spoil grounds and to some extent the outer limit of the dredged channel can be classified as point sources, and it therefore has to be carefully considered whether 3D effects could lead to additional impacts not covered by the impact assessment performed on the basis of the 2D modelling. The following is considered for Placement Site C and the outer limit of the dredged channel:

- The 3D current effects are small compared to the overall current regime as shown previously.

- The 3D effects seem predominantly to lead to differences in the main current directions.
- The overall range of current directions are well represented by depth-averaged currents, see Figure 2 to Figure 5.
- In the main current directions, the 2D approach adds conservatism.
- With the limited 3D current effects, any effect on the impact zones is likely to be localised. There are no sensitive receptors in close proximity to the sites, and even if there were localised changes to the impact zones, this would not lead to changes in the assessment of habitat loss.
- Testing with a 3D model till date, see Appendix E, which included a channel section close to the outer limit of the channel as well as Placement Site C, has not given reasons for concern.

For the Placement sites D and E in deeper water, the tidal currents are weaker and the wind driven 3D effects become significant.

Proposed placement at Sites D and E per the Dredging and Disposal Plan is limited to clean-up dredging operations, and the area is considered less sensitive due to the remoteness from sensitive habitats. This operation has therefore not been prioritised and not included in the dredge scenarios till date.

Further Works

To further address the reviewer concerns, the dredge scenario covering the outer section of the channel is presently being run in the 3D model to ensure that the derived impact zones from the 2D modelling are conservative .

A scenario for Placement Site D is presently being set up in the 3D model.

Conclusion

In conclusion, it is DHI's opinion that the 2D scenario approach provides a conservative assessment for the majority of the spill sources. 3D current effects are present, but small, at the outer part of the channel and the primary Placement Site C, and potential effects of 3D currents on the derived impact zones at these areas are insignificant compared to the effects of other variables. 3D current effects at the much deeper Placement Sites D and E are significant, and although the limited placement planned for these sites combined with the large distance to sensitive receptors make significant impacts unlikely, it is proposed to establish a spill scenario for Site D to be simulated in a 3D model.

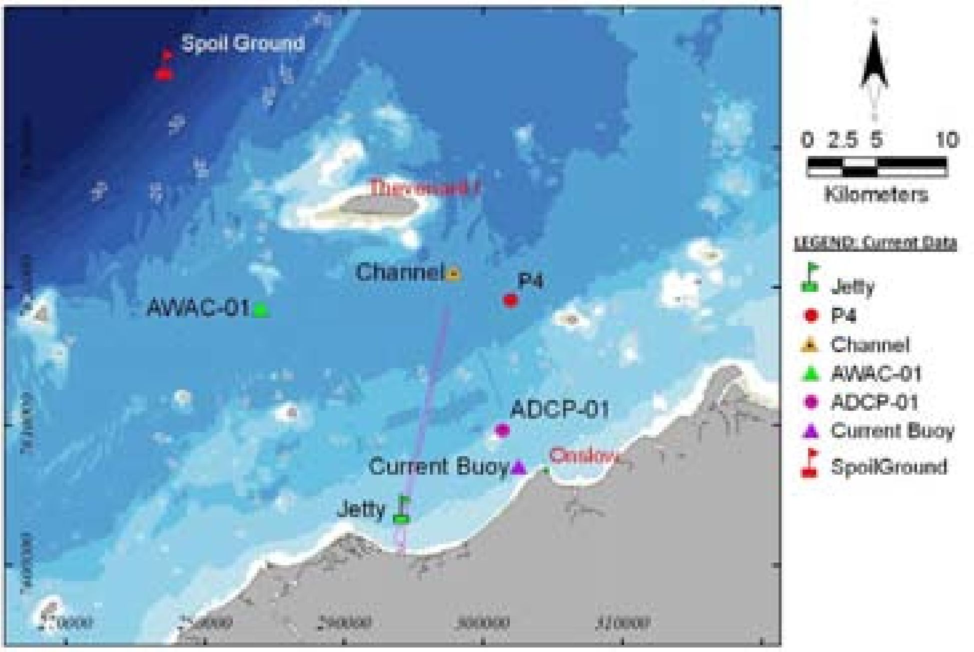

Figure 1 *Locations of current measurements used in the present note.*

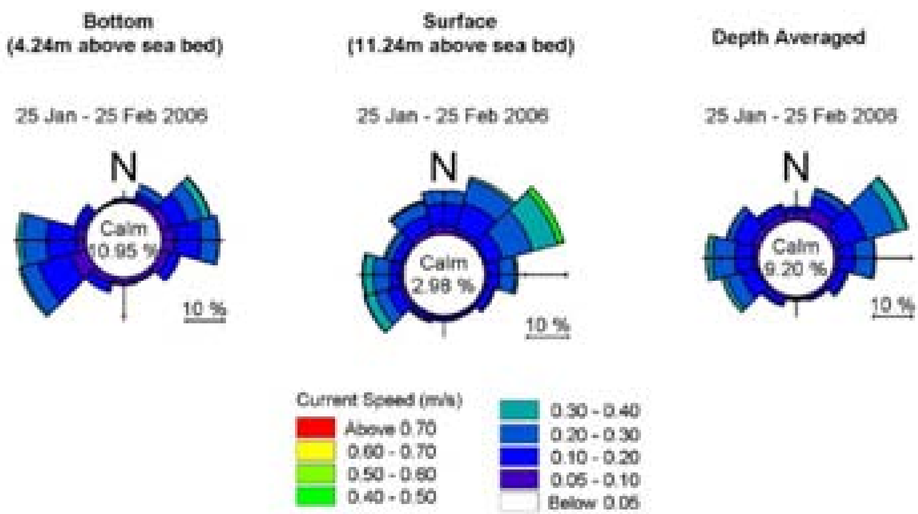

Figure 2 *Monthly current roses for bottom, surface and depth-averaged currents at the "P4" location, see Figure 1.*

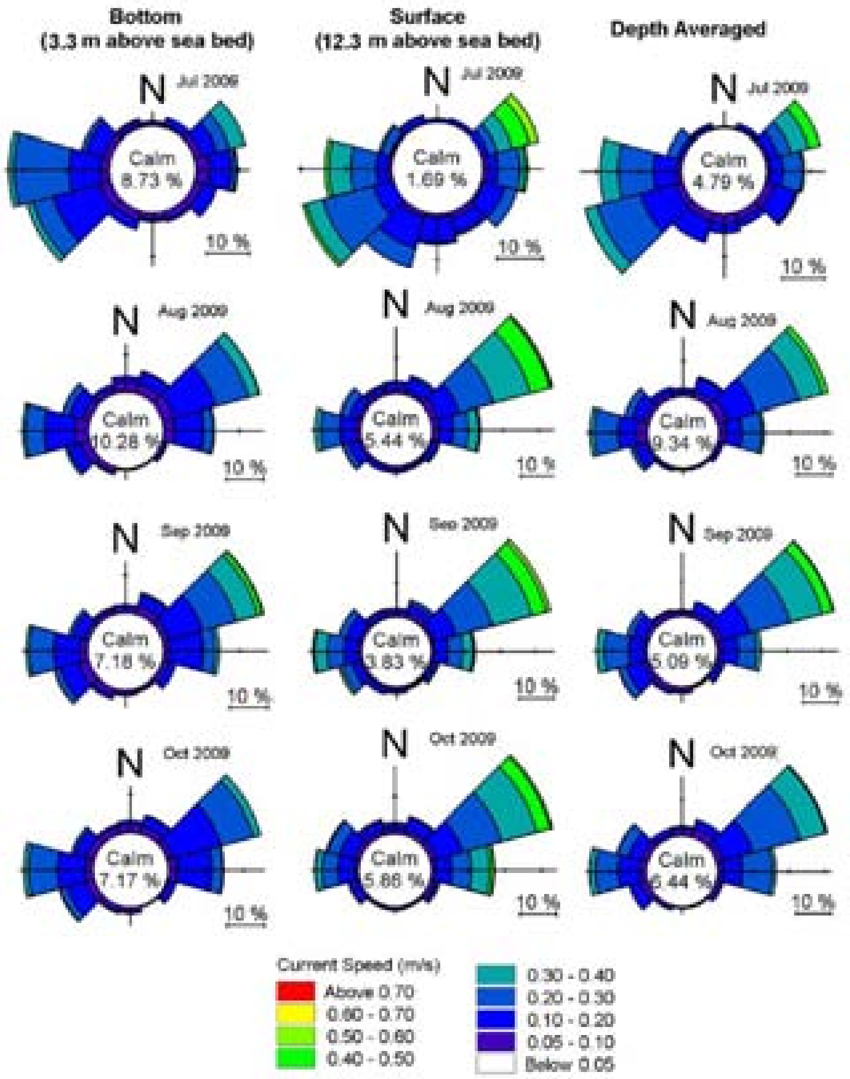

Figure 3 *Monthly current roses for bottom, surface and depth-averaged currents at the "Channel" location, see Figure 1.*

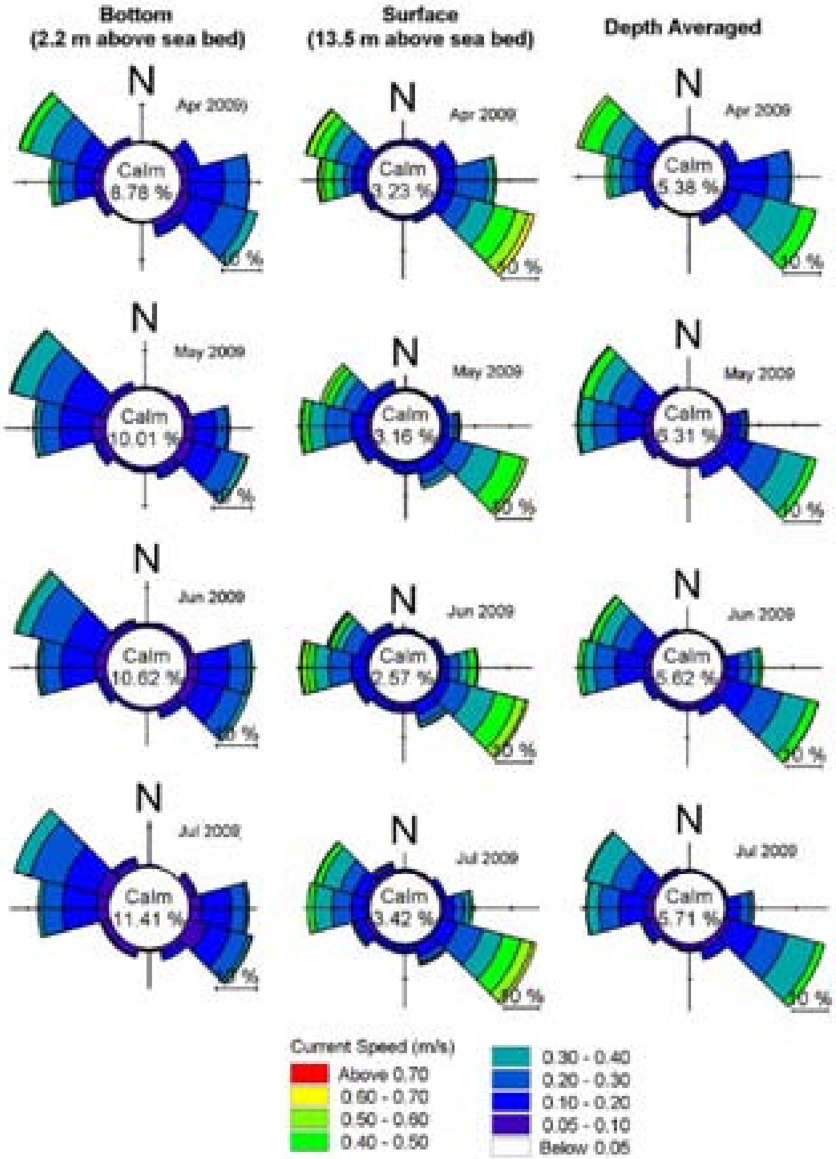

Figure 4 Monthly current roses for bottom, surface and depth-averaged currents at the "AWAC-01" location, see Figure 1, for April – July 2009.

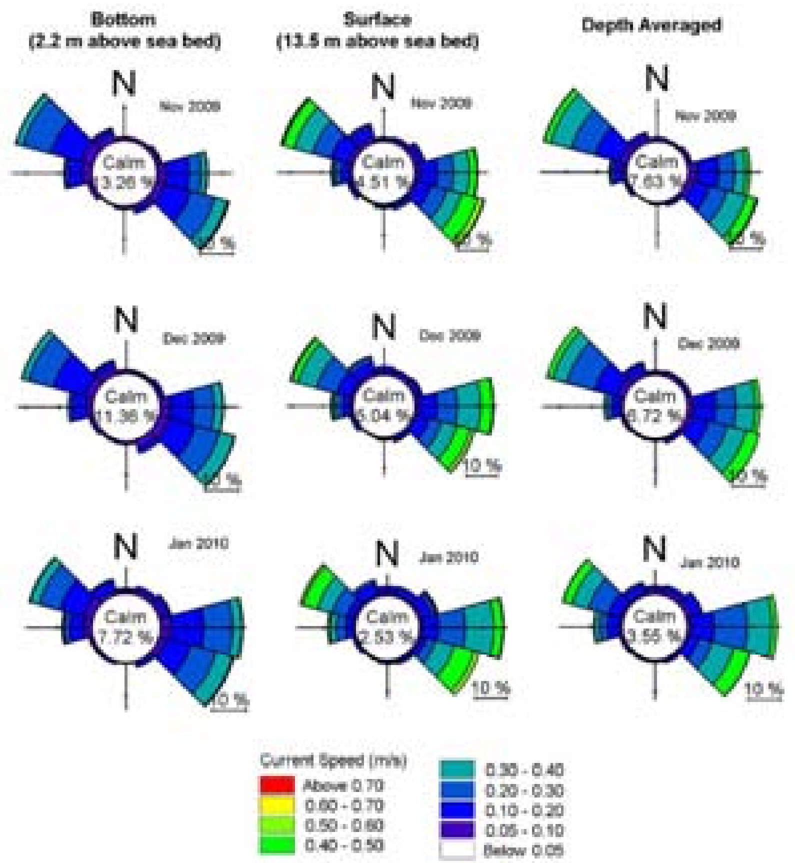

Figure 5 *Monthly current roses for bottom, surface and depth-averaged currents at the "AWAC-01" location, see Figure 1, for November 2009 – January 2010.*

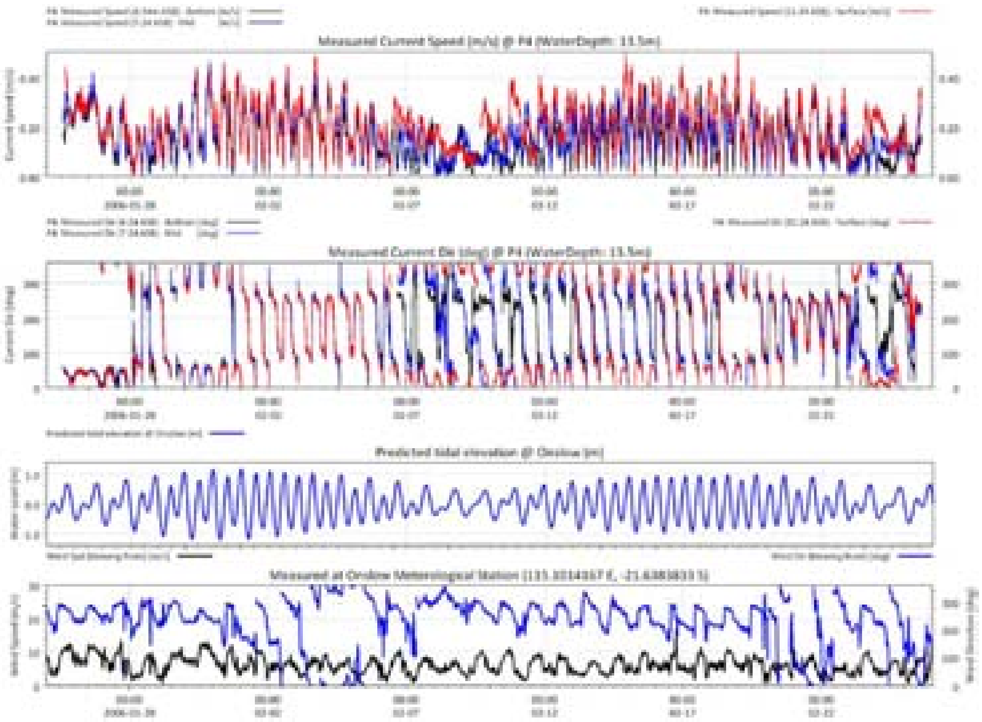

Figure 6 *Time series of currents at bottom, mid depth and surface part of the water column from the "P4" location, see Figure 1, together with simultaneous water level and winds from Onslow Met Station.*

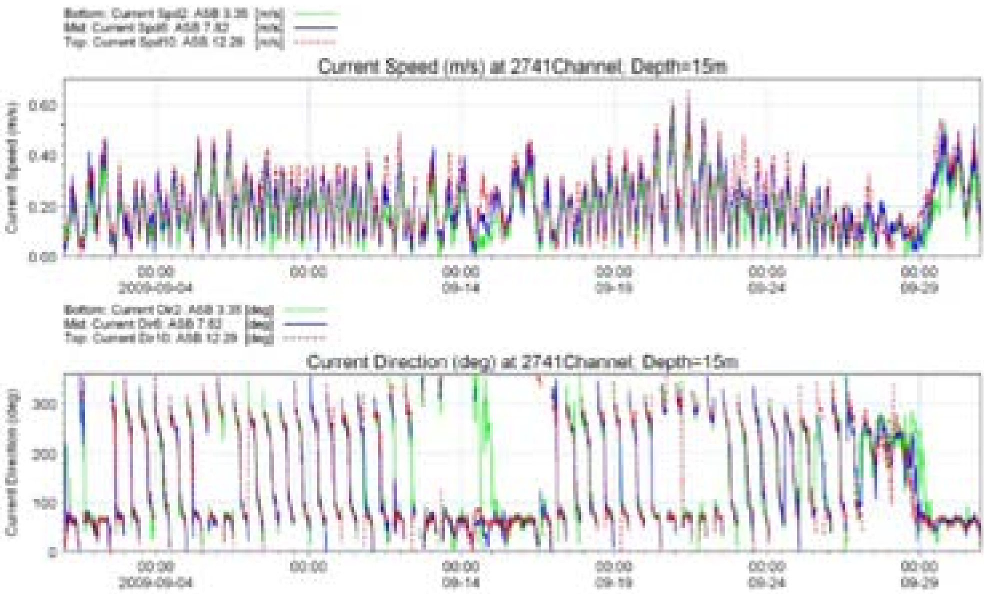

Figure 7 *Time series of currents at bottom, mid depth and surface part of the water column for September 2009 from the "Channel" location, see Figure 1.*

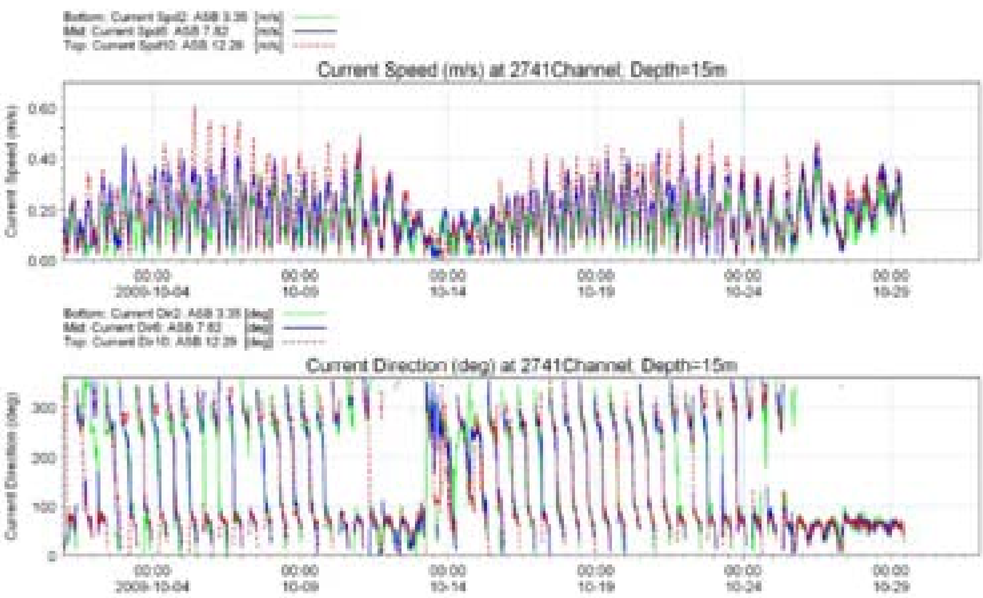

Figure 8 *Time series of currents at bottom, mid depth and surface part of the water column for October 2009 from the "Channel" location, see Figure 1.*

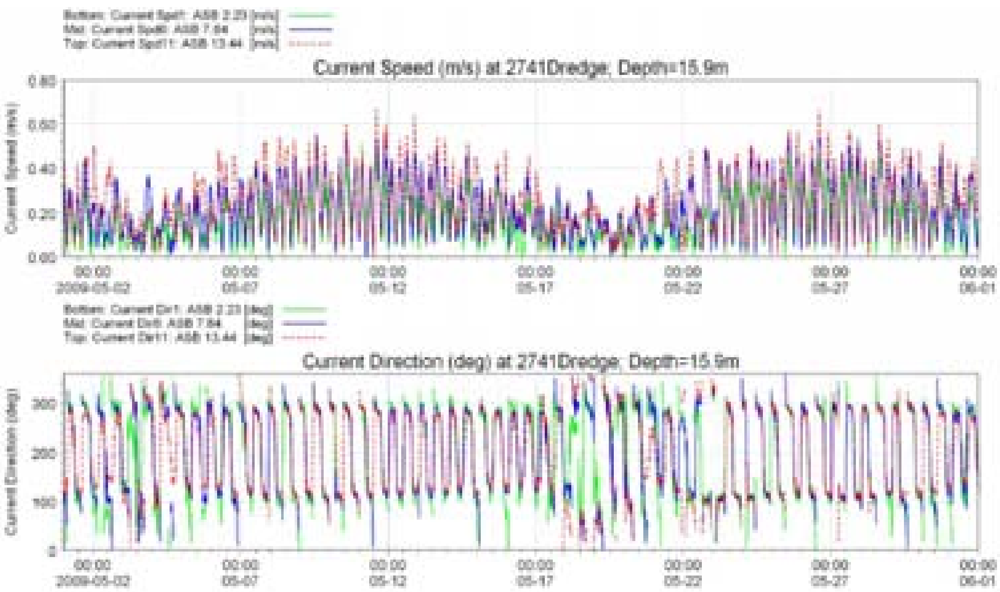

Figure 9 *Time series of currents at bottom, mid depth and surface part of the water column for May 2009 from the "AWAC-01" location, see Figure 1.*

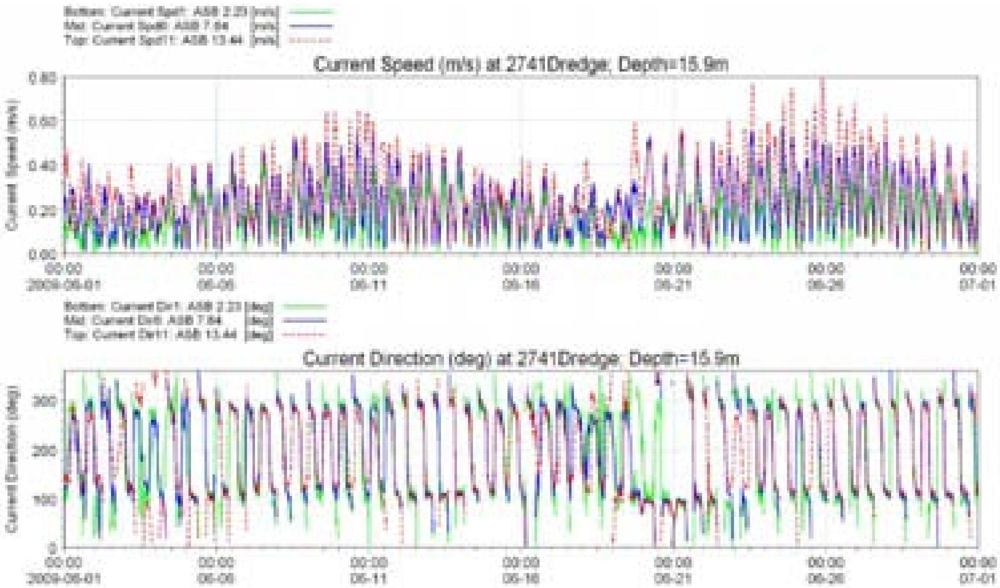

Figure 10 *Time series of currents at bottom, mid depth and surface part of the water column for June 2009 from the "AWAC-01" location, see Figure 1.*

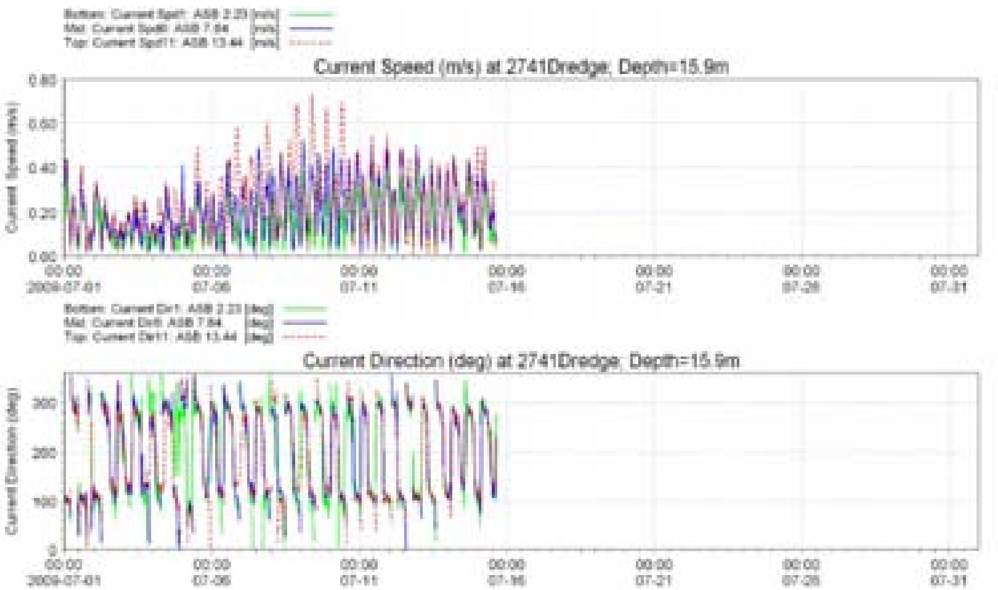

Figure 11 *Time series of currents at bottom, mid depth and surface part of the water column for July 2009 from the "AWAC-01" location, see Figure 1.*

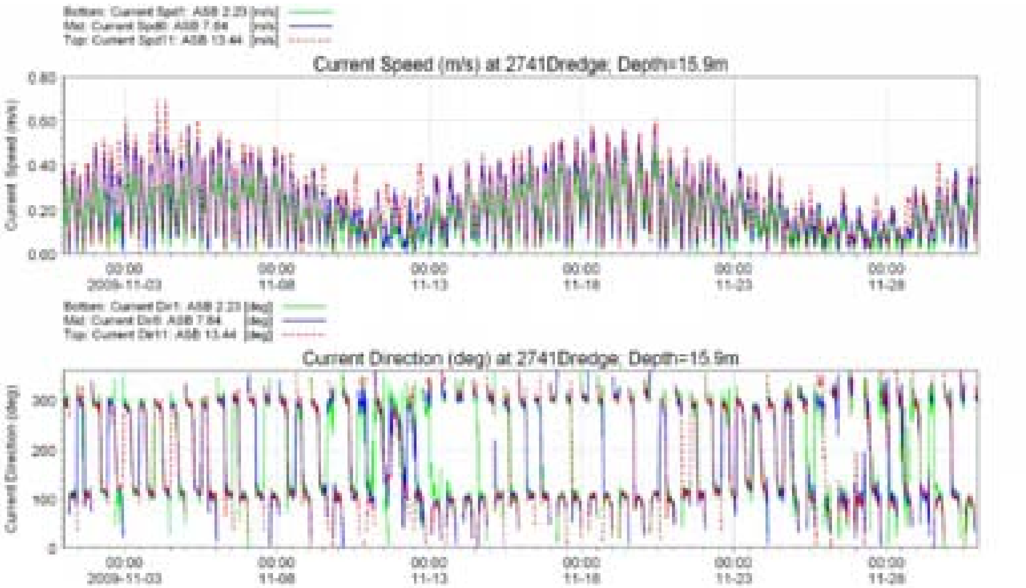

Figure 12 Time series of currents at bottom, mid depth and surface part of the water column for November 2009 from the "AWAC-01" location, see Figure 1.

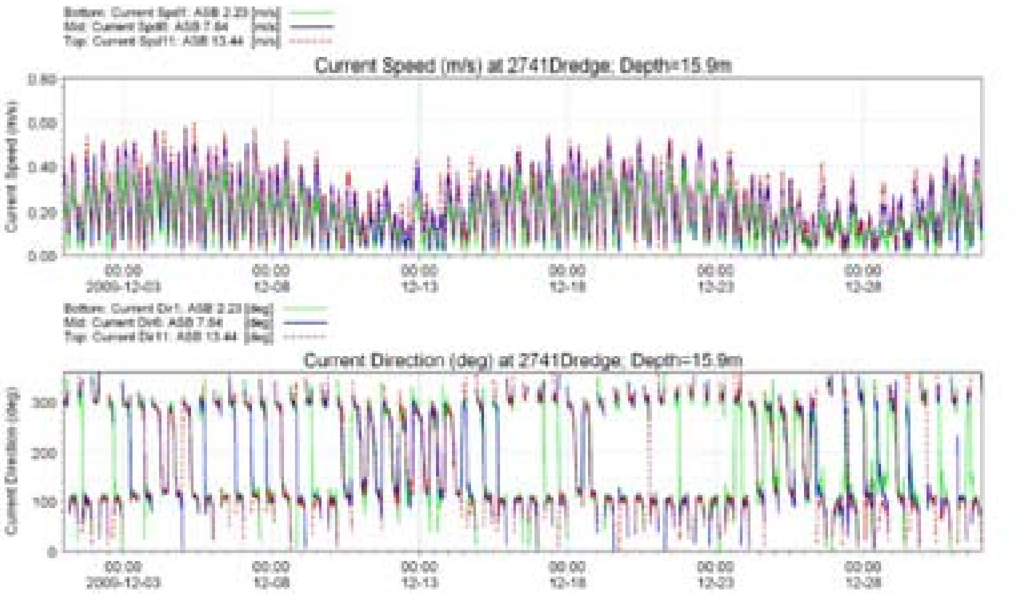

Figure 13 Time series of currents at bottom, mid depth and surface part of the water column for December 2009 from the "AWAC-01" location, see Figure 1.

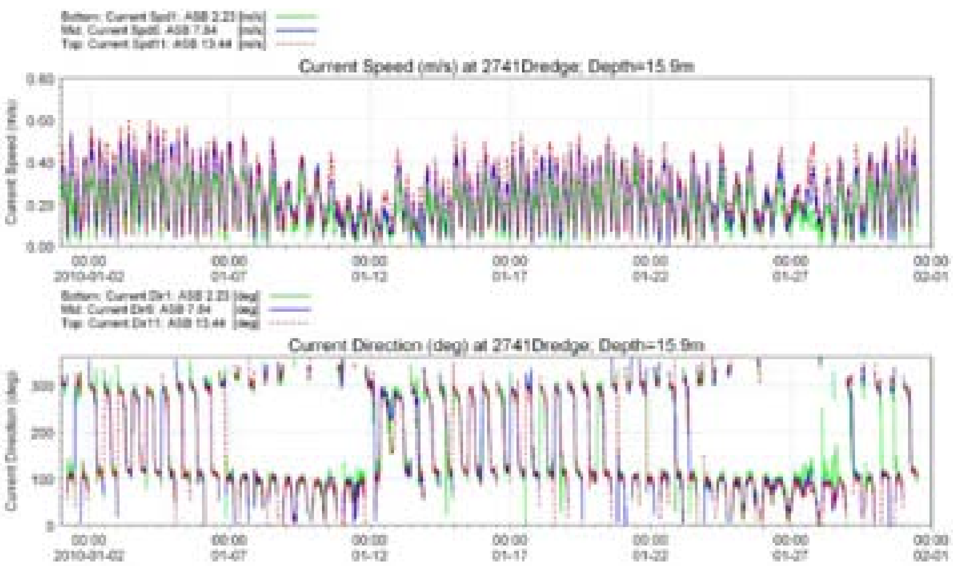

Figure 14 Time series of currents at bottom, mid depth and surface part of the water column for January 2010 from the "AWAC-01" location, see Figure 1.

2.2 Wind Data Applied in Modelling

2.2.1 Issue per Mills (2010):

Both the two- and three-dimensional hydrodynamic models applied to this study have difficulties in accurately simulating wind-driven net current flows which drive large-scale plume excursions. For both models this is largely because of the lack of an entirely satisfactory and representative source of wind forcing data for the project area and surrounding region.

For the purposes of environmental impact assessment this uncertainty has been mitigated by merging dredge plume simulation results derived separately from the two-dimensional hydrodynamic model flows driven by OMS and MesoLAPS winds. This produces a broader spatial representation of the plume, since use of the OMS winds leads to higher simulated net currents and plume excursions when movement is to the east (mainly in summer), whereas use of the MesoLAPS winds leads to higher simulated net currents and plume excursions when movement is to the west (mainly in winter).

2.2.2 DHI Response:

It is correct as described by Dr. Mills that the wind fields are critical to the simulation of net currents, and that no single wind source representative for all seasons has been available to the hydraulic studies.

The key for the impact assessment is to capture a range of net currents to ensure that the expected range that could be experienced during dredging is covered. This has, as described by Dr. Mills, been achieved by running the full set of dredging, spill and climatic scenarios with two different wind fields, which each provide a satisfactory description of summer and winter conditions, respectively.

DHI agrees with Dr. Mills's statement in his Executive Summary that this has "satisfactorily addressed" the issue.

It is noted that this issue ties in closely with the next issue related to the adopted periods for the climatic scenarios, and additional documentation that the wind fields applied in combination provide a conservative range is included in Section 2.3 below.

2.3 Climatic Scenarios

2.3.1 Issue per Mills (2010):

It is important to understand whether the wind forcing data applied to model for each of the seasonal climatic scenarios produces "strong", "weak" or "typical" net currents compared to long-term averages for these seasonal climatic types. This will have a bearing on the spatial extent and concentration/sedimentation of the simulated plume and is relevant to the provision of conservative estimates of the plume. Some discussion of this aspect was provided in draft versions of this report but has not been included in the final report.

2.3.2 DHI Response:

DHI fully agree that the climatic scenario selection is critical, and it is essential to ensure that the expected range of conditions experienced during dredging are covered in the modelling. It is noted that some of the previous discussions on the period selection and representativeness that Dr. Mills refers to as missing in the present submission are included in Appendix FF to the Modelling Report. The appendix was updated with this information after the report had been forwarded to Dr. Mills for review.

Additional metocean data from the ongoing field campaign at the Wheatstone Project area site, is facilitating a more detailed and ongoing analysis of the net currents, which is the main driver for the plume dispersion. An initial analysis of the latest set of data has been included in the present note; further analysis is planned with updated metocean data sets and this will be documented in an addendum to the EIA.

Comparisons between net currents derived from the current data and extracted from the models for the applied climatic scenarios are documented for the most relevant and new data sources available in Sections 2.3.2.1 to 2.3.2.5. Details of the comparisons are included in the subsections, while a summary of observations is listed below:

- The simulated net currents during summer and the transitional period are higher at the nearshore stations ("Current Buoy", "Jetty" and "ADCP-01", see Figure 1, using the OMS than the MesoLAPS winds.
- Simulated net currents are higher during winter using the MesoLAPS than the OMS winds, in particular at the more off-shore locations ("Channel" and "AWAC-01", see Figure 1).

- Overall, the measured net currents are found to be well represented, both in terms of directions and speeds, at all stations.
- A few “spikes” of high net current speeds in the data sets are generally associated with influence of tropical cyclones, during which dredging is most likely suspended. The spikes are generally of short duration, and the extended duration with high net currents covered by the “Summer A” scenario will give higher net easterly plume dispersion than the short-lived spikes of higher magnitude.

Overall, the analysis of the new data that has become available support the original assessment that the climatic scenarios applied for the EIA cover the expected net currents during the dredging period satisfactorily throughout the relevant domain.

Additional Work:

To further address this important issue, net currents derived from the extended period of measurements as it becomes available will be compared to the corresponding values derived from the models for the adopted climatic scenarios.

Inter-annual climatic variations such as the El-Nino / La-Nina cycle are catered for in the scenario approach as long as these inter-annual climatic cycles do not lead to extreme weather patterns that lie outside the limits of the adopted climatic scenarios for the impact assessment. Simulations are presently being carried out for the period 2002-2004, which was influenced by the La Nina cycle, anticipated to lead to a higher dominance of westerly winds, to ensure that the climatic scenarios can be considered inclusive of net currents affected by inter-annual climatic variations.

Conclusions:

Based on an initial analysis of the net currents from an extended data set and the net currents from the simulated climatic scenarios at several locations throughout the model area, it is concluded that with the combination of OMS and MesoLAPS winds, the climatic scenarios applied in the modelling cover the expected range of net currents at all available data stations within the expected impact zone.

Based on this, it is concluded that the climatic scenarios are appropriate for the impact assessment.

The analysis will be further extended as additional data from the ongoing field campaign becomes available. Further detailed assessment of inter-annual climatic variations is also being conducted.

2.3.2.1 Net Currents "Current Buoy"

Derived net currents at the Onslow Salt "Current Buoy", see Figure 1 for location, are shown derived from the model simulations with OMS and MesoLAPS winds for the EIA assessment periods in Figure 15 and from the available data period in Figure 16.

The data shows easterly directed summer net currents mostly less than 0.2 m/s but with spikes up to 0.3 m/s. The Summer B assessment period has currents generally less than 0.2 m/s, while the Summer A assessment period has more persistent spikes up to 0.3 m/s. Short duration spikes in the data exceeding 0.3 m/s in March 2007 and January 2008 are related to Tropical Cyclone Jacob and Melanie, respectively, affecting the site. Under these conditions the dredging operations would be halted. For winter, the data shows mostly westerly directed net currents up to 0.1 m/s with spikes up to 0.2 m/s. Assessment period Winter A has westerly net currents up to 0.25, while Winter B has net currents mostly below 0.15.

Overall, it is considered that the range and patterns of the net currents derived from the measurements are well covered by the climatic scenarios.

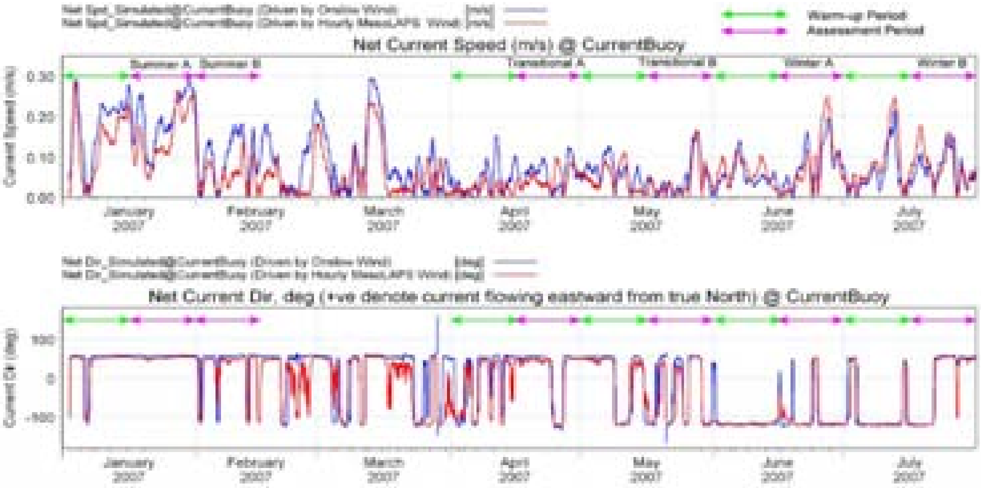

Figure 15 Net currents at the Onslow Salt Current Buoy location, see Figure 1, derived from the models driven by OMS (blue) and MesoLAPS (red) winds. The assessment periods used for the impact assessment are illustrated at the top of the plot.

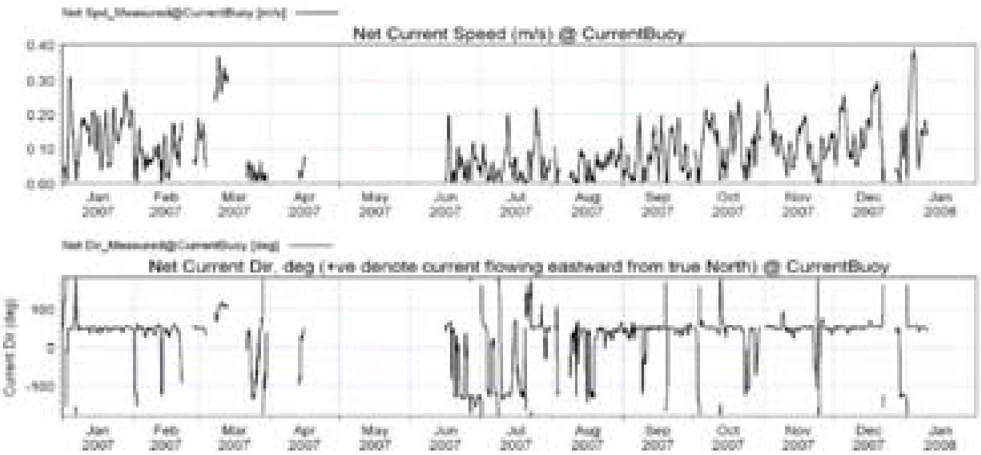

Figure 16 Net currents derived from the measurements at the "Current Buoy" location, see Figure 1.

2.3.2.2 Net Currents "Jetty"

Derived net currents at the "Jetty", see Figure 1 for location, are shown derived from the model simulations with OMS and MesoLAPS winds for the EIA assessment periods in Figure 17 and from the available data period in Figure 18.

The data shows easterly directed summer net currents mostly less than 0.2 m/s but with spikes exceeding 0.2 m/s. Considering the OMS and MesoLAPS winds, the summer assessment periods show net currents varying from less than 0.1 to an extended period exceeding 0.2 m/s, and adequately cover the range observed in the data. Data is missing during the main winter months, but all observed westerly net currents are covered by the climatic scenarios with net westerly currents up to 0.2 m/s.

Overall, it is considered that the range and patterns of the net currents derived from the measurements are well covered by the climatic scenarios.

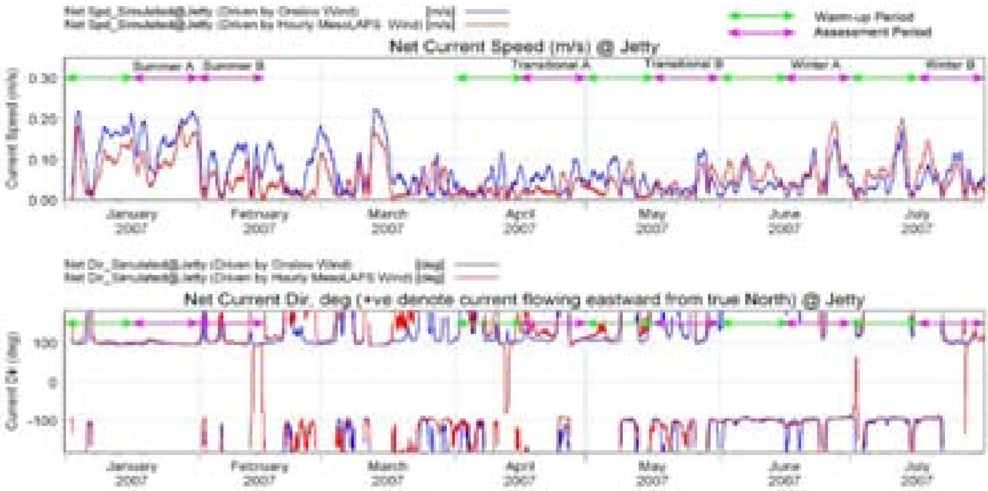

Figure 17 Net currents at the "Jetty" location, see Figure 1, derived from the models driven by OMS (blue) and MesoLAPS (red) winds. The assessment periods used for the impact assessment are illustrated at the top of the plot.

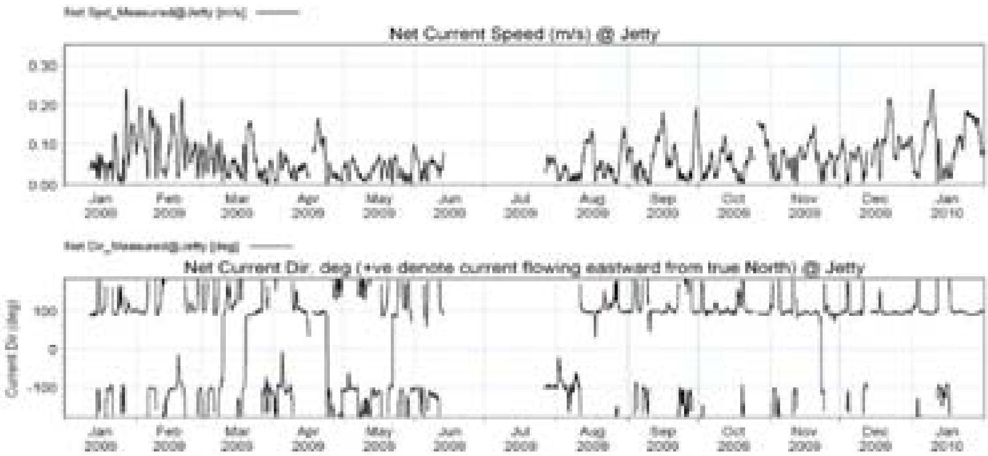

Figure 18 Net currents derived from the measurements at the "Jetty" location, see Figure 1.

2.3.2.3 Net Currents "Channel"

Derived net currents at the "Channel", see Figure 1 for location, are shown derived from the model simulations with OMS and MesoLAPS winds for the EIA assessment periods in Figure 19 and from the available data period in Figure 20.

Only a short data period is available from the "Channel" location due to loss of instrument and exchange with the AWAC-01 location. The short data period available show easterly directed net flows with spikes up to about 0.25 m/s. This is covered by the summer climatic scenarios with easterly net current spikes up to about 0.28 m/s. The data shows a sharp, short spike up to 0.35 m/s with a change in direction around 1st October. The peak is in excess of the peaks covered by the assessment periods, but the much longer duration period with persistent high net currents in Summer A will lead to higher westerly impacts than the observed short duration spike in the data.

Overall, it is thus considered that the range and patterns of the net currents derived from the limited period measurements are well covered by the climatic scenarios.

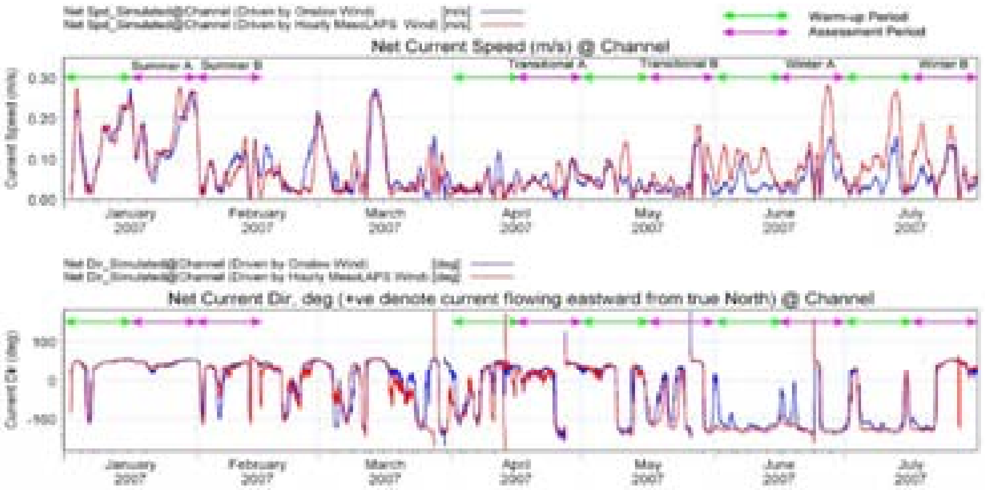

Figure 19 Net currents at the "Channel" location, see Figure 1, derived from the models driven by OMS (blue) and MesoLAPS (red) winds. The assessment periods used for the impact assessment are illustrated at the top of the plot.

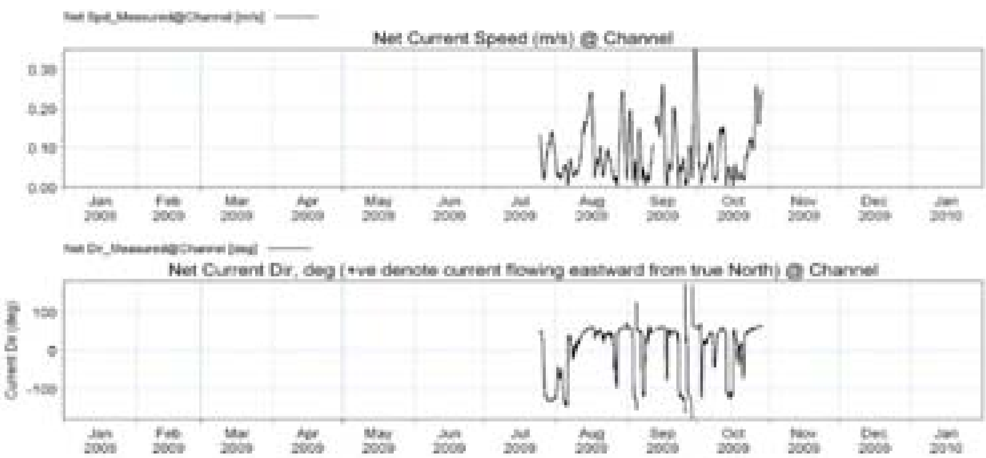

Figure 20 Net currents derived from the measurements at the "Channel" location, see Figure 1.

2.3.2.4 Net Currents "AWAC-01"

Derived net currents at "AWAC-01", see Figure 1 for location, are shown derived from the model simulations with OMS and MesoLAPS winds for the EIA assessment periods in Figure 21 and from the available data period in Figure 22.

The available data for the summer period shows easterly directed net currents mostly less than 0.1 m/s but with spikes reaching 0.2 m/s. The Summer B assessment period show net currents generally less than 0.1 while Summer A has an extended period with net currents in excess of 0.2 m/s. The winter data shows predominantly westerly net currents less than 0.1 m/s with a single spike reaching 0.2 m/s, which is well covered by the winter assessment periods considering both the OMS and MesoLAPS driven data.

Overall, it is considered that the range and patterns of the net currents derived from the measurements are well covered by the climatic scenarios.

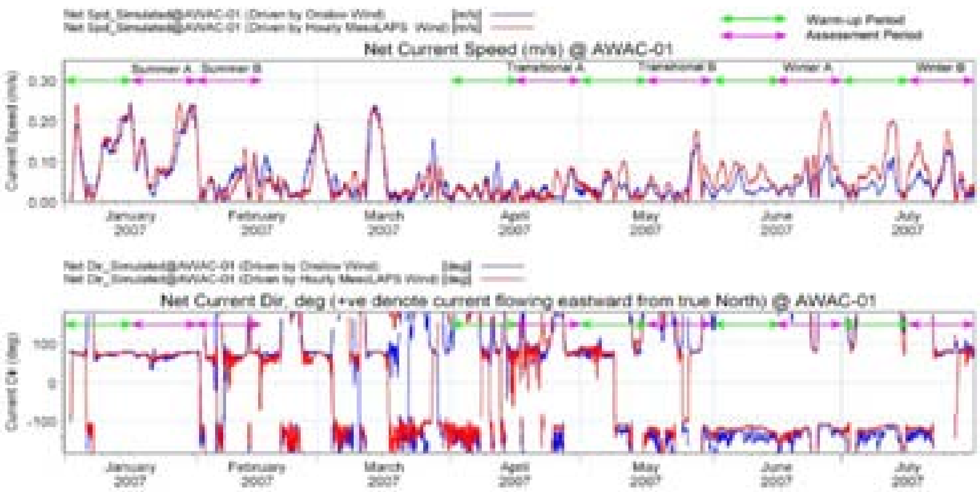

Figure 21 Net currents at the "AWAC-01" location, see Figure 1, derived from the models driven by OMS (blue) and MesoLAPS (red) winds. The assessment periods used for the impact assessment are illustrated at the top of the plot.

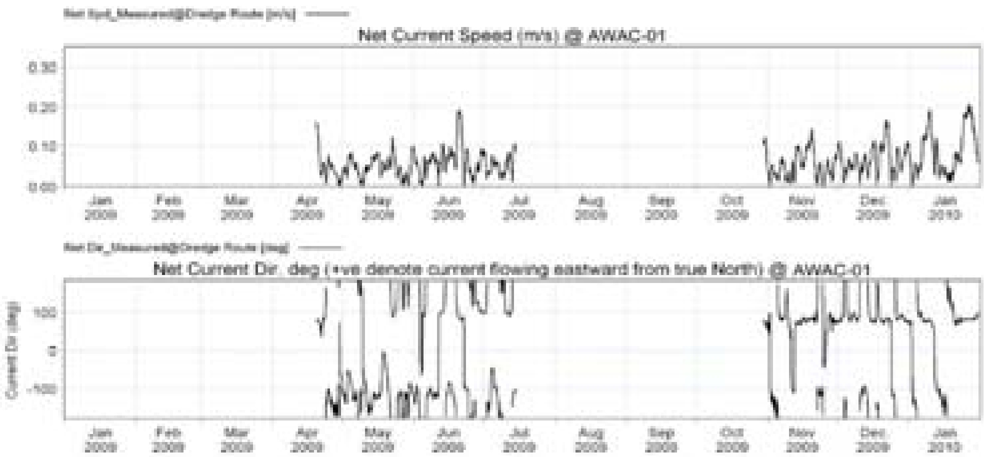

Figure 22 Net currents derived from the measurements at the "AWAC-01" location, see Figure 1.

2.3.2.5 Net Currents "ADCP-01"

Derived net currents at "ADCP-01", see Figure 1 for location, are shown derived from the model simulations with OMS and MesoLAPS winds for the EIA assessment periods in Figure 23 and from the available data period in Figure 24.

The data shows easterly directed summer net currents mostly less than 0.1 m/s but with spikes approaching 0.2 m/s. Considering the OMS and MesoLAPS winds, the summer assessment periods show net currents varying from less than 0.1 to an extended period around 0.2 m/s, covering the range observed in the data well. No data is available for the winter period from this site at this stage.

The range and patterns of the net currents derived from the measurements are well covered by the climatic scenarios during summer when data is available.

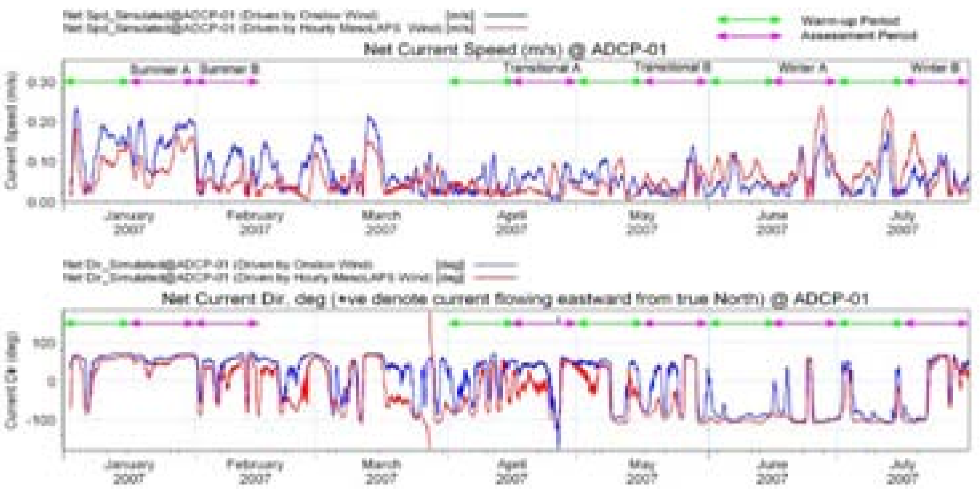

Figure 23 Net currents at the "ADCP-01" location, see Figure 1, derived from the models driven by OMS (blue) and MesoLAPS (red) winds. The assessment periods used for the impact assessment are illustrated at the top of the plot.

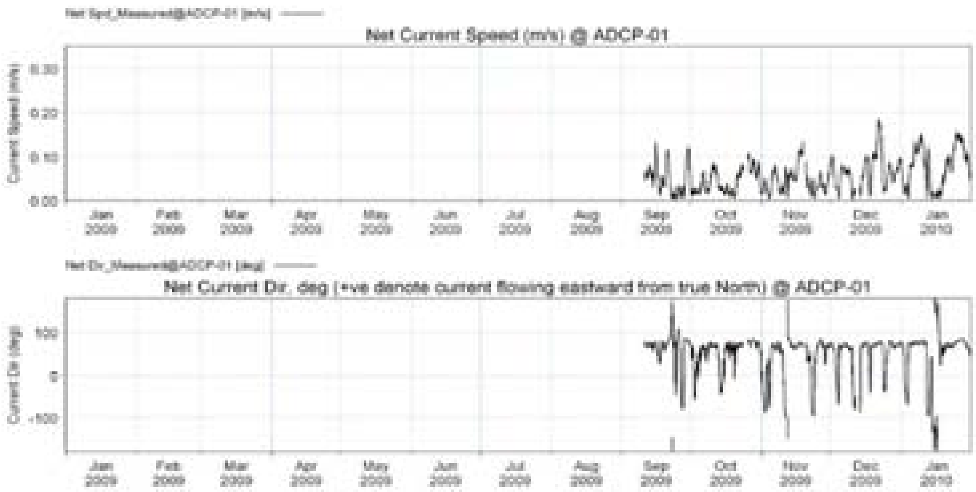

Figure 24 Net currents derived from the measurements at the "ADCP-01" location, see Figure 1.

2.4 Sediment Modelling

2.4.1 Issue per Mills (2010):

Augmenting the depth-averaged dredge plume model with an assumed form for the vertical SSC profile, taken from the work of Teeter (1986), is of potential concern. The Teeter profile is based on underlying assumptions (e.g. constant bed shear stress) which may be inappropriate in the context of modelling dredge plumes in a dynamic marine environment. As a consequence, it is possible, under some circumstances, that the model may misrepresent sediment deposition rates which in turn may result in misrepresentation of suspended sediment concentration gradients along the dredge plume axis. This is discussed in more detail in Section 7 of this review.

2.4.2 DHI Response:

Assumptions have to be made in all oceanographic numerical models, including 3D models, in relation to the bottom boundary layer and the interaction between the suspended concentrations of sediments and the bottom, i.e. sedimentation and re-suspension. No oceanographic model can fully resolve this process.

The Mike21 MT model provides the option to use a Rouse or a Teeter profile to calculate the near-bed concentration required in the deposition equation. Whereas the Teeter profile was originally derived based on simplified assumptions as pointed out by Dr. Mills, this does not necessarily mean that it is not applicable to more complex environments. The Teeter profile is widely referenced and used by the scientific community dealing with transport and sedimentation of fine sediments. The Teeter profile is dynamically adjusted in time in the model domain in the Mike21 application.

The bottom concentration (which is related to the depth-integrated concentration through the Teeter profile) is just one of several parameters controlling the sediment deposition and resuspension. The effect of the Teeter profile compared to another assumption for the relation between the near-bottom and the depth-integrated concentration of sediment is generally small in a well-mixed water column such as the Project area compared to, for instance, the impacts of critical shear stresses for deposition and erosion, which are equally required in a 3D model.

Dr. Mills in his detailed assessment in Section 7 of his review (Mills (2010)) focuses his concerns on the coarser fractions:

"If the dredged sediment spills are all fines in suspension that are vertically well mixed throughout the water column then this may not be a significant issue. However if the spills include silt sizes with greater settling velocities (e.g. 3 or 4 mm/s) that are more intermittently suspended these sediment fractions are likely to develop stronger vertical SSC profiles and the validity of using two-dimensional modelling augmented with the Teeter profile would need to be questioned."

It is noted that DHI's model suite, which the applied MT model belongs to, applies two different approaches for fine, cohesive sediments with low settling velocities and coarser, non-cohesive sediments with higher settling velocities. The applied MT model allows the inclusion of "sand" fractions, for which the Teeter profile is replaced by a local equilibrium profile between the type of sediment and the hydrodynamics, assuming this sediment is available. The present setup focuses on the finer sediments. The questions raised in relation to the coarser sediments are addressed in the following subsections.

2.5 Sediment Fractions

2.5.1 Issue per Mills (2010):

The sediment settling velocity (~ particle size) distributions of dredge spill sediments from sources other than overflow have not been specified. These sediment distributions should be documented for the various types and sources of spill and the range of expected transport behaviors should be explained. A more comprehensive justification should be provided for the number of sediment fractions (with defined settling velocities and percentage mass) and the overall range of particle sizes (settling velocities) represented in the model.

Sediment fractions presently included in the model have been assigned settling velocities of 1 mm/s or less. These fractions are expected to be fairly well-mixed (vertically) in suspension (Rouse number << 1) for much of the time and only to deposit relatively slowly when bed shear stress levels are sub-critical. In order to better represent the dredge plumes and their impacts, the model may require additional silt fractions (including settling velocities of about 3 or 4 mm/s) which are in incipient rather than full suspension for much of the time (Rouse number value of about 1) with more pronounced vertical SSC profiles, and which deposit more rapidly when bed shear stress for deposition is below critical value.

As the sediment fraction settling velocity increases the vertical profile of SSC will become less uniform and the application of a two-dimensional model less appropriate. For a typical water depth (10 m) and sediment settling velocity of 3 mm/s the settling time scale is about 1 hour and over this time period the bed stress can vary significantly during the acceleration and deceleration of the ebb and flood tidal currents, contrary to assumptions on which the Teeter profile is based.

2.5.2 DHI Response:

The sediment characterisation in the model is described in Appendix G of the report. It should be noted that experience elsewhere has shown that the sediment spill from dredging activities is not necessarily well correlated to the in-situ material to be dredged. At the EIA stage, there is rarely site specific data available on the composition of the sediments in the dredge plumes, and the characterisation will therefore have to build on experience from other sites.

DHI have a comprehensive data set from several years of continuous monitoring of dredging operations, and this has formed the basis for the characterisation of the dredge plume sediments for Wheatstone. Comprehensive and well defined measurements are only available for the overflow material as it is difficult to capture/isolate the material from most other operations. As the TSHD overflow is the main spill source for Wheatstone, it is considered appropriate to base the assessment on measurements related to this activity.

Other important spill sources include placement and CSD dredging with overflow of barges. For the placement, it can be assumed that a larger proportion of the fines have washed out with the overflow, and a relative lower percentage fines is therefore expected in the material that is being deposited at the placement site(s). Applying the particle size distribution derived from the overflow is therefore considered conservative (as this will spread further from the placement site and contribute more to potential impacts further away from the placement site compared to a coarser distribution). The overflow of barges from a CSD is not dissimilar to the overflow of a TSHD, and it is therefore reasonable to use the TSHD based data. The source related to the draghead and propeller wash disturbance is to a large degree resuspension of material spilled on previous dredge runs, i.e. the coarser material from the overflow which has settled within the dredge corridor. In the absence of other data, it is reasonable to assume for this source, the same distribution on size fractions as the TSHD overflow.

The number and distribution of sediment fractions applied in the model setup to represent the settling curve from the overflow measurements is described in Appendix G of the report. This includes a sensitivity test on the response to the number of fractions with particular focus on the finer fractions. The conclusion in Appendix G is that the model results are relatively insensitive to a larger number of fractions to represent the settling curve. A higher number of fractions to provide a finer representation of the setting curve is not warranted and will not add value due to the relatively large uncertainties related to the spill terms and sediment spill characterisation at the EIA stage.

For the concerns in relation to the coarser fractions raised by Dr. Mills in his review comment above, the following is considered.

1. The settling curve (Figure G.1 in appendix G) based on which the present distribution on fractions is derived, is based on all silt and finer fractions in the overflow, including fractions with settling velocities up to 4 mm/s.
2. The coarser fractions with settling velocities between about 0.8 and 4 mm/s are grouped into the upper 20% coarse material with a representative settling velocity of 1 mm/s. This is considered conservative as a settling velocity towards the lower end within the range will cause the sediment to remain in suspension for longer and travel further from the site.
3. A large proportion of the sand and coarser fractions are transported to the bottom through density currents at both the overflow and the placement sites. Whereas the finer sediments may be entrained in the water column through the related turbulence and return currents, this effect is smaller on the coarser fractions with higher settling velocities.
4. The oceanographic models required to simulate the potentially large impact areas over extended periods of time are not capable of resolving the near-field (to the spill source) hydrodynamics such as the density driven currents from overflow and

dumping, draghead and propeller disturbance. The model setup and spill source strength assessment, both for 2D and 3D models, is therefore tailored to the boundary of the mixing zone some distance from the source.

5. A zone of total loss/mortality of sensitive habitats is defined in the vicinity of the spill sources (dredging and placement), and the sand fractions (and coarser sediments) will predominantly settle within the dredge/placement corridor and the defined total mortality zone.
6. The existing surface layer along the dredge corridor and at the placement site is predominantly silty sand with a degree of mobility (this has been documented in modelling of non-cohesive sediments for the coastal impact assessment). Any spilled sand fractions on the existing seabed will not lead to significant changes to the existing bottom mobility and morphology that local habitats are adapted to.
7. In cases such as Wheatstone with significant sources of fines and silty sand on the surface, the relative contribution to the impacts outside of the zone of total mortality will be negligible for the spilled sand fractions.
8. In the Project area there is generally an absence of sensitive habitats in the vicinity of the spill sources likely to be influenced by any spillage of sand.

A series of model tests with coarser fractions and higher settling velocities corresponding to the upper range of silt and lower range of sand has been carried out. These demonstrate that with the simulated conditions at Wheatstone, the contribution to suspended excess concentrations from the sand fractions is negligible.

Conclusions

In the absence of site specific spill date (which is normal at the EIA stage), the comprehensive data set available to DHI from monitoring of TSHD overflow is considered the best source for sediment characterisation. The overflow data is generally considered conservative for representation of other spill sources, and has therefore been maintained for all spill sources.

The settling curve derived from the TSHD overflow is represented by 6 fractions, and sensitivity tests have demonstrated that this is of sufficient resolution given the results of the sensitivity test, previous comments about the coarser fractions and the significant inherent uncertainties related to the sediment characterisation at this stage in a dredging program.

DHI do not share Dr. Mills concern that coarser fractions are not included in the plume modelling. The modelling includes all silt fractions, and sand fractions are not expected to have any significant impacts outside the total mortality zones surrounding the spill sites. This is because the sand fractions are rapidly transported to the bottom through density driven flows, and subsequent re-suspension and transport of the sand fractions away from the spill sites in general terms is similar to the existing transport regime, which the local habitats are adapted to. Modelling of coarser fractions supports the assessment that their contribution to the impact assessment through elevated suspended concentrations is negligible for the Wheatstone spill and climatic conditions.

2.5.2.1 Test of Coarser Fractions

The potential effect of inclusion of coarser (sand fractions) in the plume modelling has been tested by simulating coarser fractions and compare to the 6 fractions included for the impact assessment. Simulation have been carried out for Dredge Scenario 6 with High spill rates for Summer, Transitional and Winter conditions to test for a range of climatic conditions.

Two additional fractions with settling velocities of 3 and 5 mm/s, respectively, are presented in Figure 26, Figure 28 and Figure 30 for summer, transitional and winter conditions, respectively. The spill source term for each of the two new fractions is the same as the spill source terms for the 4 coarser fractions in the corresponding "standard" model setups presented in Figure 25, Figure 27 and Figure 29.

The following is noted from the plots:

- There is a gradual decrease in the mean concentrations for F3 to F6 in the "standard" setup with 6 fractions due to the increase in settling velocities.
- The increasing settling velocities at the upper range of the silt fraction (3 mm/s) and the finest sand fractions (5 mm/s) leads to a rapid decrease in suspended concentrations for these fractions.
- If sand fractions were to be included in the modelling, a higher settling velocity than 5 mm/s would be required to correspond to the source strength included in the present analysis, and the contribution would be even smaller than shown for the 5 mm/s settling velocity.

Based on the tests carried out using strong summer and winter climatic conditions, which are considered most likely in maintaining the sediment in suspension, it is concluded that the relative contribution from sand fractions to the suspended sediment concentrations is negligible.

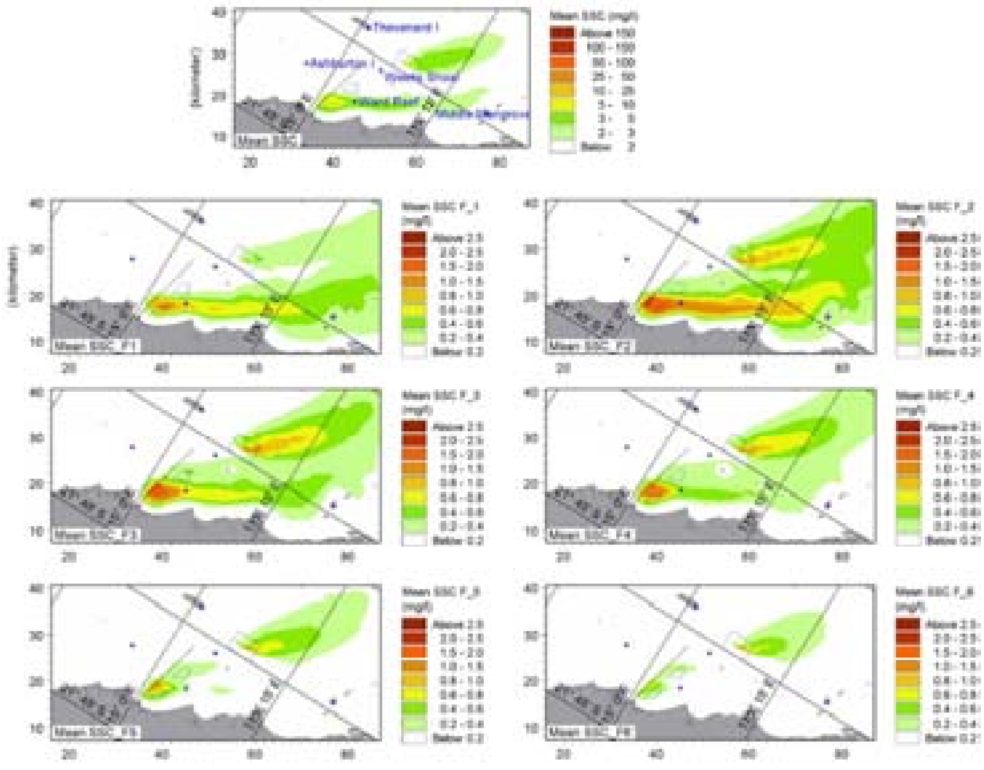

Figure 25 *Mean excess suspended sediment concentrations for Dredge Scenario 6, Summer A with High spill rates for the total number of fractions (top) and the individual 6 fractions with F1 being the finest fraction and F6 representing the coarsest fraction (1 mm/s settling velocity).*

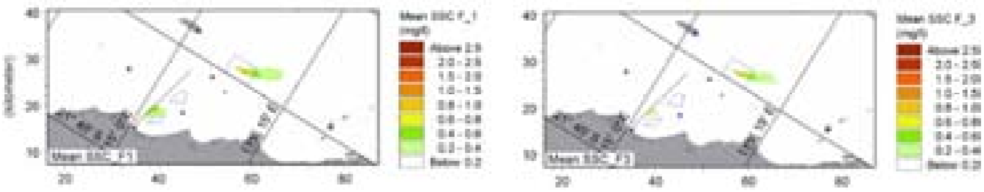

Figure 26 *Mean excess suspended sediment concentrations for Dredge Scenario 6, Summer A with High spill rates for two coarser fractions with setting velocities of 3 and 5 mm/s respectively for F1 and F3. Simulated spill rates for each of the two fractions is equal to the spill rates of the coarser fractions in the standard setup (Figure 25).*

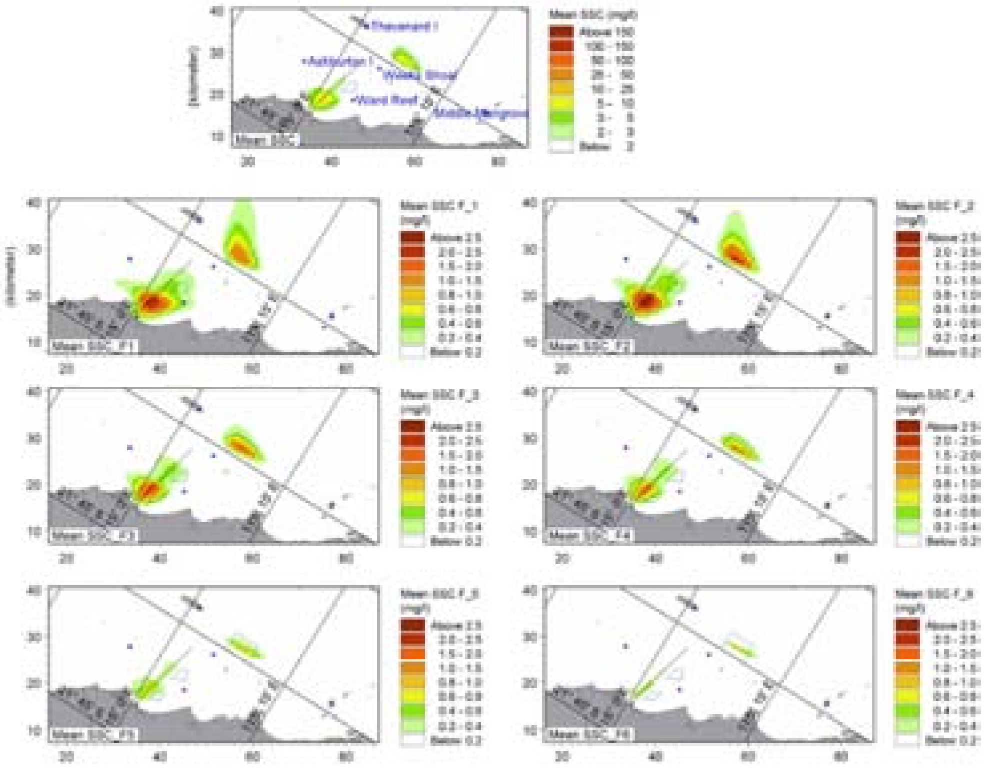

Figure 27 *Mean excess suspended sediment concentrations for Dredge Scenario 6, Transitional A with High spill rates for the total number of fractions (top) and the individual 6 fractions with F1 being the finest fraction and F6 representing the coarsest fraction (1 mm/s setting velocity).*

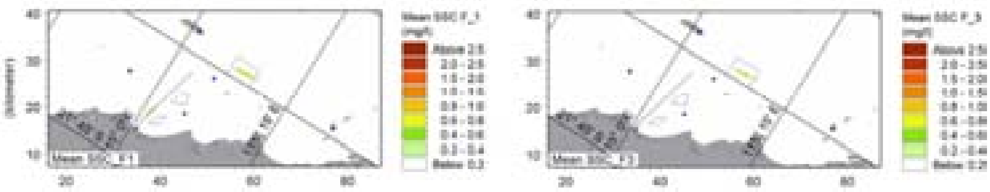

Figure 28 *Mean excess suspended sediment concentrations for Dredge Scenario 6, Transitional A with High spill rates for two coarser fractions with setting velocities of 3 and 5 mm/s respectively for F1 and F3. Simulated spill rates for each of the two fractions is equal to the spill rates of the coarser fractions in the standard setup (Figure 27).*

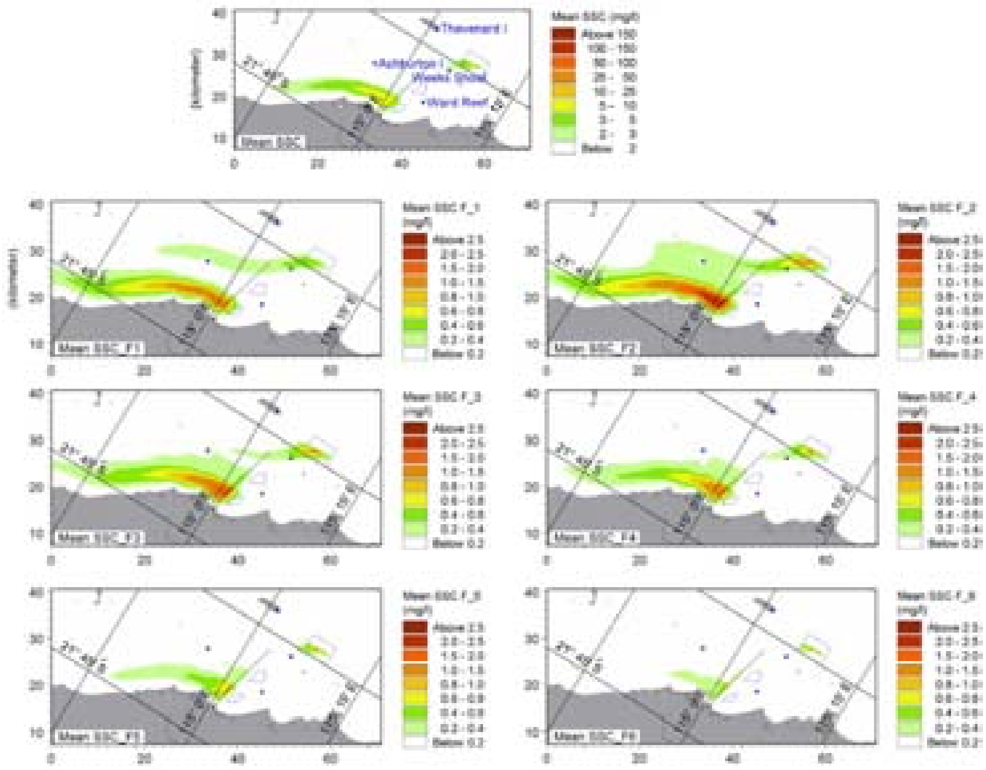

Figure 29 *Mean excess suspended sediment concentrations for Dredge Scenario 6, Winter A with High spill rates for the total number of fractions (top) and the individual 6 fractions with F1 being the finest fraction and F6 representing the coarsest fraction (1 mm/s setting velocity).*

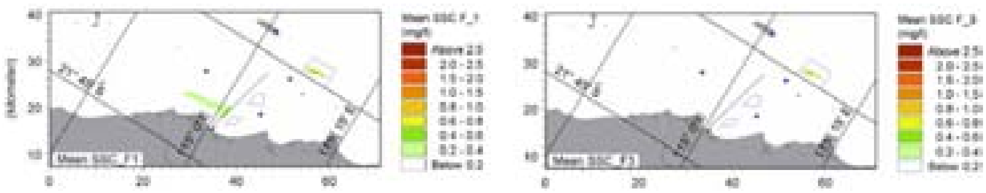

Figure 30 *Mean excess suspended sediment concentrations for Dredge Scenario 6, Winter A with High spill rates for two coarser fractions with setting velocities of 3 and 5 mm/s respectively for F1 and F3. Simulated spill rates for each of the two fractions is equal to the spill rates of the coarser fractions in the standard setup (Figure 29).*

2.6 Sediment Resuspension

Issue per Mills (2010):

The report identifies "significant and repeated resuspension of [dredged] material" by currents and waves which can regenerate plumes far from the dredge location. This has the potential to redistribute dredged sediment material (e.g. migration of areas of net sedimentation) over time-scales considerably greater than 14 days, which cannot be represented by the short-term scenario simulations.

DHI has tested the model for this effect and found that, with the present settings for the sediment fractions, there is negligible migration of the SSC footprint or net sedimentation areas over an extended simulation period. This may be because the sediment fractions specified in the model are expected to remain in full suspension for most of the time under the range of current and wave conditions encountered in the Wheatstone area.

By contrast, coarser silts fractions with settling velocities of 3 or 4 mm/s are likely to experience greater deposition rates when bed stress levels are sub-critical. The transport of these intermittently suspended coarser silt fractions is likely to differ (in rate and possibly direction) from the transport of the finer fractions represented in the model, and may not be fully represented within a fourteen day simulation period.

DHI Response:

This issue is closely related to the previous issue, and it is essentially addressed in the response to the previous issue.

Any coarser fractions not presently included in the modelling, i.e. sand fractions, generally do not differ from existing surface layer sediments at the site. Potential movement of sand and coarse silt fractions originating from the dredging activities over the bottom as bed and suspended load is thus similar to existing conditions. The local habitats are adapted to these conditions, and no additional impacts are anticipated in this respect.

2.7 Sediment Suspension by Shipping Operations

In addition to the bullet points,

Issue per Mills (2010):

It is recommended that the scope of this study be extended to evaluate the sediment suspension and plume generation caused by shipping operations (for the project operating at capacity), including when large vessels (with tug boats) are manoeuvring onto or off berths.

DHI Response:

Due to predicted limited siltation of fines in the navigation channel this is likely to be a minor if not insignificant issue. The resulting plumes will be short lasting and clearly be insignificant compared to the dredge plumes during construction. The difference is obviously that the plumes created by propeller wash will occur on a daily basis during the operational phase compared to the dredge plumes that are restricted to the construction phase.

Estimation of resuspension from propeller wash is far from straight forward. If it is considered relevant/necessary to consider this component, it is recommended to perform an assessment of the likely siltation rates of fines within the channel and berthing area as this is likely to be a limiting factor on the resuspension caused by propeller wash. Drawing an analogy to the nearby Onslow Salt navigation channel and ship berthing facility is also considered relevant.

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3 REFERENCES

Mills, D. (2010): *Review of DHI Report. Wheatstone Project, Dredge Spoil Modeling Report. Document: WHST-STU-EM-RPT-0139. DHI Report: MY5527-0 – Dredge Spoil Modeling, 10 May 2010.* Prepared for URS by Dr. Des Mills, Des Mills Marine Environmental Reviews. 8 June 2010.

Chevron Australia Pty Ltd
ABN 29 086 197 757

250 St Georges Terrace
Perth WA 6000
Australia

Tel: + 61 8 9216 4000
Fax: +61 8 9216 4444
Email: ask@chevron.com
www.chevronaustralia.com